HYDROLOGIC AND ECOLOGIC INVENTORIES OF THE COASTAL WATERS OF WEST HAWAII

Sea Grant College Program, Years 07-08

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ABSTRACT

The goal of this project was to provide information to the County of Hawaii and to the state for the intelligent management of the marine and coastal resources of West Hawaii, particularly the South Kohala and North Kona areas. This was accomplished through compilation of inventories of biological, hydrological, and some oceanographic data for four selected sites, Puakō, Waiulua, 'Anaeho'omalu, and Kīholo bays.

Evaluation was made of existing hydrologic, geologic, oceanographic, and ecologic data in order to determine the volume and influence of groundwater discharge to coastal areas as well as the biological community structure in the near-shore waters.

Research results have yielded a classification of the bays according to wave energy and groundwater intrusion. Poor circulation and high groundwater intrusion result in turbid conditions with communities of low diversity—a coastal situation suitable perhaps for a small boat harbor or marina, but undesirable for a marine park or preserve.

These results provide an excellent reference point for planning the use or development of the study sites or areas of related hydrologic and ecologic conditions. The methodology and techniques employed can be adapted for monitoring other coastal zone sites in the state.

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INTRODUCTION[1]

The Kona (west) Coast of Hawaii Island is unique in the Hawaiian archipelago in that it is both a leeward coastline protected from Hawaii's dominating northeast trade winds by high mountains and, at the same time, a coastline subject in prehistoric and historic times to the catastrophic effects of lava flows and tsunamis. Present day interest in the Kona Coast as a major resort and recreational area stems both from its aesthetic attractions, and from its recreational potential, easily accessible coral communities inshore, and deep sea fisheries offshore.

In this report we describe the topography, hydrology, and marine biota of four open ocean bays along the Kona Coast, those of Puakō, Waiulua, 'Anaeho'omalu, and Kīholo. Both topographic and hydrologic conditions have determined the marine biota, a biota which was exploited in prehistoric times as is indicated by the numerous remains of ancient Hawaiian settlements which fringe the coastline, and which today is vulnerable to modern types of exploitation.

GENERAL DESCRIPTION

The Kona or west Coast of Hawaii Island extends from the district of South Kohala in the north to Ka'u in the south. Between South Kohala and Keāhole Point in North Kona, the coastline fringes a shallow bight which is underlain by a narrow shelf sloping from the coastline to depths of more than 100 m within a few kilometers of the shore. The four bays surveyed are located within the limits of this bight.

The coastline consists of a series of open ocean bays dissected from, and lying between, relatively recent basaltic lava flows of the Mauna Loa series. Dominant wave direction is from the north, but the coastline is variously exposed to the effects of wave energy, ranging from minimal exposure on the north at Puakō to maximal exposure on the south at Kīholo. The varying exposure of the coastline to wave energy contributes to its topographical diversity; rough and cliff-like benches of aa; smooth, horizontal benches of pāhoehoe; and boulder, terrigenous and calcareous sand beaches.

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[1]E. Alison Kay, Project Associate Investigator.

The Kona hinterland is bleak and barren, crossed by lava flows dating from prehistoric times to those formed by an eruption of Mauna Loa in 1950. Between the lava flows are *kīpukas*, islands of vegetation. Rainfall is less than 30 cm (12 in.) a year. There are no perennial streams, but groundwater intrusions from subterranean wells are expressed subaerially as anchialine pools and springs along the shoreline.

Puakō Bay

Puakō, the northernmost of the four bays, is a wide bay, some 0.65 km (0.4 mile) at its mouth (Fig. 1). Prehistoric lava flows define the northern and southern termini. In the north the flow is of aa, rough and clifflike; on the south it is of pāhoehoe, low and flat and infiltrated with tidepools. The central section is comprised largely of terrigenous sedimentary beach interspersed with boulders and rubble. The beach is overhung with kiawe, *Prosopis pallida*, the lower branches of which brush the surface of the water at low tide (Fig. 2). The hinterland is dry and dusty, covered with a secondary scrub vegetation of koa-haole, *Leucaena glauca*, and other exotics. Groundwater seepage is apparent only in the southern section of the bay where swamp-like ponds occur back of the beach and intrude into the seaward tidepools.

The shallow, shoreward sections of the bay itself, at depths of about 1 m, are characterized by a substrate of basalt, rubble, and mixed terrigenous sediments. In the outer bay, at depths of about 3 m, the northern part is characterized by a series of coral-covered ridges running perpendicular to shore; in the southern section the near-shore basaltic shelf slopes gradually to depths of about 9 m and coral cover is primarily of thickets of *Porites compressa*.

Waiulua Bay

Waiulua Bay is the smallest of the four bays under study, consisting of a shallow embayment about 0.12 km at its mouth. The shoreline consists of the basalt of a prehistoric lava flow and is continuous seaward as a tidal flat with a pebble and cobble floor (Fig. 3). A boulder ramp separates the inner section from an offshore section. Beyond the rubble bar the shelf is studded with heads of the coral *Pocillopora meandrina*. Both inner and outer sections of the bay are shallow, with an average depth of about 1 m. Groundwater intrusions are an especially noticeable feature of the bay, with springs gushing from crevices along the length of the shoreline.

'Anaeho'omalu Bay

'Anaeho'omalu is one of the few areas along the coastline of Hawaii Island with a calcareous sand beach (Fig. 4). The shoreline, like that at Puako, is defined at the north and south by prehistoric lava flows. On the north the Kanikū flow is composed of brittle, aa clinkers, and, where it meets the sea, there are numerous tidepools. Shoreward the northern terminus is fringed by a margin of calcareous sand and a barrier of native marine vegetation, consisting largely of *Scaevola sericea* Vahl (beach naupaka) and *Messerschmidia argentea*. The hinterland back of the marine vegetation is studded with the largest single concentration on the Kona Coast of anchialine ponds, unique limnetic ecosystems recently described by Maciolek (1974). The seaward basaltic bench slopes towards sea level to the east and merges with the central calcareous beach. The crescent-shaped beach, some 0.32 km in length, has a steep foreslope and a well-developed berm. Beachrock found at the present beach line indicates the presence of an ancient beach. Shoreward the sand is fortified by coconut trees. The southern boundary of the bay is formed by a low, smooth, pāhoehoe flow.

Three fish ponds are associated with 'Anaeho'omalu Bay: two large ponds, Ku'uali'i and Kahapapa, and a smaller pond, Kuali'i. The ponds were partically demolished by the tsunamis of 1946 and 1960 (Kikuchi and Belshe 1970) but are still recognizable as significant bodies of brackish water. Ku'uali'i Fishpond communicates with the bay by the *mākāhā* (sluice gate) which protrudes between the Kaniku flow and the calcareous beach.

The floor of the bay is covered by white sand for distances of 30 to 50 m offshore, at depths of 3 to 4 m. Inshore the bay floor is studded with large colonies of the coral, *Porites lobata*; 20 m offshore, at depths of 3 to 4 m, the bottom topography is a flat, basaltic shelf covered) with a limestone veneer.

Kīholo Bay and Wainanali'i Pond

In 1823, William Ellis described Kīholo:

> A small bay, perhaps half a mile across, runs inland a considerable distance. From one end to the other of this bay, Tamehameha built a strong stone wall, six feet high in some places, and twenty feet wide, by which he had an excellent fishpond, not less than two miles in circumference.

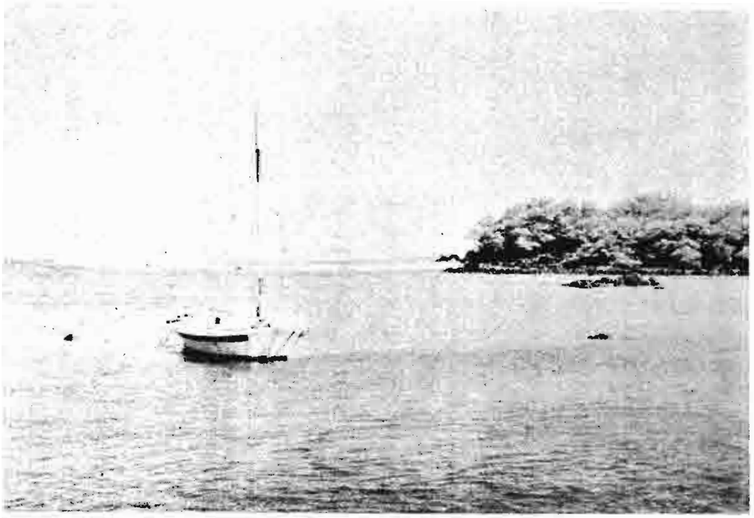

FIGURE 1. PUAKŌ BAY, KONA COAST

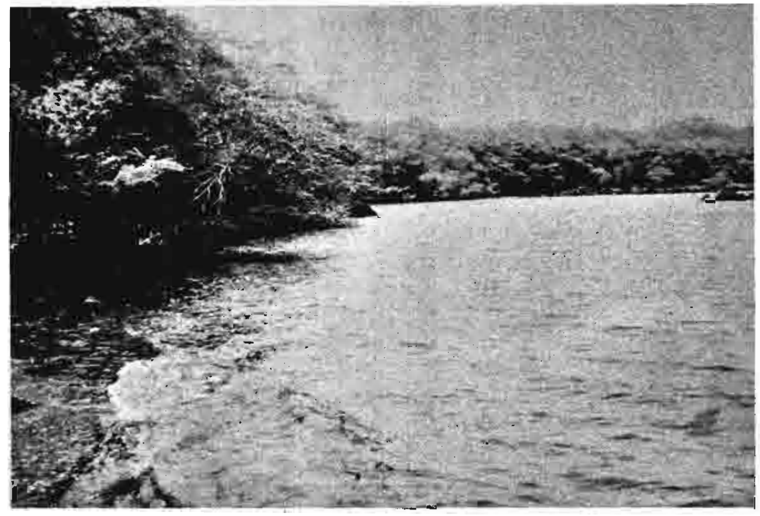

FIGURE 2. PUAKŌ BAY SHORELINE VEGETATION

FIGURE 3. WAIULUA BAY, KONA COAST

FIGURE 4. CALCAREOUS SAND BEACH AT 'ANAEHO'OMALU BAY, KONA COAST

The sea wall and most of the pond, as well as the adjacent pond, Wainānāli'i, were destroyed by the 1859 lava flow which gave the bay its present contours. Thus, the northern terminus of the bay is a major section of the 1859 lava flow which destroyed the village of Wainānāli'i and which cut off a section of the Wainānāli'i Pond as a "lagoon". The arcuate central section of the bay now consists of a basaltic boulder and black sand beach, back of which lie the remnants of Kamehameha's fish ponds. The southern section of the bay is fringed by a prehistoric lava flow.

