

ATLAS OF KANEOHE BAY: A Reef Ecosystem Under Stress

by STEPHEN V. SMITH, KEITH E. CHAVE, and DENNIS T.O. KAM

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The University of Hawaii Sea Grant Program

ATLAS OF KANEOHE BAY

A REEF ECOSYSTEM UNDER STRESS

by

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This Atlas and the research projects on which it is based were funded under the National Sea Grant Program, National Science Foundation grants GH-28, GH-62, and GH-93, and National Oceanic and Atmospheric Administration grants 2-35243 and 04-3-158-29.

February 1973



The University of Hawaii Sea Grant Program

UNIVERSITY OF HAWAII

Hawaii Institute of Geophysics

Office of the Director


February 27, 1973

TO: The People of Hawaii and Other Interested Parties

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It is a pleasure to transmit to you the "Atlas of Kaneohe Bay: A Reef Ecosystem Under Stress." This Atlas, representing extensive work by many members of the State's scientific community, is intended to describe the reef ecosystem of Kaneohe Bay, and to illustrate the influence of man upon this ecosystem.

It is the sincere hope of the writers of this Atlas that the data included herein will provide a useful basis for returning the Bay to its original condition through well-planned conservation practices. A short summary of the Atlas by Keith E. Chave, Professor of Oceanography, follows this letter.

Aloha,


George P. Woollard
Director

ACKNOWLEDGMENTS

In addition to the contributors to the text of this Atlas, we acknowledge the valuable aid of Kenneth J. Roy, Joleen Gordon, Paula S. Waterman, Lois Nishimoto, and Suzanne Morris in making the Atlas possible.

Summary of the Atlas

The ecosystem of Kaneohe Bay is subjected to two stress gradients. One, a natural phenomenon, is the gradient from northeast to southwest, from the open sea to the sheltered lagoon. The second, a man-made phenomenon, is the gradient from northwest to southeast, from essentially pure ocean water to nutrient-enriched and sediment-laden water near the center of population of the watershed. The effects of both gradients are displayed clearly in the Atlas on many of the maps that show distribution of the biota of the Bay.

The basis for the man-made stress on the ecosystem is shown graphically in Figure 4. Human population growth in the environs of the Bay has skyrocketed in recent years. The direct results of this explosion are discussed by Chave and Maragos in Section II and by Smith in Section VI A. The Bay is rapidly filling with sediments, both from land and from deteriorating reefs (Figures 14 and 15). Because of changing land uses in the watershed of the Bay, freshwater runoff from the land has limited the growth of many organisms along the fringing reefs in recent times (Figures 16 and 38, for instance). Sewage outfalls in the south Bay have enriched these waters in nutrients to dangerous levels (Section IX, and Caperon *et al*, 1971).

The effects of these stresses on the biota of the ecosystem are widespread. Figures 16 and 17, in Section VI B by Maragos, document an almost total lack of corals in the south Bay. Reef fishes are rare in the south Bay as shown by Key in Figures 27 and 28 (Section VI C). Algae, too, are rare in the south Bay as shown by Soegiarto in Figures 37 and 38 in Section VI D. An additional result of the nutrient stress is the enormous growth of the "bubble alga", *Dictyosphaeria* in mid-Bay (Figure 49), where it is killing off much of the coral and other invertebrates on the slopes of the reefs.

Kay (Section VII A) finds the shells of micromollusks in the lagoon rare and lacking in species diversity to the south, although the principal factor controlling their distribution is the northeast-to-southwest stress gradient (Figure 58). Clark, in Section VII B, notes that the high nutrient levels of south Bay are beneficial to the growth of *nehu*, the principal bait fish of Hawaii's tuna industry. This is a reversal in trend, but not an unusual ecological pattern. Miller *et al*, in Section VII C, show a distinct zonation of fish larvae in the Bay, undoubtedly related to the stress gradient. Chave notes that filter-feeding invertebrates such as sponges, tunicates, and oysters, have replaced corals in benthic habitats in the south Bay (Section VII D).

Smith (Section VIII) shows the interactions between the biota and physical factors within the Bay through a statistical analysis elegantly known as "principal component factor analysis, with varimax rotation". He shows that four "factors", related to topography, water circulation, substrate, and depth, explain significant proportions of the distribution of 55 taxa of organisms within the Bay.

Maragos and Chave in Section IX tie the overall picture together and predict the future of Kaneohe Bay. They conclude that man-made stresses on the Bay must be removed before the rejuvenation of the biota can begin, and even then the recovery of the Bay may be very slow.

We are a long way from the coral gardens of southern Kaneohe Bay described by early workers in the area, but now is the time to start the long road back.

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I. Setting and Surroundings of Kaneohe Bay

Keith E. Chave

Kaneohe Bay lies in the Hawaiian Archipelago on the island of Oahu. The island chain extends from Kure Atoll (28° , $25'$ N; 178° , $25'$ W) to South Point on the Island of Hawaii (18° , $55'$ N; 155° , $41'$ W), a distance of 2450 km. The more northerly islands—the Leeward Islands—are low islands composed of coral reefs and reef debris, resting upon truncated, extinct volcanoes. The islands at the southern end of the chain—the Windward Islands—are high volcanic islands with fringing coral reefs. Generally, the volcanic portions of the islands of the chain are geologically progressively younger, from north to south, with active vulcanism continuing on the southernmost island, Hawaii (Figure 1).

Oahu is the center of population of the Hawaiian Islands and had a population of 629,176 in 1970. Windward Oahu, including the shores of Kaneohe Bay, had a population of 47,000 in 1970. (See Section II for details on population growth adjacent to Kaneohe Bay.)

Kaneohe Bay is the largest sheltered body of water in the Hawaiian Islands. It is located at 21° , $28'$ N; 157° $48'$ W (Figure 1). Researchers investigating the Bay usually refer to the long axis of the Bay as “north - south” although the orientation is more nearly northwest - southeast. The Bay is approximately 12.8 km long, and 4.3 km broad. The bathymetry of the Bay is shown in Figure 2. (The depth contours in the Bay are given in feet below mean low water, rather than meters, because the instrument used to measure depth was calibrated in feet. All other units in the text will be given in the metric system.) In essence, the Bay is composed of a barrier reef across its mouth, with two navigable channels cutting the northern and southern ends of the reef; a lagoon containing patch and fringing reefs behind the barrier reef; and a semi-isolated body of water in the southern part of the lagoon.

The Bay was formed by rivers eroding the basalts of Oahu at a time in the geologic past when the level of the sea was several hundred feet lower than it is today (Roy, 1970). As sea level rose, reefs, reef-derived sediments, and land-derived materials filled the Bay to its present general configuration. Finally, the Bay was modified by dredging and other human activities. (See Sections II, VI A, and IX for more details on man's influence on the Bay.)

The watershed of Kaneohe Bay, shown in Figure 3, has an area of approximately 46.6 km². It is drained by a series of intermittent small streams. The boundary of the watershed is composed of near-vertical cliffs (*pali*), and thus the drainage after a rainfall is very rapid. The average rainfall in the watershed of the Bay is approximately 100 - 150 cm per year, with most of the rain falling in the winter months. Torrential rains are common. Banner (1968), for instance, reports 43.6 cm of rain on the shore of Kaneohe Bay on the day of May 2, 1965, and 15.2 cm of rain per hour at approximately noon of that day.

The climate of the Kaneohe Bay area is semi-tropical. The mean annual range of air temperatures is 18 - 29°C. Extremes range from 13.3°C to 33.8°C. The yearly range of

water temperatures is approximately 19.5 - 27.8°C. The mean water temperature for January was 21.6°C and for August, 27.4°C.

The Bay is used for a variety of purposes. Its principal use is recreational. Sailing and water skiing are very popular in the lagoon; fishing and clamming are somewhat less popular. The baitfish (**nehu**) for Hawaii's tuna fleet are caught largely in Kaneohe Bay. Moku o Loe (Coconut Island) in the southern Bay is the site of the laboratory of the Hawaii Institute of Marine Biology, a research unit of the University of Hawaii. The Bay is used by scientists from all over the world for a wide variety of marine research. Finally, the Bay is used as a sewer.

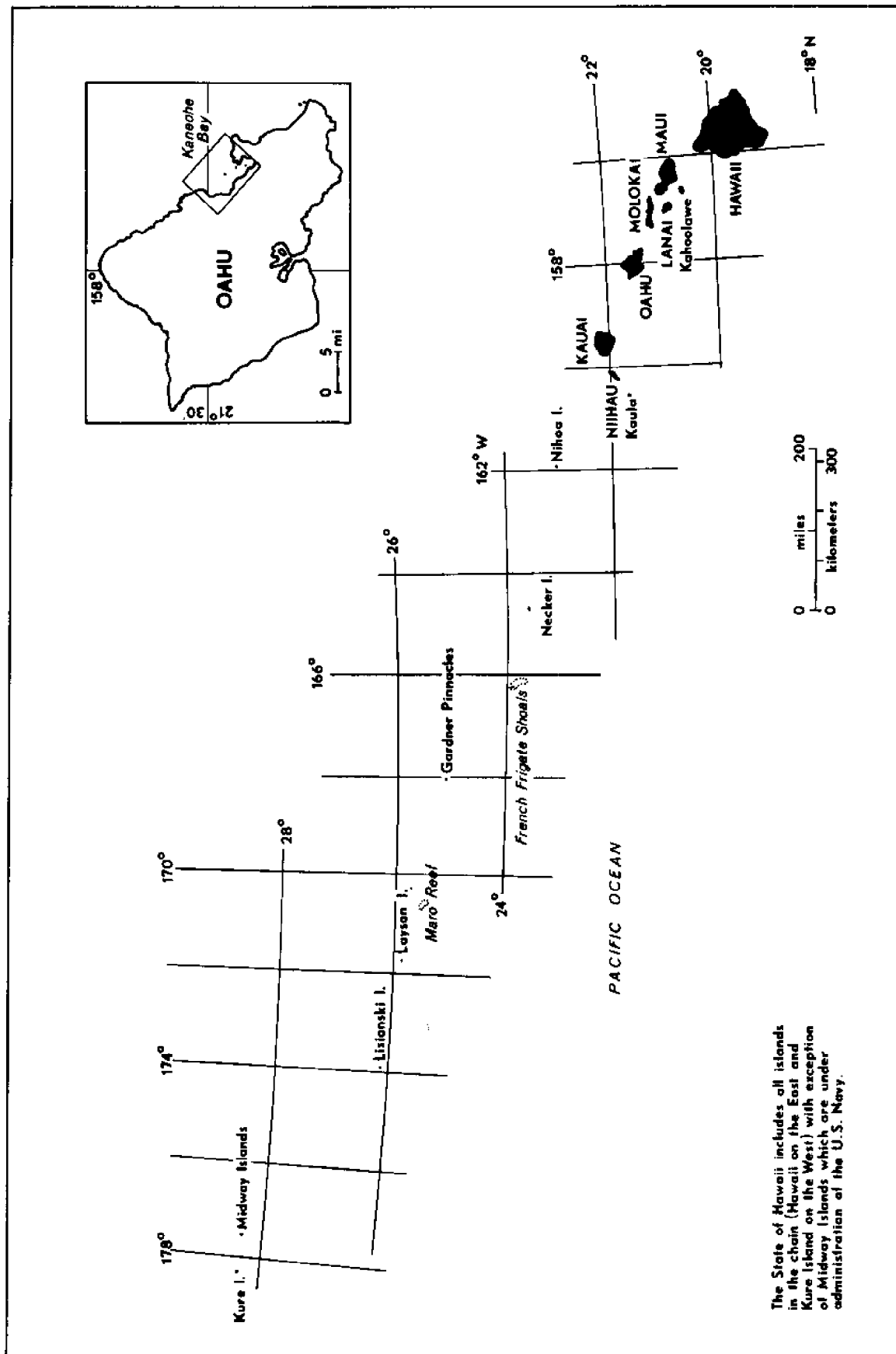


Fig. 1. The Hawaiian Islands



Fig. 2. BATHYMETRY

II. A Historical Sketch of the Kaneohe Bay Region

Edith H. Chave and James E. Maragos

Coincident with rapid urbanization, the Kaneohe Bay region has undergone much change in recent years. We present here a brief historical sketch of man's activity in the area. Additional information and source material is present in the annotated bibliography of Kaneohe Bay by Gordon and Helfrich (1970).

The Kaneohe Bay region was once the center for a large population of Hawaiians. The area had a rich mythology, and many places along the shore of the Bay were sacred to Hawaiians. Two dozen prehistorical ceremonial temples (*heiau*), the ruins of half a dozen large villages, and a complex of diked irrigation systems were present along the shores of the Bay (McAllister, 1933; Sterling and Summers, 1962).

The staple diet of the native Hawaiians was the taro plant (*kalo*), from which poi and a variety of other foods were prepared. Taro was grown in a system of terraces constructed so that stream runoff from the mountains was trapped and used as the irrigation water. Bates (1854) estimated that 2.6 km² of taro land could perpetually sustain a population of over 15,000 Hawaiians. Although the earliest population estimate for the Kaneohe Bay region was about 5,000 Hawaiians (Parker, 1835-1862) most of the low floodplains of the Bay region were once covered with taro patches. Therefore, the land could have supported a much larger population. Even by 1929, after much of the taro land was abandoned, the remaining 6.2 km² (estimated by Handy, 1940) could have supported 35,000 Hawaiians. Hawaiians cultivated other crops and made use of wild vegetation including native sugarcane, bananas, coconuts, *wauke* (from which *tapa* cloth was made), mountain apples, *Pandanus*, and sweet potatoes. Dogs, chickens, and pigs were domesticated and raised in pens (Bates, 1854; Sterling and Summers, 1962). This was truly an agrarian society.

Several ruins of fishing shrines and *heiau* signify the importance of the sea to the early Hawaiians. A main source of food was fish from the Bay waters. The fish were caught with traps or by hook and line (Cobb, 1905), and no less than 23 fishponds were built prehistorically on the shallow reefs close to the shore (Bates, 1854; McAllister, 1933). A few fishponds are still used today (Summers, 1964). Bates (1854) also noted natives gathering shellfish from the reef flats of patch reefs in the lagoon during low tide.

In the early 1820's missionaries, sailors, and adventurers followed earlier explorers to Hawaii, bringing with them their religions, customs, and diseases. As elsewhere in the Islands, the native population in the Kaneohe Bay region declined shortly thereafter; in 1833 the population was about 5,000 while in 1860 it was less than 2,000 (Parker, 1835-1862). Although most Hawaiians were converted to Christianity, they clung to their old farming and fishing practices. Consequently, in the 1860's workers were imported from China to meet labor shortages in the canefields and elsewhere. Japanese and other ethnic groups followed at the end of the 19th Century. During this period the Kaneohe Bay area population increased to about 5,000 and remained at this level until 1940 (Kittleson, 1960).

Rice replaced taro in some of the terraces. Other introductions into the area included sugarcane, coffee, papaya, and breadfruit. In drier regions to the north, cattle, sheep, horses, and goats were raised (Bates, 1854; Bowser, 1880).

The first detailed observations in Bay waters were made during the latter half of the 1800's and early 1900's. Wilkes (1845) and Dana (1872), made observations on marine geomorphology. Bates (1854) remarked on the steep slopes of lagoon reefs. Agassiz (1889) noted that reef corals were uncommon on shallow reef flats, but flourished on the outer slopes of the fringing reef along the entire shoreline of the Bay. MacKaye (1915) described 16 species and many varieties of reef corals in the "coral gardens" of the south lagoon. MacCaughy (1918) and Edmondson (1928) remarked that within the protected waters of the Bay, Hawaiian reef corals were one of the best exhibitions of living corals to be seen. Although there were attempts to introduce pearl oysters, abalone, clams, and groupers into the Bay in the 1900's, these forms did not thrive (M. Takata, pers. comm.). Thus, from the above descriptions, the impact of man upon the Bay was not severe until after the 1920's.

There were, however, subtle indications of erosion and sediment effects on the Bay. According to Bates (1854) and Agassiz (1889) many of the beaches along the Bay were dazzling white, but there were also swampy areas around the mouths of streams. Agassiz remarked that corals had succumbed to sediments in nearshore reef areas. MacCaughy (1917) noted that hills near Heeia were scarred red from erosion and that native vegetation was being gradually replaced by weeds and other introductions. Ranching activity had increased steadily; grasslands, an index of livestock activity, had increased from 700 acres in 1880 to nearly 3,000 acres in 1969 (Handy, 1940; Land Use Comm., 1969). It is quite possible that grazing facilitated increased erosion and sediment loading in the streams. In comparison with the Kaneohe Bay situation, Moberly (1963) documents the deterioration of reefs off South Molokai from livestock activity.

In 1913 the first of the large streams of the northern watershed region was tapped at its mountain source, and the water was diverted by funnels through the Koolau Mountains to irrigate the dry agricultural lands in leeward Oahu (Scott, 1968). After these diversions were constructed, total stream runoff into the Bay declined from an average of 315,000 m³/day to 182,000 m³/day (Takasaki *et al*, 1969; Gray and Lau, 1970). Despite conversion of the watershed into grazing land and the continually decreasing number of taro patches which efficiently trapped stream sediments (Handy, 1940; Plucknett, per. comm.), the bathymetric configuration of the Bay remained essentially unchanged between 1882 and 1927 (Roy, 1970; Section VI A). Perhaps decrease in stream flow counterbalanced erosional forces. Maximum and minimum rainfall readings at the gauging stations in the area, from 1833 until present, indicate that general patterns of annual rainfall did not change appreciably during this time.

Several episodes of unusual weather conditions have severely damaged coral reefs in the Bay. The tsunami of 1946 and high winds in 1947 dislodged many large coral heads from the tops of reefs and destroyed an old heiau on Kapapa Island (Sterling and Summers, 1962). In 1965 torrential rains, coinciding with low tides, flooded the Bay and killed much of the reef biota inhabiting reef tops and upper reef slopes (Banner, 1968). The affected depth was correspondingly greater in areas near where floodwaters entered the Bay than elsewhere. Banner resurveyed the damaged areas in 1968 and noted that corals were only beginning to recover at that time.

Urbanization in the Kaneohe Bay region began about 1940. In 1938, as the threat of World War II increased, military engineers began construction of the Kaneohe Marine Corps Air Station on Mokapu Peninsula. During construction of the Marine base, lagoon and channel areas of the Bay were dredged extensively. About 7.6 million cubic meters of reef materials were removed (Woodbury, 1946). Other dredging of the reefs by private land-owners has increased, especially during the past decade (Dredging permits, State of Hawaii). Almost all of the dredging operations have been confined to the south lagoon area (Figure 5).

Statistics of the Bureau of Census reveal a sharp population increase (Figure 4) from about 5,000 people in 1940 to over 47,000 in 1970. A survey made by Gilman and Co. (1969) noted that most of the increase was confined to the southern areas of the watershed. As early as 1940 a poll of Kaneohe residents (Kanahele, 1940) revealed a strong trend from a previous rural to an urban economy. The opening of cross-mountain four-lane highways in the 1960's also promoted rapid urbanization of the Bay region. The site of the first housing development used a prehistoric Hawaiian fishpond as a foundation (Cullen, 1948). Rough estimates obtained from material available at the University of Hawaii Land Study Bureau and from the Bank of Hawaii's pamphlets on construction in Hawaii for 1961 - 1970 show that between 1915 and 1945, 0.04 km² of land was bulldozed for tract homesites; between 1945 and 1970, over 2.0 km². These figures do not take into account the area utilized for streets or public buildings. Urban sprawl is now moving northward into other areas of the Bay's watershed.

The Kaneohe Marine base began dumping primary (untreated) sewage into the South Bay in the 1940's. In 1963 a Kaneohe municipal sewage treatment plant was constructed and began dumping secondarily treated sewage (settled and chlorinated) into the south lagoon. As the population climbed, the effluent of the municipal plant increased from about 2,700 m³/day to over 11,000 m³/day in 1971 (Division of Sewers, 1971).

Storm-control projects began in Keapuka in 1963 - 1965, and have since included several drainage systems in Kaneohe and Kahaluu. Before there were storm-control projects, much of the flood water eventually permeated the porous lava rock and slowly leaked into the Bay (Fan and Burnett, 1969). Flood water confined to concrete conduits now enters the Bay directly; during rainstorms, sediment discharge into the Bay can be tremendous.

Although the bathymetric configuration of the Bay remained essentially unchanged between the 1882 and 1927 surveys, in 1969 the lagoon had shoaled by about 1.6 m (Roy, 1970). About half of this material was calcareous material from reef erosion, and the remainder was terrigenous material brought into the Bay by streams and storm drains. Factors causing the infilling of the Bay after 1927 appear to be related to the increasing population density of the area.

Fan and Burnett (1969), measuring the amount of silt in streams of the area after an exceptionally heavy rain, estimated that if the same amount of terrigenous material entered the Bay three days out of each year between 1927 and 1969, it would shoal 0.5 m. Since neither rainfall nor the number of severe storms have changed appreciably from 1833 to 1970 (U. S. Weather Bureau Reports and Summaries), other factors must have led to additional shoaling of the lagoon of the Bay. Since one half of the accumulated sediment is calcareous in origin, erosion of the reef framework in recent years has been one of the suspected sources of the remainder of the sediment filling in the lagoon. (See Section VI A and IX.) Rapid erosion of the reefs is linked to urbanization of the watershed. Perhaps further research will enlighten and help us pinpoint the direct causes.

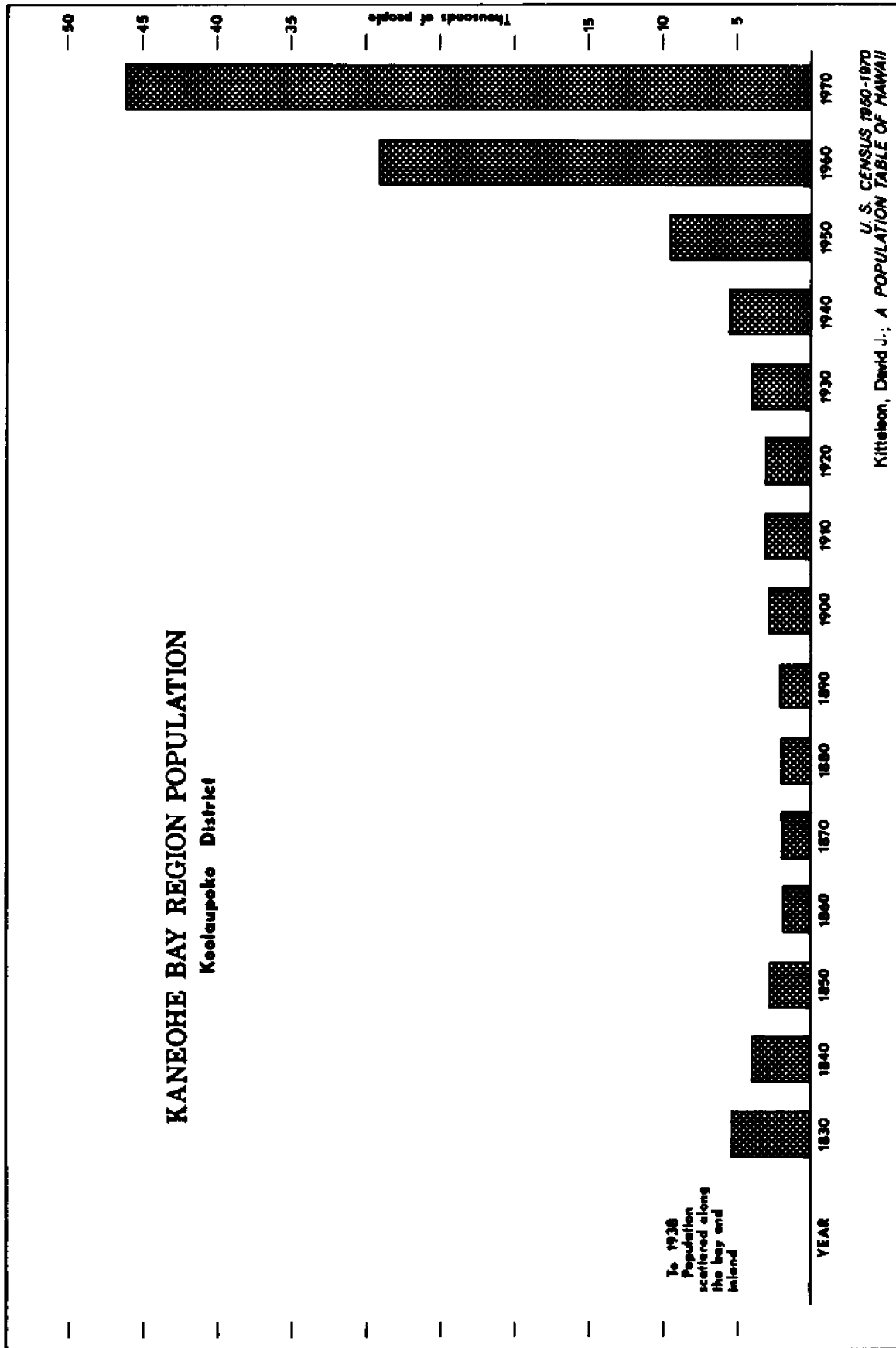


Fig. 4 Kanehoe Bay Region Population

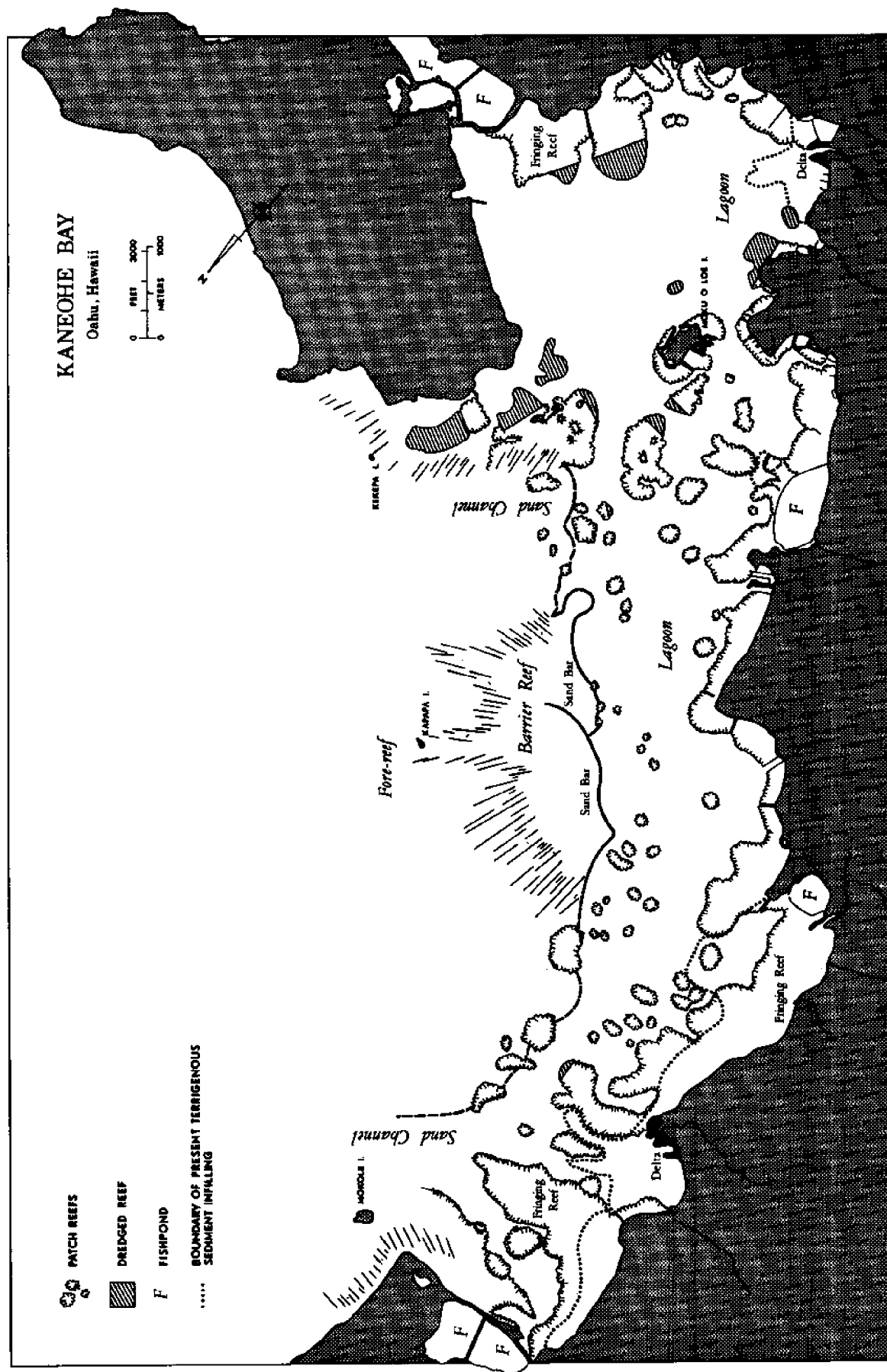


Fig. 5. PHYSIOGRAPHY

III. What Is a Coral Reef?

Keith E. Chave

A coral reef is a magnificent and complex community of marine organisms which are able collectively, through the formation of limy (CaCO_3) skeletons, to construct, modify, or maintain a shore environment.

Reefs are classified according to their spatial relationship to land. Fringing reefs abutt directly against the land and grow seaward. Barrier reefs are separated from the land by a lagoon. The lagoon is a part of the reef system, for in the absence of the barrier the lagoon would not exist in its present form. Atolls are open-ocean reefs, generally growing on a submerged volcanic base. In the case of atolls, the rigid reef completely surrounds the lagoon.

The organisms of the reef community are both constructive and destructive. The principal constructors of the outer rigid reef are the encrusting red algae, the stony corals, and the millipores, close relatives of the stony corals. The principal destructors in this environment, other than the waves, are sponges, echinoderms, mollusks, and a few groups of fishes which have become specially adapted to feed on or live in the reef framework. Occasionally, and for unknown reasons, the Crown-of-Thorns starfish, *Acanthaster*, suddenly appearing in vast numbers, will destroy large areas of coral on a reef by eating the soft flesh of the corals.

The principal lime-producers in the lagoon environment are the limy green and red algae, corals, foraminifera, and mollusks. The destructors in the lagoon environment are not too well known. Burrowing and sediment-feeding worms, and the sediment-feeding sea cucumbers may destroy some lagoon sediment.

It is obvious that if a reef community is to exist for any great length of time, the constructive forces must outdo the destructive forces.

Plants dominate the reef community. Therefore it is strongly dependent upon light. This unique assemblage has evolved in such a way that it is able to create a shore where one previously did not exist by utilizing near-surface light energy. Large plants are obvious on many reefs. The calcareous algae which contribute to the reef itself, and the fleshy algae which are an important source of food to many fishes and invertebrates are the most conspicuous. In addition to these obvious plants, many of the animals of the reef community contain within their tissue microscopic single-celled algae, called "zooxanthellae" which are important in the life and growth of the animals. These zooxanthellae are found in most of the corals and their near relatives, many foraminifera, certain mollusks, and probably other organisms.

Hawaiian reefs differ somewhat from other reefs in the Pacific, and elsewhere in the world, by having a lower diversity of most plant and animal groups. The reason for this is probably largely the result of Hawaii's great distance from the center of Indo-Pacific animal

and plant radiation in the far southwestern Pacific. Another factor, perhaps influencing the diversity of organisms in Hawaii, is the winter water temperatures of these Islands, which are cooler than those of most other tropical reef areas.

Two important groups of reef organisms which are missing in Hawaii are present throughout the rest of the tropical Pacific. These are the corals of the genus *Acropora* which commonly are major reef framework contributors, and a coral-like group, the milliporids, which encrust debris on the outer reef and contribute to its wave resistance. Their absence strongly influences the nature of Hawaiian reefs. Many Hawaiian reefs are truly beautiful communities, but due to their low diversity of organisms, they are somewhat drab when compared with reefs south and west of the Islands.

IV. Purpose and Scope of the Atlas

Keith E. Chave and Dennis T. O. Kam

The purpose of this Atlas is to provide documentation of components and interaction among components of the most thoroughly studied coral reef system in the world. In addition, the data in the Atlas demonstrate the effects of man-made stresses on a reef community, and hopefully will provide a baseline for measuring the recovery of the reef system, as man-made stresses are gradually removed from Kaneohe Bay through wise conservation measures.

A large part of the Atlas was prepared from work conducted over a four-year period as part of the University of Hawaii Sea Grant Program. In addition to the data presented in the Atlas, this Sea Grant work has or will shortly contribute to three PhD theses (James E. Maragos, Aprilany Soegiarto, and Gerald S. Key), one MS thesis (Keith Shimada), and several publications. Thus, considerably more data on the Kaneohe Bay reef system are available than are presented in the Atlas. These can be obtained from the Hawaii Coastal Zone Data Bank in the Hawaii Institute of Geophysics.

This Atlas is divided into two parts. The first is a description of the Bay and its reef systems—the substrate and the organisms. The second is an analysis of these data, describing their interactions and interrelationships. Throughout the Atlas, either implicitly or explicitly, man's influence on the Bay is shown, most commonly as a south-to-north trend, away from the center of population of the Kaneohe Bay watershed in the south.

The organisms discussed in most detail are the corals, algae, and fishes. The first two groups are the major constructive agents on the reef, contributing the lime (CaCO_3) of their skeletons to the structure of the reef itself. The fish are among the major destructive agents on the reef. An analysis of the growth of these organisms allows a CaCO_3 budget of the reef complex to be calculated.

V. Sampling and Methods

Stephen V. Smith and Dennis T. O. Kam

Much of the information in this Atlas comes from a survey of reef biota and bottom types conducted as a part of a Sea Grant project under K. E. Chave from 1968 to 1972. Data from that study include biological surveys at approximately 400 stations in the Bay. Particular emphasis was placed on taking an inventory of the benthic algae, corals, reef fishes, and substrate types. Incidental information was also gathered on other aspects of the reef community. Most of the sampling was done by skin or scuba diving.

Not all sampling methods were used at all stations. However, the following description outlines a typical station at which all sampling methods were used. Per cent cover by each substrate type was estimated by laying down a 20-meter line with marks at 0, 2, 5, 15, 18, and 20 meters. A pair of samples was taken, one on either side of the line opposite each mark. Each sampled area was a square 25 centimeters on a side, so the total area sampled along the line was 0.75 m^2 . Sampling included recording the kind of substrate under each of the 36 grid-square intersections in that 25-cm square. In addition, a sediment sample was collected for subsequent laboratory analysis. The kinds of biota (superstrate) were also recorded by this sampling procedure. Substrate data are reported as per cent cover, in Section VI A of this Atlas.

Algal sampling consisted of collecting all the conspicuous algae in a (0.16 m^2) 45-cm diameter circular ring at either end of the 20-meter sampling line. Laboratory species identification was performed on the collected material. Algal data are reported in dry-weight biomass (grams/m^2). More details are reported by Soegiarto (1972).

Coral sampling was conducted by a visual estimate of per cent cover in a quadrat 20 meters long and 6 meters wide in the immediate vicinity of a sampling line. More details are reported in Maragos (1972).

Fish counts were made by taking visual census within the same quadrat as the coral sampling. Fish sampling presents special problems which will be described in Section VI C.

Data from these surveys were recorded on field sheets, then punched on computer cards which went to create a data file. All subsequent statistical analysis using this data file was done on the University of Hawaii's IBM/360 computer.

In addition to data gathered in this fashion, the maps reported in the following sections include observations by authors of the respective sections. In order to maximize the amount of data available to the reader, presence - absence maps are included in this Atlas. Maps reporting the presence or absence of particular biota do not require hard numbers, nor do they require that observations be made of other biota. The presence - absence maps included here contain the maximum available information. Maps reporting abundance information also require no observations on other organisms, but do require hard numbers

on the particular organism. And finally, maps of patterns among the biota (factor analysis) can be provided only for those stations where data for all of the biota have been collected.