Wainānāli'i Pond (Fig. 5) is an elongate body of water formed by a cobble and sand bar lying a few hundred meters on the 1859 pāhoehoe lava which constitutes the eastern boundary of Kīholo Bay. The bar connects

FIGURE 5. WAINĀNĀLI'I POND, EASTERN BOUNDARY OF KĪHOLO BAY

with the lava at its seaward end, enclosing the head of the pond; at the landward end the bar is crossed by two shallow passes which connect the pond with the inner part of Kīholo Bay. Freshwater springs enter the pond at several points along the edge of the lava flow, with the most noticeable springs at the head (north end of the pond). Freshwater springs also enter the bay at various points along the arcuate central section of the bay.

The near-shore shallow shelf consists of black sand interspersed over a flat, basaltic shelf, and with a few coral colonies. At depths of 3 to 4 m, *Porites lobata* is the dominant coral in the bay, extending more than 50 m out into the bay; at depths greater than 9 m, *Porites compressa* cover increases over *P. lobata*.

Local Geology[1]

The study area is underlain by lava flows from Mauna Kea, Mauna Loa, and Hualālai. The flows are predominantly aa with some pahoehoe. The rocks are almost completely basaltic with small areas of ash and trachyte. A map of the surface geology of the study area is presented in Figure 6; for hydrologic purposes, the study area extended to the summits of the three volcanoes. The soil cover of the study area in the gulches, and where it occurs elsewhere, is generally very thin. For the most part, soil cover is practically nonexistent.

The northern part of the study area is covered by flank flows from Mauna Kea. The lavas of Mauna Kea are of two series: the older Hāmākua volcanic series (capped by Pahala ash) in the north, and the younger Laupahoehoe volcanic series in the south. The lavas of the Hāmākua volcanic series, capped by Pahala ash, are generally moderately to highly porous and permeable, and freely yield water to wells. A narrow strip, about 3 km (2 miles) wide, of the Pleistocene lavas of the Laupāhoehoe volcanic series, extends to within 2 km (1.5 miles) of the coast. The lavas of the Laupāhoehoe volcanic series, extends to within 2 km (1.5 miles) of the coast. The lavas of the Laupāhoehoe volcanic series are poorly to moderately permeable and not as permeable as the rocks of the Hāmākua volcanic series, but because of their limited thickness and areal extent, their effect on groundwater is probably small. The Hamakua volcanic series is covered by Pahala ash which is generally less permeable than the lavas, but not sufficiently impermeable to produce perched water.

South of the Mauna Kea flows are the historic and prehistoric lavas of the Ka'u volcanic series, the youngest lavas from Mauna Loa, which are highly permeable, and small areas of pumice cones and trachyte lava flows which are of minimal consequence to groundwater in this study. (A detailed geologic description of the entire area can be found in Stearns and Macdonald (1946).

Geological controls on the seaward discharge of groundwater in the study area are poorly known. The extension of the northeast rift of Hualālai, which might conceivably act to channel flow into the basal groundwater lens, was interpreted as line H in Figure 7 from data of an audiomagnetotelluric (AMT) survey and an aeromagnetic survey (Adams et al. 1969). The

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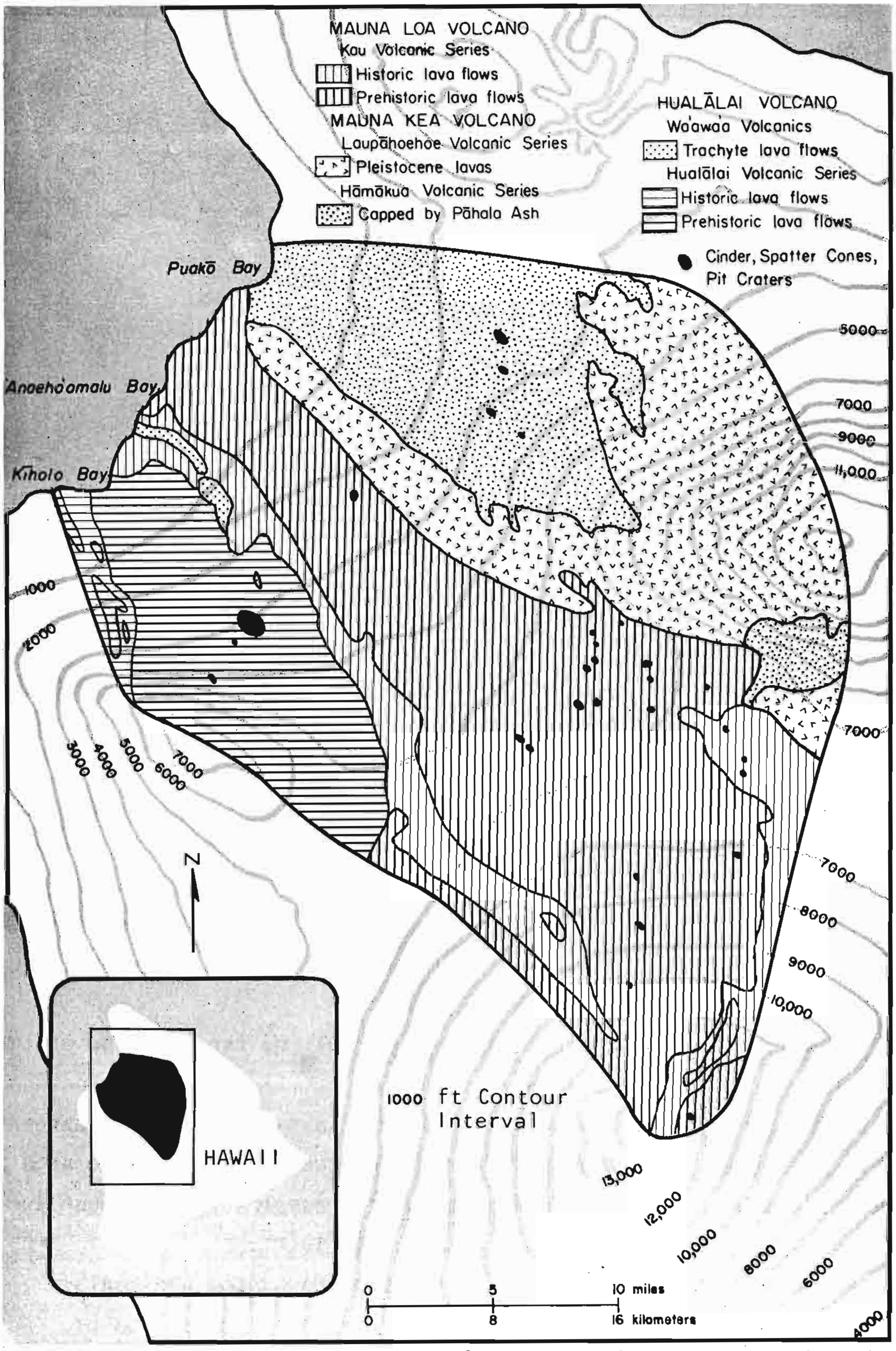
[1]L. Stephen Lau, Project Associate Investigator.



SOURCE: Adapted from Macdonald and Abbott (1970).