Our sampling procedures have yielded about 200 species of benthic algae, corals, and fishes in the Bay. In order to cut down on the tremendous potential number of maps, we show the presence - absence of only those organisms occurring at 10 per cent or more of the 209 stations used for factor analysis. A 5 per cent cutoff is used for the presence - absence factor analysis (Section VIII). The presence - absence maps distinguish two different kinds of information. A dot (either large or small) indicates the location of stations used for subsequent factor analysis (Section VIII). A circle, either closed (i.e., a dot) or open, indicates locations in the Bay at which the organism in question has been found. Only the most abundant or important organisms are illustrated by abundance maps.

In addition to presence - absence and abundance maps, we include maps showing the number of species and total abundance at a station of the three major groups (corals, fishes, algae). Each group examined is discussed by the respective investigator.

VI. Detailed Surveys

Under the Sea Grant Program of the University of Hawaii, four important aspects of the Bay ecosystem were surveyed in detail: the distribution of substrates, corals, fishes, and algae. These are described in Sections VI A - D.

VI. A. Substrate of the Bay

Stephen V. Smith and Dennis T. O. Kam

Various questions may be asked about the nature of the sea floor—the substrate—of Kaneohe Bay. Among the environmentally important substrate characteristics to be considered in this section of the Atlas of Kaneohe Bay are the water depth (or bathymetry), the landforms (or physiography), the kinds of sediment, the composition of the sediment, and the changes in certain of these characteristics over the last 80 years. These kinds of information can be navigationally useful; they can be useful in determining the distribution of organisms in the Bay; and they can be useful indicators of the present and past environments of the Bay.

Little need be said about the bathymetry of the Bay; the bathymetric chart (Figure 2) is a relatively self-explanatory contour map. Physiography (Figure 5) is perhaps the most useful general information and comes from the bathymetric chart. Much of the discussion of physiography is modified from Roy (1970). Additional information comes from direct observation, from air photographs, and from earlier maps of the Bay referred to by Roy.

The Bay can be immediately divided into reef and non-reef areas. The standard navigational definition of a reef—a consolidated rock hazard to navigation with a depth of less than 10 m—is useful in Kaneohe Bay. Most of the areas shown to be reefs in Figure 5 conform to this definition.

There are at least two convenient ways to categorize the Kaneohe Bay reefs. The first approach is to divide them into ocean reefs versus lagoon reefs. Such a division is shown by the dashed line in Figure 5. The reasons for this terminology will eventually become obvious.

The more conventional terminology involves three main categories. There are fringing reefs along the coastline of Oahu and the smaller islands; patch reefs dotting the Bay as “fringing reefs without islands to fringe”; and the barrier reef blocking the mouth of the Bay.

Within these categories are further subdivisions. Reef flats, as the name implies, are broad flat areas on the tops of all the reefs. These areas are usually less than 1.5 m deep. Reef flats are present on the patch and fringing reefs as well as on the shoreward portion of the barrier reef. The term reef flat as applied here will be modified slightly in subsequent paragraphs to indicate low-energy reef flats. Reef slopes are the abrupt transitions (about 30° slopes) from the reef flats to the adjacent deeper water area. Such slopes occur on the patch and fringing reefs, as well as on the shoreward edge of the barrier reef. The seaward side of the barrier reef slopes gently to about 18 m as a zone distinctly different from the reef slopes. This gently sloping area may be called the fore-reef. Such fore-reef areas are also present seaward on the fringing reef outside of the Bay proper. A broad transition zone separates the barrier reef flat from the fore-reef. Roy (1970) referred to the landward edge of this zone as the “algal ridge”, but the feature is a feeble imitation of classical algal ridge structures. The term of Clausade *et al* (1971), “reef flat with coral alignments and sandy

couloirs", is appropriate to the zone, but is too awkward for common usage. In this atlas that zone will be referred to as the high-energy reef flat, and the reef flat discussed previously will be called the low-energy reef flat. Thus the barrier reef flat and the seaward portions of the fringing reefs grade gradually from the high-energy to the low-energy reef flats; patch and fringing reefs near the two channels are indicative of high-energy reef flats; and patch and fringing reefs behind the barrier reef entirely lack the characteristics of high-energy flats.

In general, the division between lagoon and ocean reefs is also a division between patch/fringing reefs and the barrier reef. Within the lagoon, the patch and fringing reefs are little different from one another and both are greatly different from the barrier reef. However, seaward of the lagoon reef-ocean reef boundary, the patch reefs and fringing reefs resemble in most respects the barrier reef more than they do their lagoonward counterparts. That is the reason for the distinction.

Man's intervention has added still another type of reef by modifying patch and fringing reefs into dredged reefs which have reef tops substantially below the depth of most reef flats. Incidentally, dredging has also completely obliterated a number of reefs in the Bay.

Non-reef areas include two relatively deep-water provinces—the lagoon floor landward of the barrier reef and two large sand channels extending from the lagoon to the open ocean. Shoaling sand bars, primarily along the lagoonward edge of the barrier reef, also occur. Mud flats are shallow muddy areas which encroach upon adjacent reef-flat areas. These mud flats are partially natural and partially due to man's intervention. As discussed elsewhere in this Atlas, various human activities in the Kaneohe Bay watershed have vastly increased the rate at which sediment enters into the Bay, thus contributing to the increased area covered by these mud flats. The mud flats derive their sedimentary material from streams, and distinct deltas are present at several stream mouths.

Human reclamation has actually removed some areas from the confines of Kaneohe Bay. Numerous fish ponds are old, yet obvious, examples of reclaimed land. Less obvious, but much newer, are the areas of landfill where the Bay has been filled to a height above sea level and subsequently developed.

It will be useful in other sections of this Atlas to refer to various aspects of the Bay relative to the physiographic terminology which has been developed here.

The kinds of sedimentary materials making up the substrate are also important. Six broad categories of material comprise at least 90 per cent of the Bay substrate: sand, mud, hard bottom, live coral, dead coral, and coral rubble. The distribution of each substrate is distinctive relative to these physiographic provinces.

Sand (material between 0.062 mm and 2 mm in diameter) is most abundant on the low-energy reef flats, in the sand channels, on the shoaling sand bodies, and on the reef slope of the barrier reef (Figure 6). It is present in less abundance on the fore-reef and the high-energy reef flat, and is virtually absent from the lagoon floor. The nature of the sand varies considerably from province to province. The reef-flat sand is variable in grain size, poorly sorted, and stable. The sand of the shoaling sand bodies, the slope of the barrier reef, and the sand channels is well sorted and shows evidence of considerable transport. Sand on the fore-reef is primarily confined to the numerous gulleys down which this material is transported seaward.

Mud (finer than 0.062 mm) is the overwhelming component of the lagoon floor sediments and of the mud-flat sediments (Figure 7). It is absent from the sand channels and from the ocean reefs.

Hard bottom (Figure 8) is primarily confined to the barrier reef, increasing in abundance from the lagoonward edge of the barrier reef to the high-energy reef flat, and is constantly important across the fore-reef. This hard bottom is largely eroding limestone, the remnants of some earlier depositional episode in the Bay. Part of this limestone is lithified sand-dune material; both the island of Kapapa and the low ridge seaward of Kapapa are the remnants of such dunes. Much of the hard bottom material is "reef rock", probably some relatively recent and some old material. Gulleys through the hard-bottom material are locally prominent on the fore-reef.

Live coral (Figures 9 and 16) is abundant on the patch and fringing reef slopes down to depths of 9 m, less so south of Moku O Loe Island than north of it. While live coral is practically ubiquitous in the high-energy reef flat and fore-reef areas, it covers a relatively small portion of the bottom there. Ideally, Figures 9 and 16 should be identical. They are not because the two methods of measuring live coral cover differ somewhat. Nevertheless, the two maps are very similar to one another.

Dead coral (Figure 10) reflects a relationship to live coral, combined with the effects of a recent climatological episode. Dead coral is most common on the high- and low-energy reef flats and on the upper portion of the lagoon reef slopes. These areas were subjected to a major "coral kill" as a result of combined high rainfall and low tides during a storm in 1965 (Banner, 1968).

Coral rubble (Figure 11) illustrates much the same distribution pattern as dead coral. The major difference between the two patterns is the more widespread distribution of rubble as a result of sediment transport away from the sites of major coral growth. This transport is most obvious as a high concentration of rubble on the fore-reef.

The chemical and mineralogical composition of the sedimentary materials is a further useful environmental indicator. Per cent calcium carbonate generally divides the sediments into those which are land-derived (no CaCO_3) and those which originate in the Bay from the calcifying reef organisms there or from erosion of the hard limestone bottom. Virtually no CaCO_3 comes from the land or from organisms living on the lagoon floor. The carbonate percentage map (Figure 12) clearly delineates streams where land-derived material enters the Bay. These areas show carbonate content below 50 per cent. Reef areas show carbonate content above 75 per cent. The 75 per cent CaCO_3 boundary cuts down the length of the lagoon, suggesting that CaCO_3 in the lagoon sediments is primarily washed or eroded landward off the barrier reefs. The sand bar on the lagoonward portion of the barrier-reef flat (Figure 5) reflects this landward transport of calcareous reef material. The patch and fringing reef tops do not seem to be contributing significantly to the total volume of lagoon sediment.

Figure 13 offers further evidence of the origin of CaCO_3 in lagoon sediments. Aragonite is a CaCO_3 mineral, and it is possible to measure what fraction of the CaCO_3 in a particular sediment is aragonite. The aragonite map demonstrates that patch and fringing reefs are high in aragonite, while the barrier reef and lagoon both have lower aragonite contents. Thus, the lagoon carbonates appear to be washed in from the barrier reef. The

southeastern portion of the lagoon is an exception to this pattern. It is likely that the high aragonite content of the sediment there reflects degeneration of the fringing reef, and perhaps dredging of patch reefs.

The final aspects of Kaneohe Bay substrate to be considered are the changes in the substrate characteristics over the last several decades. Some of these changes—in the form of man's purposeful or inadvertent alteration of Bay physiography—have already been mentioned. Other more subtle influences are also present and may be more pervasive.

Roy (1970) had documented an extremely large lagoon infilling within the last 40 years—an average of 1.6 m. By contrast, no filling and perhaps even a slight deepening of the lagoon seems to have occurred during the previous 40 years (Figures 14 and 15). For a number of reasons, it is difficult to estimate what that deposition means in terms of a potential time to fill the Bay. In the first place, it is likely that the period of rapid infilling started more recently than 40 years ago, so the observed deposition is 1.6 m during something less than 40 years, rather than 1.6 m in 40 years. (See Section II.) Secondly, as the Bay does fill in, water circulation will probably tend to remove proportionally more of the material than it does now. That effect may prolong the period before the Bay fills. Realizing these shortcomings, Roy (1970) predicted that half of the lagoon is likely to be less than 3 m deep within 150 years, or sooner.

The pattern is not simply one of input of land-derived detritus into the Bay. From Figure 12 it appears that approximately half of the sedimentary material in Kaneohe Bay is CaCO_3 , or internally derived. (Roy, 1970, estimated 72 per cent; we believe that figure to be too high, based on more extensive sampling since his study.) Thus not only the deposition of land-derived sediment has increased in the last 40 years over the previous 40 years. It seems likely that erosion of the main reef over the past 40 years, or some portion thereof, has been more severe than previously. Assuming that increased erosion explains the high CaCO_3 content of the lagoon sediment, we do not know how much of the increase to attribute to alteration of the biological community. In any event, it seems almost certain that human activity is a direct or indirect factor.