FIGURE 6. SURFACE GEOLOGY OF THE WEST HAWAII STUDY AREA FROM PUAKŌ TO KĪHOLO BAYS

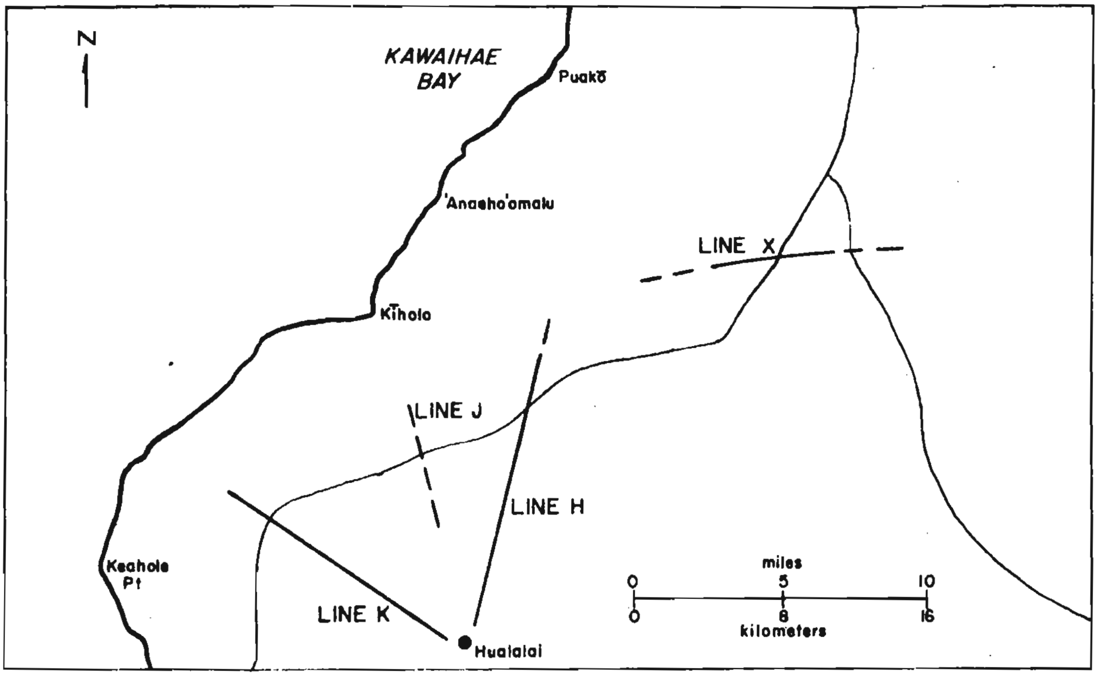


FIGURE 7. MAJOR STRUCTURAL FEATURES INDICATED BY AUDIOMAGNETOTELLURIC AND AEROMAGNETIC DATA

higher, apparent resistivities occurring in the area north of line X as detected by the same AMT survey were attributed to the higher resistivity of the Mauna Kea lava or to a higher water table depressing the salt-brackish interface. It was interpreted that the rift zones, defined by the lines H and X, probably have low permeability and, therefore, funnel the basal water into a swath between Hapuna and 'Anaeho'omalu bays. Electrical resistivity profiles made from Puakō to 'Anaeho'omalu bays narrowed anomalous apparent resistivity to the line segments Q and R in Figure 8. However, no extensive discharge of fresh water has been reported.

The AMT and aeromagnetic data agreed well on the position of the two anomalies given as lines J and K in Figure 7. Line K is the known northwest rift of Hualālai and line J is without apparent surface expression. These two lines diverge from the possible groundwater recharge area of the Hualālai summit. The structural controls of basal water movement are therefore probably not significant (Adams et al. 1969).

Dikes could occur within rift zones of Mauna Loa and Hualālai, impounding groundwater to levels above those of the basal water bodies. No dike outcrops or dike rock in the study areas have been observed or previously reported; however, they could occur deep below the surface.

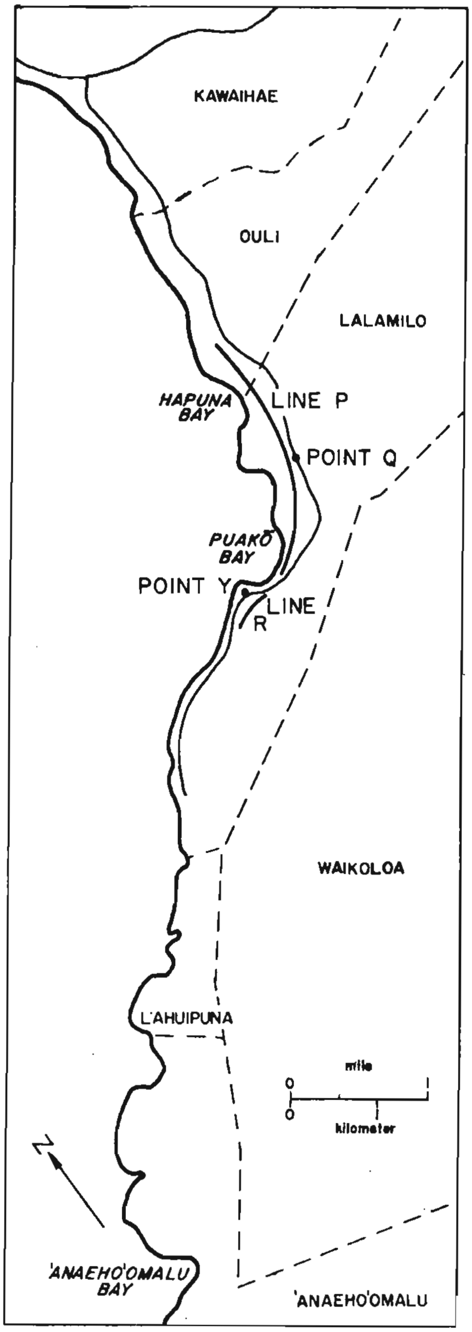


FIGURE 8. TWO LINES, P AND R, CORRESPONDING TO THE RELATIVELY HIGH APPARENT RESISTIVITY ANOMALIES, ARE SHOWN FOR THE HAPUNA-PUAKŌ BAY AREAS. POINTS Q AND Y ARE CONSIDERED TO BE REPRESENTATIVE SITES FOR LINES P AND R, RESPECTIVELY. (AFTER ADAMS ET AL. 1969)

HYDROLOGY[1]

Climate

The study area is characterized by low rainfall, high to moderately high evaporation, high temperature, and at times strong winds. A few storms occur during the winter months bringing about areally-wide rainfall that may account for most of the annual rainfall.

In general hydrologic data are extremely scarce and, therefore, the totals and distributions of the hydrologic variables are difficult to define. The inadequacy of data necessitated the installation of evaporation pan stations to estimate potential water loss through evaporation and transpiration before a water budget could be constructed. This, in general, posed severe limitations on the degree of desired accuracy.

RAINFALL. Rainfall accounts for virtually all the precipitation for the study area, although snow falls on the summits of Mauna Loa and Mauna Ke'a during the winter months.

The mean annual rainfall for the area is 63 cm (21 in.) with a range from about 102 cm (40 in.) in the uplands to less than 25 cm (10 in.) in the coastal plains (Fig. 9). There is a gradual increase in rainfall with elevation to a maximum of 51 to 76 cm (20 to 30 in.) on the northern slopes of Mauna Loa.

Rainfall controls are the high mountains of Mauna Ke'a and Mauna Loa, both rising above 3,962 m (13,000 ft), and an atmospheric inversion generally prevails at an elevation between 1,290 to 1,829 m (4,000 to 6,000 ft) with high humidity below the inversion level and drier conditions above. Thus, the tradewinds coming generally from an east-northeasterly direction are effectively blocked and trapped and unable to reach the study area. There is, however, some spillage of orographic rainfall over the plateau or saddle area between the mountains, thus recharging the groundwater in the Waimea area, which is located to the north of the study area. Still another area, but of lesser importance, is the general area of Pōhakuloa, located between Mauna Ke'a and Mauna Loa. In both cases, the isohyetal patterns quite evidently reflect the effects of deflection and diversion around the mountain passes. The sea breeze phenomenon which brings considerable rain to Kailua-

[1] L. Stephen Lau, Project Associate Investigator.

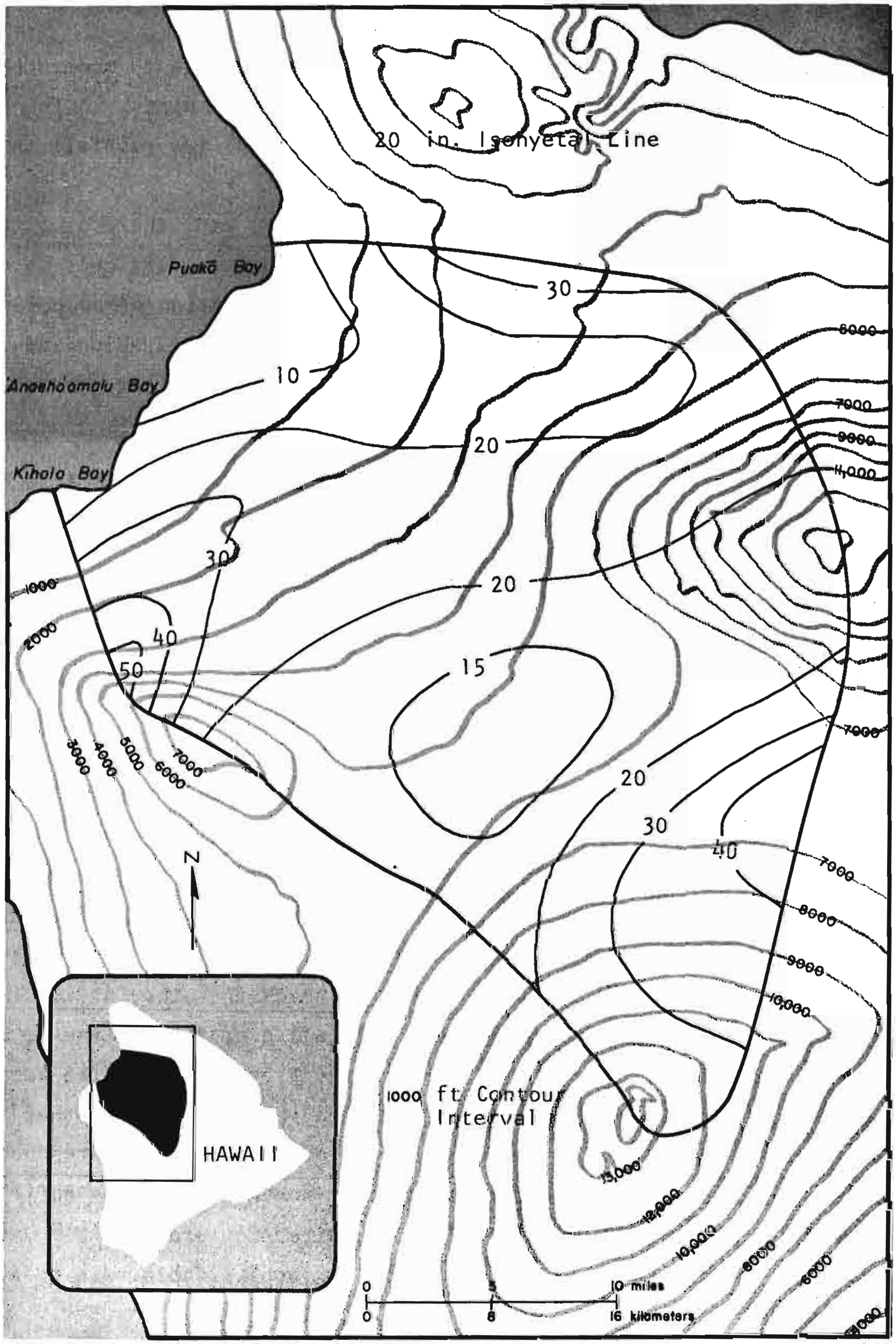


FIGURE 9. MEAN ANNUAL RAINFALL, KONA COAST

Kona, which is just south of the study area, is effective only in raising humidity rather than in increasing rain.