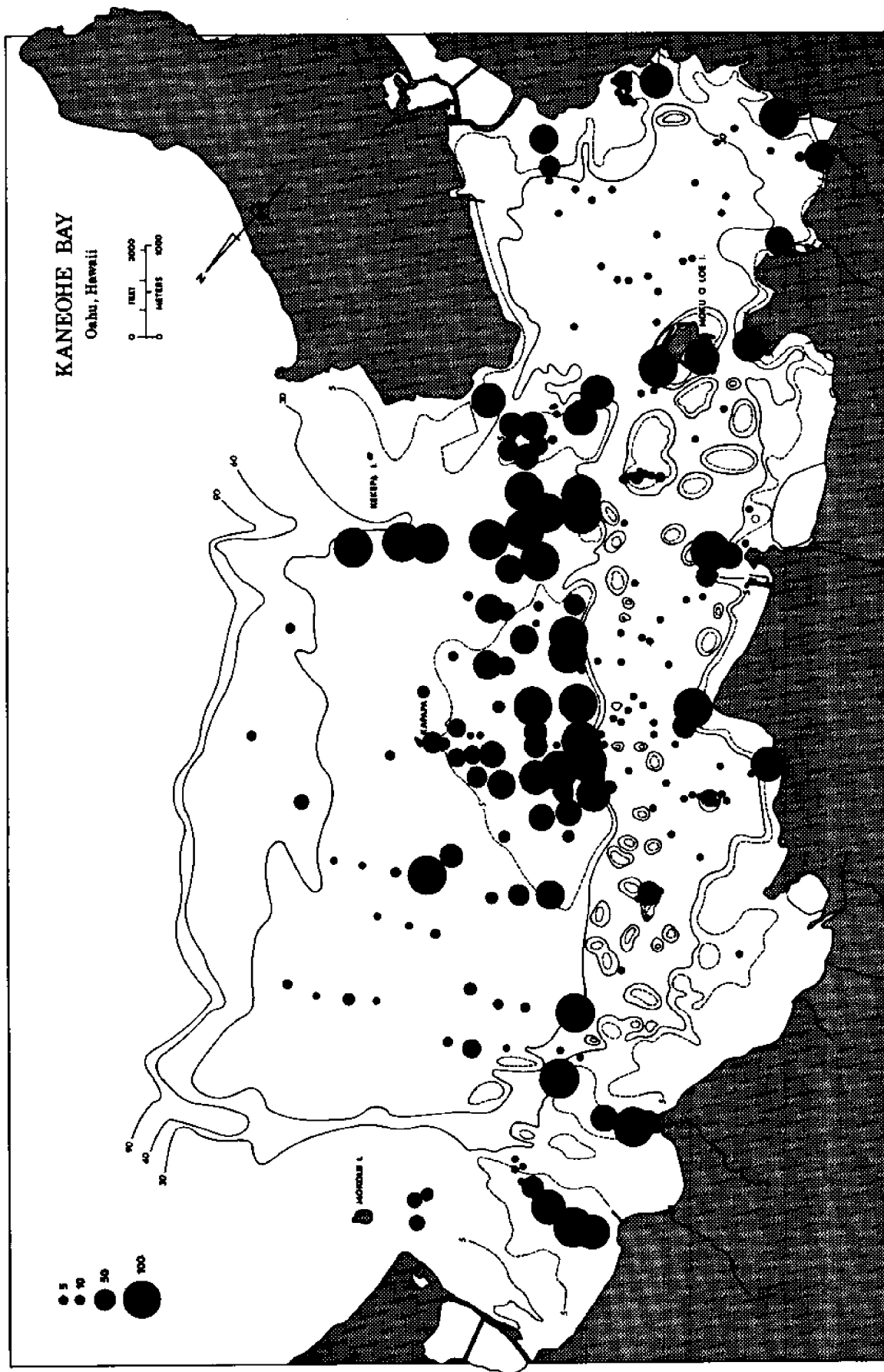


Fig. 6. Per cent cover of Sand

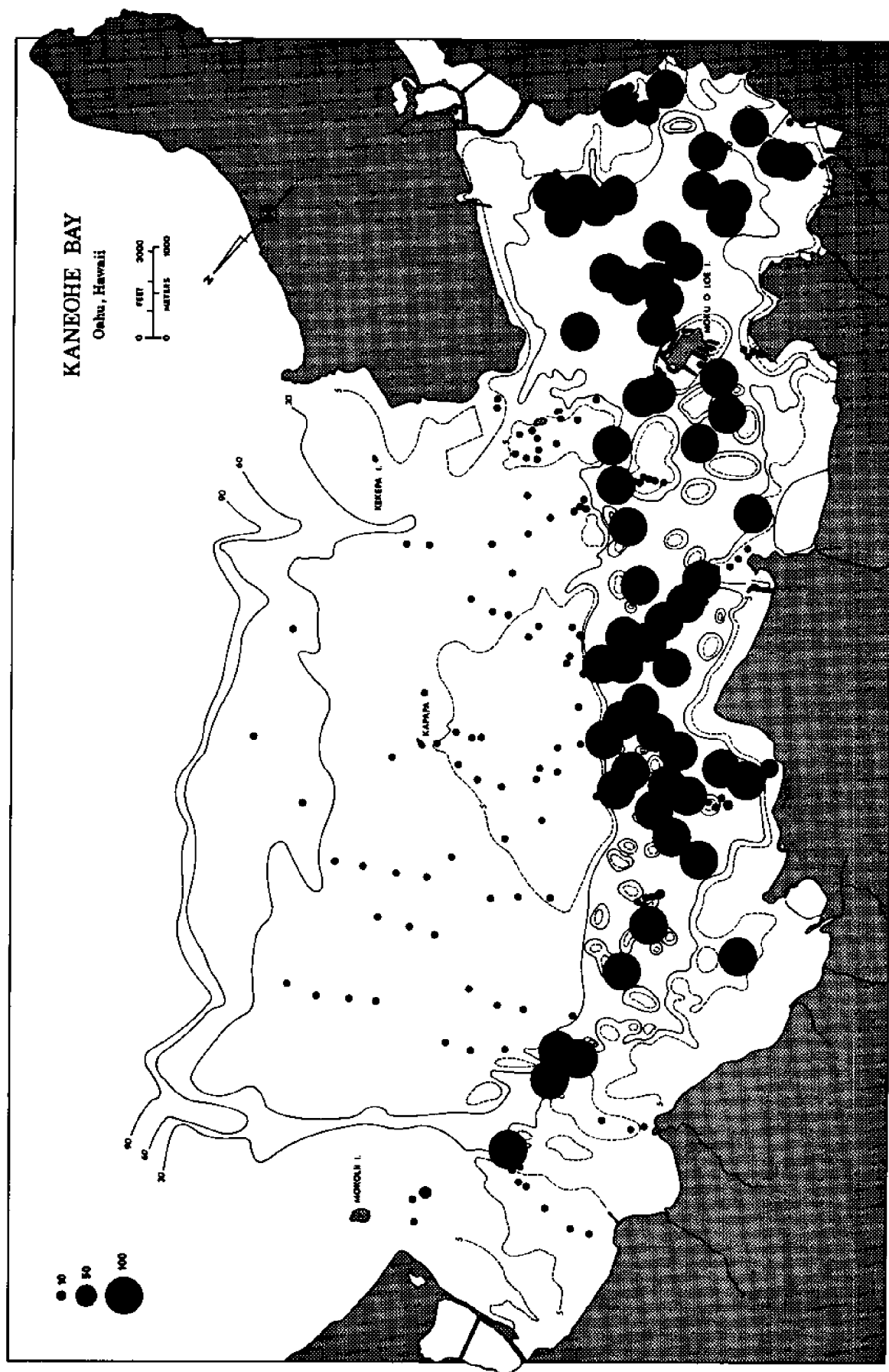


Fig. 7. Per cent cover of Mud

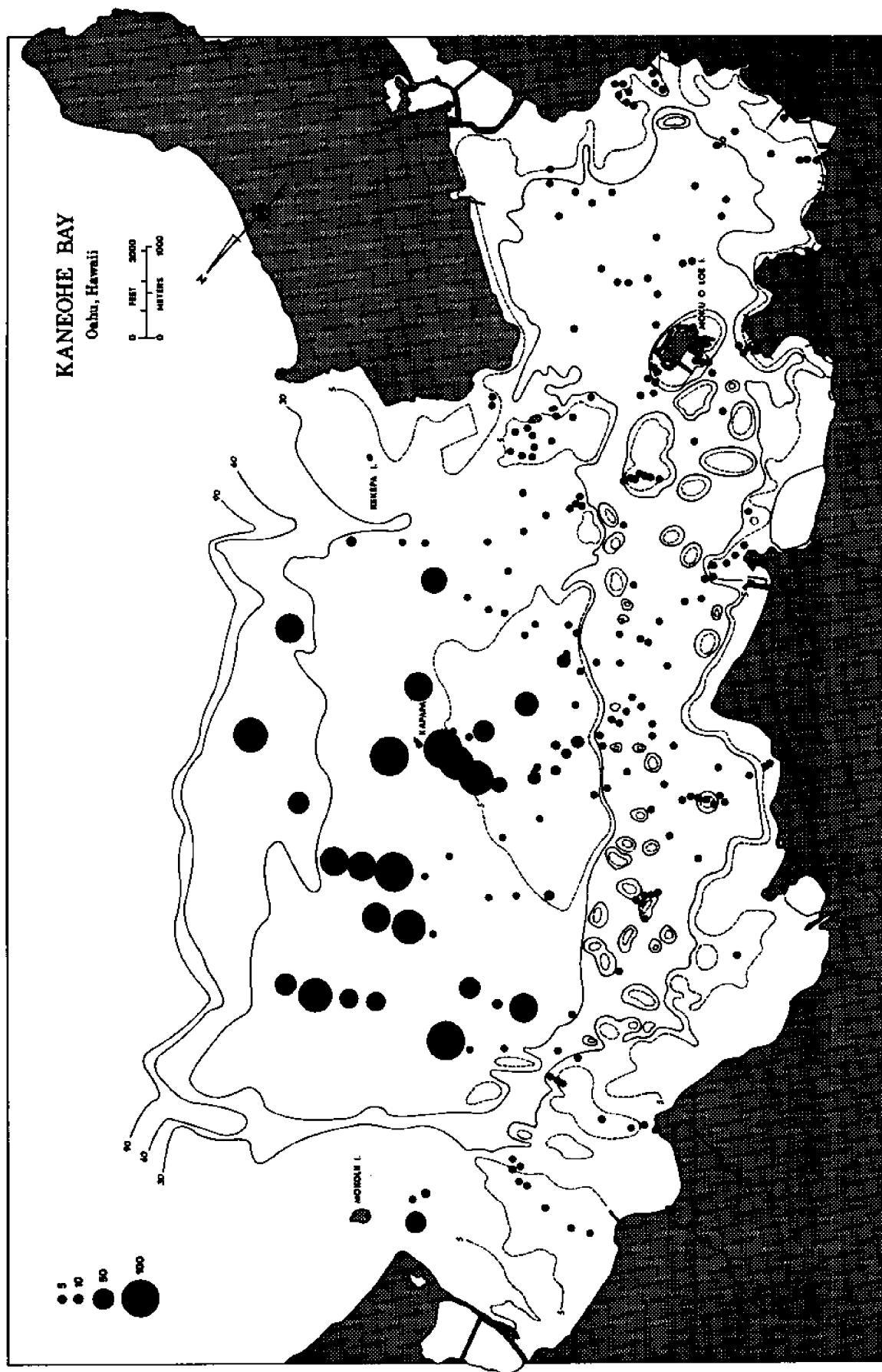


Fig. 8. Per cent cover of Hard Bottom

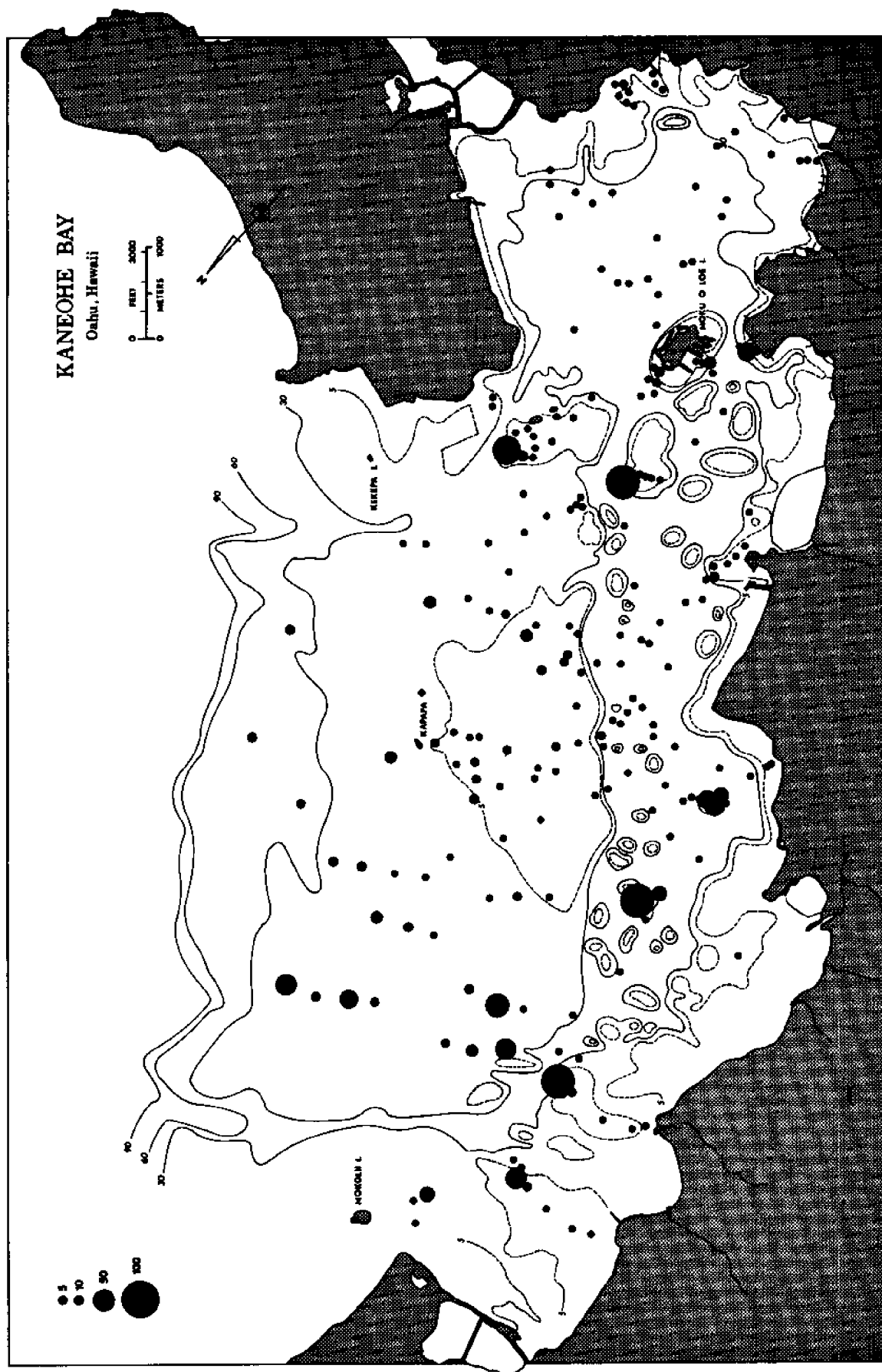


Fig. 9. Per cent cover of Live Coral

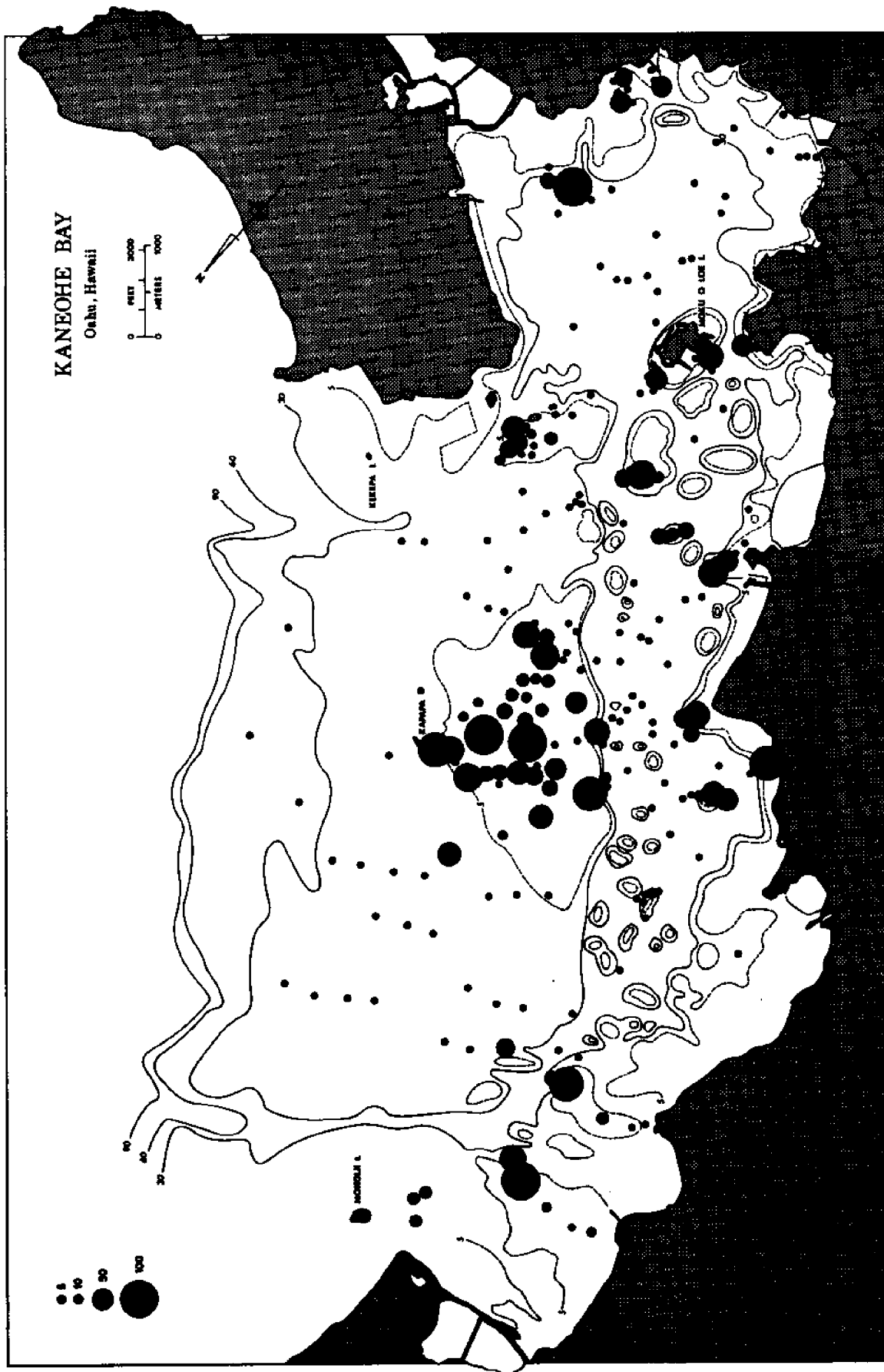


Fig. 10. Per cent cover of Dead Coral

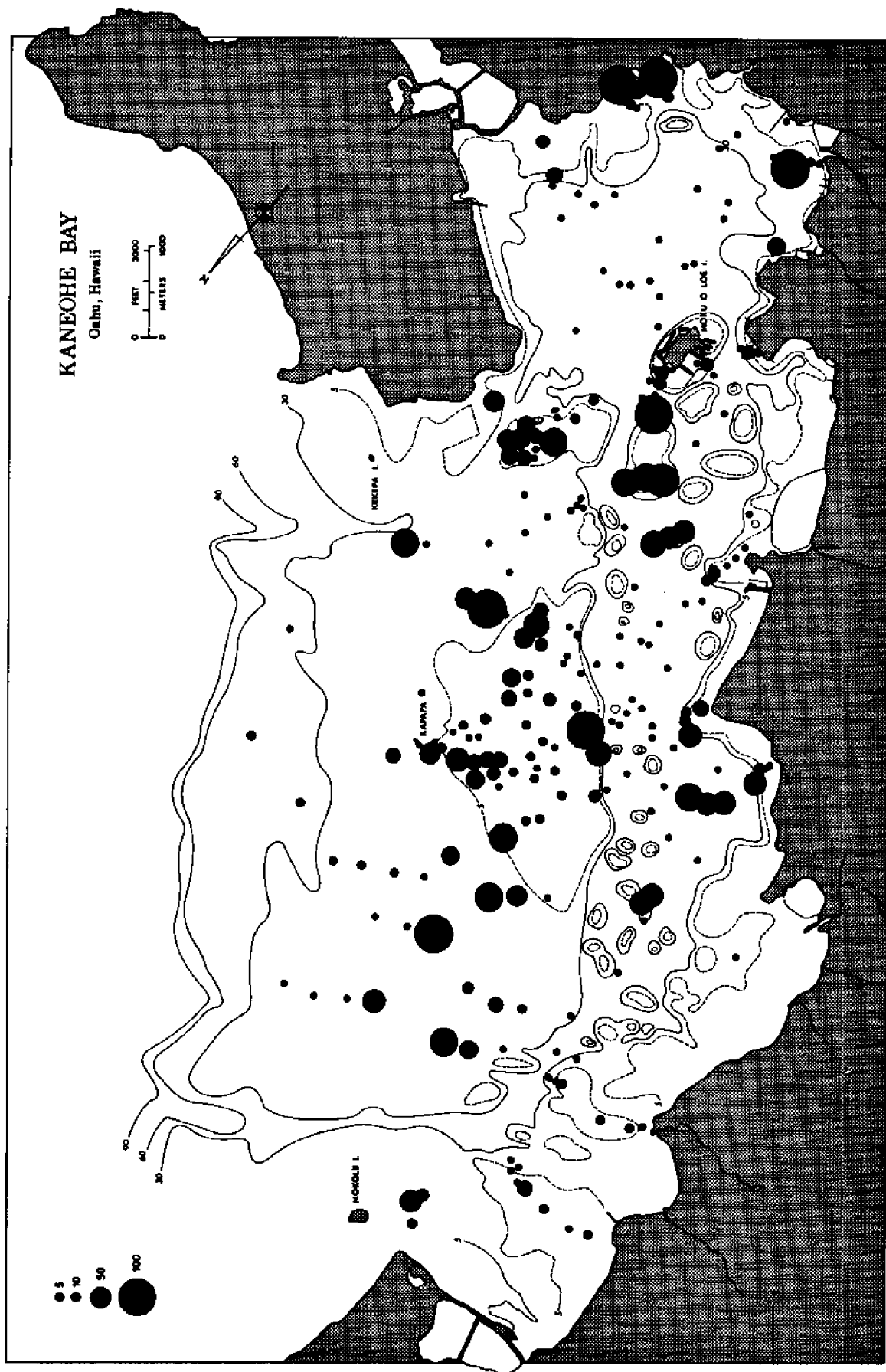


Fig. 11. Per cent cover of Coral Rubble

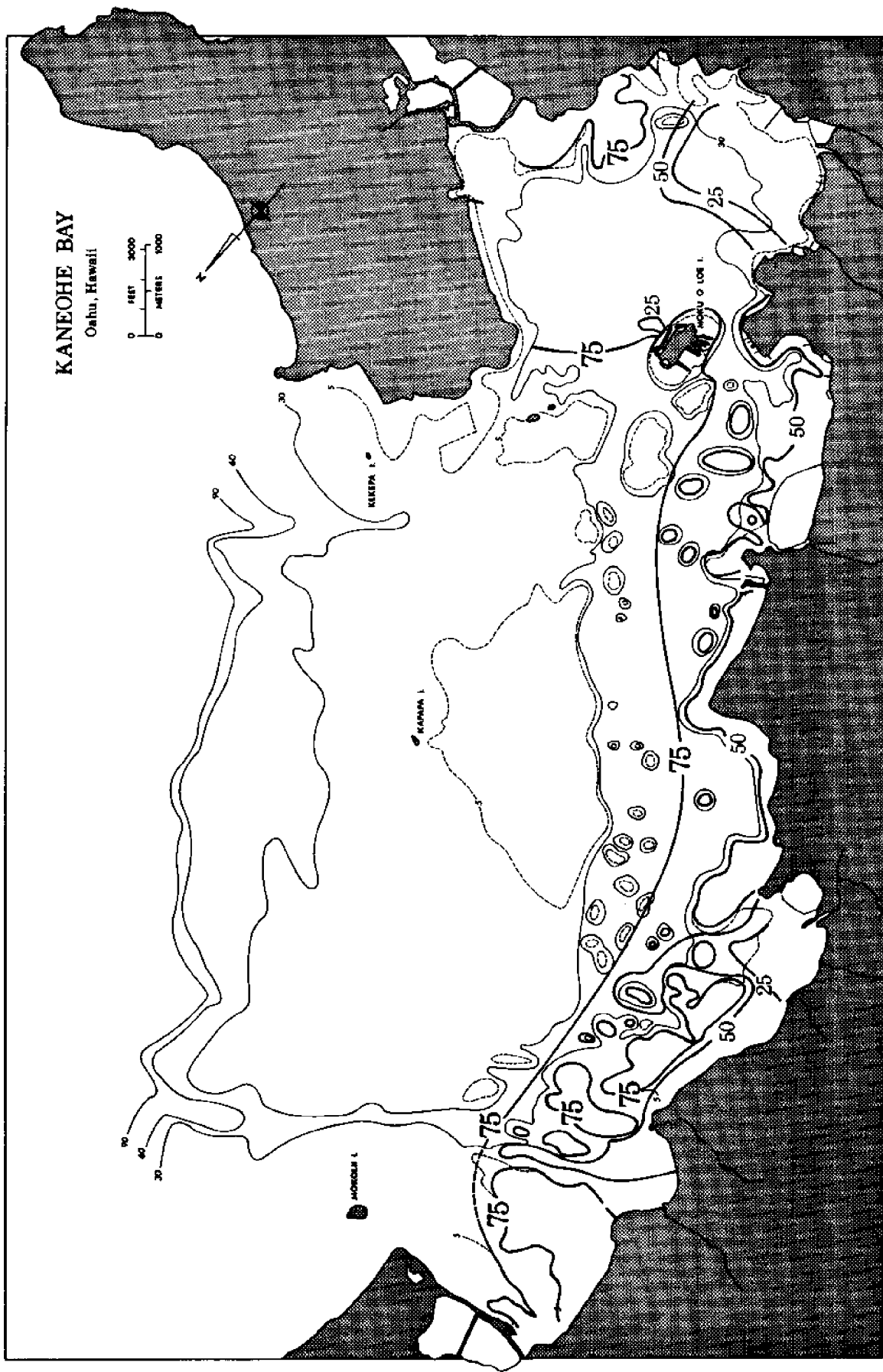


Fig. 12. Generalized map of per cent Calcium Carbonate in the Sediments

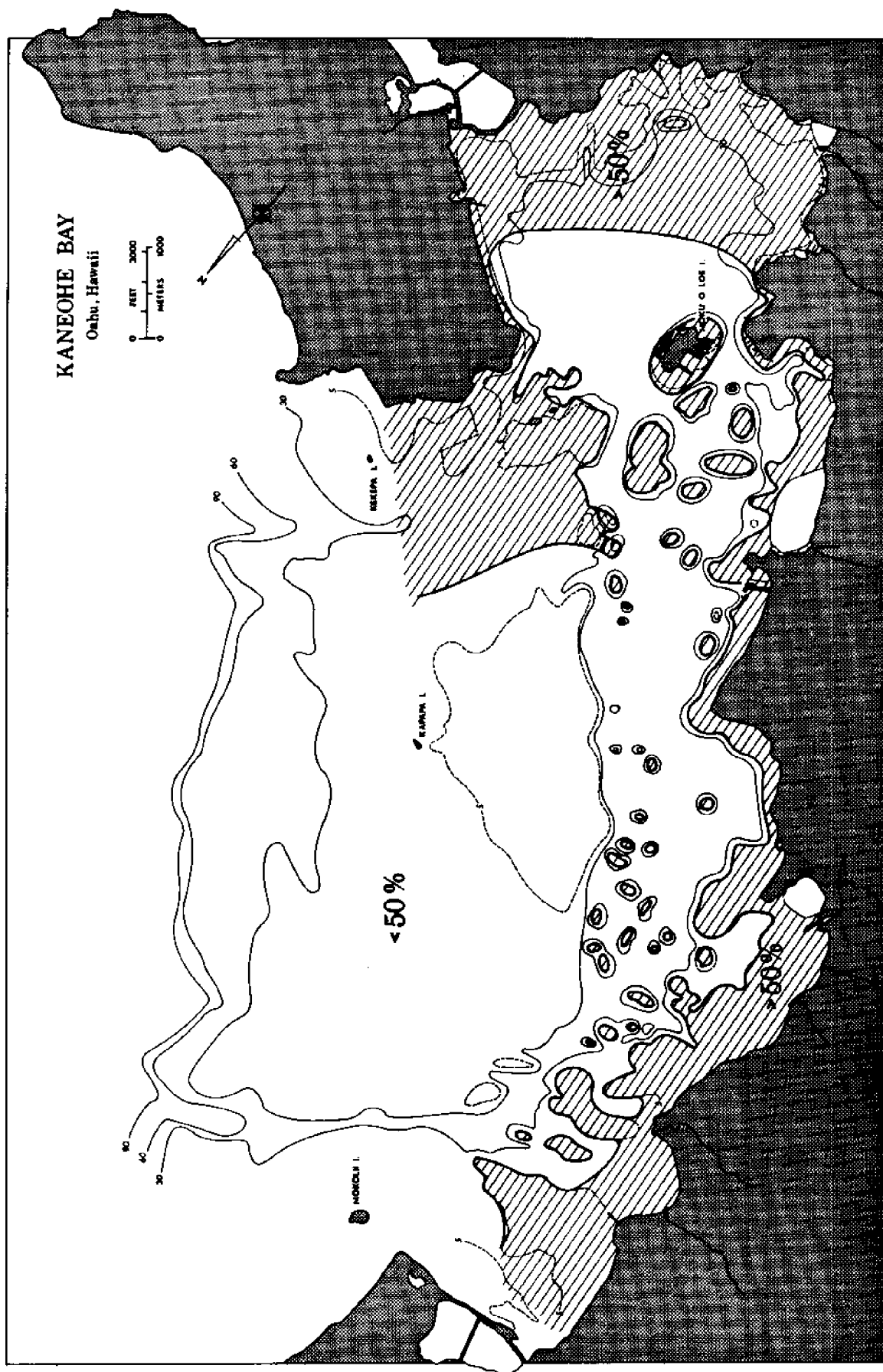


Fig. 13. Generalized map of per cent Aragonite in the Calcium Carbonate

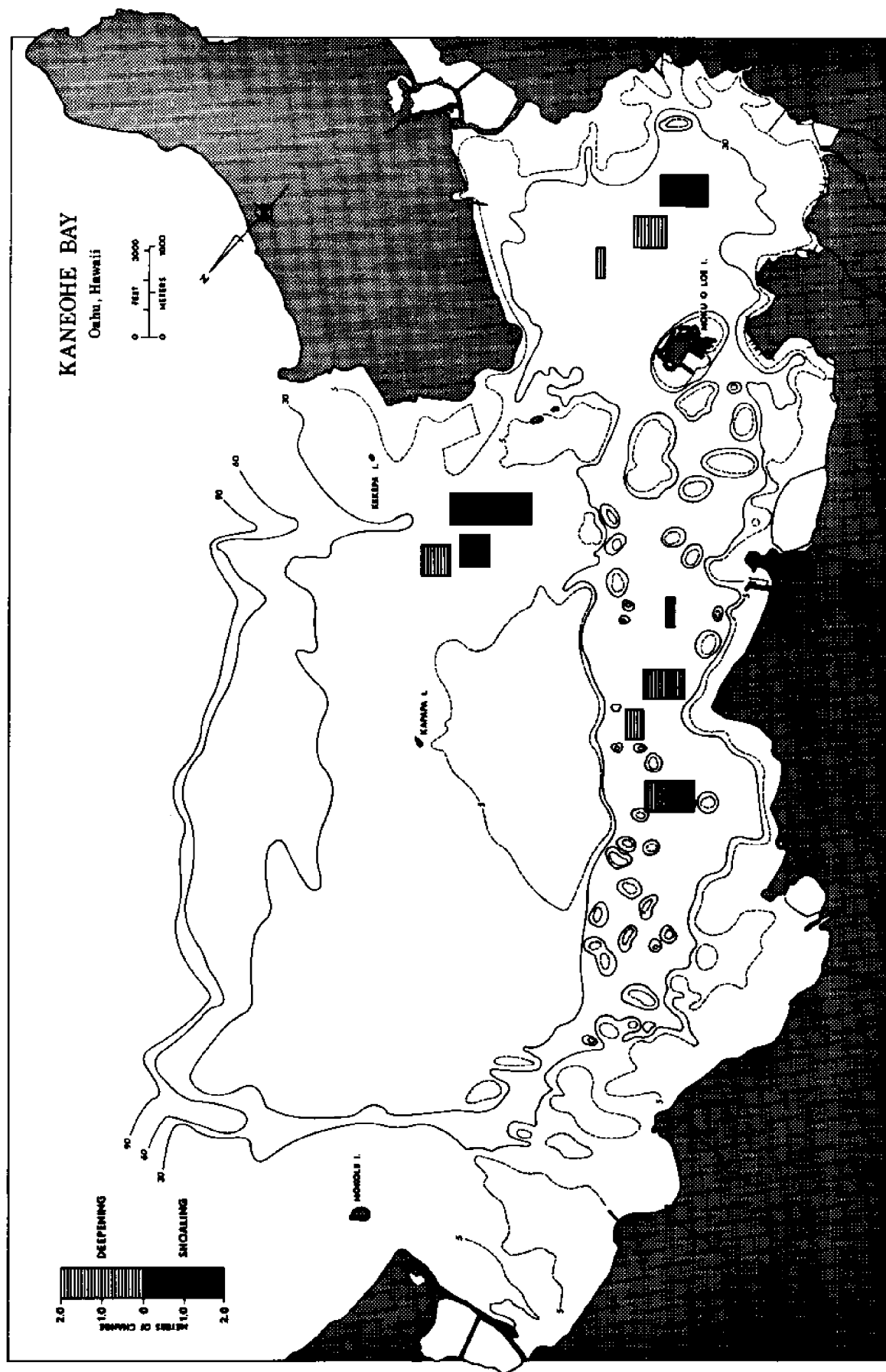
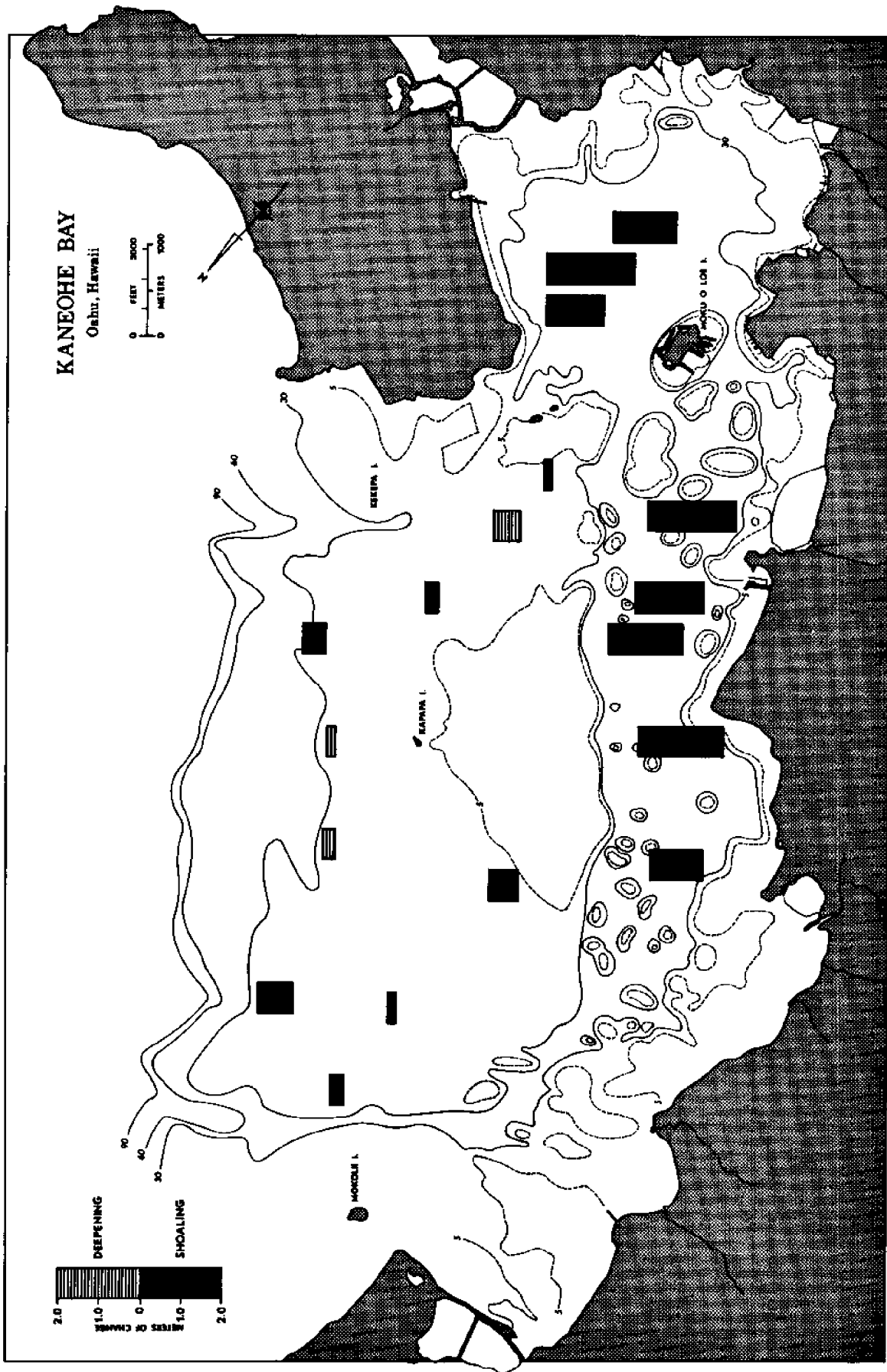


Fig. 14. Change in Bay depth between 1882 and 1927 (after Roy, 1970)



VI. B. Distribution and Abundance of Reef Corals

James E. Maragos

The regional abundance and distribution of reef corals in Kaneohe Bay are controlled by local circulation, water-chemistry patterns, and substrate type. On protected, northern Bay reefs, corals are consistently more abundant than on outer, exposed reef areas or in South Bay (Figures 9 and 16). MacCaughey (1918) and Edmondson (1928) also noted that in the protected areas of Kaneohe Bay, coral abundance was greater than elsewhere. Wave action and abrasion by suspended sediments appear to be the principal agents in reducing coral coverage in high-energy regions of the Bay (Maragos, 1972). Grigg, Maragos, and Townsley (in preparation) also suggest that conditions are sub-optimal for corals where wave energy is greater for reef areas on the coast of the island of Hawaii. For both studies, it was found that no one species could grow to a sufficiently greater size than the others to dominate the substrate where physical conditions were unfavorable. This lack of dominance enabled more kinds of corals to coexist on exposed reefs than on sheltered ones. Probably as a consequence, more coral species are found at each station in the outer portions of Kaneohe Bay lagoon stations. This generalization is apparently also true elsewhere in the Pacific. Both Mayor (1918) and Wells (1957) have suggested that coral abundance is inversely proportional to coral diversity on other Pacific reef areas.

On windward Hawaiian coasts, protected environments are uncommon, so coral growth is generally suboptimal in these areas. On some leeward coasts and other protected areas such as Kaneohe Bay, conditions are more favorable for corals; usually one or two species, *Porites compressa* and *Montipora verrucosa*, dominate all other forms, resulting in a low diversity as measured by number of species present at a sampling station. In Kaneohe Bay *Porites compressa* accounts for 85 per cent of the total coral cover for lagoon reefs.

In the southern lagoon, both the number of species and coral abundance drop off markedly (Figures 16 and 17). Maragos (1972) has shown that coral growth and survival potential are significantly reduced in these areas of the Bay where nutrient enrichment and dredging activities have been greatest. Also, in recent years large amounts of land-derived sediments have accumulated near the mouths of large streams and have killed off all corals in these nearshore environments (Figure 16).

The geographic presence - absence distributions of the six most frequently present reef corals in Kaneohe Bay are presented in Figures 18 - 26. Some of the corals are more common in the outer portions of the Bay, while others are more abundant in the lagoon. Some are equally common in both environments. *Porites compressa* and *Montipora verrucosa* are found in all areas of the Bay (Figures 18 and 19) but both are much more common inside the lagoon (Figures 20 and 21). *Fungia scutaria*, a free-living solitary form, is restricted to protected lagoon reefs, and is absent in the southeastern portion of the Bay (Figure 22). *Pocillopora damicornis* is found commonly in both the inner and outer portions of the Bay, but does not occur in deeper water (Figure 23). *Porites lobata* and *Pocillopora meandrina* are generally restricted to outer high-energy areas of the Bay. These corals are also found on some inner reef areas where surge and circulation conditions are strong, such as near the channels through the barrier reef (Figures 24 - 25). *Porites lobata* is the

dominant coral on exposed reefs (Figure 26). Maragos (1972) has plotted the presence - absence distribution for all 30 species of corals found within the Bay. In general, the geographic distribution of each reflects the generalization that some are more adapted than others to protected or exposed environments. All of these findings show that circulation patterns normally control the regional distribution of individual coral species within the Bay. The abundance maps (Figures 20, 21, and 26) also illustrate that coral coverage is extremely patchy. Stations close by one another often show marked differences in coral abundance. The factors responsible are sediment cover, substrate composition, and biotic factors (Maragos, 1972). Introduction of stressed conditions—nutrient enrichment and reef dredging—into the south lagoon areas of the Bay in recent years has also produced a north - south gradient in coral abundance and diversity (Figures 16 and 17).

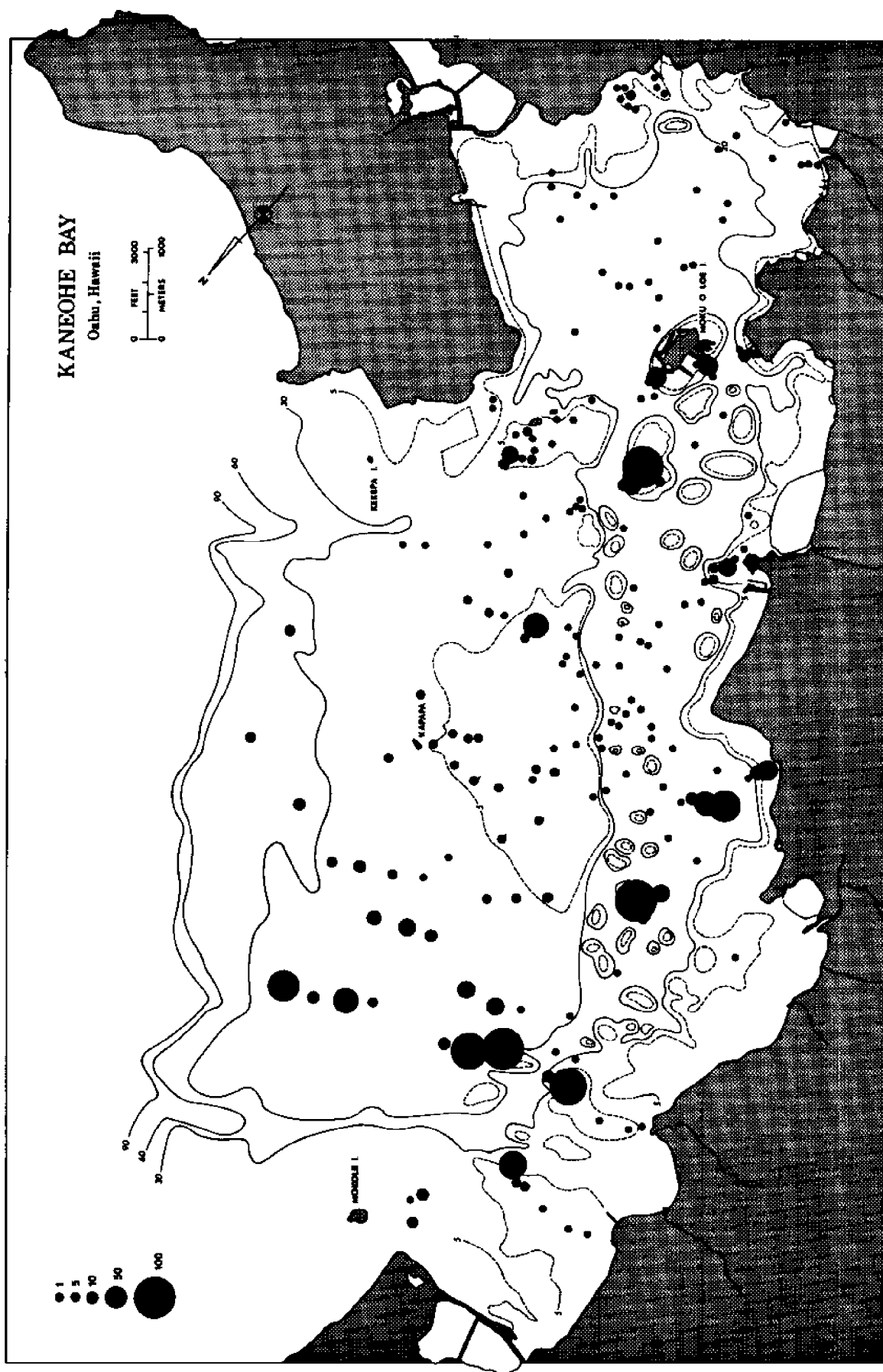
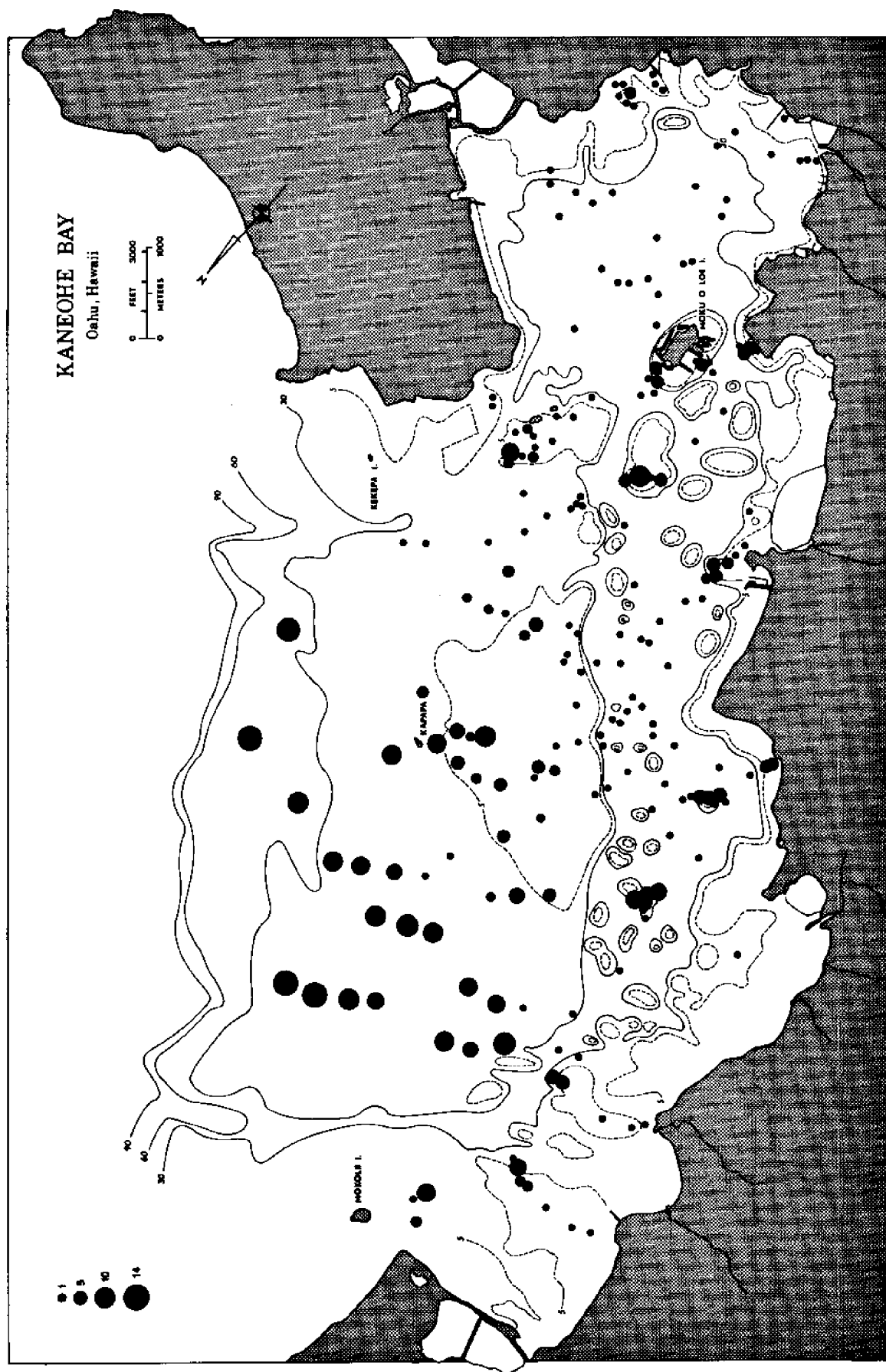
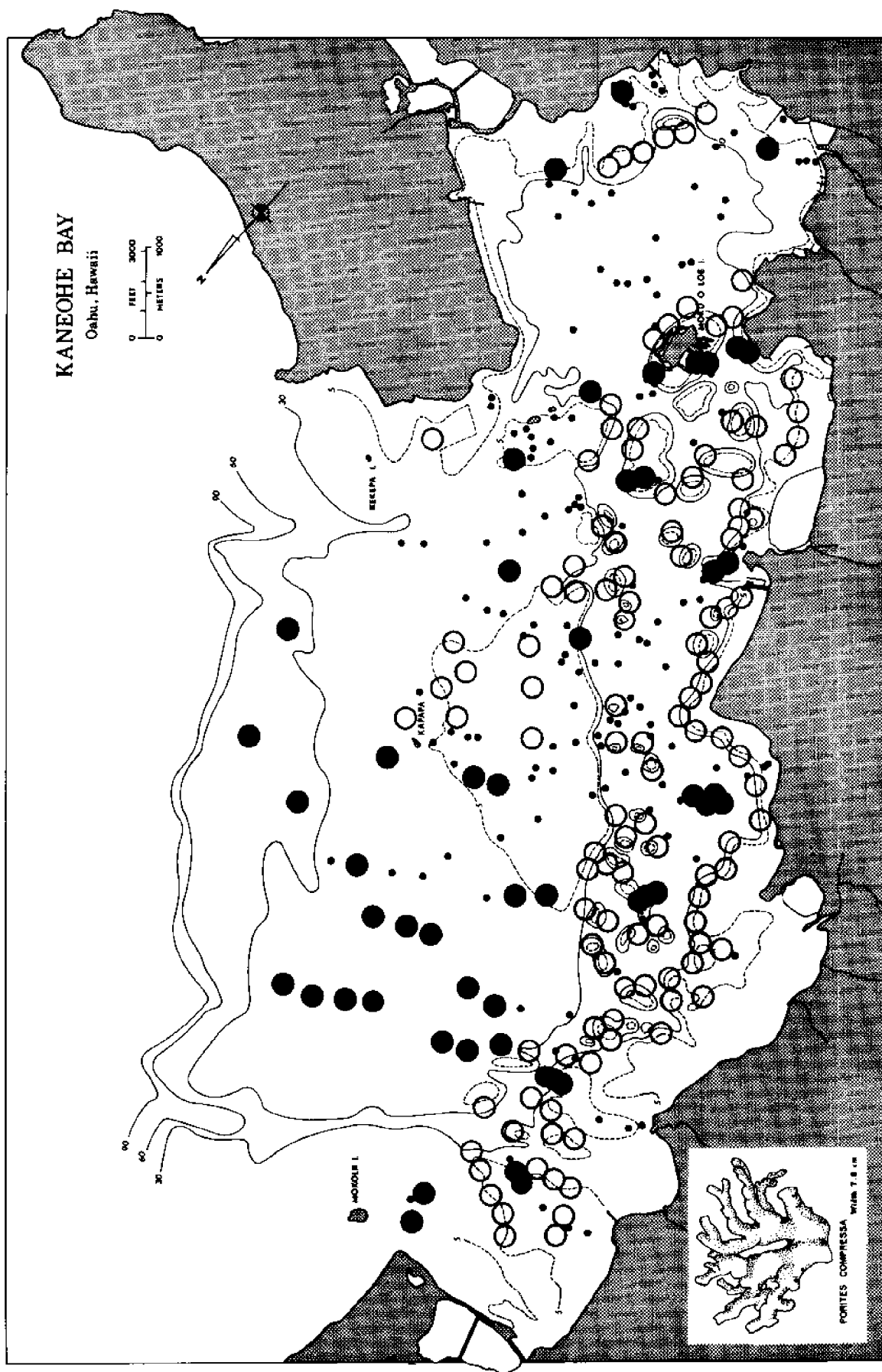
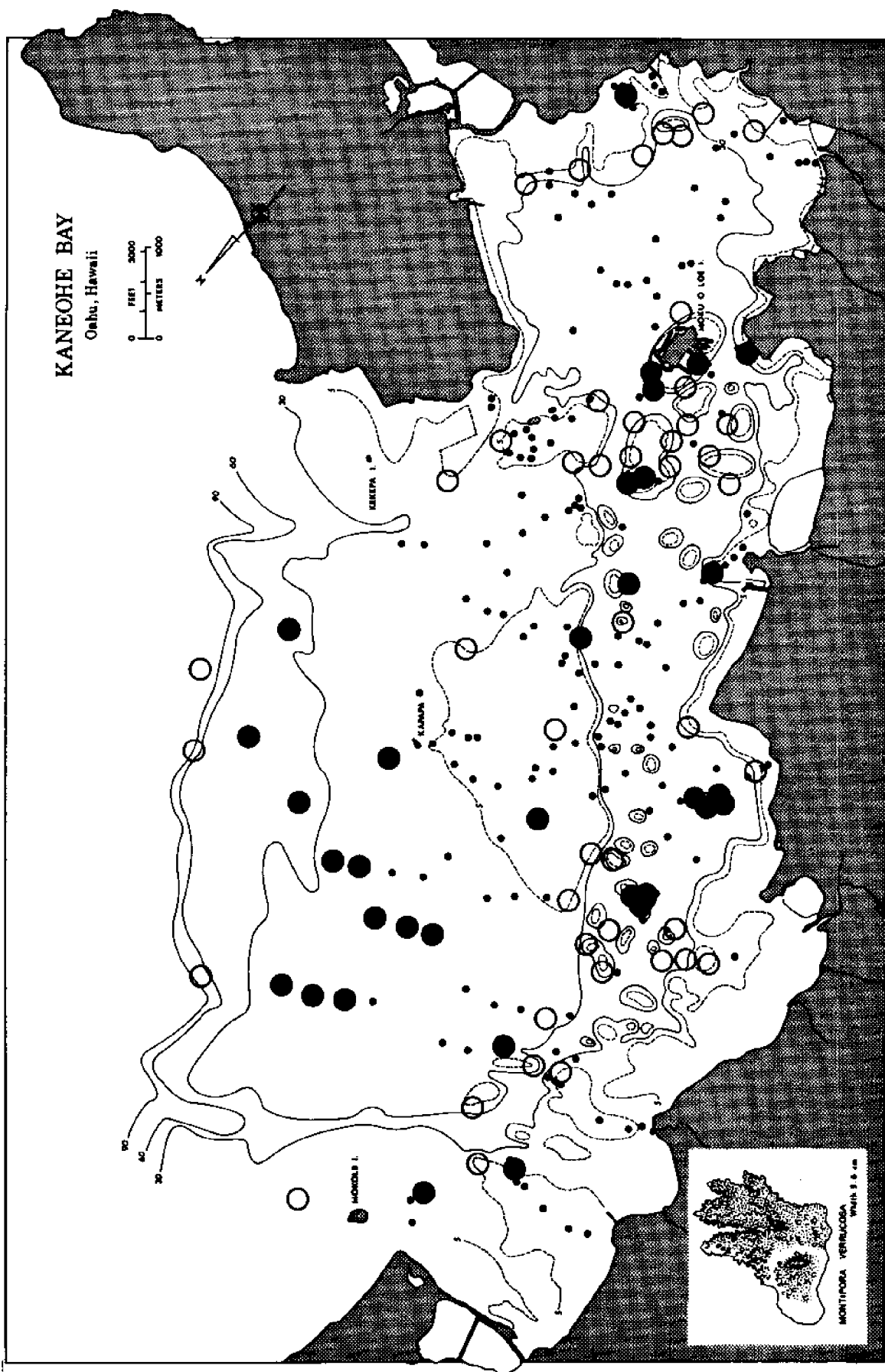