The average monthly rainfall at the coastline of the study area, such as Puāko, reaches a low of approximately 0.6 cm (0.25 in.) in June, July, and August and a high of no more than 5 cm (2 in.) in January.

For the purpose of this study, it is essential to recognize that the major groundwater recharge is due primarily to winter storms which bring about moderate to high intensity rain over a large area in a period of a few hours. Thus, screening of the already few rainfall stations with daily rainfall records narrowed down to only 6 stations which were selected for water budgeting in this study. Table 1 shows the average monthly and annual rainfalls for the four individual years.

TABLE 1. AVERAGE MONTHLY AND ANNUAL RAINFALL FOR SIX STATIONS 1952, 1955, 1958, 1961

	Station Name and Number					
	Hu'ehu'e	Kamuela	Ke'amuku	Puakō	Pu'u Anahulu	Pu'u Wa'awa'a
	92.1	192.2	96.1	95.1	93.1	94.1
Average Monthly	(in.)					
January	3.51	4.11	2.52	2.25	1.62	2.40
February	2.74	3.96	1.57	0.27	2.51	2.25
March	4.14	2.86	3.34	1.19	2.91	3.90
April	2.78	2.81	1.34	0.11	1.62	1.46
May	3.67	1.92	0.92	0.17	0.93	1.19
June	5.84	1.78	0.71	0.38	1.84	2.28
July	1.55	3.62	1.08	0.79	1.96	2.00
August	1.56	3.01	0.74	0.15	0.40	0.86
September	3.54	0.64	0.50	0.41	1.45	1.21
October	1.48	1.96	0.58	0.47	0.81	1.65
November	3.12	2.67	2.59	0.63	1.99	1.62
December	2.90	2.40	1.66	0.91	1.09	1.36
Average Annual	36.83	32.06	17.53	7.71	19.12	22.19

NOTE: in. x 2.54 = cm.

EVAPORATION. Evaporation data from which potential evapotranspiration may be estimated for water budgeting is almost nonexistent for the study area. The closest evaporation station, Lālāmilo (191.4), is lcoated outside the study area and is, at best, an approximation of the mid-elevation section. Transposition of data from other dry leeward regions from other islands, such as Lahaina, Maui, was considered a poor approximation because of the possible evaporation-suppressing effect of the sea breeze known to be effective in the area. It was finally decided to install temporary, simple wash tub-type evaporation pans at two locations within the study area to obtain short-term records for both the winter months of 1975 to 1976 and the summer months of 1976. The monthly averages are respectively 0.46 cm/day (0.18 in./day) and 0.91 cm/day (0.36 in./day), reflecting a distinct seasonal variation.

TEMPERATURE AND WIND. The study area is characteristically sunny, dry, and frequently windy. The mean temperature ranges from about 24°C (76°F) near the shoreline to below 10°C (50°F) on the mountain summits (Fig. 10). Wind data are scarce. During the course of evaporation measurements, there were four consecutive days (23 to 26 March 1976) with average wind velocities from 56 to 88 km/hr (35 to 55 mph).

Surface Water Drainage

There are no perennial streams in the study area. In the upland areas, the natural drainage net is slightly developed as represented by a number of gulches, the most extensive being 'Auwaiakeakua in Waikoloa (Fig. 11). None of these intermittent stream gulches reaches the ocean; 'Auwaiakeakua Gulch terminates about 2 km (1 mile) landward from Puakō. There are no intermittent streams in Pu'uwa'awa'a, the area south of 'Anaeho'omalu because of recent lava flow cover (lava flow of 1859). Streamflow discharge data are nonexistent for the study area.

Because of the highly porous and permeable surface, the absence of less permeable materials, such as soil, and the low rainfall for the study area, much of the remaining water is lost to infiltration and becomes unavailable to surface runoff. However, the upper reaches of gulches carried discharge during periods of infrequent, intense storms recorded at two gage stations located at about the 762-m (2,500-ft) elevation level west of Mamalahoa Highway (Hwy. 19) on the eastern slopes of Mauna Loa. Because of the surficial geology, stream hydrology, and lack of direct streamflow discharge into the ocean, surface water drainage will not constitute a part of the water budget study.

Land Use and Water Development

For the most part, the land remains in a near natural state, i.e., arid lava land. Cattle ranches, notably Parker and Pu'uwa'awa'a, represent most