Fig. 16. Per cent cover of Corals







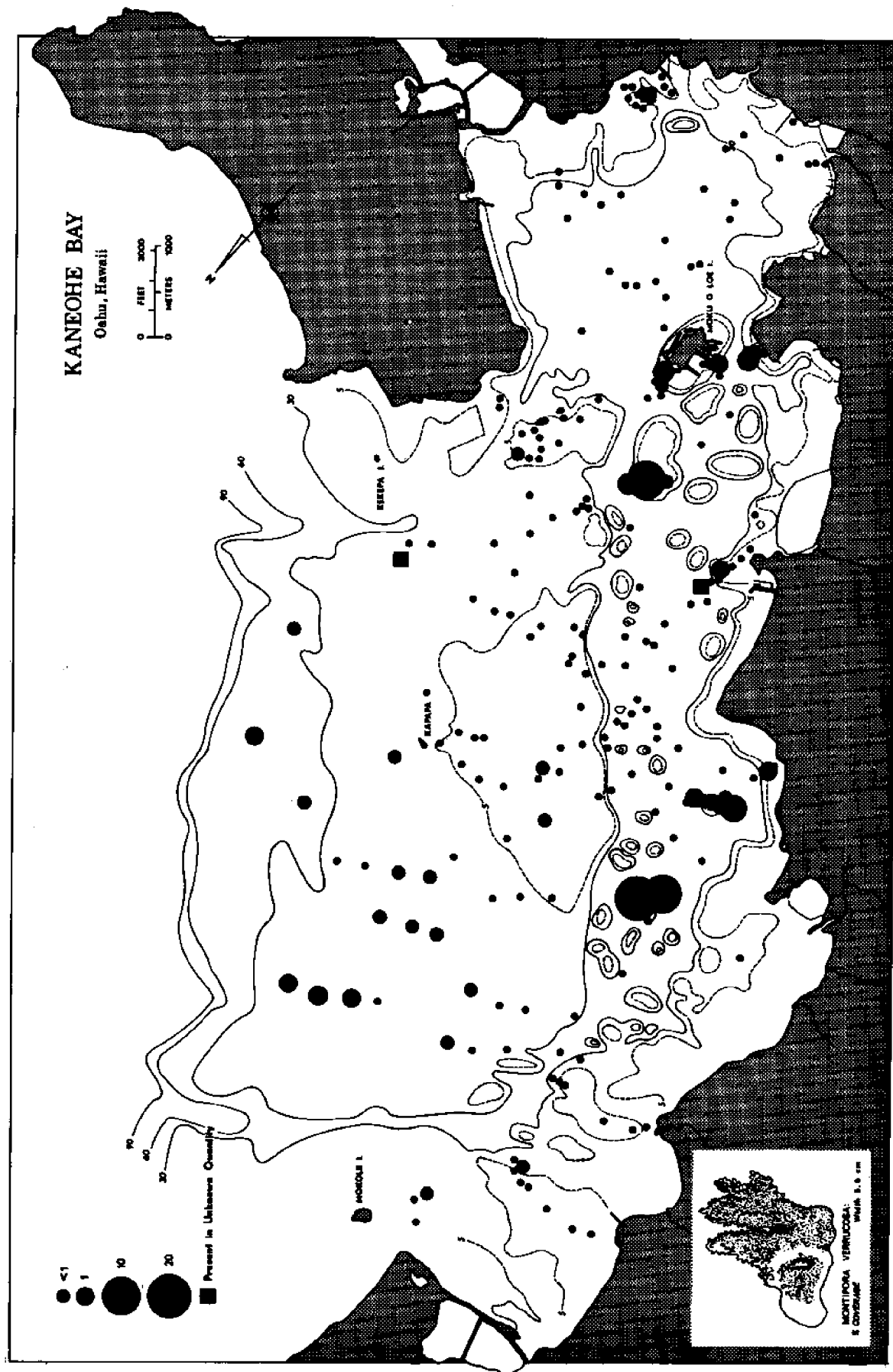


Fig. 21. *Montipora verrucosa*; per cent cover

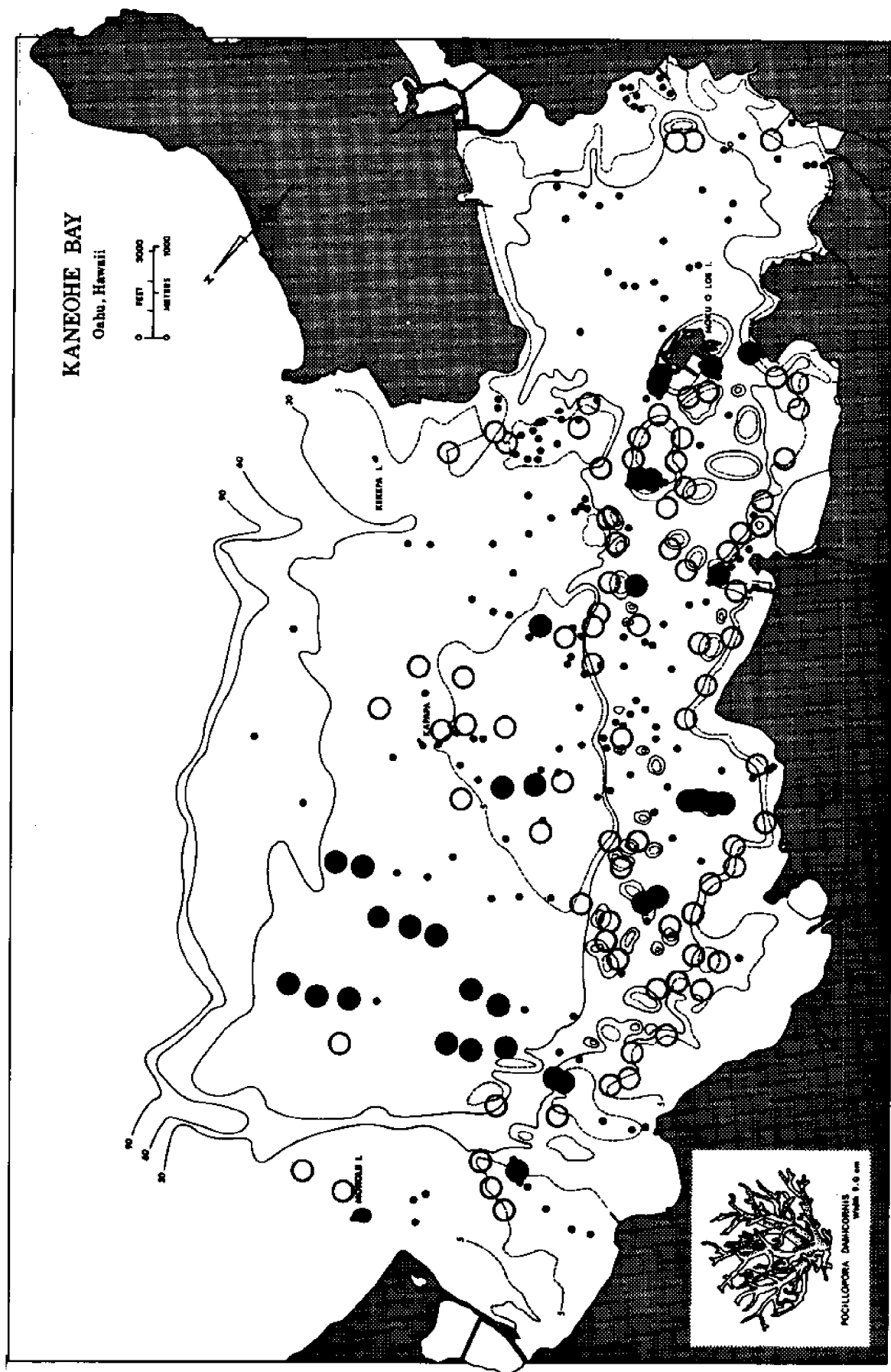


Fig. 23. *Pocillopora damicornis* P/A

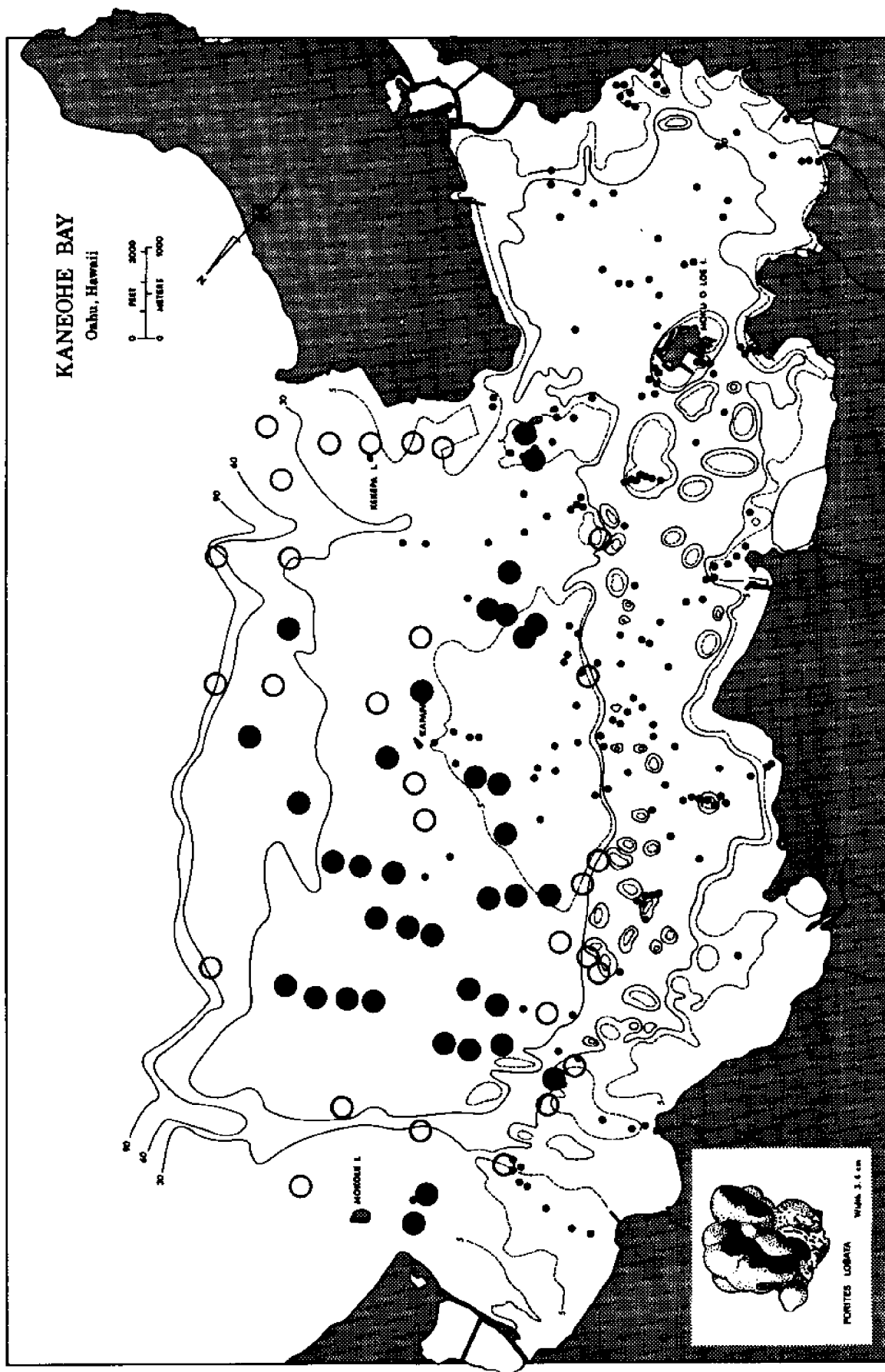


Fig. 24. *Portites lobata* P/A

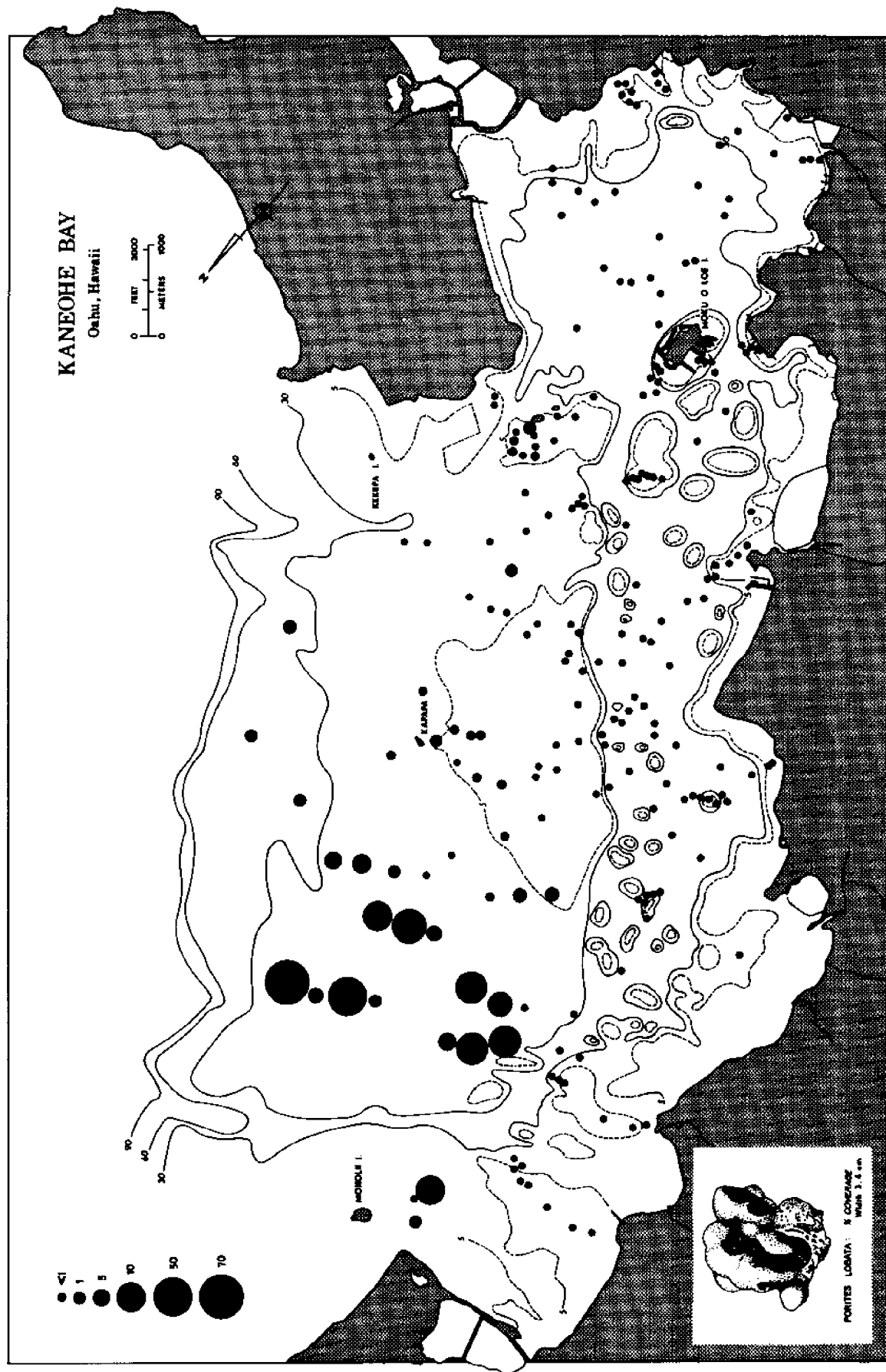


Fig. 26. *Porites lobata*; per cent cover

VI. C. Reef Fishes in the Bay

Gerald S. Key

Sampling

Sampling nearshore marine fishes, many of which are highly motile organisms, presents problems, errors, and biases not encountered in surveying the sedentary or sessile benthic plants and animals. In part because of their mobility, these same fishes do not generally respond as directly to physical parameters (waves, salinity, turbidity, etc.) as do the benthic organisms, but more often appear to respond to the influence of these physical parameters on the fishes' food supply or habitat.

Because of these special problems, and allowing for sampling errors, a between-station comparison of the fishes is perhaps best effected on a presence - absence basis. On the other hand, the average abundance of a species within a given environment (reef flat, etc.) appears to serve as a fairly good indicator of that species' habitat preferences. A primary aim of this entire Sea Grant project has been to arrive at meaningful group-to-group (corals vs. algae vs. fish) comparisons of the distribution and abundances of the Kaneohe Bay biota.

The fishes were counted using a visual survey technique modified from Brock (1954). Since many of the stations were located in areas which were very heterogeneous on a localized scale, a 500-foot-long transect line as used by Brock would have sampled several distinct habitat types (sand, rubble, live coral, etc.), and this would have invalidated comparisons of the fishes with the benthic plants and animals that were censused simultaneously. A 20-m by 6-m sampling area was chosen as being most suitable for our purposes. The length of the fish transect line (20 m) and the width of observation (3 m on either side of the line) were chosen as being wide enough to give a reasonable sample, but narrow enough to be unaffected by water visibility (which seldom fell below 3 m). With the above method of sampling, it was not possible to sample either secretive or nocturnally active species of fish. Additional descriptions of the Kaneohe Bay fish fauna can be found in Gordon and Helfrich (1970), Wass (1967), Baldwin (in preparation), and Section VII B of this Atlas.

Two important fish genera presented particular sampling problems. Because of the difficulty of distinguishing in the field the juveniles of the three common species of *Scarus* in the Bay (*S. sordidus*, *S. dubius*, *S. perspicillatus*), these forms have been collectively reported as "*Scarus* spp.". While such a practice is to be avoided whenever possible, it is not without precedent for this genus (Wass, 1967; G. Losey, pers. comm.). Owing to the apparently similar distribution and habitat requirements of the juveniles of these species, it is also unlikely that this practice has introduced serious errors into the ecological implications of our analyses.

Another sampling problem involved enumerating the goby, *Psilogobius mainlandi*. This species is commensal with at least two species of alpheid shrimps in the burrows which the shrimp build in the sand (Baldwin, 1972). However, not all of the burrows in a given area

contain *P. mainlandi* (or the shrimp), and the gobies generally dart back into their burrow far in advance of the observer. Thus, while *P. mainlandi* was frequently seen in certain sand-flat environments, it was not possible to arrive at a reasonable estimate for the number of individuals of this species at a given station. We have therefore recorded only the presence of this species, rather than its abundance at each station.

As noted above, our method of sampling the fishes did not include a count of the cryptic or nocturnally active species. The failure to sample these groups has introduced certain biases into the data reported below. For example, the preponderance of individuals observed were either benthic herbivores or benthic omnivores, both of which tend to be active during the daylight. On the other hand, many carnivorous species tend to be active at night. Thus, common reef carnivores such as the cardinalfishes (Apogonidae) and squirrelfishes (Holocentridae) are poorly represented in our data. Secretive species such as the eleotrid, *Asterropteryx semipunctatus*—which is probably present in most of the reef environments of Kaneohe Bay—and cryptic fishes such as some of the rockfishes (Scorpaenidae) are also underrepresented in our data.

Wass (1967) has compared the results of visually counting the fishes living on a patch reef in Kaneohe Bay with those that he obtained by surrounding the same reef with a net and collecting the fishes by poisoning them with rotenone. He found only a moderate relationship between these two methods of sampling. He concludes, as did Brock (1954), Bardach (1959), and Randall (1961), that provided the limitations and biases of the visual-counting technique are recognized by the investigator, this technique is still probably the best method available to the fish ecologist for censusing a fish fauna with a diversity of habits and habitats such as is found on most coral reefs.

The considerations discussed above should be borne in mind when interpreting the data presented below, and the reader is cautioned about extrapolating our results to other areas in the Hawaiian Islands or to data collected by other means.

Diversity, Distribution, and Abundance

Figure 27 shows the fish fauna diversity, in terms of the number of fish species per station. The pattern is not unlike that for corals (Figure 17), many of which serve as "vertical relief" for fishes. There are generally more species of fish in the northern quarter of the Bay, no doubt due in part to the generally more favorable water and substrate conditions there, and to large areas of unsuitable habitat (lagoon floor and reef tops) in the inner portion of the Bay.

The two diverse areas (20-plus species) that occur in the inner portion of the Bay are also of interest. Both of these high-diversity areas are located directly shoreward of the channels at either end of the barrier reef, suggesting that the conditions which might reasonably be expected to occur in those two areas (e.g., increased water circulation and wave action) tend to increase the diversity of fish species to a level comparable with areas seaward of the barrier reef. While the nature of the bottom differs between these two inner high-diversity areas and the outer high-diversity areas, the amounts of bottom not covered by sand and mud (Figures 8 - 11) and vertical relief are comparable. This further suggests that the sluggish circulation of the inner Bay, and the resultant decrease in water quality, may have acted (and continues to act) to reduce the amount of suitable habitat for many fish species.

The abundance of fishes (Figure 28) also is strongly influenced by "vertical relief", with stations showing over 100 fish being largely associated with reef edges.

Figures 29 - 36 present the distributional patterns for eight common reef fish species which have been selected as representative of the Kaneohe Bay fish fauna as a whole. Figures 29 and 30 show the distribution of two common wrasses (Labridae) *Thalassoma duperreyi* (hinalea lau wili) and *Stethojulis axillaris* (o'maka) respectively. Both of these species are apparently omnivores (Hiatt and Strasburg, 1960; Wass, 1967; Key, unpublished data), and both have very similar distributional patterns, showing a moderate preference for the northern part of the Bay. However, their average abundance (Table 1) in these areas of occurrence differs considerably. With the exception of the patch-reef tops for which there are very few samples, *T. duperreyi* shows only a slight preference for the lagoon reef-slope environment and is otherwise fairly evenly distributed throughout these five environments. *S. axillaris*, on the other hand, shows a marked preference for the high-energy reef flat and fore-reef environments. Thus, while the distributions of these two species are quite similar on a presence - absence basis, *S. axillaris* shows an apparent preference for the outer portion of the Bay.

Figures 31 - 33 present the distributional data for three other common reef species. *Scarus* spp. (uhu) and *Acanthurus triostegus sandvicensis* (manini) are both benthic herbivores, while *Chaetodon miliaris* (lauhau) is a benthic carnivore (Key, unpublished data). *Scarus* spp., which is by far the most abundant "species" observed in our census of Kaneohe Bay, is most abundant in the fringing-reef top and lagoon-reef slope environments, although it is not uncommon elsewhere (Table 1). In relative abundance, however, *Scarus* spp. tends to avoid the fore-reef areas seaward of the barrier reef. Since the larger parrotfishes, especially *S. perspicillatus*, were only observed in our census at those stations seaward of the barrier reef, age-specific differences in the distribution of the three species of the genus *Scarus* may exist.

The manini (*Acanthurus t. sandvicensis*) shows a marked preference for the ocean-reef environments, again with the exception of the patch-reef top environment. It tends to be least abundant in the reef-slope environment, where *Scarus* spp. is most abundant. While juvenile *Scarus* and manini of all ages appear to feed on the same general food items (filamentous algae), insufficient data exist to demonstrate whether the differences in abundances of these fishes are due to competition for food or some other factor.

The distribution of *Chaetodon miliaris* is typical for a species which occurs in all the environments of Kaneohe Bay, but is not particularly abundant in any of them. Nor does this species show any particular preference for a given environment.

Figures 34 and 35 present the distributions for two plankton-feeding damselfishes (Pomacentridae), *Abudefduf abdominalis* (maomao) and *Dascyllus albisella* (aloiloi). Both these species tend to avoid the high- and low-energy reef flats, *Abudefduf abdominalis* slightly more so than *Dascyllus albisella*. This same distributional pattern is reflected in the abundances of these two species (Table 1), which tend to be higher in the deeper water areas of the barrier reef and along the reef slopes. This pattern of abundance is even more pronounced for *Chromis ovalis*, a planktivorous damselfish not shown in our maps. *C. ovalis* was only observed in the fore-reef environment, where it is abundant. Of course this pattern of distributions and abundances is to be expected of planktivorous reef fishes which generally require protective cover in close proximity to the deeper water in which they feed.

Both of these prerequisites are met in those environments in which these species occur and are most abundant.

Figure 36 demonstrates the distribution of a goby, *Psilogobius mainlandi*, which is totally restricted to a specific habitat, in this case, low-energy reef flats dominated by sand. *P. mainlandi* is absent from all other habitats and is absent from sand habitats in which the sand is unstable due to current or wave action. Thus, while Ahu o Laka Island and certain areas seaward of the barrier reef are nearly 100 per cent sand, they lack *P. mainlandi* because the sand is constantly being removed and redeposited.

As discussed above, it was not possible to enumerate *P. mainlandi* with our sampling method. However, general observations indicate that the areas of their relative abundances would be ranked: fringing reef flat > barrier reef flat > patch reef flat > lagoon reef slope > fore-reef. This also would constitute a ranking of the amount of suitable habitat in each environment.

The results of our fish-census work agree with the findings of other workers (Brock, 1954; Hiatt and Strasburg, 1960; Bardach, 1958; Randall, 1963; Wass, 1967) who have studied the distribution and abundance of coral reef fishes. In general, the greatest concentration of species and individuals was in areas where the amount of protective cover was the highest. Some species (e.g., *Scarus* spp., *Acanthurus t. sandvicensis*, *Chaetodon miliaris*) live and feed in these areas, while others move out from these areas to feed in the water column (*Abudefduf abdominalis*, *Dascyllus albisella*, *Chromis ovalis*) or on the surrounding bottom, the weke (*Mulloidichthys samoensis*). It is not known to what extent these populations move between adjacent areas of protective cover, but the consensus of our work and that of the above authors is that areas of deep water and/or featureless bottom generally act as barriers to the migrations of most reef species.

TABLE 1. AVERAGE ABUNDANCE OF
COMMONEST REEF FISH SPECIES IN KANEOHE BAY

Species	Mean Abundance, Measured as Number of Fish per Station				
	Lagoon Reef Flat	Patch Reef Flat	Fringing Reef Flat	Barrier Reef Flat	Fore Reef
<i>Pranesus insularum</i>	0.0	10.7	0.0	0.0	0.0
<i>Mulloidichthys samoensis</i> . .	0.0	0.0	0.8	2.1	0.7
<i>Paraupeneus porphyreus</i> . . .	0.3	0.0	<0.1	0.1	0.0
<i>Chaetodon miliaris</i>	1.0	1.1	0.4	0.5	0.3
<i>Dascyllus albisella</i>	6.0	3.9	1.0	1.4	6.4
<i>Abudefduf abdominalis</i>	7.8	0.1	1.9	0.7	10.2
<i>Pomacentrus jenkinsi</i>	0.2	1.1	<0.1	0.2	0.3
<i>Chromis ovalis</i>	0.2	0.0	0.0	0.0	22.1
<i>Labroides phthirophagus</i> . . .	0.5	0.4	0.1	0.0	0.0
<i>Stethojulis axillaris</i>	0.7	0.1	1.6	5.5	4.2
<i>Thalassoma duperreyi</i>	4.3	7.5	1.1	2.1	2.1
<i>Gomphosus varius</i>	0.7	1.8	0.2	0.1	0.0
<i>Scarus spp</i>	73.2	11.1	24.3	18.0	1.4
<i>Acanthurus triostegus</i>	2.4	0.1	2.1	8.2	4.8
<i>A. dussumieri</i>	3.0	0.0	0.0	<0.1	2.2
<i>Ctenochaetus strigosus</i>	1.0	0.4	0.3	0.0	0.6
<i>Zebrasoma flavescens</i>	1.6	2.5	<0.1	<0.1	0.2
<i>Psilogobius mainlandi</i>	-	-	+	-	-

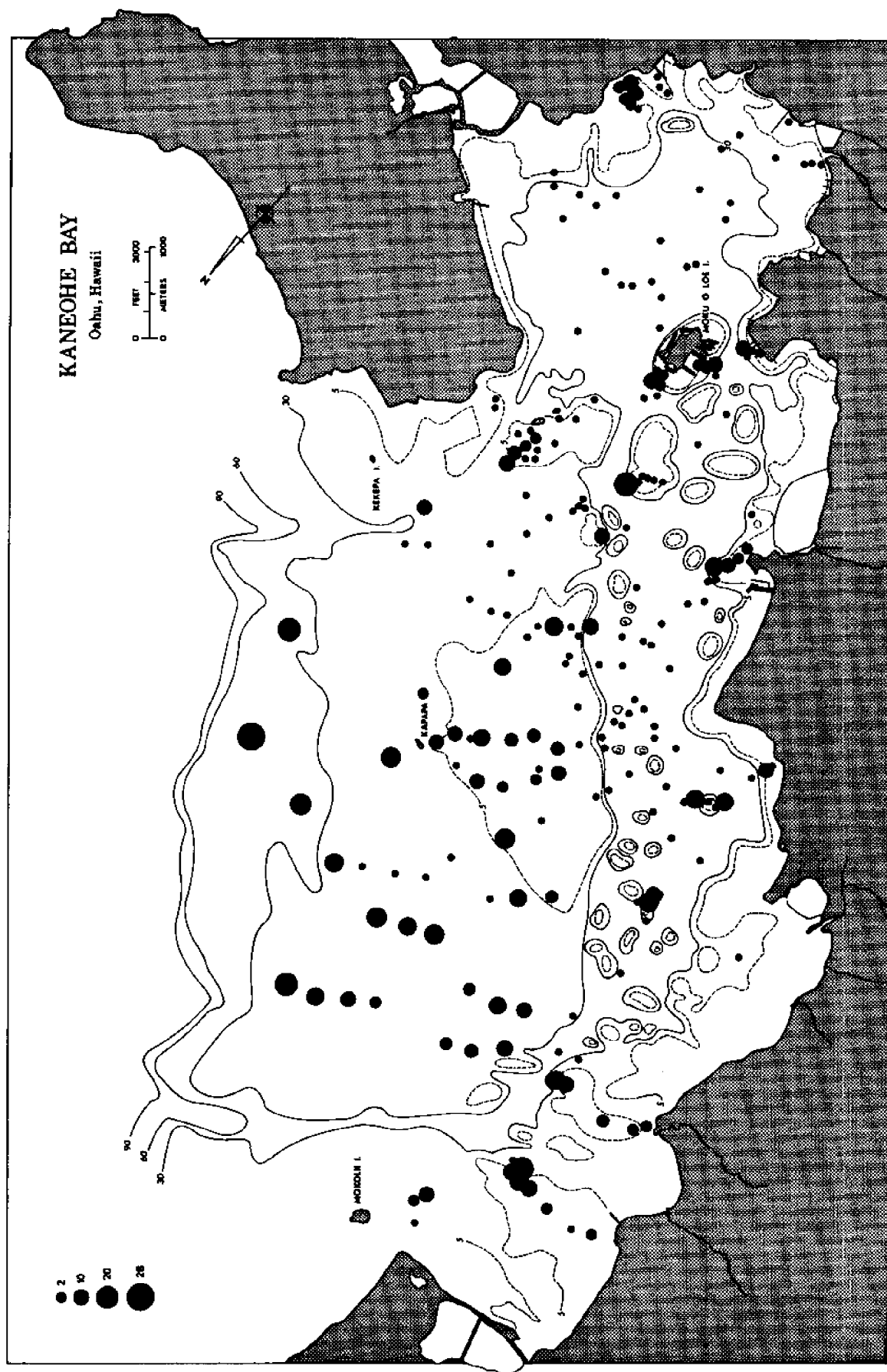


Fig. 27. Number of Species of Fish at a station

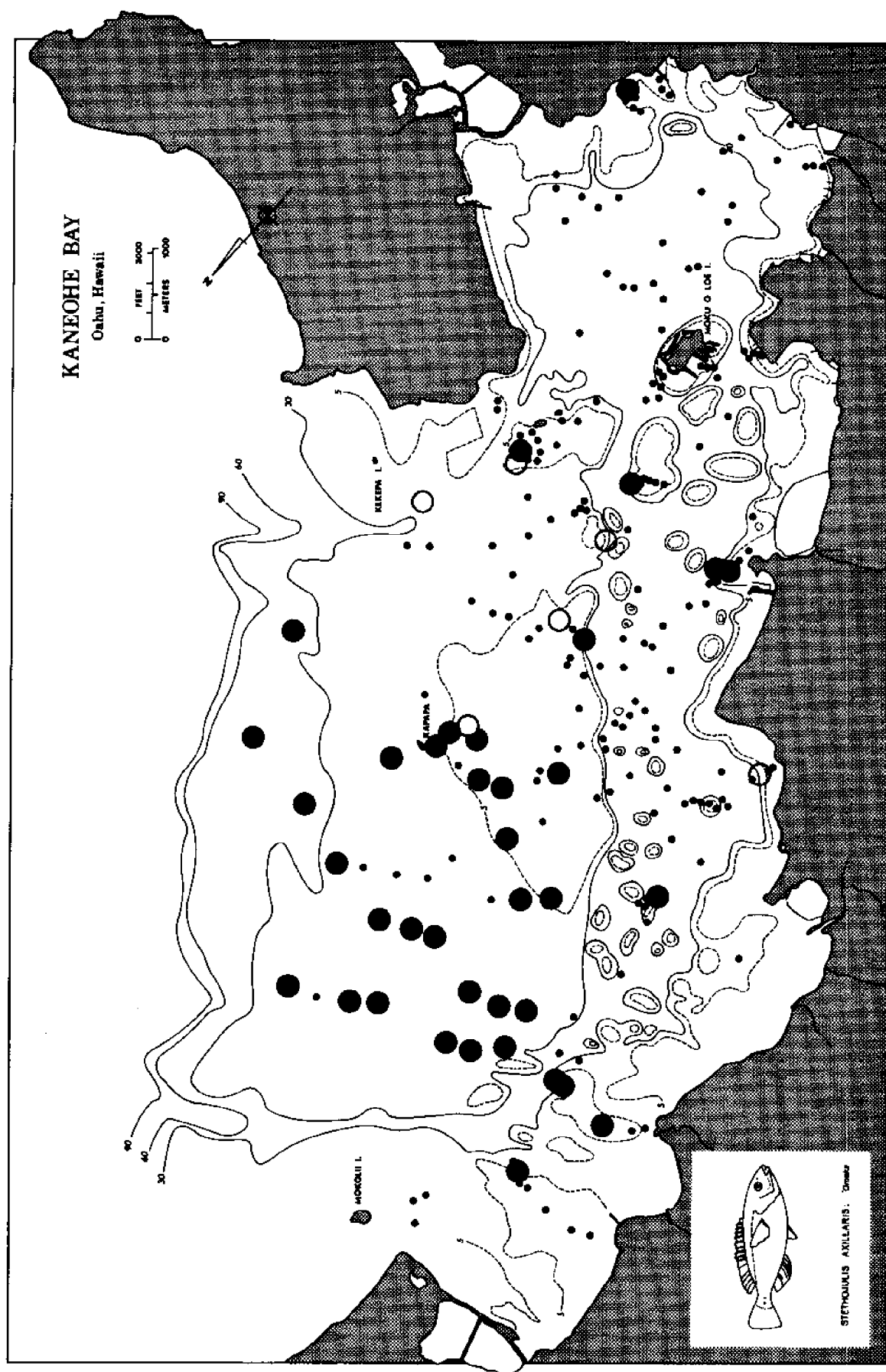
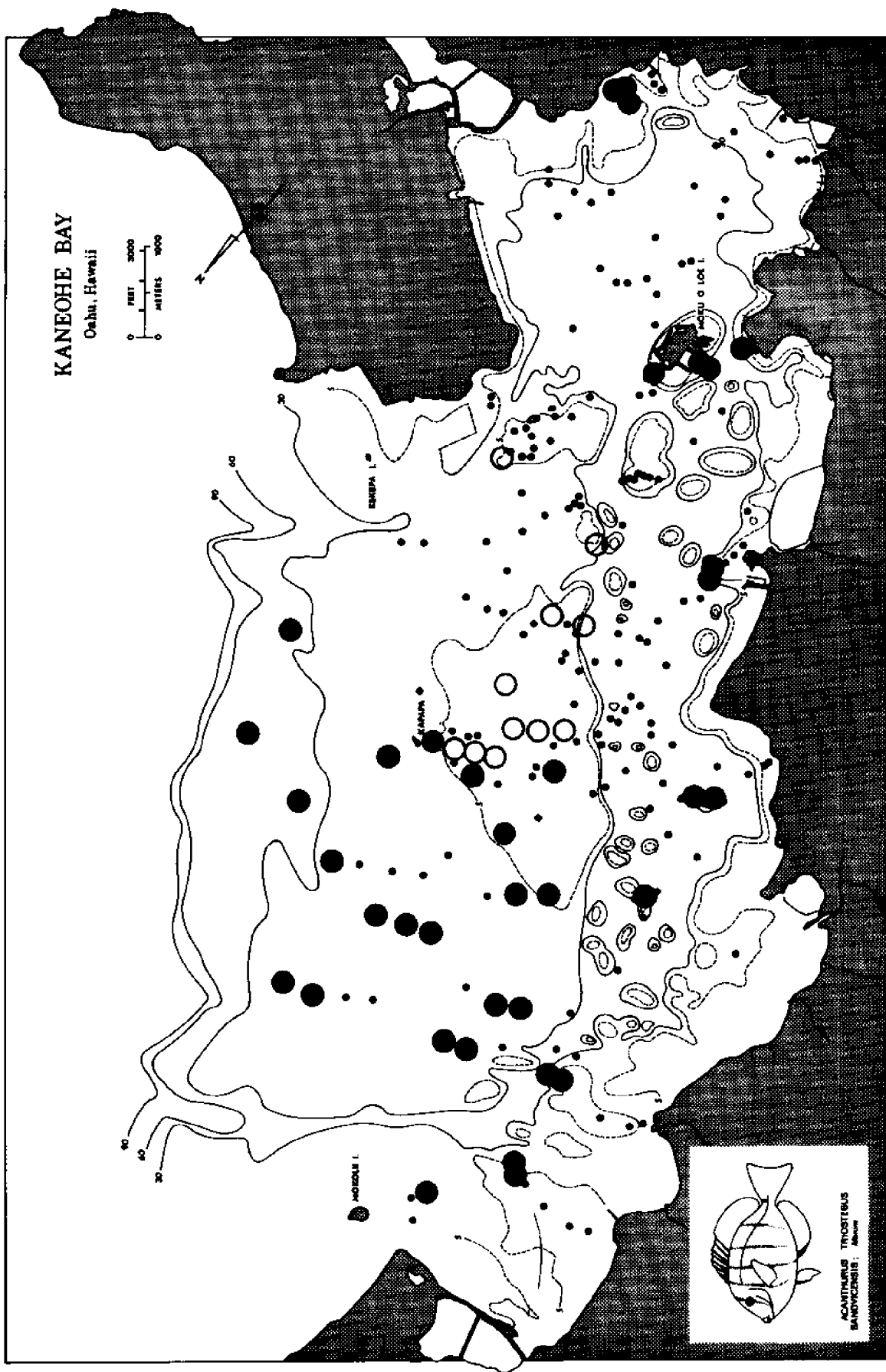


Fig. 30. *Streptococcus axillaris* P/A



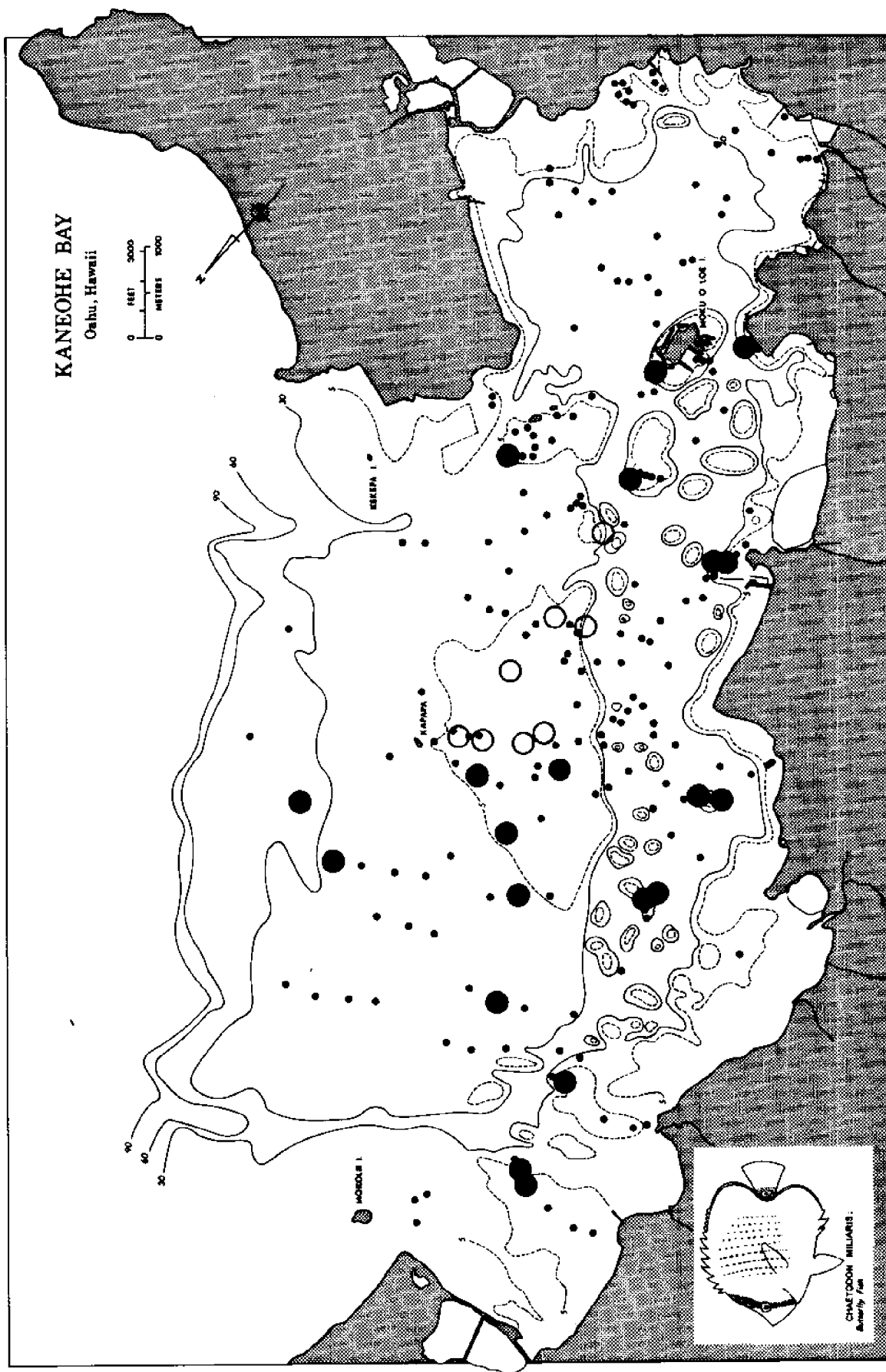


Fig. 33. *Chaetodon miliaris* P/A

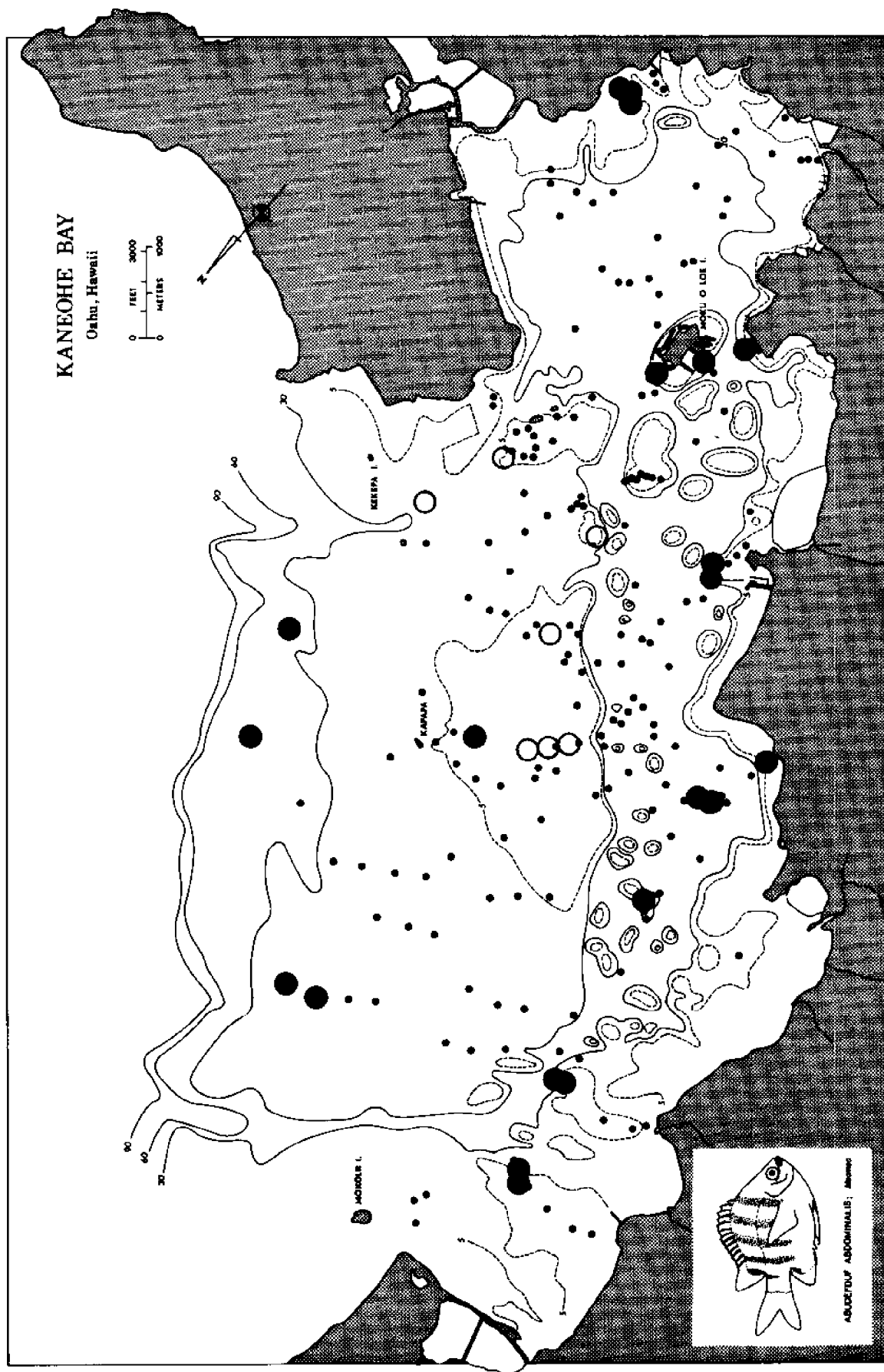


Fig. 34. Abundant abdominal P/A

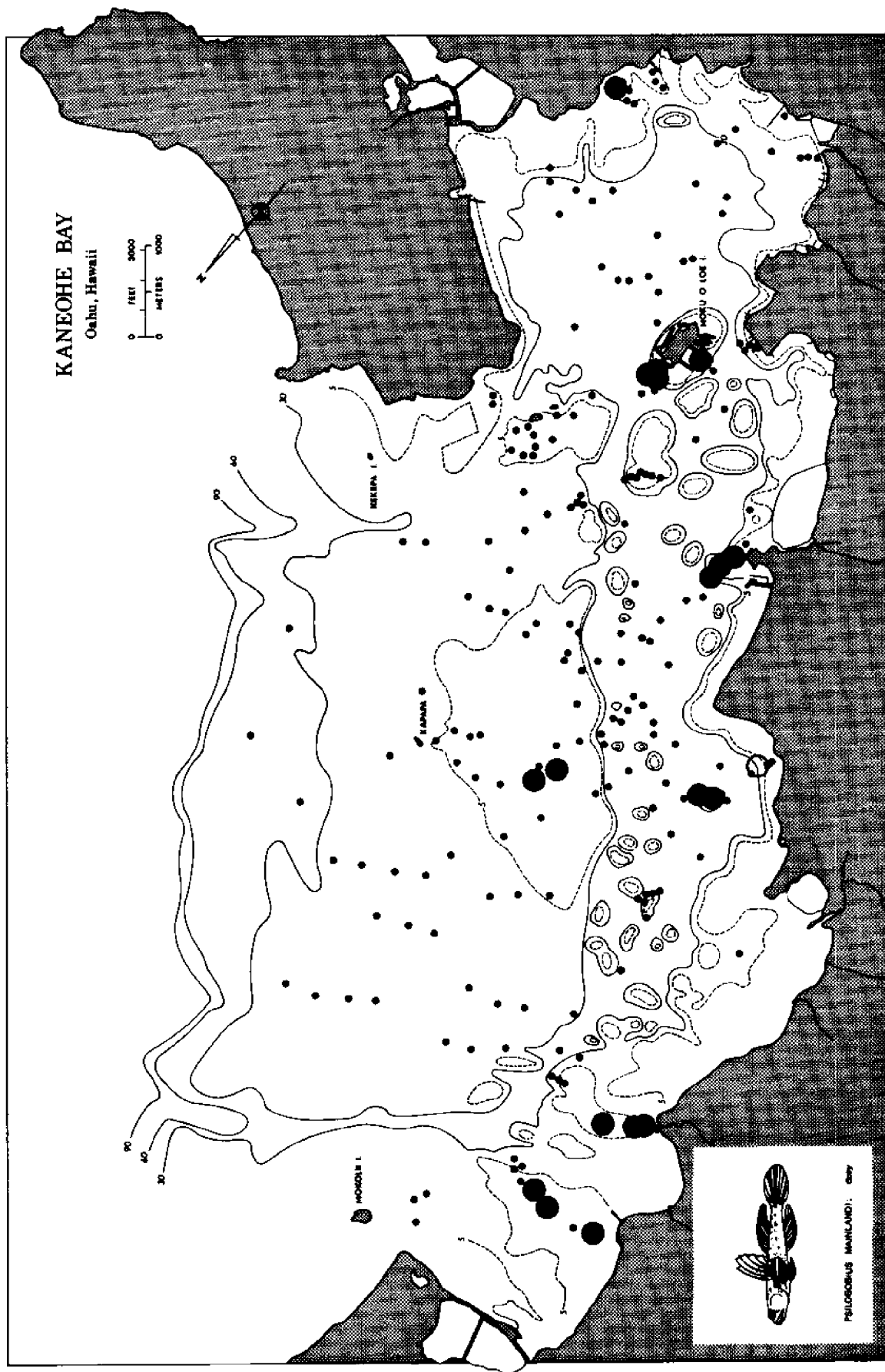


Fig. 36. *Psilogobius mainlandi* P/A

VI. D. Benthic Algae of the Bay

Aprilany Soegiarto

In the last four years, over 360 stations have been surveyed in order to determine the role of the benthic algal communities in the Kaneohe Bay reef complex. Eighty-seven species of benthic algae have been recorded from these stations. However, only 29 species were present at five per cent or more of the stations, and only 14 species at ten per cent or more of the stations.

Figure 37 shows the approximate number of species found in the surveyed area. Benthic algae reach maximum numbers of species in the high-energy surf zone around Kapapa Island. The number of species decreases in all directions from there. Toward shore the decrease is due, in part, to the diminishing water motion and associated changes in the substrate. Seaward of the high-energy reef flat, the decrease in diversity is due to the increasing depth and the consequent decrease in light.

At the lagoon edge of the barrier reef only five to ten species of algae are found; fewer still are found in the lagoon depths. In the fore-reef the diversity decreases rapidly below the breaker zone, but is more or less maintained at the five-to-ten species level to a depth of 15 meters. On the fringing and patch reefs the diversity normally is low, except where these reefs are directly exposed to the incoming surf.

Figure 38 shows the geographical distribution of total standing crop of benthic algae in Kaneohe Bay. As with the floral diversity, the standing crop of benthic algae on the barrier reef reaches its maximum value (over 250 g dry weight/m²) in the surf zone, and generally decreases in all directions. On the fringing and patch reefs the standing crops are generally low. Exceptions to this are the inner reefs which are exposed to wave action, and the reefs of the central lagoon where almost uni-algal stands of *Dictyosphaeria cavernosa* occur on the steep reef slopes (Figure 49).

Sargassum echinocarpum (limu kala-lau-nunui), a brown alga (Figure 39), is one of the four species of *Sargassum* found in Hawaiian waters, and it is the most common one. In Kaneohe Bay it is found mainly in high-energy environments, although it has been observed growing relatively well in calm waters. The standing crop of *S. echinocarpum* is large in the high-energy zone (Figure 40). It reaches its maximum in winter months, decreasing markedly in early spring, and reappearing gradually during the summer. It serves as a host for a wide variety of calcareous and non-calcareous epiphytic algae.

Jania spp. (limu huluilio), a red alga (Figure 41), is one of the genera of sediment-producing articulate coralline algae. It normally grows epiphytically on other algae, although it may grow on rubble or other hard substrates. Its distribution is limited to high-energy environments, and it is absent from the southern part of the Bay. One of the epiphytic species, *J. capillacea*, demonstrates a marked seasonality in Kaneohe Bay. It appears in the fall months on species of *Sargassum*, increases in abundance, and its standing crop reaches a maximum of about 100 g dry weight/m² in late winter, and nearly disappears, along with its host, in early spring.

With few exceptions, the distribution of *Laurencia* spp. (limu palewawae), a red alga (Figure 42), in Kaneohe Bay is similar to that of *Jania*. Both are limited to high-energy environments, and are absent from the southern part of the Bay. *Laurencia* is an economically valuable seaweed.

Five species of *Dictyota* (limu lipoa), a brown alga (Figure 43), are known from the Hawaiian Islands. Of these, four are found in Kaneohe Bay. They normally grow epiphytically on larger algae, such as *Sargassum*, and are distributed similarly to their hosts.

Acanthophora spicifera is a red alga with no Hawaiian name (Figure 44) and has only recently "invaded" Hawaiian waters (Doty, 1961). This is why there is no Hawaiian name for this limu. At the present time this alga is very common, covering the shallow parts of Hawaiian reefs. In Kaneohe Bay it is widely distributed, growing best on sandy bottoms, and in calm waters (Figure 45).

Dictyopteris australis (limu lipoa), a brown alga (Figure 46), is one of three species of this genus found in Hawaii. This alga is generally responsible for the distinctive odor of "rotten" seaweed on Hawaiian beaches after heavy storms. In Kaneohe Bay *D. australis* is abundant in the high-energy reef flat and fore-reef environments, and it may cover much of the bottom at depths greater than 6 m (Figure 47).

Dictyosphaeria cavernosa (limu lipuupuu), a green alga, is widely distributed in the tropical Pacific and Indian Oceans and the Caribbean Sea. In recent years this large green alga has become a center of attention because of its response to eutrophication processes, such as those going on in Kaneohe Bay. Except for the southeastern part, *D. cavernosa* is widely distributed in the Bay (Figure 48). Its growth reaches phenomenal proportions on the walls of the patch and fringing reefs in the central part of the lagoon (Figure 49). In this part of the Bay, the standing crop may reach as much as 1000 g dry weight/m², as compared with 5 g dry weight/m², the average standing crop of this alga on the barrier reef.

With the exception of the southern part, *Hypnea* spp. (limu huna), a red alga (Figure 50), enjoys a wide distribution in the shallower portions of Kaneohe Bay. However, each species seems to have a distinct habitat. Some species grow epiphytically on larger algae, while others grow on rocky surfaces in the breaker zone. Due to its high content of agar, *Hypnea* is listed as one of the seaweeds of economic importance.

Because of its small size, *Polysiphonia* spp. (limu hawane or pu-'alu), a filamentous red alga (Figure 51), contributes little to the algal biomass in Kaneohe Bay. However, it is very common in the shallow portion of the Bay. Hollenborg (1968a and b) recorded numerous species of *Polysiphonia* from Kaneohe Bay. Most species grow epiphytically on larger algae, but some grow on sandy or silty bottoms.

The following algae, along with *Jania* discussed earlier, have skeletons of CaCO₃, and therefore contribute directly to the mass of the reef.

Padina japonica (limu pepe-iao), a brown alga (Figure 52), is the commonest species of this genus in Hawaii, and it is the one which is most highly calcified. *P. japonica* is widely distributed across the ocean-reef areas of the Bay. It grows on both sandy and hard substrates, reaching a maximum standing crop in the summer months, after the abundance of *Sargassum* decreases.

Halimeda is one of the most important sediment-producing green algae in tropical reef ecosystems. Its distribution includes all of the shallow warm waters of the world. In the Hawaiian Islands, *H. discoidea* (limu ekaha) is the most common species. In Kaneohe Bay it is primarily found on the ocean reef (Figure 53). Its standing crop varies from 1.7 g dry weight/m² on the fringing reefs, to over 75 g dry weight/m² on the barrier reef (Figure 54).

Hydrolithon reinboldii (no Hawaiian name), a red alga (Figure 55), occurs over the shallow-water portion of Kaneohe Bay, except the southeastern part. This species is the most important crustose coralline alga in the Bay. *H. reinboldii* tolerates a wide range of salinities—17 per mil to 50 per mil (Soegiarto, 1972). Normal salinity in Kaneohe Bay is about 33 per mil. This partly explains why this alga is able to grow on the fringing reefs, close to land, where salinities may drop markedly when it rains. *H. reinboldii* grows as a crust, completely surrounding dead coral and other rubble. It can be recognized by its rough surface texture and its greyish-purple to dark-purple color.

Porolithon gardineri (no Hawaiian name), a red alga (Figure 56), is another important species of crustose coralline algae. It is distributed primarily on the high-energy reef flats. In Kaneohe Bay, *P. gardineri* develops well in the north, where it covers over 10 per cent of the bottom.

Most of the known algal or "lithothamnion" ridges of the Indo-Pacific region are composed primarily of *Porolithon onkoides* (no Hawaiian name), a red alga (Figure 57). It is very abundant in Kaneohe Bay, being widely distributed across the reefs of the Bay, including the southeastern portion of the Bay, but there only in a dying state. This alga is pale to bright pink in color, and is crustose and chalky in texture. It grows on various hard substrates, such as dead coral and basalt rocks. It develops best in intertidal areas exposed to heavy surf.

Perhaps the three encrusting red algae discussed here lack Hawaiian names because the early Hawaiians did not recognize them as limu or algae.

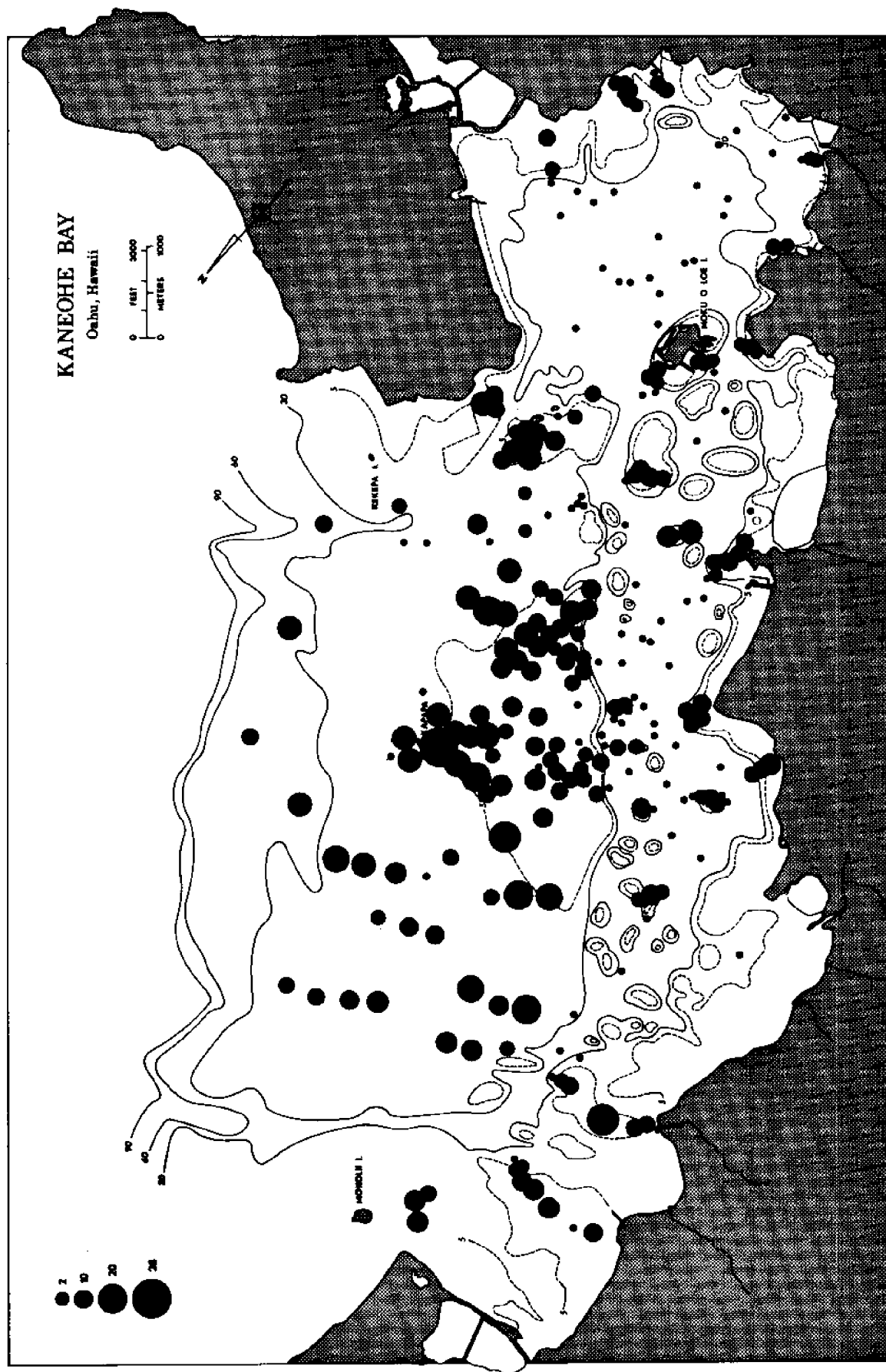
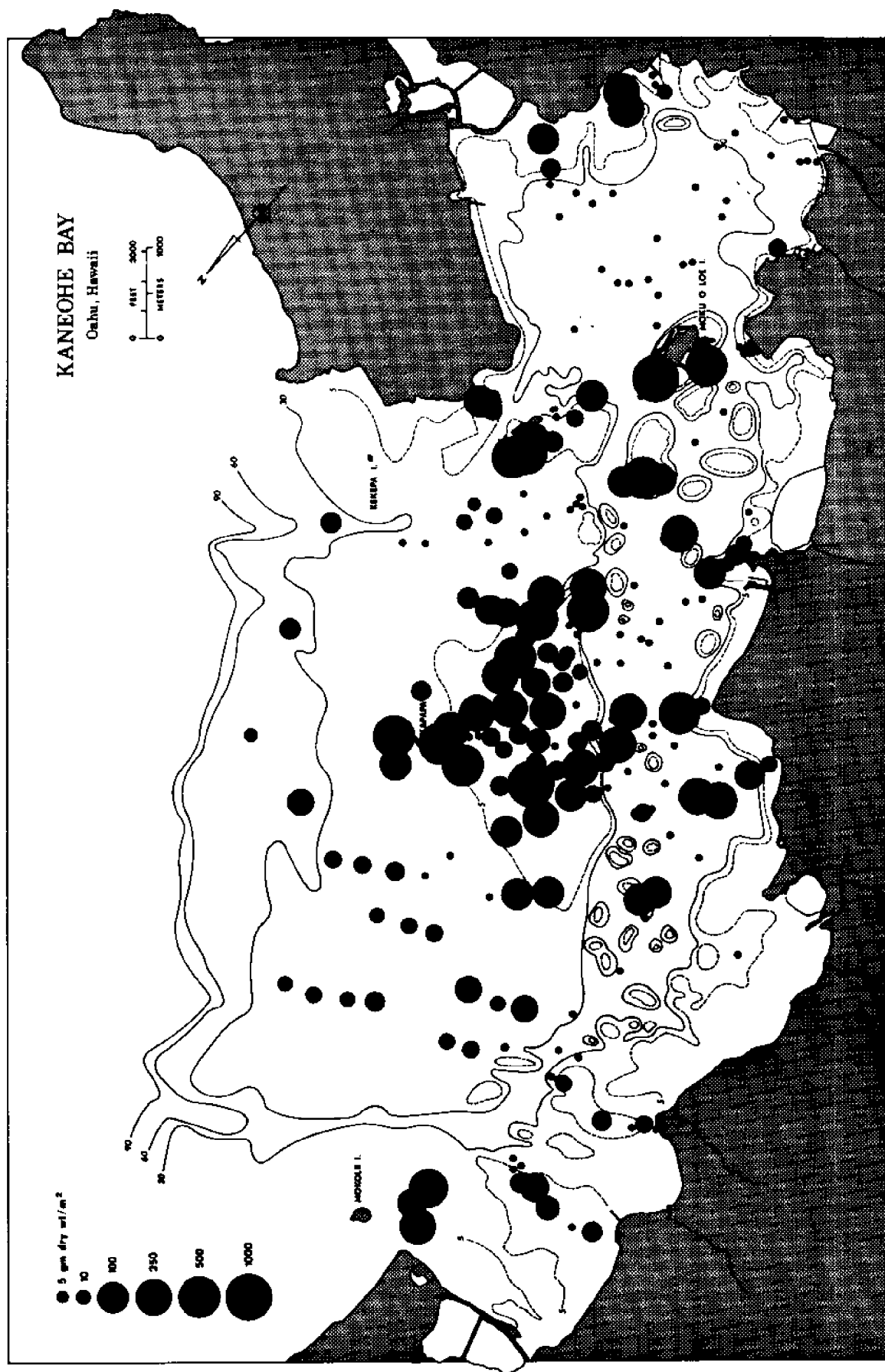
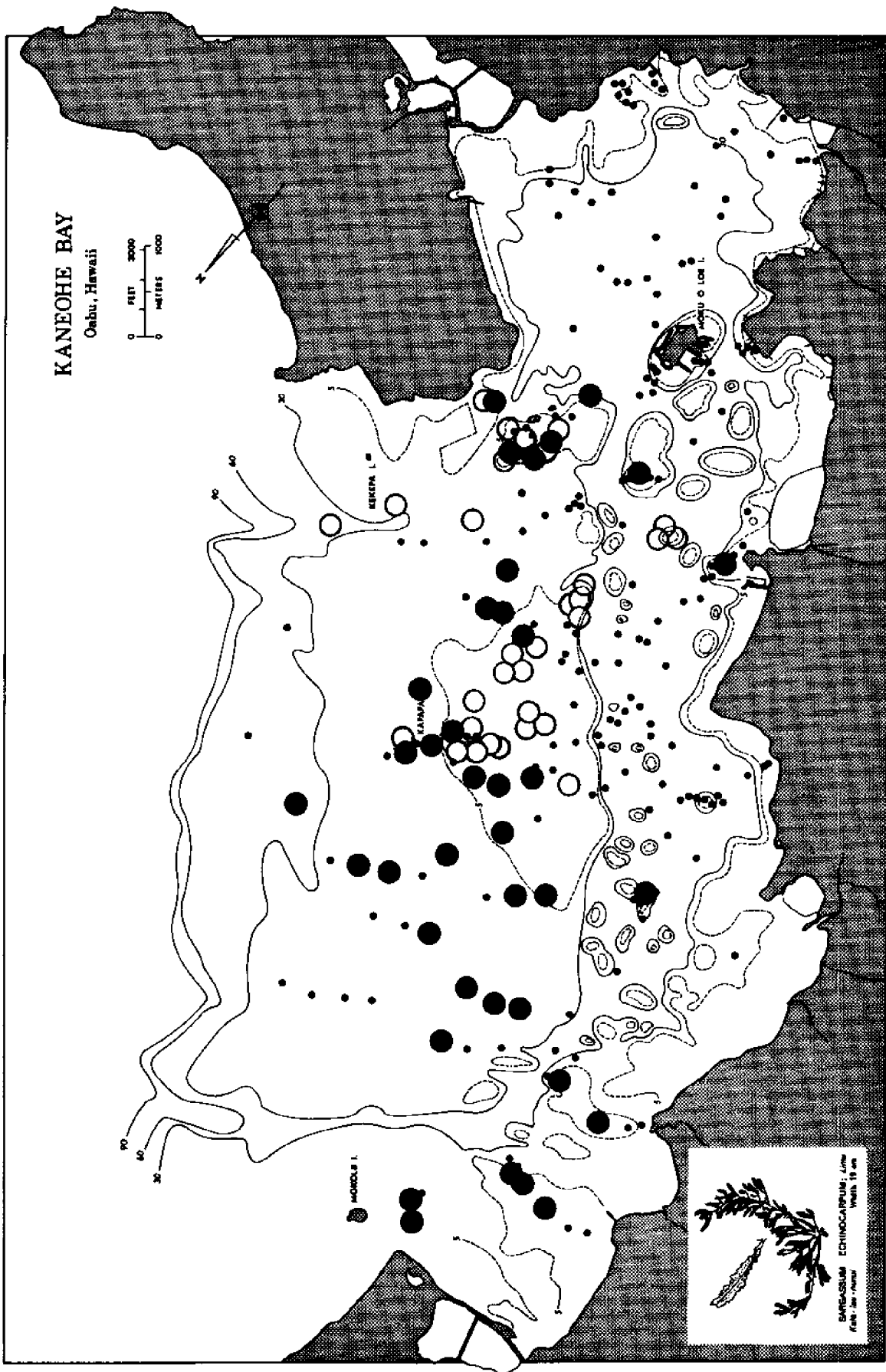
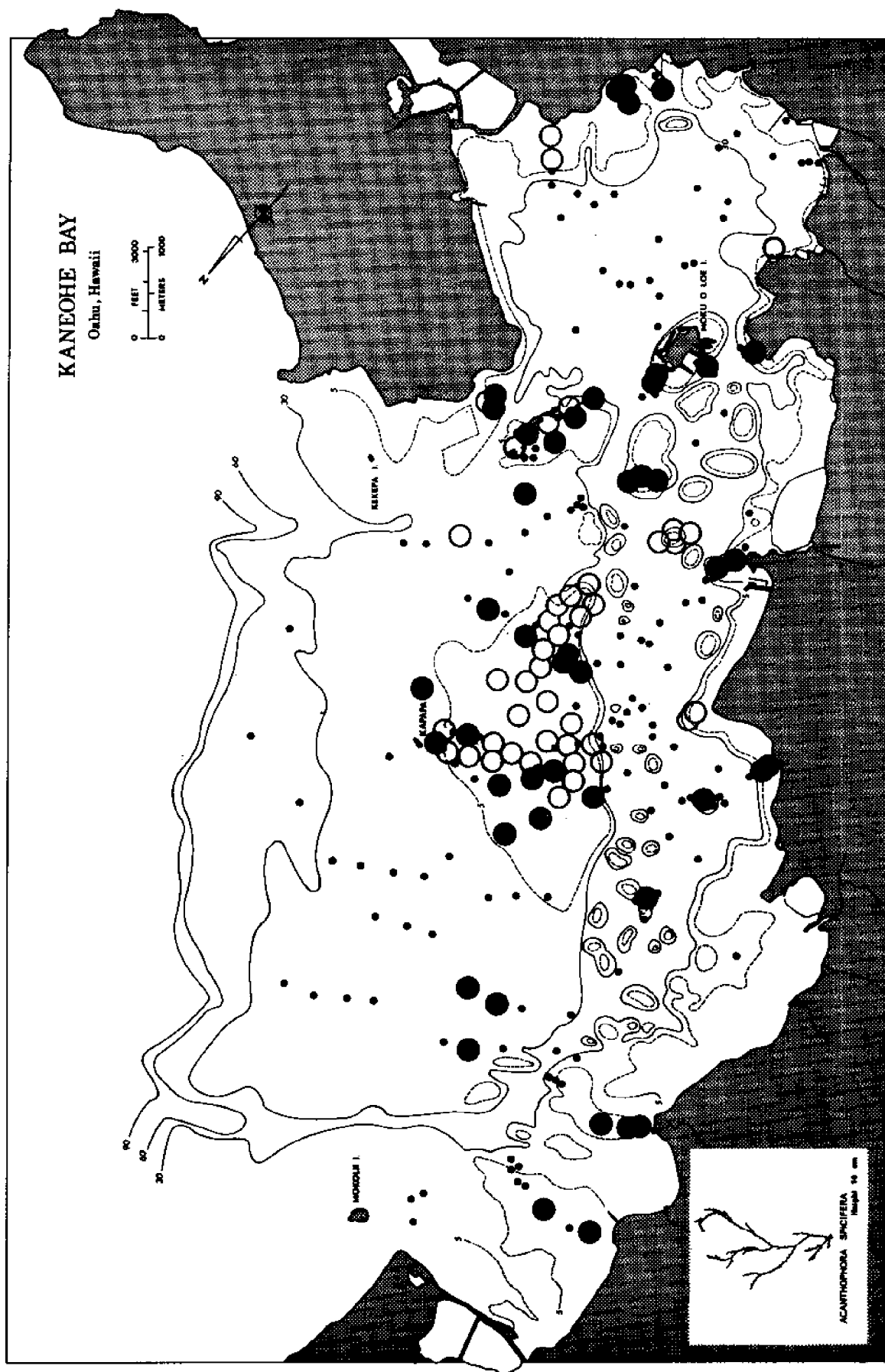
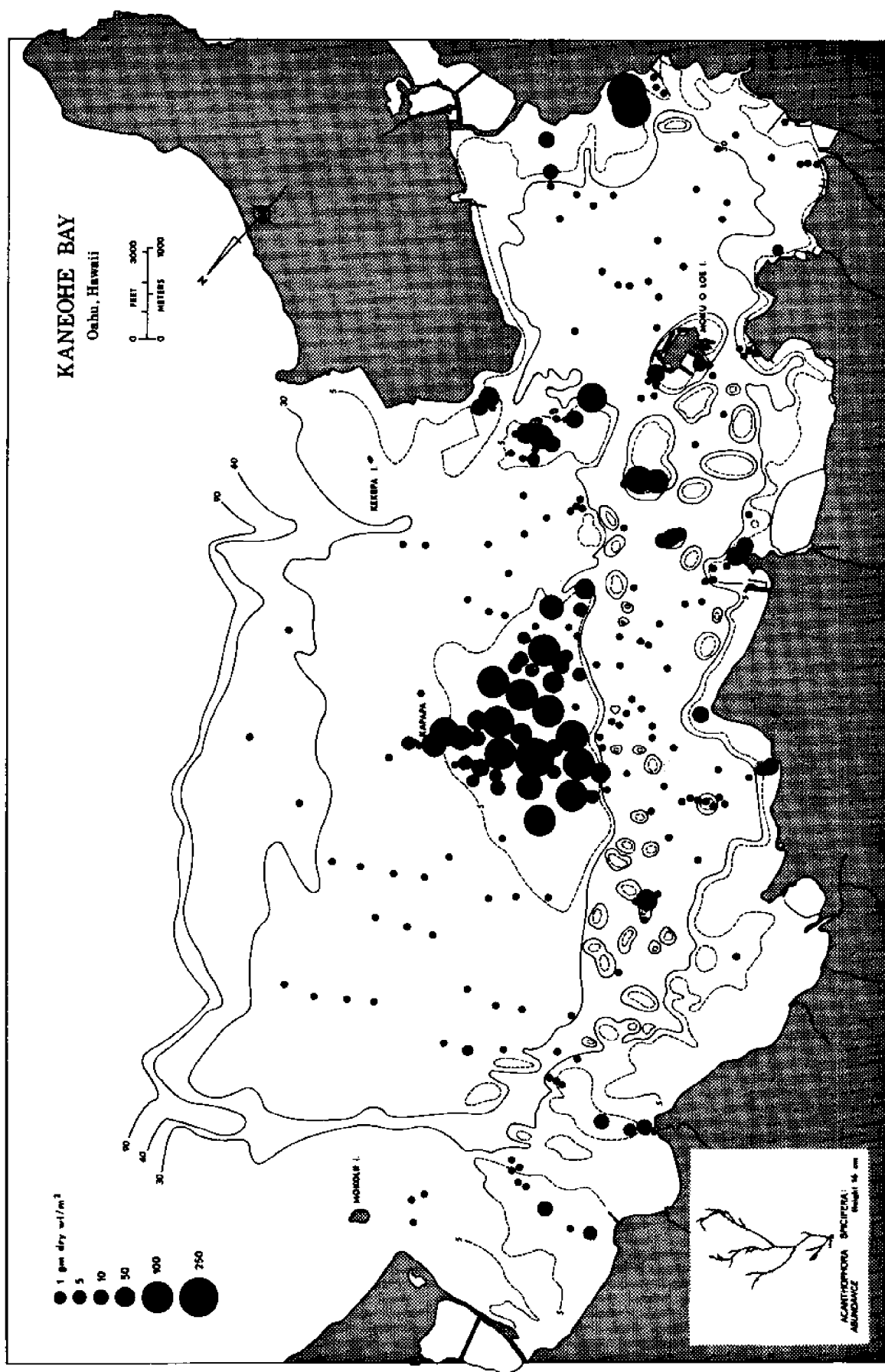