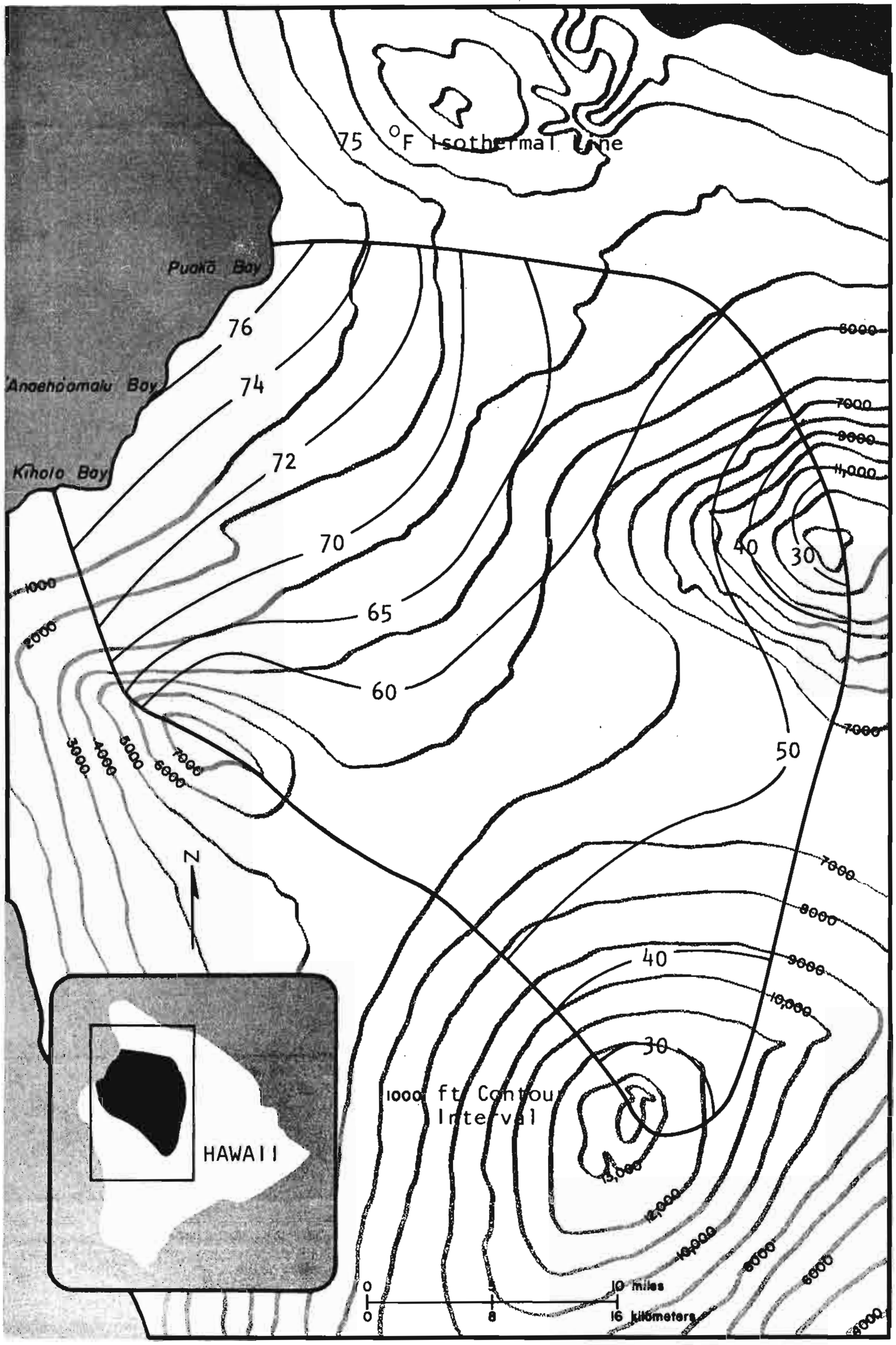


FIGURE 10. MEAN TEMPERATURE, KONA COAST

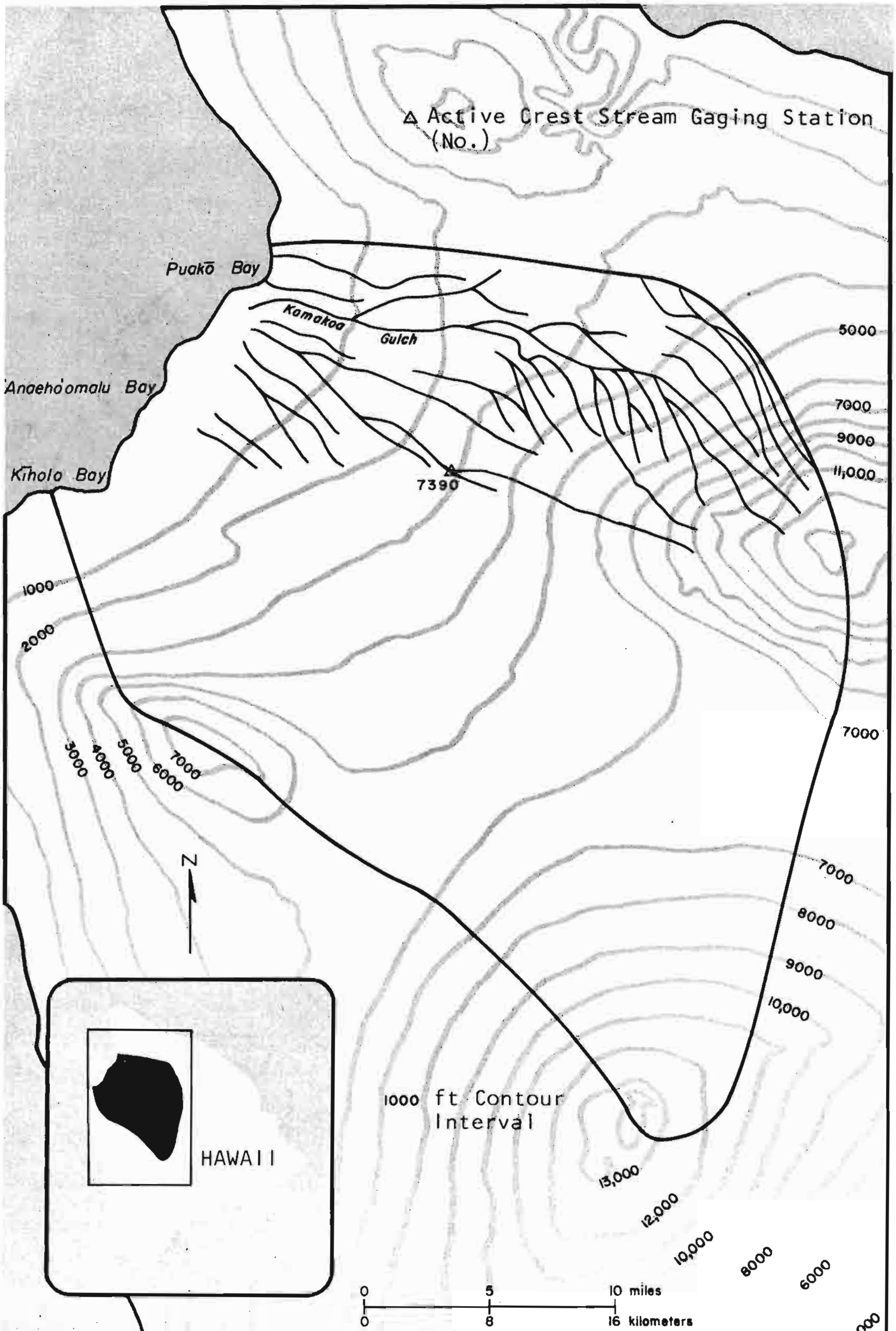


FIGURE 11. STREAM-GAGE STATIONS, KONA COAST

of the present land use. The only major urban land use plan now being slowly implemented is Waikoloa, a hotel-urban residential development complex controlled by Boise Cascade. At present, the development consists of a golf course-recreational center, less than 100 houses, many miles of wide highway, and the basic utilities for urban subdivision. A new state highway, Kaahumanu Highway, completed and opened to public use in 1976 skirts the coastline.

For water supply, there are three drilled wells operated by Waikoloa: Parker Wells 4 and 5 (7 km [4.6 miles] from the coast; 365-m [1,200-ft] approximate elevation), and Parker Well 1 (6 km [4 miles] from the coast, 260-m [850-ft] approximate elevation). Contrary to all water wells in the Kawaihae and South Kohala areas, Parker Wells 4 and 5 produce fresh water of exceptional quality. Parker Well 1 water is expectedly brackish with a chloride concentration of about 500 mg/ℓ. Farther south is Pu'u Wa'awa'a Well (5 km [2.8 miles] from the coast; 275-m [900-ft] approximate elevation), the only other producing well in the area with a chloride concentration of about 300 mg/ℓ. Pumpage averaged 1,022 m^3/day (0.27 mgd) from Parker Wells 4 and 5 for the calendar year 1975, and 2,839 m^3/day (0.75 mgd) from Parker Well 1 for the first 6-mo. period of 1976. Pu'u Wa'awa'a Well pumpage is unknown but is believed to be of small quantity. Domestic waste water effluent from the Waikoloa development is discharged into an injection well.

These water wells and a number of drilled holes in the study area together with wells outside the study area are listed in Table 2 and located in Figure 12.

Groundwater

The known groundwater occurrence in the study area is, for the most part, a thin basal lens with the water level located generally only a few feet above the sea level and with a slightly sloping water table toward the ocean. The gradient is not determined except for the Kawaihae-Puakō area (Fig. 13) which is 0.24 km/ha (1.3 ft/mile). The lens water is slightly brackish with increasing salinity towards the ocean.

The only exceptions to the low water level and the brackish water quality are Parker Wells 4 and 5 which had a reported high water level of 5 m (16 ft) and a low chloride concentration of less than 30 mg/ℓ. This high-head, low-chloride anomaly is probably caused by subsurface dikes that im-

TABLE 2. WELLS AND DRILLED HOLES IN THE AREA FROM PUAKŌ TO KĪHOLO BAYS

USGS No.	Description	Static Head (ft)	Chlorides (mg/ℓ)
4858-01	Kona Village Well 1	4.0	370
4858-02	Kona Village Well 2	1.8	378
4858-03	Kona Village Well 3	2.8	300
4953-01	Kīholo Well (Pu'u Wa'awa'a Well)	2.6	345
5452-01	Boise Cascade Parker 7 (drilled hole)	--	1,000
5548-01	Boise Cascade Parker Well 1	6.1	500
5552-01 to -05	Boise Cascade Parker 6 (5 drilled holes)	1.5	1,500
5648-01	Boise Cascade Parker 2	5.1	380
5745-01	Boise Cascade Parker Well 5	16	30
5745-02	Boise Cascade Parker Well 4	--	--
5948-01	Hapuna Beach Well	2.6	430
6048-01	Kawaihae Exploratory Well No. 2	3.3	500
6049-02	Mauna Kea Beach 3 Hawaii Well 17	2.0	900
6049-03	Mauna Kea Beach Well 4	1.0	1,600
6147-01	Kawaihae Well 16	5.2	250
6148-01	Kawaihae Well 14	3.3	300
6148-02	Kawaihae Exploratory Well 1	3.3	300

SOURCE: Miyasato (1974).

pound water to an exceptional height and separate and protect the impounded water from the salt water. By means of radiocarbon dating described in the section on Water Quality, the Parker Wells 4 and 5 water is determined to have a radioisotopic age substantially older than that of the basal water area.

Along the coastline of Waiulua and Kīholo bays, there occur many discrete points of visible, concentrated and gushing discharge from the basal lens. These two coastlines are formed by historic or prehistoric lava flows with typically highly porous and permeable rock. Coastal discharge of basal water probably also occurs but in a more uniform and diffused manner along other shorelines, such as at 'Anaeho'omalu Bay. A considerable part of the 'Anaeho'omalu shoreline is a beach composed of mostly medium-textured calcareous sand. Seepage through these sediments would cause a diffused discharge. Variation of the shoreline porosity and permeability will thus create a nonuniform discharge into the ocean even though there may be a uniform flux of groundwater approaching the shoreline from the inland recharge area. Furthermore, the strong ocean waves and currents at open shorelines would quickly obliterate any characteristic basal water quality