Fig. 37. Number of Species of Algae at a station









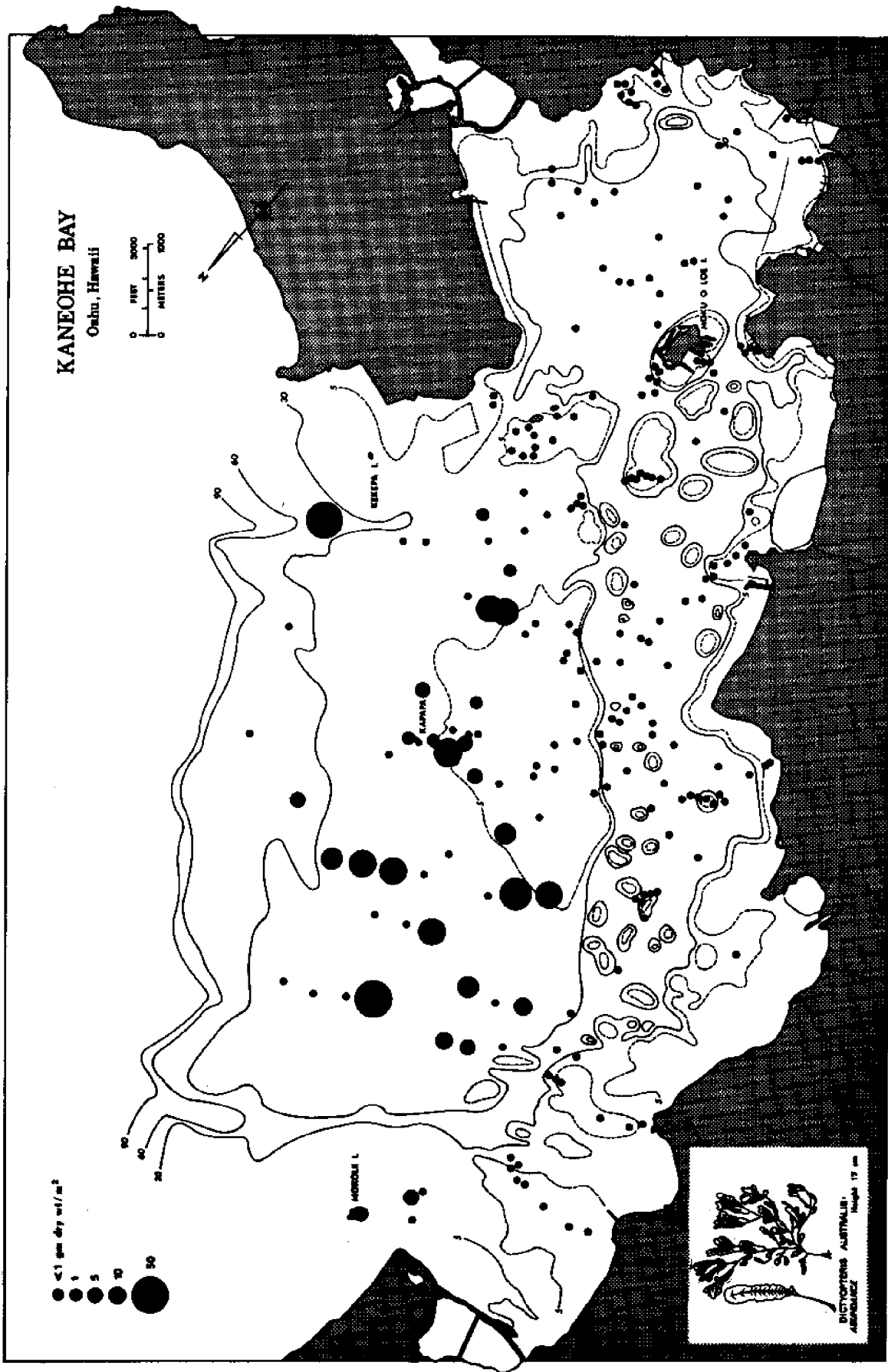


Fig. 47. *Dictyopterus australis*: abundance

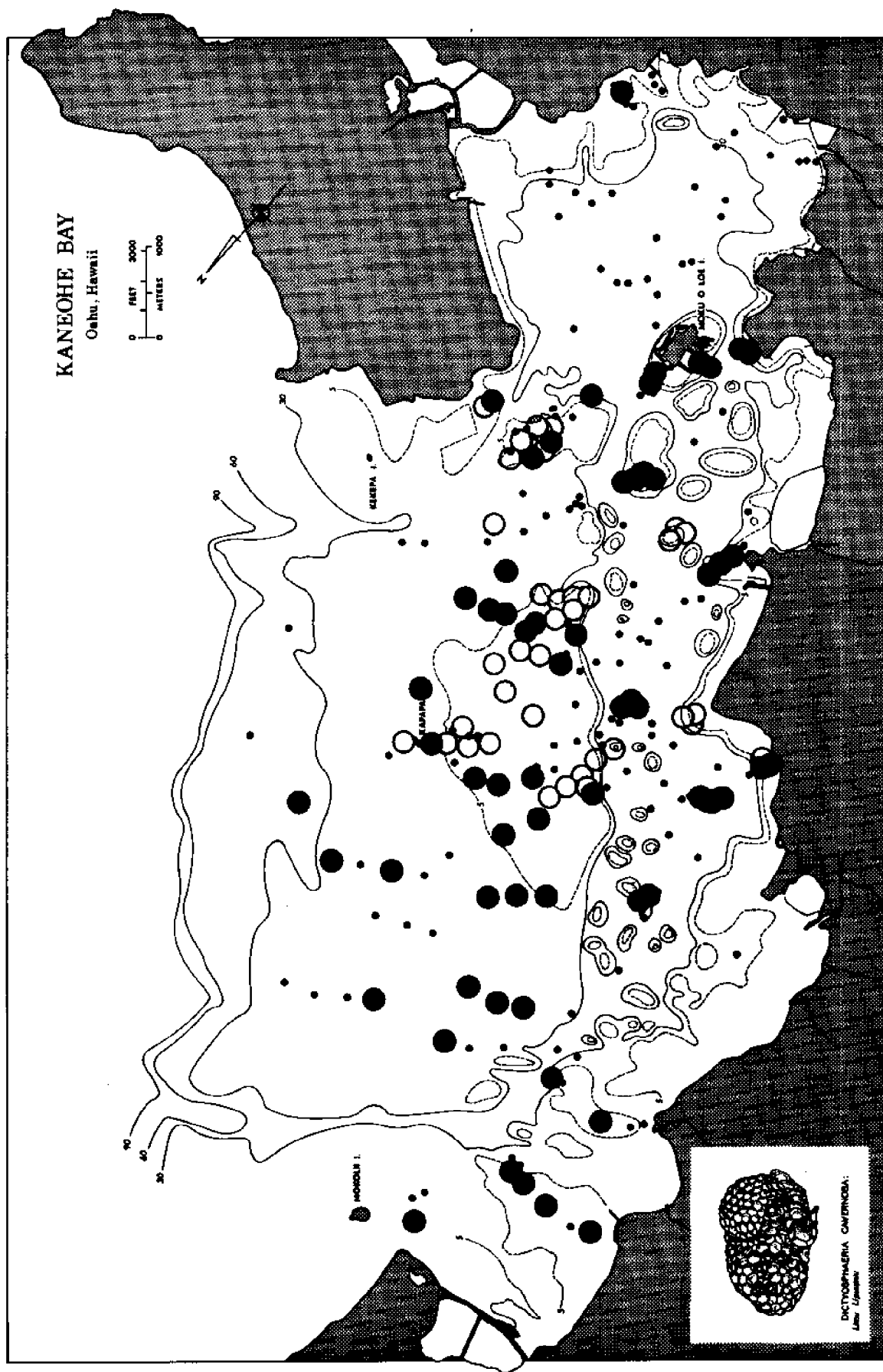


Fig. 48. *Dictyosphaeria cavernosa* P/A

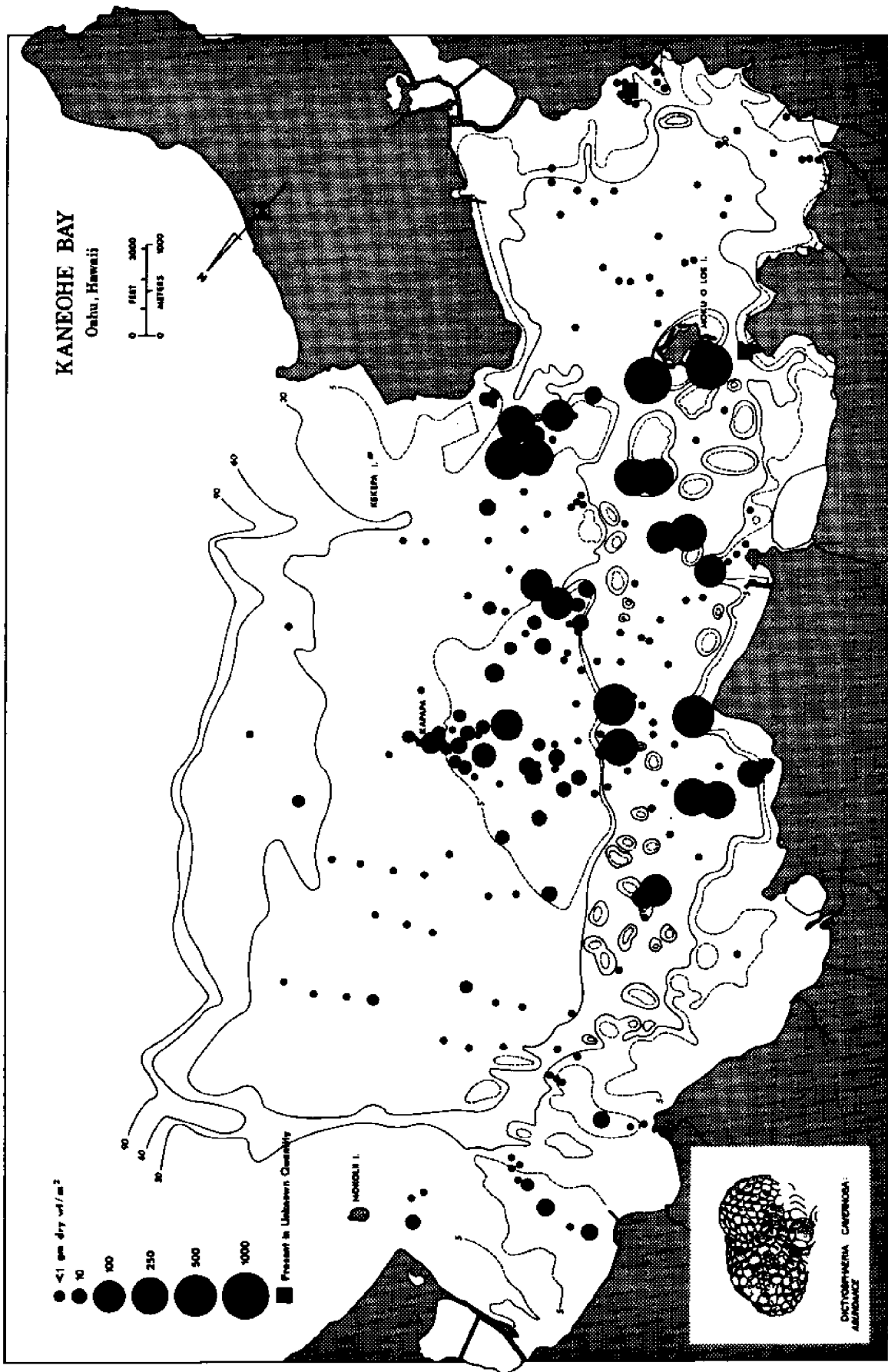
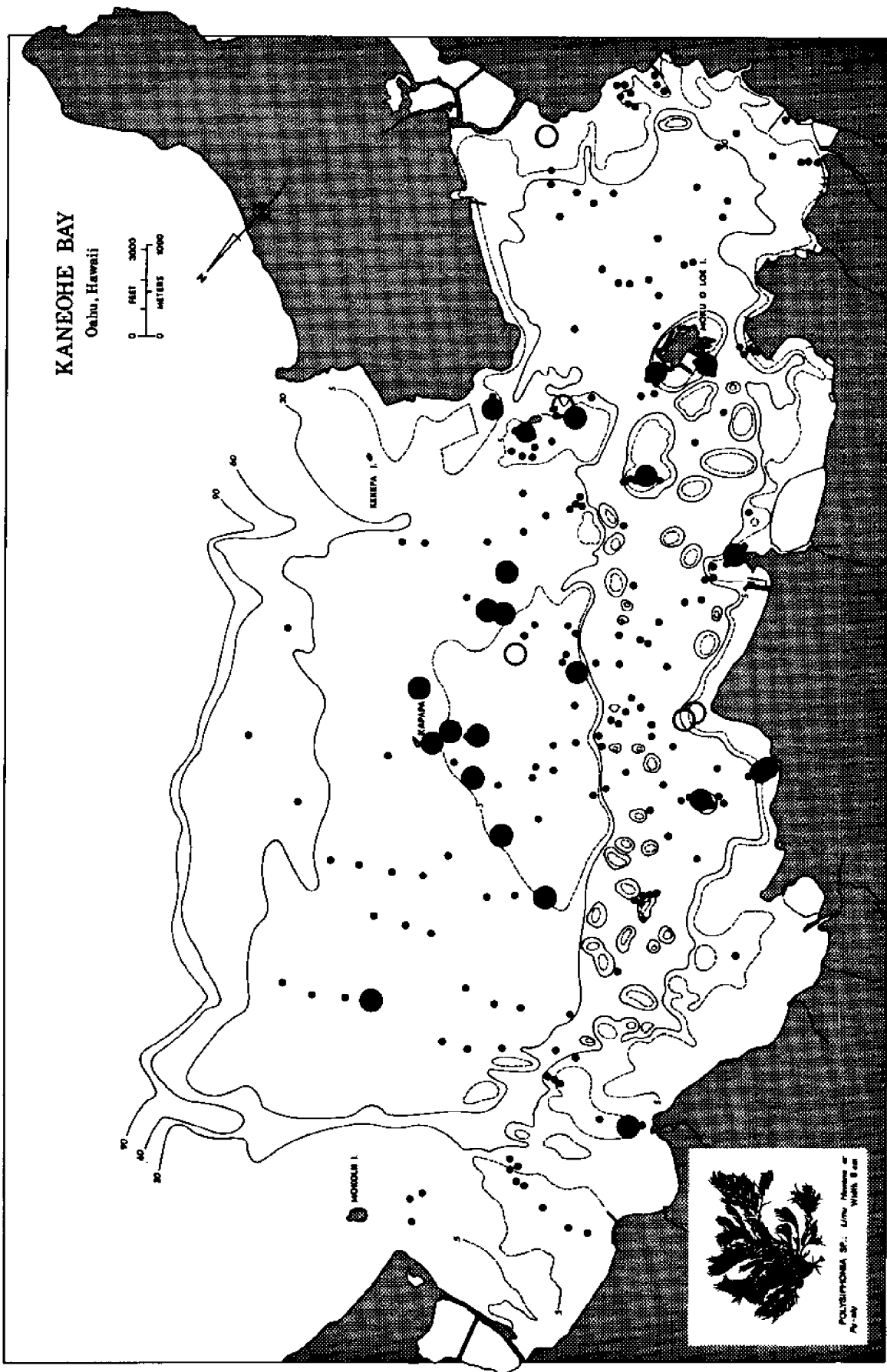


Fig. 49. *Dictyosphaeria cavernosa*; abundance



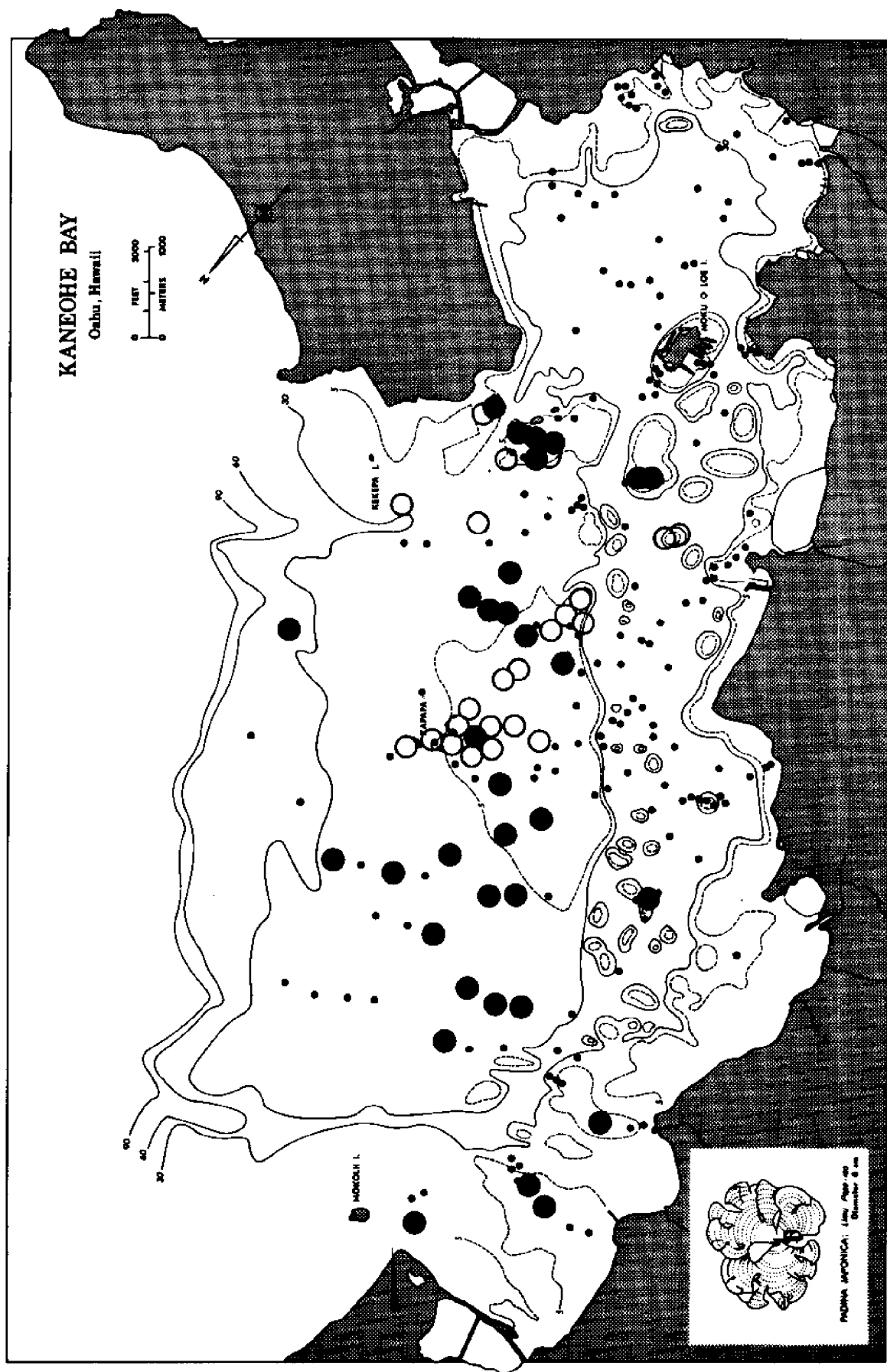


Fig. 52. *Padina japonica* P/A

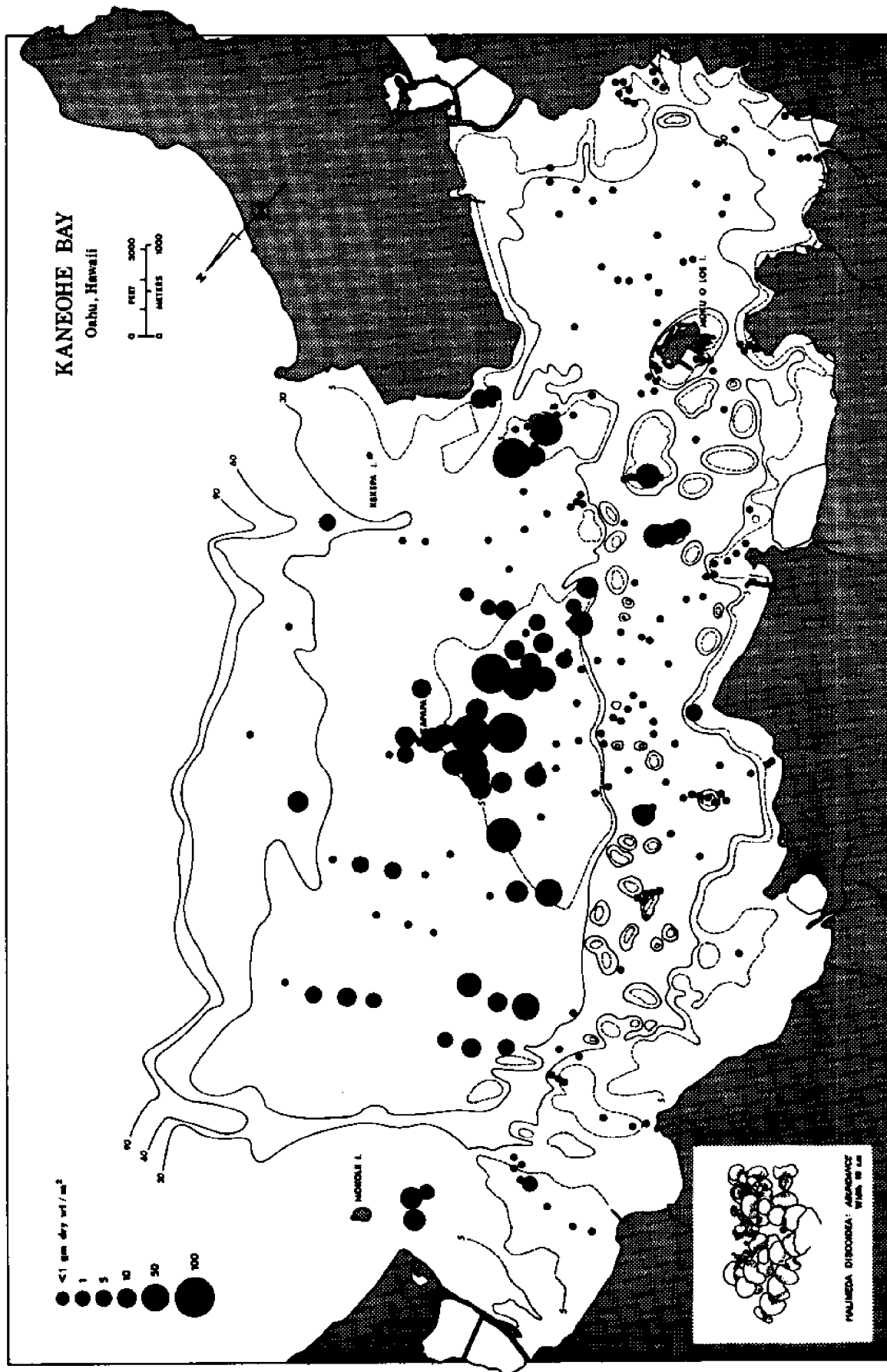
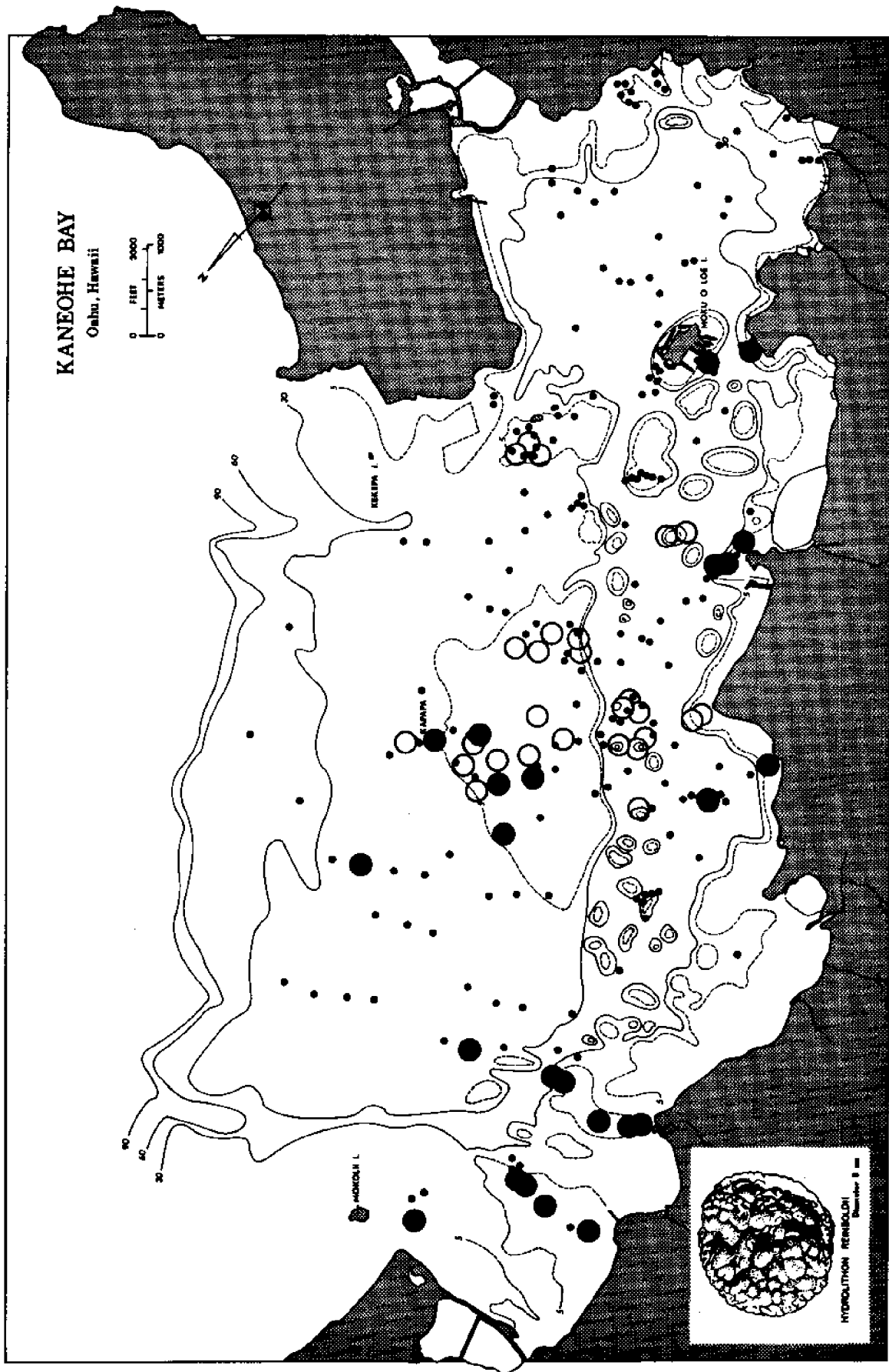
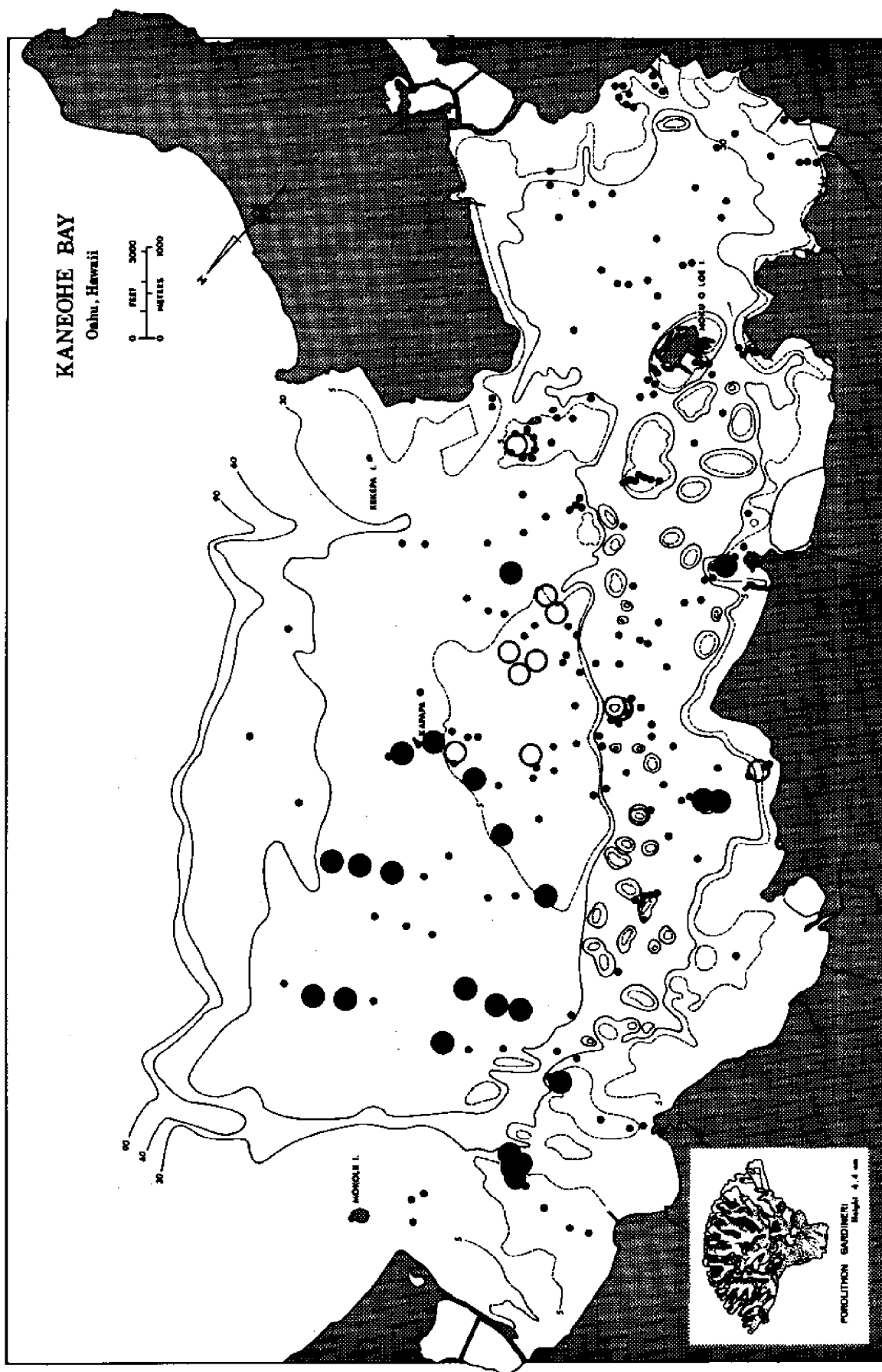
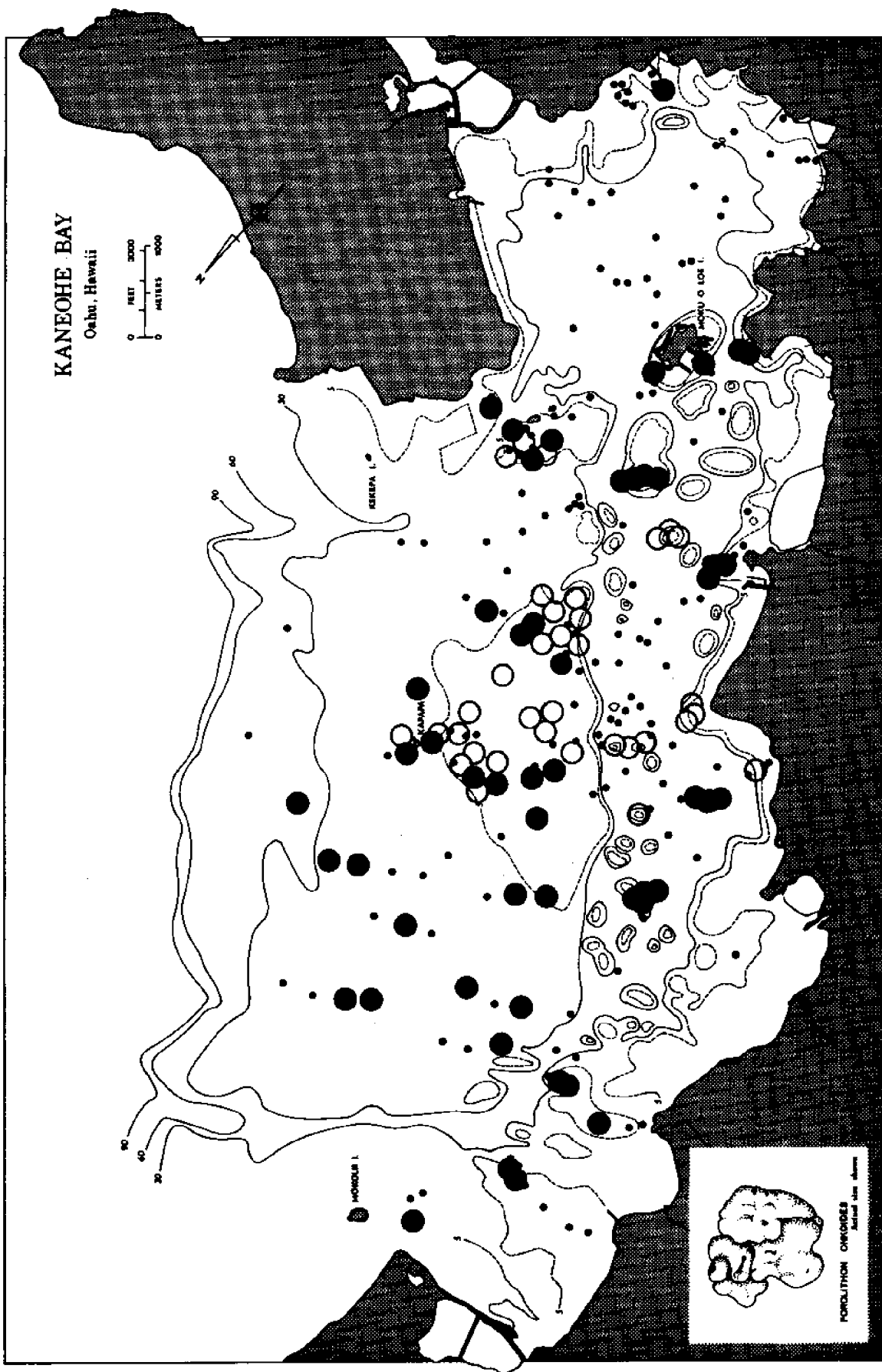


Fig. 54. *Halimeda discoidea*; abundance







VII. Other Surveys

Several biologists not directly associated with the Sea Grant coral reef project have made valuable surveys in Kaneohe Bay. They have generously contributed to this Atlas.