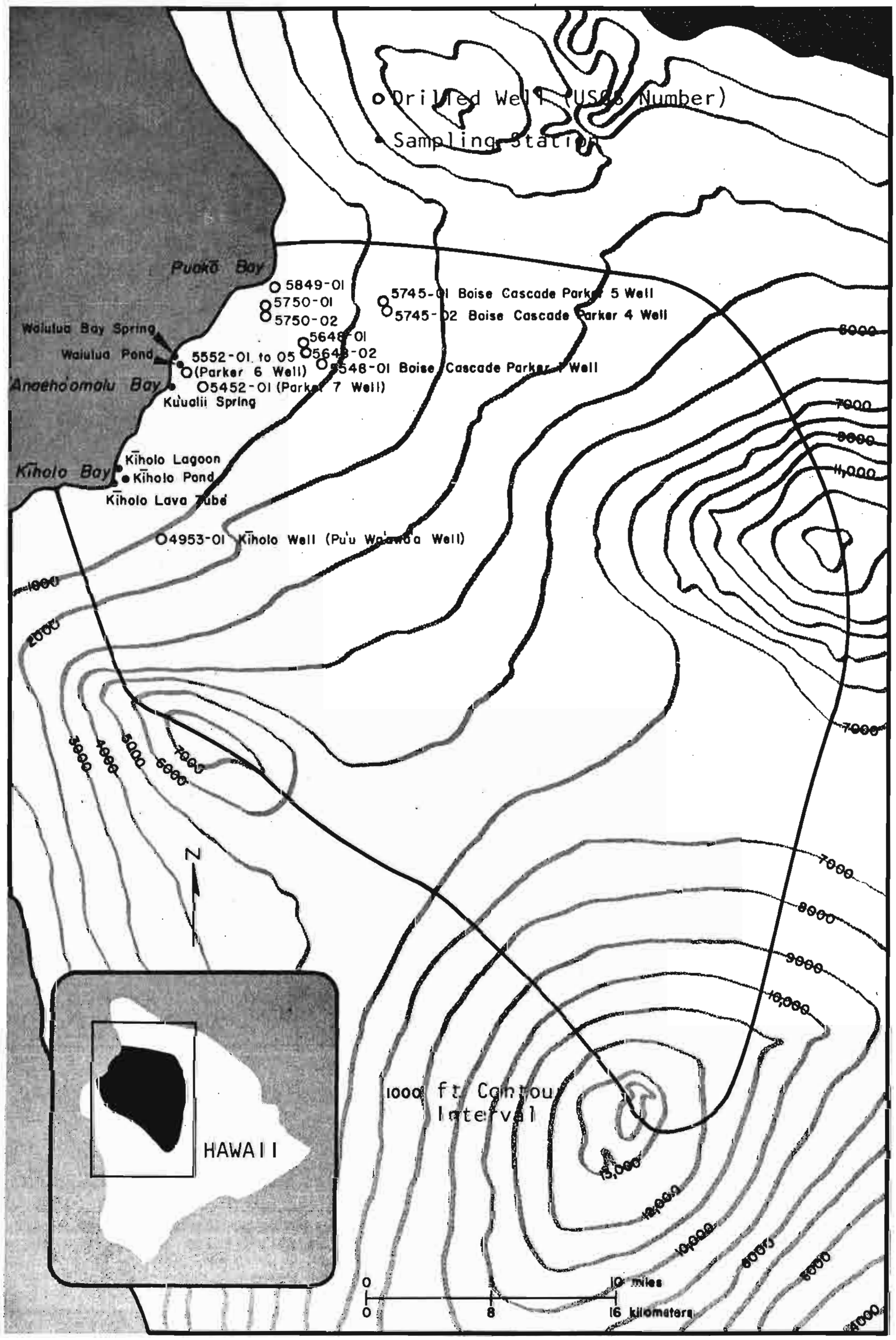


FIGURE 12. WATER SAMPLING STATIONS AND DRILLED WELLS, WEST HAWAII STUDY AREA

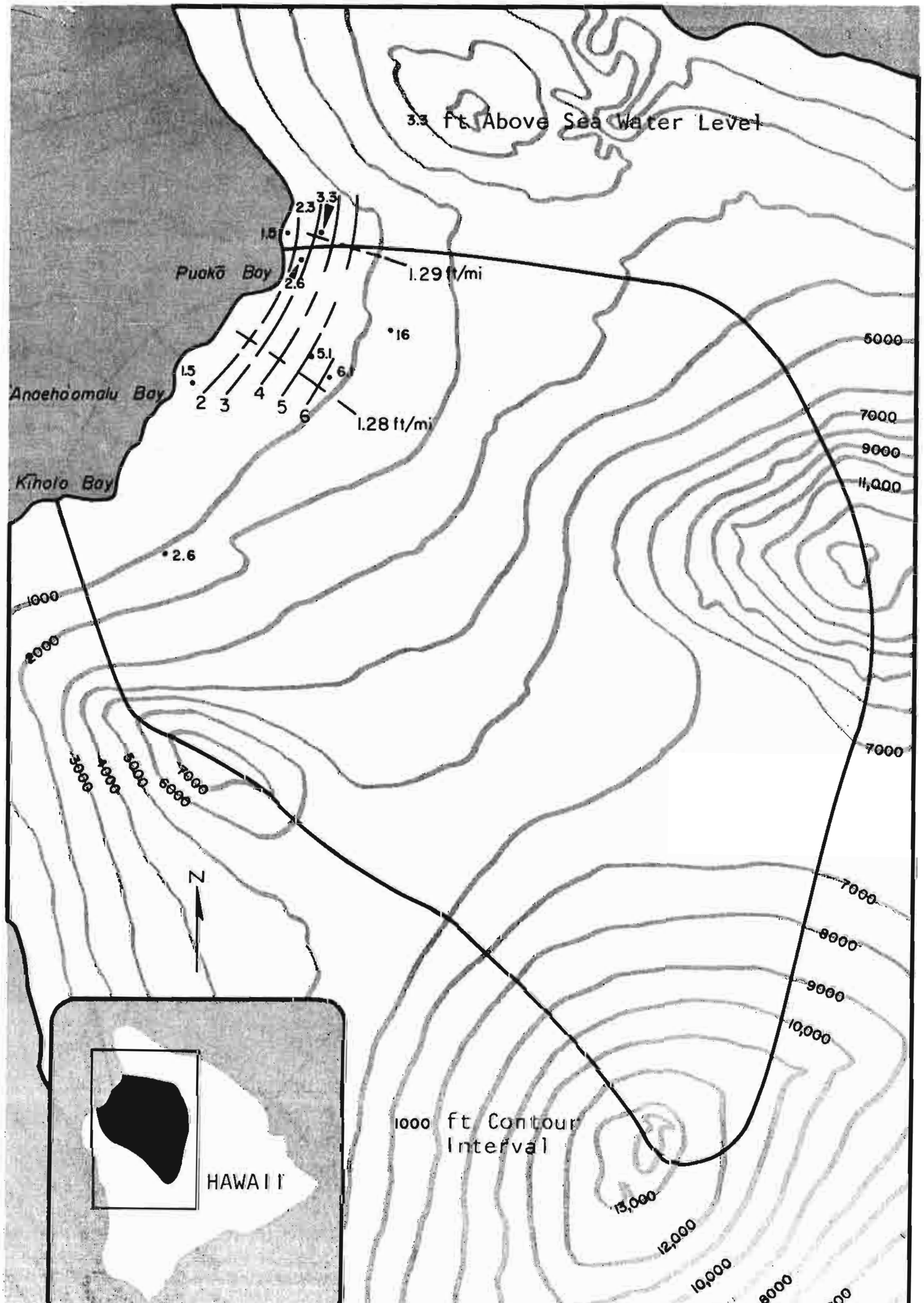


FIGURE 13. GROUNDWATER GRADIENT, KAWAIHAE TO PUAKŌ AREA

parameters, such as low salinity and low temperature, in the coastal water. In contrast, at both Waiulua and Kīholo bays, the basal water from these visible concentrated spring discharge points drains into a partially enclosed embayment, rather than into open coastal waters. The discharged water floats on top of the coastal water and forms a persistent layer of water of low salinity and low temperature, varying in thickness on the order of a few inches and in areal extent. These were the only coastal waters in the study area exhibiting such easily observable and measurable phenomena. A detailed hydrographic and water quality description of the Wainānāli'i Pond at Kīholo is given in a later section.

Water Quality

Samples of groundwater, near-shore pond water, and coastal water were collected from a net work of 11 regular sampling stations and a few selected locations from October 1974 to October 1975. The water quality parameters analyzed include nitrogen (total, ammonia, organic, nitrite and nitrate), phosphorus (total, soluble), chemical oxygen demand, bacterial indicators (total coliform, fecal coliform, and fecal streptococcus), chloride, electrical conductivity, turbidity, and solids (total, volatile, suspended, volatile, suspended, volatile suspended). Several groundwater samples were assayed for tritium, radiocarbon, and ^{13}C. Table 3 presents the mean and range of the chemical parameters. The complete data are included in Appendix Table A.1.

CHLORIDE. The average chloride concentration in the basal water was in the slightly brackish range (501 mg/ℓ at Parker Well 1) with an annual variation of ±50 mg/ℓ for a distance as far as 6 km (4 miles) inland from the coastline. In the south at Pu'u Wa'awa'a Well, the average chloride concentration was slightly brackish and fresher (322 mg/ℓ) than the Parker Well 1, even though the Pu'u Wa'awa'a Well is closer (5 km or 2.8 miles) to the coastline. This difference may be due to the higher rain water recharge in the south although the pumping differential could mask the natural differential.

The average chloride concentration increased seaward as expected as greater tidal effects were felt. The average chloride concentration was 1,662 mg/ℓ in a shoreline pond 0.2 km (0.1 mile) from Waiulua Bay and 1,066 mg/ℓ in a lava tube less than 0.2 km from the shoreline at Kīholo Bay. The water from the two shoreline springs was more brackish: 2,653 mg/ℓ at Ku'uali'i Pond and 2,922 mg/ℓ at Waiulua Bay. At Wainanali'i Pond at Kīholo Bay where the sampling point was directly affected by high tides, not only the average of concentration was high (4,611 mg/ℓ), but also the range of concentration varied the widest (770 to 9,450 mg/ℓ) among all the sample locations.

ELECTRICAL CONDUCTIVITY AND TOTAL SOLIDS. The electrical conductivity data correlated well with the chloride concentration data as expected since the ocean water was the only significant source in the area for both chloride and the electrically conductive solutes. The total solids data correlated well with the electrical conductivity data since the dissolved solids concentration expectedly accounted for nearly all of the total solids in the water samples.

NITROGEN. The average nitrate nitrogen concentration in Parker Wells 4 and 5 water was 1.1 mg/ℓ, satisfying drinking water standards and accounting for over 90% of the total nitrogen. The highest nitrate nitrogen concentration in the more inland part of the basal was respectively 0.8 mg/ℓ at Parker Well 1 (6 km or 4 miles from the shoreline) and 0.9 mg/ℓ at Puu Waawaa Well (5 km or 2.8 miles). The nitrogen is significantly derived from nitrogen-fixation plants, such as kiawe (*Prosopis pallida*), which is plentiful and is known to produce nitrate. No other known source of nitrogen exists in the area except for the small quantity of sewage treatment effluent. Irrigation return flow from the Waikoloa Golf Course is discounted as a source because of the great nitrogen removal capability of the sod-soil system (Lau et al. 1975) and the small quantity of return flow. A small anomaly exists at the Parker Well 6 where nitrate nitrogen accounts for 66%, rather than the 80% or or more, of the total nitrogen in all other sampled waters.

The nitrate nitrogen concentration in the basal water decreased seaward to about 0.6 mg/ℓ at the Waiulua Pond station and the Kīholo lava tube station near the shoreline. This decrease is mostly accounted for as the effect of salt water dilution because ocean water has a much lower concentration of nitrate than the groundwater, and mixing with salt water by tidal effects becomes greater towards the ocean.

The areal distribution of total phosphorus in the groundwater has a great similarity with that of nitrogen; however, the concentrations are dif-

TABLE 3. MEAN AND RANGE OF SELECTED WATER QUALITY PARAMETERS, OCTOBER 1974 TO OCTOBER 1975

	Chloride (mg/ℓ)		Elec. Cond. (µmhos/cm)		Tot. Sol. (mg/ℓ)		Vol. Sol. (mg/ℓ)		Susp. Sol. (mg/ℓ)		VSS (mg/ℓ)	
	Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range
Parker Well 4	26	23-25	261	106-485	201	160-242	12	12	3.9	0.6-10.2	1.8	1.8
Parker Well 5	25	21-28	265	177-455	208	170-229	42	20-64	1.4	0.4-3.0	2.3	2.3
Parker Well 1	501	445-550	1,318	460-1,950	1,240	1,216-1,264	166	163-168	4.5	0.8-19.0	8.4	0-16.8
Parker Well 6*	830	798-850	2,216	1,060-3,000	1,944	1,906-1,997	297	270-320	47.0	1.0-118.4	4.8	0.4-12.1
Pu'u Wa'awa'a	322	310-350	1,053	800-1,400	852	758-946	62	62	2.1	0.6-5.2	0.4	0.4
Waiulua Bay Spring†	2,922	2,322-3,700	7,103	4,450-10,000	5,774	5,172-6,376	1,056	970-1,142	3.9	1.0-6.5	2.5	2.5
Waiulua Pond*	1,662	1,625-1,700	5,350	5,200-5,500	3,582	--	664	664	1.5	0.4-2.6	0	0
Ku'uali'i Spring†	2,653	1,816-3,949	4,967	4,000-5,500	5,968	3,994-7,542	748	748	28.8	2.4-76.4	8.2	8.2
Kīholo Lava Tube*	1,066	972-1,160	2,690	1,800-3,400	2,351	2,248-2,502	342	328-355	1.1	0.6-1.8	0.3	0.3
Wainānāli'i Pond‡	4,611	770-9,450	15,950	9,900-22,000	7,408	--	--	--	--	-- --	--	--
Ocean Water (Outside Waiulua Bay)	18,186	--	14,000	--	36,633	--	--	--	--	--	--	--

TABLE 3--CONTINUED.

	$NO_2 + NO_3$-N		Total N		Total P		Sol. P		Turbidity (FTU)		COD (mg/ℓ)	
	(mg/ℓ)											
	Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range
Parker Well 4	1.099	0.646-1.510	1.162	0.680-1.640	0.089	0.080-0.110	0.072	0.059-0.080	1.4	0.4-2.9	37.8	4.7-79.0
Parker Well 5	1.081	0.467-1.450	1.200	0.487-1.630	0.080	0.063-0.100	0.066	0.059-0.080	2.1	0.6-4.8	24.6	0-50.0
Parker Well 1	0.824	0.547-0.980	0.977	0.567-1.182	0.102	0.065-0.190	0.057	0.040-0.090	4.8	0.4-16.0	65.2	0-172.9
Parker Well 6*	0.578	0.396-0.670	0.878	0.630-1.266	0.104	0.053-0.120	0.071	0.050-0.110	30.8	1.3-152	72.0	0-220
Pu'u Wa'awa'a	0.867	0.810-0.940	0.919	0.819-1.020	0.114	0.093-0.150	0.062	0.031-0.085	0.6	0.2-1.1	44.0	0-67.0
Waiulua Bay Spring†	0.558	0.480-0.675	0.652	0.480-0.790	0.056	0.047-0.070	0.051	0.038-0.064	1.0	0.9-1.1	64.9	23.7-106.1
Waiulua Pond*	0.619	0.553-0.686	0.724	0.711-0.737	0.071	0.045-0.097	0.061	0.045-0.077	1.1	1.0-1.2	45.0	16.0-74.0
Ku'uali'i Spring†	0.731	0.403-1.274	0.863	0.600-1.287	0.077	0.063-0.088	0.070	0.050-0.090	11.2	0.3-28.0	109.7	35.5-200.0
Kīholo Lava Tube*	0.603	0.379-0.770	0.704	0.460 0.903	0.074	0.050-0.100	0.068	0.040-0.120	0.9	0.7-1.5	56.5	8.9-90.0
Wainānāli'i Pond‡	0.807	0.644-1.209	0.939	0.570 1.217	0.075	0.068-0.083	0.098	0.048 0.170	1.2	1.0-1.5	97.5	97.5
Ocean Water* (Outside Waiulua Bay)	0.160	--	0.160	--	--	--	--	--	--	--	--	--

*Tide-affected groundwater.
†Shoreline spring.
‡Coastline water samples, corresponding to Station X_3 in Figure 28.

ferent. The highest concentration was present in the more inland part of the basal water: 0.102 mg/ℓ at Parker Well 1 and 0.114 mg/ℓ at Puu Waawaa Well. The groundwater near the shore had a lower total phosphorous concentration: 0.071 mg/ℓ at Waiulua Pond and 0.074 mg/ℓ at Kīholo lava tube. At the shoreline discharge points, the concentration was 0.056 mg/ℓ at Waiulua Spring and 0.077 mg/ℓ at Ku'uali'i Spring. The soluble phosphorus accounts for nearly all the phosphorus present in the spring water at Waiulua and at Kīholo.

The groundwater discharge into the ocean definitely supplies an important and sustained source of nitrogen for the near-shore coastal water. For example, the average concentration at Waiulua Bay spring is over 400% higher than that in the coastal water. Likewise, a continuous enrichment of phosphorus in the coastal water takes place in the groundwater discharge since the average concentration in the groundwater is about 100% higher than that in the coastal water. However, it is less than obvious whether there is a discernible enrichment effect on the biota in Waiulua and Kīholo bays where the concentrated groundwater discharge takes place.

MICROBIOLOGICAL WATER QUALITY. The coliform concentration of the water examined was low and without indication of fecal contamination. The only possible exception was the Kīholo lava tube site which showed a moderately low concentration of fecal coliform and fecal streptococci. These could be caused by animal wastes.

RADIOISOTOPIC AGE. Tritium was determined for a number of groundwater samples collected in 1975 by the Water Resources Research Center Environmental Tritium Laboratory. The results listed in Appendix Table A.2 indicate a uniformly low tritium activity level and an isotopic age of less than 50 years relative to the time since the rain water entered the ground. The results for the basal water were not unexpected because of the known low rainfall in the study area and, thus, the low groundwater recharge. However, the results do not differentiate the relative age between the basal water (Parker Well 1, Puu Waawaa Well) and the assumed dike water (Parker Wells 4 and 5).

Three, 60-gal water samples were subsequently collected in 1976 and assayed for radiocarbon (^{14}C) by the same laboratory. The results listed in Appendix Table 2 have been adjusted for carbon 13 using chemical data obtained from supplementary water samples and by criteria developed in an Oahu groundwater study (Hufen 1974). Theoretically speaking, a comprehensive study should be made for arid regions, such as the study area, in order to check the value of the several constants used in the computation of the radiocarbon age; however, the magnitude of work would be far beyond the scope and the available resources for this study. The average adjusted radiocarbon age for Parker Well 5 water is about 1,800 years while Parker Well 1 water is of recent age. The age differential is considered great and supports the groundwater impoundment theory for the area. Further, it implies limited capacity of the impoundment and necessary management measure for the development of the groundwater from Parker Wells 4 and 5. A prudent measure would be monitoring the water level and the associated pumpage from the wells for a number of years to obtain another indication of the impoundment and to assess the balance between recharge and pumpage.

Water Flux

Water flux discharging from the land mass into the ocean is primarily groundwater flux. The surface water contribution should be negligible. For the purpose of water budgeting under present water and land use conditions, the groundwater flux can be approximated by the groundwater recharge. Three water budgets, each with increasing refinement, have been constructed, yielding successively improved estimates of the groundwater recharge. These estimates were checked independently with two different hydraulics methods. Direct field measurement of the groundwater flux was not feasible.

WATER BUDGETS. The basic equation of water budgeting is that the groundwater recharge equals rainfall less evapotranspiration, surface runoff, and net extraction. The surface runoff and the net groundwater extraction (pumpage minus return flow) should be negligible for the study area. The boundary of potential recharge is assumed to coincide with the boundary of the watershed since the aquifer is phreatic and since there are no known geologic boundaries that would significantly invalidate the assumption.

For the first budget, the entire watershed was taken as a single unit. The areal rainfall was taken to be the average of the mean annual rainfall of the five rainfall stations. All four years of rain record (1952, 1955, 1958, 1961) were selected and utilized because of the concurrence and completeness. Since there was a nearly total lack of evaporation data for the area, pan evaporation data were transposed from climatically similar areas of other Hawaiian islands to the study area. The annual groundwater recharge was determined to be 7.1915 x 10^6 m^3 (19 bil gal) by the first budget. This would be equivalent to a basal water flux of 7,526 m^3/day/km (3.2 mgd/mile) of coastline.

The methodology and data base were improved in several ways for constructing the second water budget. Daily rainfall data were used and the watershed was divided into 6 subwatersheds, each encompassing one of the rain stations and treated separately in water budgeting before totaling the entire watershed. It was assumed that the daily rainfall that is less than a threshold value is held temporarily in a shallow zone below the surface and subsequently evaporates. Only the daily rainfall exceeding the threshold value, after an estimated evapotranspiration is subtracted, is contributory to groundwater recharge through deep percolation. The threshold value was based on estimated values of field capacity of the rock and soil. The evapotranspiration values were transposed from evaporation pan data from climatically similar areas with due adjustment because of the moderate sea breeze effective in the project area.