VII. A. Micromollusks

E. Alison Kay

Mollusks are of great value in ecological and paleo-ecological studies because they leave fossil remains identifiable to species. The remains of micromollusks—that is, of mollusks with shells less than 10 mm in greatest diameter—are of special interest in that they can be recovered easily from sediments in sufficient quantities for statistical analysis. Because the habits of many molluscan species are known, at least in the Hawaiian Islands, distribution patterns exhibited by these organisms are useful indicators of local environmental conditions. They provide a basis for the recognition of intertidal and subtidal communities, and certain types of bottom communities such as those dominated by frondose algae and those comprised of coral or rubble. Information on the trophic structure of the communities of which micromollusks have been a part can also be obtained from the patterns of distribution, by inference. This study explores some of the distribution patterns shown by several micromolluscan species in Kaneohe Bay, Oahu.

Surficial sediments from 41 stations in Kaneohe Bay were analyzed by sorting shells from 25- to 50-cm³ volumes of sediments under a dissecting microscope. The average number of shells occurring in the samples was 241; the range was from 1395 to 5. The shells were identified to species and the dominant species analyzed in terms of the assemblages in which they occurred and of their distribution within Kaneohe Bay.

The Kaneohe Bay micromolluscan fauna comprises approximately 80 species, of which about 72 are gastropods and 8 are bivalves. As is characteristic of most other marine ecosystems in the Hawaiian Islands, gastropods predominate both in numbers and species. The Kaneohe Bay gastropod:bivalve ratio of 90:10 has a somewhat higher proportion of gastropod species than occurs in the over-all ratio calculated for Hawaii of 82:18 (Kay, 1967).

Three assemblages of gastropods are distinguishable in Kaneohe Bay (Fig. 58). Two major assemblages exist within the inner Bay, a *Bittium/Obtortio/pyramidellid* assemblage characteristic of the reefs fringing the lagoon and of the patch reefs within the lagoon, and a *Rissoella* assemblage found on the inner barrier reef and in the channel in the southern part of the Bay. The outer bay within the barrier reef is characterized by a *Tricolia/Rissoina/Cithna* assemblage which follows a pattern almost the reverse of that of the *Bittium/Obtortio/pyramidellid* assemblage.

The composition of the outer Bay assemblages is shown in Figure 59. *Tricolia* is the dominant form at all the stations except for the outermost station. There is also a trend for *Cithna* to play an increasingly dominant role in the assemblages in the deeper waters of the outer Bay.

The proportions of the dominant species in the *Bittium/Obtortio/pyramidellid* assemblages are shown in Figure 60, which also shows that *Bittium* and the pyramidellids are not restricted in their occurrence to the inner Bay; their contribution to the outer Bay assemblages is, however, relatively small. Within the inner Bay there is a general tendency for the pyramidellids to become increasingly numerous toward the southern parts of the Bay, with the exception of the assemblages found at Moku o Loe Island.

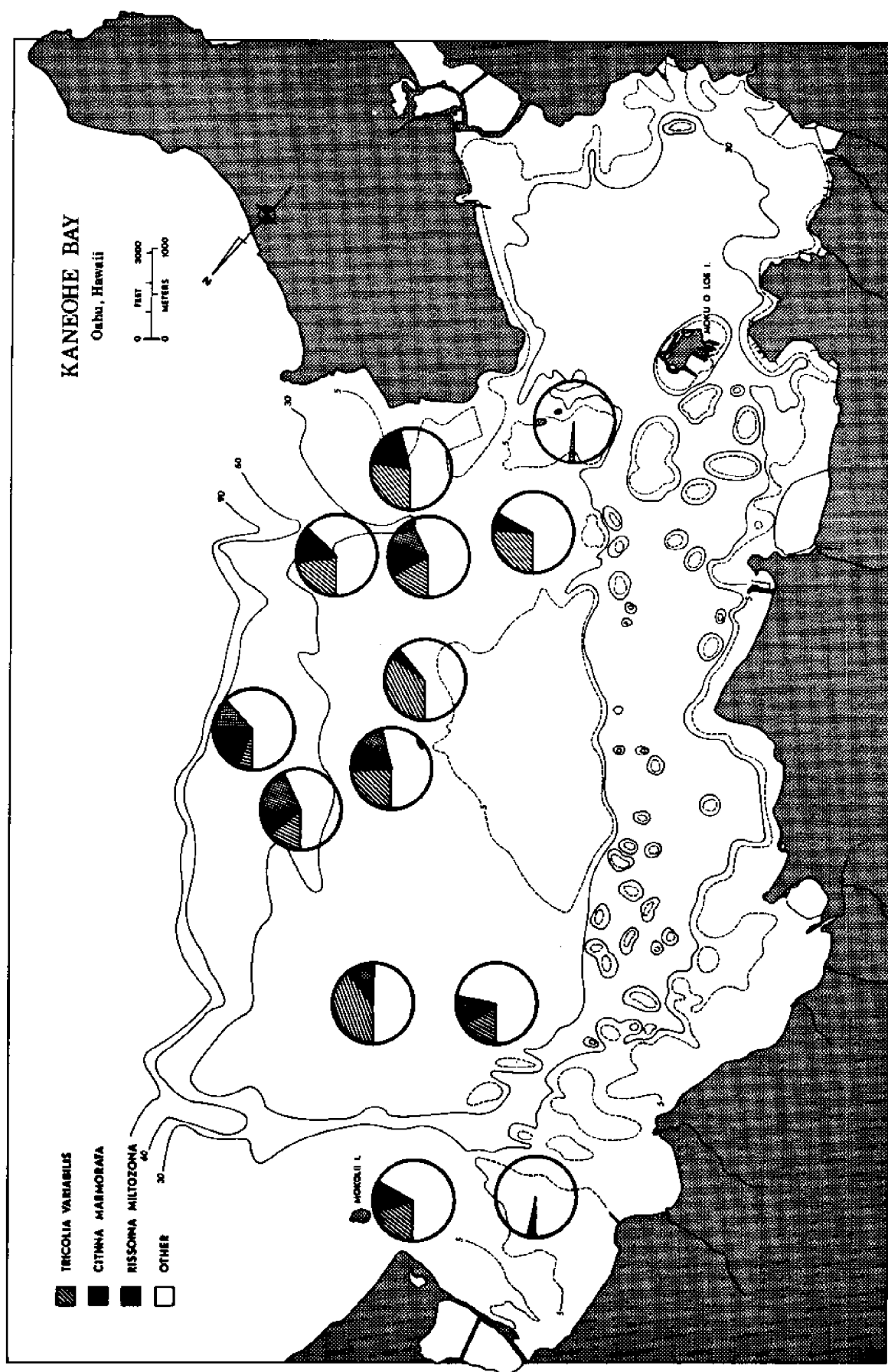
The *Bittium/Obtortio/pyramidellid* and the *Tricolia/Rissoina/Cithna* assemblages, although differing in species composition, are both represented by an average of about 30 species, with the exception of the southernmost Bay stations which averaged 9 species per station. When the average numbers of shells per volume of sediments are calculated, the *Tricolia/Rissoina/Cithna* and the *Rissoella* assemblages are more comparable, with 16.4 and 15.8 shells per cm³ respectively, than is the *Bittium/Obtortio/pyramidellid* average of less than 10 shells per cm³ of sediment per station. In the inner Bay there is a noticeable decline in both numbers of species and numbers of shells: only 1.6 shells per cm³ of sediment were recorded for the six stations in the southernmost extremity of the Bay.

The *Bittium/Obtortio/pyramidellid* assemblage is comprised of two mesogastropod herbivores and a pyramidellid which is presumably ectoparasitic. Observations elsewhere in Hawaii indicate that *Bittium zebrum*, the dominant species of *Bittium* in the assemblage, is a ubiquitous shallow-water intertidal form associated with rubble or loose rock substrate, where it feeds on small forms of algae. *Obtortio pupoides* also appears to be primarily associated with loose, rocky substrates; elsewhere in the Islands it is found only on fringing reefs. Pyramidellids are, for the most part, apparently ectoparasitic in habit, associated with sedentary invertebrates such as the mollusks *Ostrea*, *Crepidula*, and *Vermetus*, worms, and sponges. Although the feeding habits of the dominant pyramidellid in the assemblage, *Odostomia oodes*, are not known, it is of interest that the only other area in Hawaii where this pyramidellid comprises a dominant portion of micromolluscan assemblages is in Pearl Harbor where there is an abundance of sessile invertebrates.

Rissoella sp. is both ubiquitous and euryhaline, occurring in Hawaii in tidepools whose salinity is both higher and lower than normal. *Rissoella* feeds on detritus associated with surface sediments and is often found alive in sediments which have an obviously high organic content.

The three species comprising the *Tricolia/Rissoina/Cithna* assemblage are herbivores, but differ in their patterns of depth distribution. *Tricolia variabilis* is perhaps the most widely distributed of all mollusks in the Islands, found from high, shallow, shoreline pools to depths of more than 50 meters. In shallow waters, *Tricolia* is associated with frondose algae. *Rissoina miltozona* browses on small algae and is often found with *Tricolia*. *Cithna marmorata*, the third member of the assemblage, is a predominantly subtidal form elsewhere in Hawaii, occurring only occasionally on fringing reefs but becoming a dominant member of micromolluscan assemblages at depths of from 6 to 10 meters.

The distribution patterns of the dominant assemblages of micromollusks in Kaneohe Bay reflect differing conditions of depth, substrate, algal growth, and community structure. In the inner Bay the predominance of *Bittium* and *Obtortio* indicate a shallow water to intertidal situation, with a rubble substrate which has little frondose algal growth. The *Bittium/Obtortio* component of the assemblages is similar to that found on other fringing reefs in the Islands. The pyramidellid component of the assemblage on the Kaneohe Bay reef is, on the other hand, unique in the Islands, reflecting an abundance of sedentary invertebrates such as *Ostrea* and *Crepidula*. The *Rissoella* assemblages indicate sandy areas with considerable organic content in the sediments. In the outer Bay the predominance of *Tricolia* and *Rissoina* suggest the occurrence of dense stands of frondose algae, while *Cithna* is associated with greater water depth and less exposure to intertidal conditions.



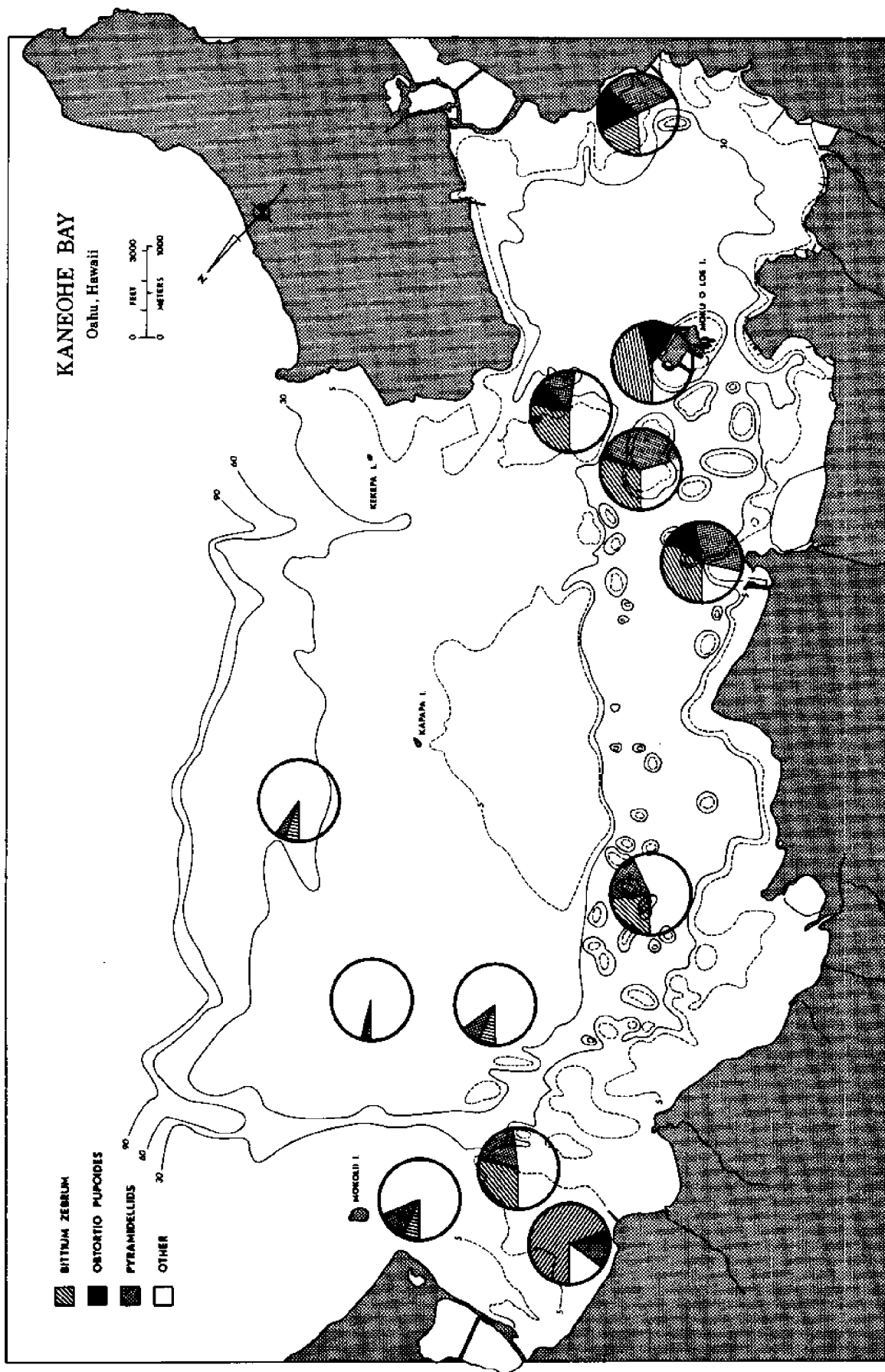


Fig. 60. Composition of Assemblages of the Lagoon Reef - Micromollusks

VII. B. Fishes of the Open Water

Thomas A. Clarke

The fishes considered here are those not usually associated with the bottom or, because of their behavior, not normally recorded in visual censuses or poisoning over reef areas. Little organized research has been done on these species. With the exception of the *nehu* and the hammerhead sharks, most of the data presented here were obtained by preliminary surveys with gill nets and a small purse seine or were collected incidentally during other studies. Conclusions must be regarded as tentative.

The species considered are typical of enclosed, highly productive, semi-estuarine areas in Hawaii and are uncommon in exposed areas. In Kaneohe Bay, most appear to be more abundant in the southern sector and gradually disappear to the north. They are often abundant, however, in small areas in the north end of the Bay such as Kahaluu Bay, where conditions are similar to those of the southern sector.

The most important and numerous of these fishes is *Stolephorus purpureus* (*nehu*), a small anchovy. It is the principal baitfish for the local skipjack fishery. The adults aggregate in shallow areas by day. The principal baiting grounds are in the southern Bay and in Kahaluu Bay. At night, the *nehu* disperse into deep water where the fishermen collect them by night-light. Purse seine data indicate that they are not in schools at night, but night-light catches often contain only one size class, indicating some sort of aggregation behavior.

Nehu are zooplankton feeders. The larvae eat principally micro-copepods (Burdick, 1968). Hiatt's (1951) data on feeding of adult *nehu* are suspect in that the fish were collected by night-light and were probably eating the plankton attracted to the light. His data indicated that the adults take principally crustaceans. Analysis of fish caught by purse seine, a less biased sample, indicates that the *nehu* feed nonselectively at night, eating few larger copepods or decapod larvae and mostly small forms such as barnacle larvae, crab zoeae, and mollusk veligers—the three most abundant zooplankters at the time of sampling. Adults collected inshore during the day also had full stomachs. In addition to zooplankton, benthic crustaceans such as isopods and tanaids were eaten frequently.

During the day, *nehu* are preyed upon by diverse inshore fishes: sharks, carangids, lizard fishes, and barracuda. At night their principal predators are probably *Elops hawaiiensis* (*awa awa*) and *Scomberoides sancti-petri* (*lae*).

The *iao*, *Pranesus insularum*, occurs principally over or adjacent to shallow reef areas. It appears to feed on both zooplankton and benthic organisms. A few adults were collected at night by purse seine about 100 m from the reef, but samples from the middle of the Bay contained only larvae. The *makiawa*, *Etrumeus micropus*, is another zooplankton-eating fish; it is fairly abundant on occasion in Kaneohe Bay.

The larger fishes which feed in mid-water are *Elops hawaiiensis* (*awa awa*); the needlefish, *Strongylura gigantea* (*aha aha*); the half-beak, *Hemiramphus depauperatus* (*ihe ihe*); and the carangids, *Caranx mate* (*omaka*), *Scomberoides sancti-petri* (*lae*), and *Trachurops crumenophthalmus* (*akule*). The *akule* is more typical of offshore areas; it occurs in Kaneohe Bay irregularly, but sometimes in fair abundance. All but the *awa awa*

and lae probably feed principally on larger zooplankton. As mentioned above, the latter two species and possibly larger omaka are probably the principal predators on nehu. Awa awa also forage over reef tops. The juvenile lae are frequently found among schools of nehu or iao and appear to eat scales from these fishes.

Several species of larger predators that occur in the open waters feed principally on reef organisms. The most abundant of these is the hammerhead shark, *Sphyrna lewini* (mano kihiki). Kaneohe Bay is a pupping ground for this species (Clarke, 1970). Adults (200 - 300 cm total length) enter principally between April and October to deliver and breed. The pups (40 - 90 cm) remain in the Bay about three months. During the summer, several thousand are present in the southern end.

During the day, the pups are found principally in the turbid, deep areas at the far south end of the Bay. At night they disperse throughout the southern end and forage near the reefs. The principal food of those caught near coral-covered reefs was small reef fishes, especially juvenile scarids, and alpheid shrimps. Over silt or rubble-covered areas the commonest food items were crustaceans, again mostly alpheid shrimp. The pups are eaten by adult male hammerheads and *Carcharhinus limbatus*, (mano).

C. limbatus were taken fairly frequently in the Bay. Most specimens collected were newly born pups (ca. 75 cm total length); adults were taken only near the Sampan Channel. The sandbar shark, *C. milberti*, and tiger shark, *Galeocerdo cuvieri* (mano niuhi), are also taken in the Bay, but rather infrequently.

Two carangids, *Caranx melampygus* (omilu) and *Caranx ignobilis* (pauu), are quite common in the open waters of the Bay. They were frequently taken at night in gill nets set near the reefs, and most had fed on reef organisms—principally crabs, shrimps, and stomatopods. These species appear to occur in the Bay mostly as juveniles up to 20 - 25 cm standard length; the adults occur in deeper, exposed areas.

Another carangid, *Gnathanodon speciosus*, (paopao ulua), occurs in the Bay as large adults (up to 1 m), as well as juveniles. Juveniles of this species and those of the omaka are frequently found associated with floating objects or medusae in the Bay. The adults appear to feed on smaller epibenthic organisms (Hobson, 1963).

VII. C. Larval Fishes

John M. Miller, William Watson, and Jeffrey M. Leis

Only recently have systematic surveys of larval fishes been initiated in Kaneohe Bay. So far, the data have been only partially analyzed. These data are from two main sources. First is a bi-weekly day and night sampling of fish eggs and larvae from South Kaneohe Bay and in the Sampan Channel (Figure 61) (Watson, Leis, and Miller, Sea Grant Project R/04-01, ms. in prep.). The quantitative results of this investigation will be forthcoming; at present, only certain generalizations which have emerged, especially regarding the seasonality of species, are included. The second source of data is a monthly transect study of horizontal variation in larval fish diversity from Mokolii Island through the South Bay (Figure 61) (Miller, Sea Grant Project R/06-01). This investigation was designed to detect responses of fish larvae to environmental differences along the NW-SE axis of the Bay. For present purposes, data from two cruises during winter, 12 January and 24 February 1972, and two cruises during summer, 14 June and 26 July 1971, are summarized.

Samples from the transect study were lumped from three arbitrarily defined zones in the Bay (Figure 61); North Bay, from Buoy 15 northward; Mid-Bay, from Buoy 15 to Buoy 25; and South Bay, from Buoy 25 southeastward across the southern basin. Ecologically, these zones represent three major habitat categories or water mass types. North Bay is essentially open ocean water. Mid-Bay is a mixture of open ocean water recently transported over the large reef system and through the Sampan Channel (Bathen, 1968). This mid-Bay water mass also includes some surface water (and attendant plankters) transported from South Bay on outgoing tides. In contrast, the water of South Bay has a much longer residence time (Bathen, 1968) than either of the other two zones. It also serves as a nutrient trap for the sewage outfalls of Kaneohe and KMCAS. These waters are considerably more eutrophic than the rest of the Bay (Caperon *et al*, 1971), and larvae surviving in South Bay would seem to be relatively hardy species.

The relative abundance of the fish larvae in these three zones of the Bay are shown in Table 2. Also included are their seasonal (winter and summer) relative abundances. See the Table legend for notation.

It is possible to distinguish two factors which determine the occurrence of certain species within the above zones, namely, reefs and incoming tides—i.e., water transported from offshore. Both of these are especially apparent within the Mid-Bay zone, which includes the largest reef in the Bay, and the Sampan Channel—one of the major import routes of offshore water to the Bay (Bathen, 1968). Species whose larval densities appear to be positively correlated with reefs and incoming tides through the Channel are indicated in Table 2 by the symbols R and C, respectively.

In general, species found mainly in the lee of reefs are those with demersal eggs, usually attached to the hard substrate. Chief among these are Blenniidae, Gobiidae, Pomacentridae, Hemirhamphidae and Belonidae.

Species whose larvae were taken mainly from the Sampan Channel typically have pelagic eggs. The adults of some of these species occur primarily in open ocean pelagic water. Coryphaenidae, Exocoetidae, Gempylidae, Scombridae, Moridae, and Carangidae are

examples. The larvae of certain other families of fishes occur primarily in the Channel; however, the adults of these are usually associated with deeper reefs. Presumably, these species spawn in the waters overlying their habitat. Most of the Scorpaenidae, Bothidae, Holocentridae, Antennariidae, and Labridae are included in this group. Finally, larvae of the bathypelagic groups Myctophidae, Gonostomatidae, Stomateidae, Microdesmidae, and Lampridiformes occur almost exclusively in the Channel, presumably transported as eggs or larvae from some distance outside the Bay.

Shannon-Weaver diversity indices (Pielou, 1969) were calculated according to the formula:

$$D = - \sum P_i \log_2 P_i$$

where P_i equals the fraction of the total individuals represented by each species for the winter and summer transect samples from the North, Mid-, and South Bay. The winter data followed the expected trend, namely decreasing diversity toward South Bay. Values for North, Mid- and South Bay were 3.612, 2.921 and 2.743 respectively. The summer values (2.039, 1.362 and 2.590, in the above order) were unexpected for two reasons. First, the values were all lower than corresponding values in the winter, and second, the highest index occurred in South Bay. Both of these discrepancies were partly attributable to dominance of the summer samples by one species (*Pranestes insularum*), especially in Mid-Bay. The overall number of species in the summer (26) was similar to that in winter (29). The winter samples were dominated by *Abudefduf abdominalis*.

Twenty species were taken predominantly in winter and 11 in summer. Most species, however, were present year-round.

Samples from both the Sampan Channel and South Bay showed dramatic increases in numbers of individuals and species at night. For example, winter Sampan Channel samples averaged 46 individuals of 8 species/1000 m³ in the afternoon and 352 individuals of 15 species at night. Corresponding summer values were 47 individuals of 8 species/1000 m³ and 419 individuals of 21 species/1000 m³.

It must be emphasized that the above generalizations are not without exception. Occasionally, all of the above "Channel larvae" are taken well inside the Bay. Likewise, larvae typically associated with reefs have been captured far from reefs. These exceptions are to be expected, however, especially when one considers the poor swimming capabilities of early larvae. As the larvae grow, their vagility increases, and their distribution patterns reflect more their habitat preferences.

The larval fish fauna of Kaneohe Bay is thus a mixture of transported species and species from eggs spawned within the confines of the Bay. Certainly, the relative abundance of larvae bears little resemblance to that of the resident adult species. Certain larvae, e.g. of Acanthuridae, Labridae, Scaridae, and Chaetodontidae, prominent in the Bay as adults, have been rarely encountered in our samples. And, as mentioned above, larvae of fish which are strictly bathypelagic as adults have been taken.

The utility of Kaneohe Bay as a nursery ground remains to be adequately assessed. The occurrence of larvae of a species may or may not mean dependence on the Bay as a nursery ground.

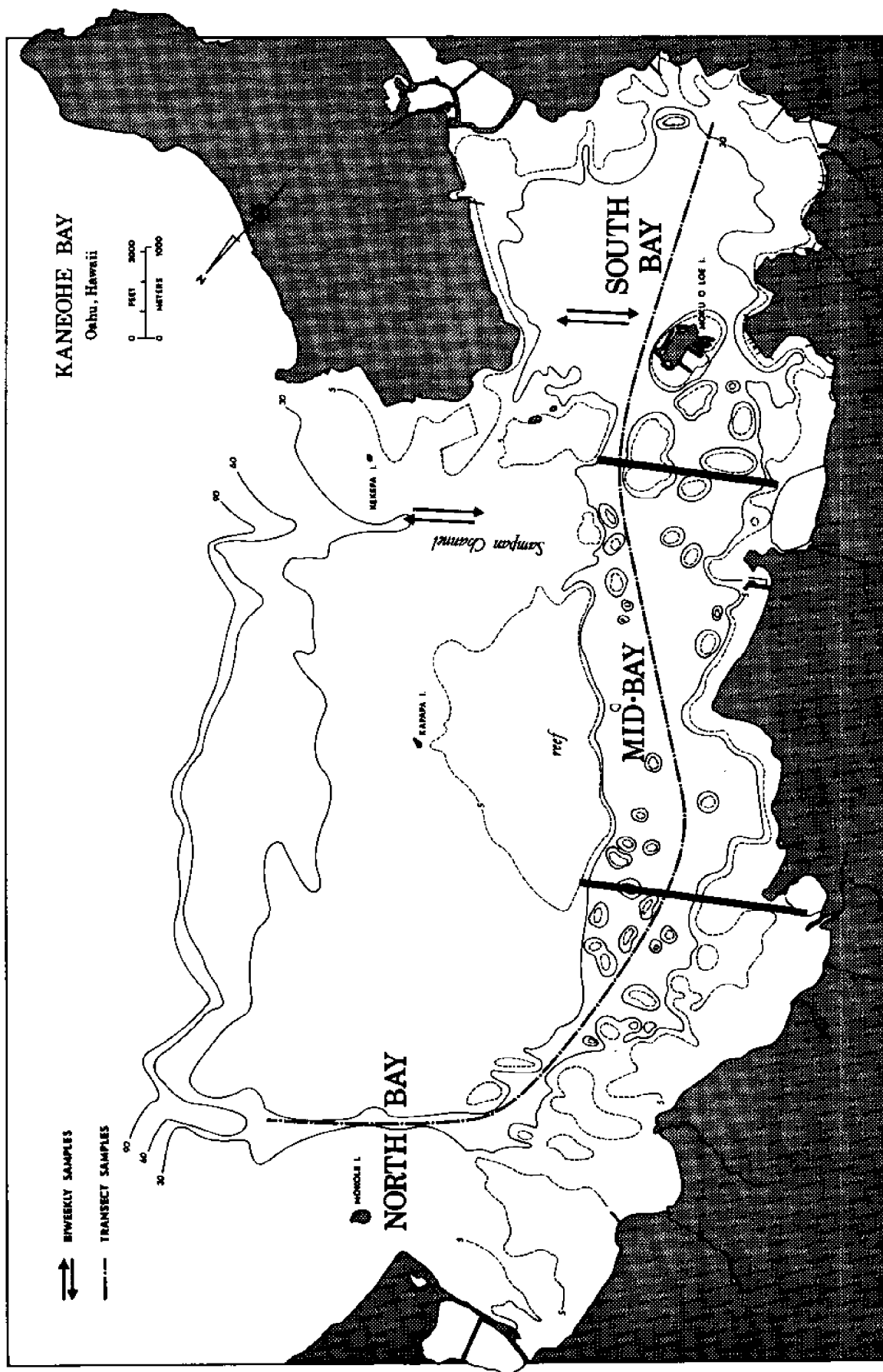


Fig. 61. Larval Fish Zones

TABLE 2. DISTRIBUTION OF LARVAL FISH IN KANEOHE BAY

Family Genus, species	Region			Affinity
	North Bay	Mid-Bay	South Bay	
Dussumeriidae				
<i>Etrumeus micropus</i>	/w			
Engraulidae				
<i>Stolephorus purpureus</i>	/w	s/ww	ss/wwww	
Gonostomatidae				
<i>Cyclothone</i> sp.				C
<i>Vinciguerria nimbaria</i>				C
Synodontidae				
<i>Saurida gracilis</i>				
Myctophidae				
<i>Lampadena</i> sp.				C
<i>Lepidophanes</i> sp.				C
<i>Ceratoscopelus</i> (2 sp.)				C
<i>Diaphus</i> (2 sp.)				C
<i>Taaningichthys</i>				C
Exocoetidae	s/	s/		C
Belonidae				
<i>Strongylura gigantea</i>		s/	s/	R
Hemirhamphidae (3 sp.)			s/	
Atherinidae				
<i>Pranesus insularum</i>	sss/w	ssss/ww	ssss/ww	
Syngnathidae				
<i>Hippocampus kuda</i>			s/	
<i>Syngnathus</i> sp.				C
<i>Doryrhamphus melanopleura</i>				C
Scorpaenidae (3 sp.)				C
Apogonidae				
<i>Apogon brachygrammus</i>	/w	ss/ww	sss/wwww	R
<i>Apogon</i> (4 sp.)				C
Carangidae				
<i>Caranx mate</i>		s/	ss/	
<i>Gnathanodon speciosus</i>		ss/w	ss/	
<i>Seriola</i> sp.		/w		C
Coryphaenidae				
<i>Coryphaena hippurus</i>				
Kyphosidae				
#78		/w		
Pomacentridae				
<i>Abudefduf abdominalis</i>	s/ww	ss/wwww	sss/wwww	R
<i>Pomacentrus jenkinsi</i>		/w	s/w	R
Mugilidae				
<i>Mugil cephalus</i>	/w			

TABLE 2. DISTRIBUTION OF LARVAL FISH IN KANEOHE BAY (cont'd)

Family Genus, species	Region			Affinity
	North Bay	Mid-Bay	South Bay	
Sphyraenidae				
<i>Sphyraena barracuda</i>	s/			
Blenniidae				
<i>Enchelyurus brunneolus</i>	ss/w	sss/wwww	ss/s	R
<i>Entomacrodus marmoratus</i>				
<i>Exallias brevis</i>	/w	/w	/w	
<i>Omobranchus elongatus</i>	s/	ss/ww	ss/ww	R
#5	s/	s/ww	ss/ww	
#10	s/			C
Trypterygiidae				
<i>Trypterygion atriceps</i>	/w		/w	C
Schindleriidae				
<i>Schindleria pietschmanni</i>			(night)	C
<i>S. praematurus</i>				C
Callionymidae				
<i>Callionymus decoratus</i>	s/w	s/w	s/ww	
Gobiidae				
<i>Bathygobius fuscus</i>		/w		C
#2	/w	s/	s/	
#5	s/	/w	s/ww	
#6	s/	ss/ww	s/ww	
#8	/w	/ww	/w	
#9	s/w	/www	s/ww	
#10		/w		
#11	s/	/w	/w	
#12		/w	/w	
#17a		/w		
#45			s/	
#166	/w	/w		
<i>Oxyurichthys lonchotus</i>				C-S
Eleotridae				
<i>Asteropteryx semipunctatus</i>			/w	
Gempylidae				
<i>Pr. Gempylus serpens</i>				C-W
Scombridae				
<i>Thunnus albacares</i>				C-w
<i>Euthynnus yaito</i>				C-w
Bothidae				C
Tetraodontidae				
<i>Arothron</i> sp.	s/		s/	

s = summer

w = winter

C = Sampan Channel

R = near reefs

s = rare in summer

sss = in nearly all summer samples in moderate numbers

ss = usually occur in small numbers in summer

ssss = dominate most samples in summer

Corresponding notation for winter (w) samples.

VII. D. Other Invertebrates

Edith H. Chave

The Kaneohe Bay survey has shown that some invertebrates, other than corals and micromollusks, are common in the Bay, but the factors controlling their distribution have not been studied in detail. For a complete listing of invertebrates which have been found in the Bay, see Gordon and Helfrich (1970).

The most abundant echinoderms in the Bay are the sea urchins *Echinothrix diadema* (wana) and *Echinometra mathei* (ina uli), and the sea cucumber *Holothuria atra* (loli). The urchins are common on the exposed part of the barrier reef, to a depth of about 60 feet seaward. Neither species is common in the north or south lagoon, nor on the patch or fringing reefs near the shore. *Holothuria* is found on the barrier reef, on the reefs near Coconut Island, and on other sand-covered fringing reefs of the south lagoon, away from the sewer outfalls. A delicate pink, wormlike sea cucumber, *Ophiodesoma spectabilis*, is common in the Bay, especially in the southern section of the lagoon.

Sponges are abundant in the south and central Bay. They may occur growing epizooically on plants or animals, or on hard substrates. Little is known of the sponges of the Bay.

Tunicates (sea squirts) and rock oysters (*Ostrea sanvichenis*) are generally restricted to the south lagoon and reef slopes near stream mouths. These organisms are active filter feeders and may thrive in this nutrient-enriched water where plankton productivity is usually high.

Serpulid worms with their calcareous tubes occur on hard substrates throughout the Bay. Burrowing clams, snapping shrimp, and other burrowing crustaceans occur on sandy substrates throughout the Bay. All of these groups appear to be more dependent on the substrate than other factors.

Spiny lobsters, *Panulirus*, (ula) are rare in the Bay. Their distribution is probably fisherman-dependent. They are most commonly found on shallow reef flats bathed by breaking waves. Lobsters have been noted at the bottom of lagoon reef slopes in the northern part of the Bay.

VIII. Factor Analysis of Presence-Absence Data

Stephen V. Smith

The preceding sections of this Atlas have included numerous maps showing the distribution of various organisms in Kaneohe Bay. If the reader interested in general information about the Bay was not overwhelmed by the number of maps, he probably was struck by the similarities among many of them. The purpose of this section is to reduce that general impression of similarities to a small set of objective maps which capture the essence of those similarities.

The technique to be used involves a conceptually simple, although mathematically tedious, procedure known as "principal component factor analysis, with varimax rotation". The reader interested in more details about the techniques should consult Rummel (1967, 1970) or Harman (1967) for extensive discussions and lengthy bibliographies. Examples of the use of factor analysis for environmental interpretation include Goodall (1954), Cassie (1963), Cassie and Michael (1968), Barkham and Norris (1970), Smith (1971), and Hughes *et al* (1970). Smith is preparing a more technical treatment of the factor analysis data presented here, as well as the analysis of additional Kaneohe Bay data. The present discussion considers factor analysis strictly as a method of pattern recognition, illustration, and interpretation, with little regard for underlying theory. The data used here include the presence or absence of 55 taxa in Kaneohe Bay, as recorded at 209 sampling stations. These taxa comprise all of the algae, corals, reef fishes, and other invertebrates found at more than 10 sampling stations (5 per cent of the stations) in the Bay. Table 3 lists the taxa used in the analysis: 23 algae, 12 corals, 18 reef fishes, and 2 echinoderms. Patterns typifying a number of these taxa emerge from the factor analysis, and these biota, in turn, typify the distribution patterns of many less abundant or less conspicuous biota of Kaneohe Bay.

Two kinds of information relevant to the present discussion result from factor analysis. In the first place, there is a table telling the degree of relationship between each variable (or organism) and each of the patterns. The patterns, which are called "factors", are mathematically defined to be underlying similarities in the distribution of the variable. These similarities can be positive or negative. That is, an organism may show a tendency to be associated with a factor, or a tendency not to be associated with that factor. These possibilities may be put still another way. Given the presence of a factor at some location in the Bay, there may be a likelihood that a particular organism is present at the location. Or the presence of the factor may make it likely that the organism is not present. Or the presence of the factor may say nothing about the likelihood of finding that organism to be present.

The other major information derived from factor analysis is the degree to which a particular sampling locality exhibits a given factor, or pattern. Analogously to the discussion above, a sampling station may show a distinct affinity for the pattern or it may not. The degree of relationship between a station and a factor is determined by the degree to which that station does (or does not) have biota related to the pattern.

Certain organisms are widely recognized to be good indicators of important aspects of the environment (so-called "environmental indicator organisms"). Factor analysis patterns should also be useful environmental indicators. They serve this function two ways: they provide objective reinforcement of like distribution shown by various organisms, and they highlight patterns which may be too subtle to recognize from the distribution of any one organism.

Four interpretable factors emerge from the aforementioned Kaneohe Bay data. Table 3 presents the relation of the factors to the biota used in the analysis; Figures 62 - 65 show the relationship of the factors to the sampling locations; and the discussion below provides an interpretation of the factors. The relation of each organism to each factor is rated in Table 3 as "very strong", +++ (greater than 50% of the variability in the organism's distribution explained by the factor); "strong", ++ (25 to 50% explained); moderate, + (10 to 25% explained); and "no significant relationship" (less than 10% explained). Negative relationships all proved to be at the "nonsignificant" level. Consequently, in the following analysis no provision need be made for recording negative relations. The discussion which follows considers the relation between each factor, the biota, and the physiographic unit of the station.

Factor A shows a very strong positive relationship to 3 taxa of fishes; a strong positive relationship to 9 fishes and 4 corals; and a moderate positive relationship to 4 fishes and 3 corals (Table 3). Furthermore, the factor tends to be concentrated on the slopes of the patch and fringing reefs as well as on the fore-reef (Figure 62). This factor appears to be most closely related to adequate shelter for fishes. The fishes seek shelter in areas of high topographic relief, and some coral species tend to create such a relief. However, the relief can develop in other ways (e.g., the ledges and gulleys cut into the hard bottom of the fore-reef). The strong relation of the factor to the lagoon reef slopes reflects the intricate network developed there by corals, particularly *Porites compressa*. The somewhat spottier fore-reef pattern indicates the distribution of large sheltering coral heads and/or erosional relief on the hard bottom.

Factor B shows a very strong positive relationship with one alga; strong positive relationship with 9 algae, 3 corals and 1 fish; and a moderate positive relationship with 7 algae and 5 fishes (Table 3). The factor is concentrated in the high-energy reef flat and is also present on the fore-reef (Figure 63). The pattern apparently reflects an affinity for high circulation and/or surge. The fishes, in turn, are likely to be feeding on the corals and algae, as well as on the oceanic plankton found in the areas.

Factor C is strongly positively related to 6 corals; positively related to 4 corals, 1 alga, both echinoderms, and 1 fish (Table 3). The factor is primarily associated with the fore-reef and the patch reef slopes and also associated with the high-energy reef flat (Figure 64). This pattern seems likely to be a response to suitable substrate. The suitable substrate is most likely to be hard bottom, as exemplified by the numerous fore reef stations related to the factor. However, the corals can themselves provide adequate substrate on the lagoon reef slopes. The difference between factors B and C is a subtle one, in that high surge tends to create hard substrate by removal of loose material. However, the substrate can be provided (e.g., on the lagoon reefs) by biological construction in the absence of rapid sediment deposition and substrate burial. Furthermore, the abrasion which can be associated with high surge in the presence of abundant sand particles in the water may be detrimental to the factor C organisms but tolerable to factor B biota. The general absence of the factor on the

slopes of the fringing reefs is likely to represent the somewhat more abundant mud (and therefore less suitable substrate) there than on the patch reefs.

And finally, Factor D relates strongly to 4 algae and 1 fish and moderately to 4 algae (Table 3). The factor is primarily associated with low-energy reef flats but does extend somewhat into the high-energy flat (Figure 65). The factor is rather clearly related to depth; several explanations are possible. The shallow areas receive the most light, so the algae may be responding to a need for high light intensity. On the other hand, they may be more tolerant of water warming or ultraviolet radiation associated with this light. The one fish (a goby) lives in stable sandy areas such as the reef flat, and the algae are species which can grow on stable sand substrate.

Other generalities emerge, besides those explicitly related to each of the four factors discussed above. In the first place, only reef organisms were used in the analysis, so only reef associations emerge. The lagoon floor stations stand out as a group for their lack of relation to any of the factors—obviously because as non-reef stations they lack the characteristics of any reef environment. In a sense, that lack can be treated as an additional pattern.

The geographic distribution of the factors has been considered from the standpoint of physiography, which is largely sensitive to changes along the short (SW - NE) axis of the Bay. That is, one traverses most rapidly from one physiographic province to another along that axis. There is also a general strong gradient in water quality along the long-direction axis from NW to SE. This gradient extends from water which is near-oceanic in characteristics towards the northwest to water greatly influenced by terrigenous modification (high nutrients and silt; low salinity) in the southeast. This lengthwise gradient is generally applicable only to the waters which bathe the lagoon reefs (Smith, 1971; Bathen, 1968). "Terrestrial water" (particularly with respect to lowered salinity and increased silt content) also affects the shallow delta and surrounding areas toward the northwestern end of the Bay.

Three of the factor patterns (A, C, and D) are well developed on the lagoon reefs, and all of these patterns appear suppressed in those areas of terrigenous effects on water quality. Siltation may be the major effect on both factors A and C. In the case of Factor A, siltation may tend to mask relief. Factor C, the substrate factor, is depressed in the high-siltation areas simply because organisms related to the factor cannot tolerate the masking of the hard substrate which they require. Either siltation or depressed salinity may restrict the reef-flat organism from being more prevalent in the southeastern portion of the Bay. Of course, the general absence of the Factor B (circulation/surge) pattern from the lagoon reefs may be largely attributable to a sensitive response of the appropriate biota to water quality.

In summary, four patterns typify much of the variability seen in 55 of the most common and conspicuous reef organisms in Kaneohe Bay. These 55 organisms can be assumed to have distributions similar to the distribution of less common or less conspicuous biota. The patterns can be interpreted as a response of the organisms to topographic relief; to water circulation or surge; to satisfactory substrate; and to water depth. These patterns can be related to both physiography and water quality. Benthic algae are primarily sensitive to circulation/surge and secondarily to depth; corals are primarily sensitive to substrate, secondarily to topographic relief, and thirdly to circulation/surge; and reef fishes are primarily sensitive to relief and secondarily to circulation/surge.

TABLE 3. RELATION OF FACTORS TO BIOTA IN KANEOHE BAY

ORGANISM	FACTOR			
	A	B	C	D
ALGAE				
Lyngbya sp.				++
Bornetella sp.				+
Codium arabicum		++		
Dictyosphaeria cavernosa		+		+
Halimeda discoidea		+++		
Microdictyon sp.		+		
Colpomenia sinuosa		++		
Dictyopteris australis		++	+	
Dictyota spp.		++		
Padina japonica		++		
Sargassum echinocarpum		++		
S. polyphyllum		+		+
Acanthophira spicifera				++
Champia parvula		++		
Hydrolithon sp.				++
Hypnea spp.		+		++
Jania spp.		++		
Laurencia spp.		++		
Liagora hawaiiiana		+		
Polysiphonia macrocarpa				
red calc. P. onkodes		+		
P. sand. P. gardineri		+		
Peyssonelia rubra				+
CORALS				
Cyphastrea ocellina	+			
Fungia scutaria	+		+	
Leptastrea bottae			++	
Montipora verrucosa	+		++	
Montipora patula	++		+	
Zoanthus sp.			++	
Pavona explanulata	++			
Pocillopora meandrina		++	++	
Pocillopora damicornis	++		++	
Porites compressa	++		++	
Porites lobata		++	+	
Psammocora stellata		++	+	

TABLE 3. RELATION OF FACTORS TO BIOTA IN KANEOHE BAY (cont'd)

ORGANISM	FACTOR			
	A	B	C	D
ECHINODERMS				
<i>Holothuria atra</i>			+	
<i>Echinothrix diadema</i>			+	
FISHES				
<i>Parupeneus porphyreus</i>	+			
<i>Chaetodon miliaris</i>	++			
<i>Dascyllus albisella</i>	++			
<i>Abudefduf abdominalis</i>	++			
<i>A. imparipennis</i>	+		+	
<i>Pomacentrus jenkinsi</i>	++			
<i>Stethojulis axillaris</i>	++	++		
<i>Thalassoma duperreyi</i>	+++	+		
<i>Cheilio inermis</i>		+		
<i>Gomphosus varius</i>	++			
<i>Scarus</i> spp.	+++	+		
<i>Zanclus cornutus</i>	++			
<i>Acanthurus triostegus sanvicensis</i>	+++	+		
<i>A. leucopareus</i>	+	+		
<i>A. dussumieri</i>	+			
<i>Ctenochaetus strigosus</i>	++			
<i>Zebrassoma flavescens</i>	++			
<i>Psilogobius mainlandi</i>				++

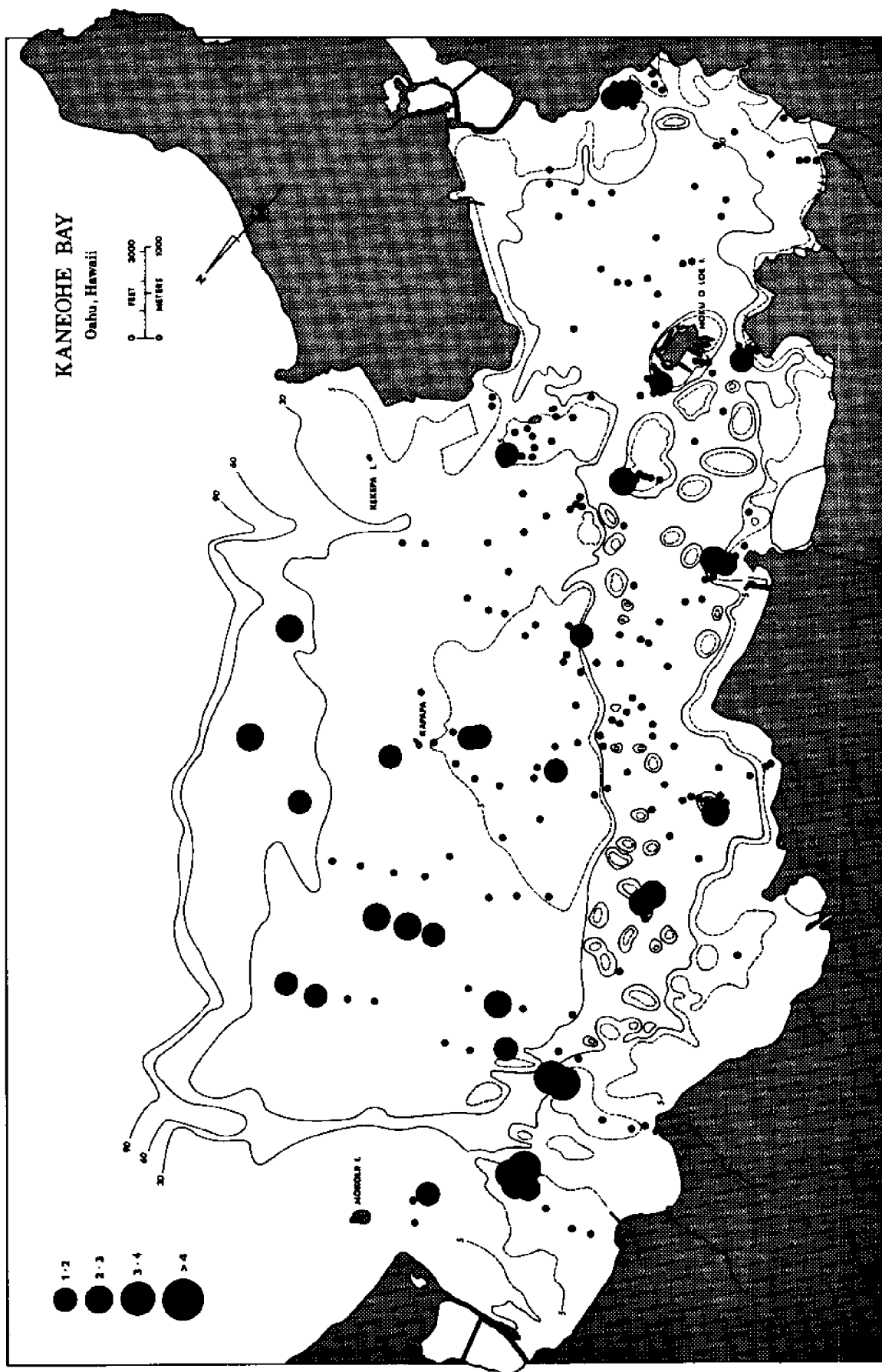


Fig. 62. Factor A

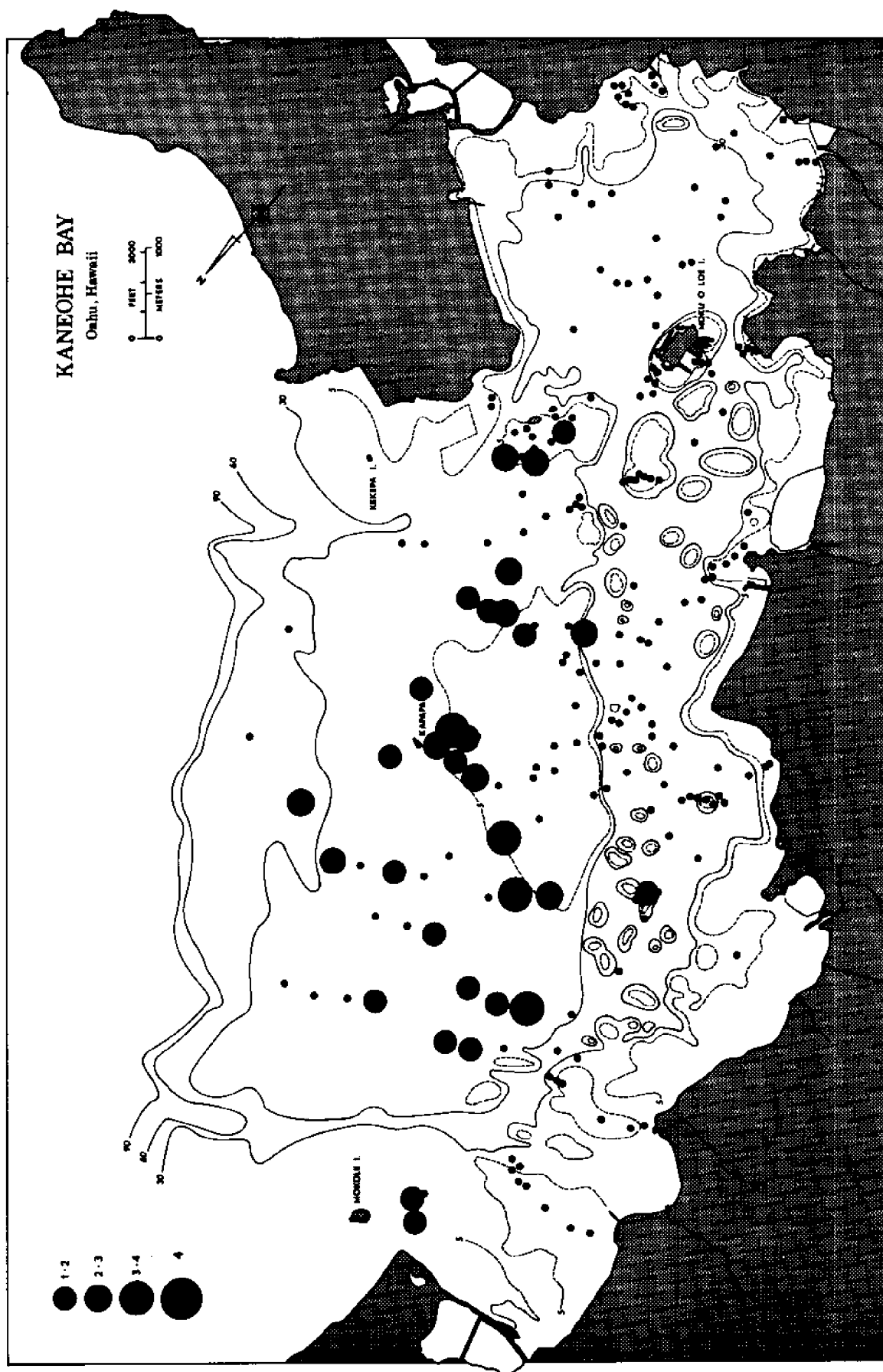


Fig. 63. Factor B

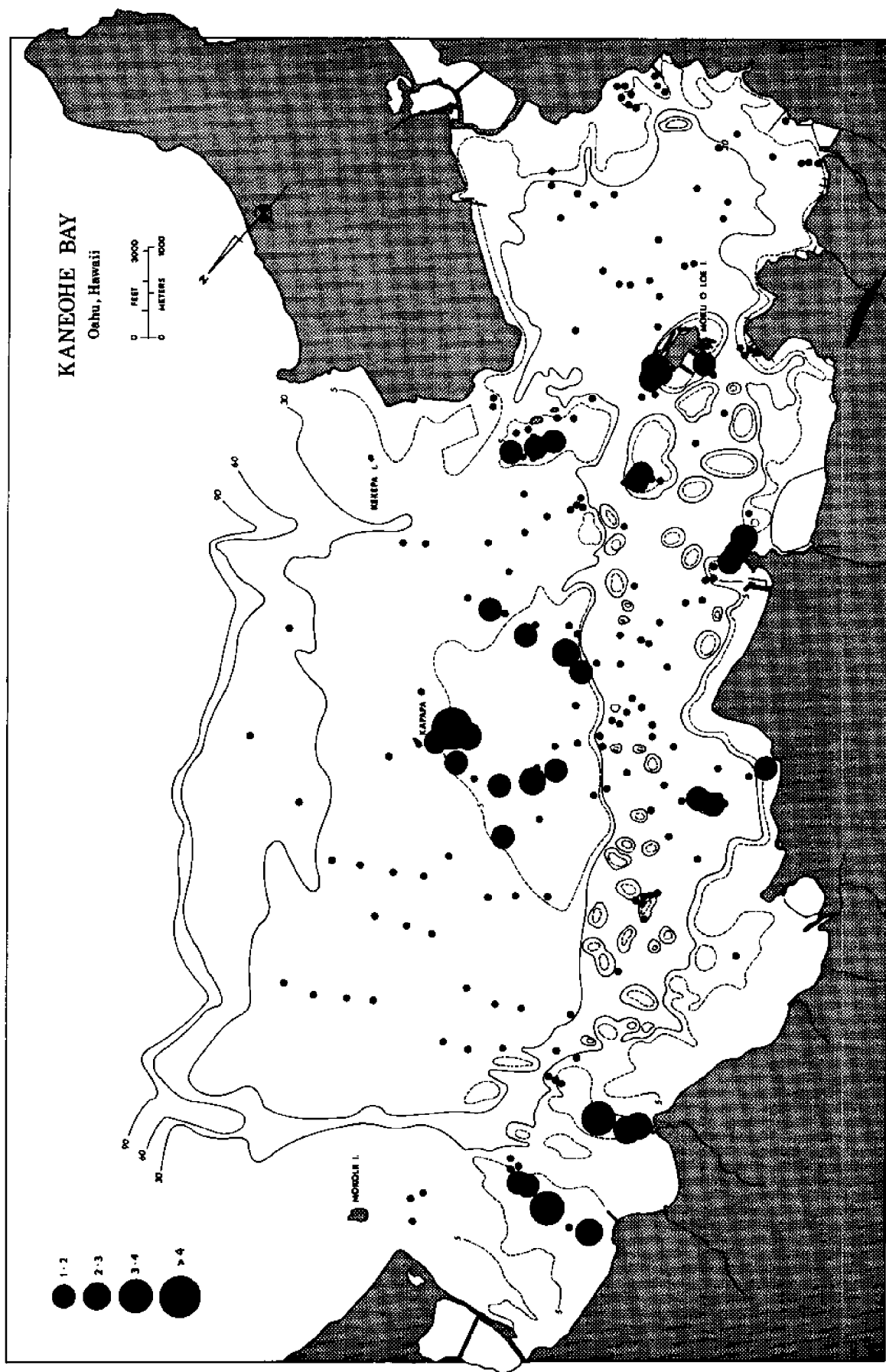


Fig. 65. Factor D

IX. Stress and Interference of Man in the Bay

James E. Maragos and Keith E. Chave

The impact of recent activities of man on the Bay has been tremendous. Most of the change has taken place in the lagoon, where circulation is sluggish and turnover rates of the water are slow. A similar situation has been observed at Palmyra by Dawson (1959). The major factors affecting the nature of the lagoon are sedimentation, dredging, freshwater floods, and nutrient enrichment due to the input of sewage. These influences are not independent of each other.

Changes in the water column show a distinct south-north gradient (Bathen, 1968, and Smith, 1971). Gradients complexly related to water quality show in the sediments (Section VI A) and in the biota (Section VIII).

Sedimentation on the lagoon floor has increased markedly in recent years (Roy, 1970, Section VI A). Near shore the infilling sediments are largely of terrigenous origin. This is probably strongly influenced by changes in land uses in the watershed of the Bay (Section II). Further offshore the sediments infilling the lagoon are carbonate in composition, apparently from reef erosion. Smith *et al* (1970) estimated that the erosion of carbonate exceeded gross production by reef organisms. Finally, Steinhilper (1970) showed that a significant amount of organic carbon is being deposited in the lagoon sediments.

Dredging activities have been very destructive to the benthic communities of the Bay. These effects have been locally extreme (Roy, 1970, Section VI A), directly destroying reef areas and causing increased turbidity through the resuspension of sediments. Surveys of many of the previously dredged areas revealed that recovery of corals on reefs dredged below 9 m has not occurred at all, and that these dredged areas are being covered by sediments (Maragos, 1972). Other reef organisms have been inhibited from recolonizing these same areas. On shallow reef slopes, recovery of reef organisms on dredged surfaces has been slow. In the south lagoon recolonization by corals has not occurred at all. Bosch (1967) surveyed these reefs before sewage was discharged into the Bay and noted that corals had not recovered during the 25 years since the dredging. Brock *et al* (1966) noted that deterioration of reefs adjacent to dredged areas at Johnston Island continued long after dredging operations ceased, because of increased sedimentation. There is little information about the effects of dredging on other benthic organisms in the Bay. Sponges, bryozoans, tunicates, and anemones are common on dredged surfaces in South Bay.

The effects of fresh water on the biota of the Bay are complex. The volume of fresh water entering the Bay has decreased due to the tunnels through the Koolaus, but changes in land use have increased the rate of runoff (Section II). The freshwater kill of 1965 is the best documented example of the effects of flooding on the Bay biota (Banner, 1968). Although the water-column organisms were undoubtedly affected, recovery probably occurred quickly. Damage to the benthos was long-term. Banner resurveyed some damaged areas in 1968 and noted permanent changes in the reef biota. Some groups recovered quickly after the "kill", but corals and other benthic invertebrates were only beginning to recover three years later. Later observations (Maragos, 1972) indicate that corals are rapidly

recolonizing deeper reef slopes damaged by the floods and some colonies are larger than 20 cm in diameter. At depths less than 1 m, recovery of corals has not occurred. Near Moku-o-loe Island, soft corals (*Zoanthus*) have replaced reef corals on shallow reef flats previously surveyed by Gordon and Kelly (1962). Floodwaters are not the only fresh waters affecting the Bay biota. Normal runoff will naturally limit the distribution of benthic organisms through occasional lowering of the salinity of the nearshore waters.

Chemical inputs into the Bay influence the distribution of the biota. These inputs include nutrients from sewage and streams, hypochlorite, pesticides, and probably heavy metals. Of these materials, probably nutrients from sewage have the strongest effect (Bathen, 1968; Quan, 1969; Young *et al*, 1970; Caperon *et al*, 1971). As the human population and sewage discharge increased, so did the levels of phosphate in the Bay (Bathen, 1968; Caperon *et al*, 1971). Because of restricted circulation patterns and proximity to outfalls, nutrient levels are highest in the south basin, and decrease in other areas of the lagoon and Bay.

According to Piyakarchiana (1965), water-column organisms were quick to respond to the 1964 increase in sewage discharge into the Bay. Organic carbon, productivity, zooplankton, and phytoplankton levels are now highest in the south basin and drop off rapidly with increasing distance from the outfalls (Steinhilper, 1970; Clutter, 1969; Peterson, 1969); Caperon *et al*, 1971). Some nektonic organisms are also more abundant in the south lagoon. Clarke (Section VII B) concluded that semi-estuarine fish are more numerous in the south, probably because the zooplankton food supply is also greater. Reef fish appear to be numerous in the south basin (Key, Section VI C). Perhaps substrate relief is still sufficiently adequate to offer protected cover for these fish. Miller (Section VII C) concludes that probably only the hardy forms of fish larvae survive in the south basin. Nevertheless, in the summer the highest larval fish biomasses occur in the south lagoon. Although biomass of water-column organisms has been higher, diversity of planktonic organisms has been lower (Clutter, 1969; Peterson, 1969). Planktonic population levels are also unstable in the south basin (Clutter, 1969; Caperon *et al*, 1971). Population instability may be an indirect result of high nutrient levels in the water column (Caperon *et al*, 1971).

The effects of nutrient loading on the benthos of the Bay are shown throughout the Atlas. These effects may be direct or indirect. High productivity of phytoplankton in enriched waters may decrease light penetration and affect the growth and competition among light-dependent organisms. Reef corals have been especially affected. Recent studies (Maragos, 1972) indicate that reduced light-penetration resulting from increased productivity of the water column could affect the growth and survival of corals. This could be applied equally to other benthic autotrophs. Soegiarto (Section VI D) noted that many common lagoon algae are absent from the south basin. Calcareous algae are still present, but are dying off. Coral growth is scarce in the south basin, in both biomass and the number of species. Some of this is undoubtedly the effect of prior dredging activities, but intact reefs in the south, far from dredged areas, are also devoid of common reef organisms. Resurveys of areas visited previously by Gordon and Kelly (1962) and Bowers and Bridges (1963) reveal documented decline in coral abundance in the south Bay. The most convincing evidence is that corals transplanted to the south basin invariably died (Maragos, 1972). The length of survival of the corals was directly proportional to the distance from the outfalls. Sediments were not the sole cause of the coral mortality, because many corals died before sediments could accumulate. In addition, south-basin corals grew more slowly and erratically, and displayed bizarre growth forms.

Some organisms appear to gain a competitive advantage from nutrient loadings. Nutrient enrichment of the Bay may have indirectly caused the decline of other lagoon-reef communities outside the south basin. Bosch (1967) noted that in 1963 large mats of the alga *Dictyosphaeria cavernosa* were growing over living corals. By 1967 the alga was very common in many areas of the Bay (Nishimoto, 1967). Takanaka (1970) noted that major concentrations of the alga were confined to lagoon areas north of the south basin behind the barrier reef and near the south channel. Soegiarto (Section VI D) noted that abundance of the alga reached 700 g dry weight/m² in places. Maragos (1972) and Banner and Bailey (1970) carried out surveys of this alga in 1970. *Dictyosphaeria* was nearly absent in the north lagoon where flushing and circulation of water are greatest (Figure 50). The alga was also nearly absent in the south lagoon, probably for the same reasons corals are no longer found there. On all other patch reef and fringing reef slopes in the lagoon, *Dictyosphaeria* flourished and is now the most abundant benthic alga there. At shallower depths, corals seem better able to resist attacks from this alga, probably due to better light and circulation conditions for coral growth. Otherwise *Dictyosphaeria* grows up and over corals, mostly *Porites compressa*, and forms continuous mats, eventually smothering all reef organisms beneath. This is also accompanied by breakdown of the coral skeleton by acid dissolution or other processes (also in Banner and Bailey, 1970). Unlike other algae, seasonal fluctuations in the biomass of *Dictyosphaeria* are slight and enable the organism to retain its dominance of bottom cover during all times of the year.

Steinhilper (1970) estimated that in the south Bay a significant percentage of the total carbon, fixed by organisms in the water column, was deposited in the lagoon sediments. Bathen (1968) noted low oxygen concentrations in South Bay near the bottom, presumably due to higher biological and chemical oxygen demand. This stress situation has different effects on different organisms. Reef fishes are motile and are able to avoid the respiratory stress by leaving the area (Section VI C), although certain other fishes appear to adapt to it (Sections VII B and VII C). A few worms and crustaceans live comfortably in this low-oxygen environment, perhaps as a result of some physiological adaptation and perhaps as a result of lack of competition. Most sessile benthic invertebrates such as corals (Section VI A) and micromollusks (Section VII A) are strongly inhibited by the low oxygen or toxic substances associated with it. Similar patterns are shown by the associations of factors (Section VIII).

The present low diversity of corals and other benthos in the south is most likely associated with anoxic conditions in the bottom substrates. Anoxic conditions are toxic to most aerobic organisms and promote attack on these forms by anaerobic organisms.

There is considerable evidence of anaerobic conditions in the Bay sediments. Gundersen (1969) showed that sulfate-reducing bacteria in the water column were more numerous near the bottom, and speculated that anaerobic conditions prevailed in the sediments. DiSalvo (1969a, b, c, 1971 a, b) noted that anaerobic organisms were common in sediments and interfered with aerobic bacterial functioning. Other evidence was that sediments were black and smelled of sulfide gas. Sorokin (1970) measured redox potentials of -300 mv and sulfide concentrations of 400 mg/liter 6 to 8 cm below the sediment surface in Kaneohe Bay. He concluded the situation was a potential disaster for the reef communities, because of the easy liberation of toxic hydrogen sulfide gas. Recently, Mackenzie (pers. comm.) has noted sulfides in near-surface sediments of carbonate composition.

The association of sulfides and reef mortality has been noted in the past (Guppy, 1889; Cooper, 1966; Banner, 1968; Copeland and Wilkes, 1969). During coral transplant studies by Maragos (1972) some specimens of *Fungia* were killed by toxic substances in sediments and not by the sediments themselves. The effect of the toxic substance was reduced in sediments where circulation was notably improved; this seems to implicate anaerobic conditions as the cause of the coral deaths. It was also noted that the new naturally occurring corals still alive in the south basin are restricted to the shallow outer edges of reef flats where circulation is best and the probability of anoxic conditions least. There are undoubtedly other causes for the decline of corals in the south basin. Recently Jokiel and Townsley (in preparation) noted that a coral-eating flatworm is more prevalent in the south basin and that bacterial attacks on corals are more numerous. Also, tunicates, bryozoans, sponges, oysters, and sabellids outcompete transplanted corals for space in the south (Maragos, 1972).

Johannes (in press) speculated that another toxic substance, hypochlorite, dumped into sewage during the treatment process may have caused the death of reef organisms. However, a study by Davis (1971) revealed that the effect of chlorine, released from the hypochlorite, on coral planulae is transitory and restricted to the immediate vicinity of the outfall; her conclusions were that hypochlorite could not have caused the decline of corals in the Bay. However, there may be effects of chlorine on other stages of coral development which may affect their survival. The toxic effects of pesticides and heavy metals on marine organisms have been studied widely. Little is known of these effects in Kaneohe Bay.

Kaneohe Bay is an estuary: a body of salt water partially surrounded by land, and affected by the land. For this reason, many types of stresses discussed and illustrated in this Atlas are natural and have only been highly magnified by man's influences. Estuaries are characterized by freshwater runoff, sediment deposition, and restricted circulation. Man has simply modified them.

If pre-urban conditions were to be reestablished within the Bay, one might presume the coral reef communities would recover. Under such conditions recovery would at best be slow, as evidenced from past studies. Erosion of the reefs cannot be stopped until the environment becomes more favorable to corals and other carbonate producers. Sewage discharge into the Bay must therefore be stopped. Removal of sewage, however, will alleviate only one of the stresses. Dredged reefs later covered by sediment may not recover until the sediment is removed. Further sediment discharge into the Bay must also be curtailed; this involves a basic overhauling of land-use practices and flood-control philosophy. The continued erosion of the barren hillsides of the watershed must also be controlled.

There is evidence suggesting that pre-urbanization conditions in the sediments and water column may not be reestablished quickly. It is not known how long it will take the sediments to become aerobic. Also, nutrients are being stored rapidly in the sediments (Kaya, 1971). Phosphate concentrations are much higher in sediments than in the water column, and the supply is building up. Although leaching of phosphate from the sediments occurs (Kaya, 1971), it is not known how long significant quantities of phosphate will remain in the sediments after sewage discharge is stopped. Phosphate influx back into the water column may keep productivity levels and organic loading of the sediments high, long after the sewage is removed. This in turn may keep substrates in the Bay hostile to corals and other benthic biota for extended periods of time.

If all stresses are alleviated, the coral reefs within the lagoon of the Bay may recover, but only slowly and not completely. In contrast, changes in the plankton and nekton communities would probably occur more rapidly because they would respond differently to the stresses. Life cycles of plankton are much shorter and dispersal is more efficient than for reef corals and other benthos. Recovery time of reef corals is measured in decades. In this regard, displacement of benthic reef communities has more severe and longer-lasting effects. Thus, it becomes important to insure that reef areas as valuable and unique as those in Kaneohe Bay be preserved from future degradation by man.

The factors responsible for the decline of the reefs are not just restricted to Kaneohe Bay. As human population levels continue to rise, more and more reefs will be subject to dredging, sewage discharge, and terrigenous sedimentation.

Remedial Action

For several years citizens and scientists alike have been aware of—and concerned about—the pollution problem within the Bay. Indecision and disagreements among civic leaders and scientists have prevented remedial action, which has caused more and more of the Bay environment to be affected. The results of a large, multi-disciplinary pollution study on Kaneohe Bay in 1969 were that the Bay was not badly polluted (Honolulu Star Bulletin, July 19, 1970). However, that study lacked input from benthic ecologists, and did not include diving surveys of bottom substrates. Assessment of the severity of the pollution problem in the Bay was defined from a public-health viewpoint. Changes in the water column did not reflect the changes within benthic communities.

Scientists themselves, especially trained ecologists, should govern impact studies and participate in the establishment of water-quality standards. Ecological parameters should include benthic indicator organisms. Reef corals may be useful "pollution" indicator organisms for many areas of Hawaii, because of their importance to reefs, their apparent sensitivity to man-induced stresses, their fixed sessile nature, and their longevity. Concurrent with the establishment of valid water-quality standards must come better-defined grading, replanting, and sewage-disposal ordinances. Methods such as solid-waste disposal should be evaluated, in order to lessen the impact of man on marine environment. Finally, enforcement of water-quality and other standards will insure protection of natural areas. Any future consideration should include prompt action to prevent destruction of natural areas.

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