The probable value for the annual groundwater recharge for the watershed based on the second budget was 11.355 x 10^7 m^3 (30 bil gal), which is equivalent to a basal water flux of 11,760 m^3/day/km (5.0 mgd/mile) of coastline. Probable maximum and minimum values were also obtained based on a range of value for the assumed budget parameters. These maxima and minima represent a rather wide range, reflecting uncertainty in the assumed values of the several parameters.

The improvements made for the third and final water budget included utilizing daily pan evaporation data, fragmenting the watershed into thousands of "cells" (average size 0.195 $mile^2$) for which the water budget was made, utilizing a high-speed digital computer, and the SYMAP mapping technique. These improvements enabled computed recharge values for the individual cells. Summation of recharge over time (daily) and space (cells) was made to obtain annual recharge values for the four-year study period. The results are summarized in Table 4.

HYDRAULIC METHODS. The two hydraulics methods are different from each other and from the water budget approach in both methodology and much of the data base. The first hydraulics method is an approximate application after Cooper as adopted by Mink (1975). The second hydraulics method is an approximate application of Darcy's law.

TABLE 4. ANNUAL GROUNDWATER RECHARGE FOR THE WATERSHED

	Groundwater Recharge Max.	Prob.	Min.
Annual, mil gal/yr			
1952	90,360	59,778	38,105
1955	68,451	31,150	11,902
1958	62,036	33,041	13,858
1961	69,634	27,866	11,206
Average Annual,			
mil gal/yr	70,120	37,959	18,768
in.	5.7	3.1	1.5
% of Ann. Rainfall	27.1	14.8	7.1
Average Annual			
mgd	192	104	51
mgd/mile coastline	11.8	6.4	3.2

NOTE: Basin area = 711.13 miles^2,
Coastline length = 16.3 miles,
Mean annual rainfall = 21 in.

Under idealized conditions, where no caprock occurs, seepage from a basal lens will be uniformly distributed across a strip of near-shore water whose seaward width, x, depends upon the flux from the lens, hydraulic conductivity of the aquifer, K, and the density difference between fresh and ocean water divided by the density of fresh water, a. The relationship is:

$$Q = 2\ a\ K\ x\ L$$

where Q is the freshwater flux for specified length of shoreline L. In this application, it is recognized that the project aquifer is occupied by a brackish water lens with a zone of transition of water density rather than a classical freshwater lens with a sharp freshwater-salt water interface. The computed flux is presented in Table 5 as a function of seepage width and hydraulic conductivity of the basalt; the selected range of values for these two parameters is believed to be reasonably representative of the field conditions.

TABLE 5. COMPUTED BASAL WATER FLUX, METHOD I

Computed Basal Water Flux, mgd/mile of Coastline			
Seepage Width, x (ft)	Hydraulic Conductivity (ft/day) 1,300	2,700	4,000
1	2.57	5.33	7.90
2	5.14	10.66	15.80
3	7.71	15.99	23.70

The second computation method involves the application of Darcy's law as a first approximation of the seaward basal water flux across a groundwater contour. At the 1.5-m (5-ft) groundwater contour, the gradient was 0.25 m/km (1.3 ft/mile). The freshwater thickness could be reasonably assumed to be that of the Ghyben-Herzberg depth plus the freshwater head (40 • 5 + 5 = 205 ft). Table 6 presents the computed basal water flux as a function of the hydraulic conductivity.

TABLE 6. COMPUTED BASAL WATER FLUX, METHOD 2

Hydraulic Conductivity (ft/day)	Computed Basal Water Flux (mgd/mile of coastline)
1,300	2.59
2,700	5.38
4,000	7.96

EVALUATION. The seaward flux of basal water, which is assumed to be equivalent to the groundwater recharge under the existing condition on a long-term basis, is determined to range between 27,754 and 7,526 m^3/day/km (11.8 and 3.2 mgd/mile) of coastline with the probable value being 15,052 m^3/day/km (6.4 mgd/mile) or 393,640 m^3/day (104 mgd) for the whole area. The probable value is equivalent to 15% of the mean annual rainfall for the area; this probable value is supported by a value of 20% reported by the Hawaii Water Resources Regional Study (1975). This probable value is larger, but is believed to be more reliable, than those obtained by the first and second water budgets (5.0 for the second budget and 3.2 for the first budget). The flux values, as determined by the two hydraulic methods, fall within and support the above values determined by water budgeting.

NUTRIENT FLUXES. The computed value of nitrogen and phosphorus fluxes is based on the probable groundwater flux and the average concentration of these water quality parameters present in the groundwater at sufficiently inland locations. These values presented in Table 7 are intended to represent the nutrient fluxes that are terrigenous with minimum dilution effects by the transition zone water.

TABLE 7. NITROGEN AND PHOSPHORUS FLUXES

Flux	Average Concentration[1] (mg/ℓ)	Flux	
		lb/day/mile	lb/day[2]
Total Nitrogen	0.948	45.24	737
Nitrate + Nitrite Nitrogen	0.840	40.08	653
Total Phosphorus	0.108	5.15	84
Soluble Phosphorus	0.060	2.86	47

SOURCE: B.Y. Kanehiro (1977, Tech. Rep. No. 110).
[1]Average of Parker Well 1 and Puu Waawaa Well.
[2]Length of coastal line = 16.3 miles.

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APPENDIX TABLE A.1. WATER QUALITY DATA FOR SOUTH KOHALA COASTAL AREA, OCTOBER 1974 - OCTOBER 1975

Sampling Station	Date	Total Solids	Vol. Solids	Susp. Solids	VSS	Turb.	Elec. Cond.	Total N	NH_4-N Org. N	NO_3 + NO_2-N	Total P	Sol. P	Cl^-	COD	Total Coli.	Fecal Coli.	Fecal Strep.
		(mg/ℓ)				FTU	μmhos/cm	(mg/ℓ)							(no./100 mℓ)		
Parker Well 1	Oct 74	1216	168	0.8	ND	<1	1680	1.182	0.289	0.893	0.038	0.038	496.0	ND	--	<3	--
"	Feb 75	1241	163	19.0	16.8	16.00	1180	0.810	0.010	0.800	0.130	0.060	503.0	87.1	23(Mar)	<3	<3
"	May 75	1264	---	0.4	--	0.15	460	1.180	0.200	0.980	0.090	0.090	550.0	50.0	<3	<3	<3
"	Jul 75	--	---	1.4	--	6.50	--	1.150	0.250	0.900	0.190	0.040	510.0	172.9	43	--	--
"	Aug 75	--	---	>1.0	--	0.40	1950	0.567	0.020	0.547	0.065	0.059	445.0	16.0	--	<3	--
"	Oct 75	--	---	---	--	--	--	---	---	---	---	---	---	--	9	<3	<3
Parker Well 4	Feb 75	242	12	1.8	1.8	1.80	192	0.900	0.000	0.900	0.070	0.070	27.0	79.0	<3(Mar)	<3	<3
"	May 75	160	---	0.6	--	0.39	106	1.430	0.090	1.340	0.110	0.080	28.0	30.0	<3	<3	<3
"	Jul 75	--	---	10.2	--	0.43	--	1.640	0.130	1.510	0.080	0.080	23.0	37.6	4	<3	--
"	Aug 75	--	---	3.0	--	2.90	485	0.680	0.034	0.646	0.095	0.059	25.0	4.7	--	--	--
"	Oct 75	--	---	---	--	--	--	---	---	---	---	---	---	--	<3	<3	<3
Parker Well 5	Oct 74	224	64	3.0	--	<1	240	1.587	0.387	1.200	0.076	0.058	24.1	ND	--	--	--
"	Feb 75	229	20	2.3	2.3	4.80	177	0.990	0.000	0.990	0.080	0.070	25.5	40.0	<3(Mar)	<3	<3
"	May 75	170	---	0.4	--	0.87	188	1.310	0.010	1.300	0.100	0.080	28.0	50.0	93	<3	<3
"	Jul 75	--	---	1.0	--	0.56	--	1.630	0.180	1.450			21.0	30.1	>24000	<3	--
"	Aug 75	--	---	0.4	--	3.10	455	0.487	0.020	0.467	0.063	0.059	26.0	2.96	--	--	--
"	Oct 75	--	---	---	--	--	--	---	---	---	---	---	---	--	4	<3	<3
Parker DH* 6, N-2	Oct 74	1924	300	9.6	1.8	5.20	3000	0.895	0.313	0.582	0.053	0.052	833.8	62.4	--		
Parker DH* 6, N-4	Oct 74	1948	320	18.2	0.4	2.60	2640	0.972	0.429	0.543	0.060	0.053	813.9	ND	--		
Parker DH* 6, N-3	Feb 75	1997	270	118.4	12.1	152	1630	0.630	0.000	0.630	0.150	0.070	832.0	83.2	<3(Mar)	<3	<3
"	May 75	1906	---	115.4	--	22	1060	0.650	0.000	0.650	0.120	0.090	798.0	220.0	4	<3	<3
"	Jul 75	--	---	19.6	--	1.30	--	0.860	0.190	0.670	0.120	0.110	850.0	60.2	<3	<3	--
"	Aug 75	--	---	1.0	--	1.60	2750	1.266	0.870	0.396	0.120	0.050	850.0	5.9	--	--	--
"	Oct 75	--	---	---	--	--	--	---	---	---	---	---	---	--	4	<3	<3
Parker DH* 7	Oct 74		---	379.8	--	--	1810	1.260	0.886	0.374	0.150	0.031	521.1	ND	--		
Puuwaawaa Well	Mar 75	946	62	5.2	0.4	0.60	960	0.980	0.140	0.840			310.0	67.0	<3	<3	<3
"	May 75	758	---	0.6	--	0.18	800	0.860	0.020	0.840	0.100	0.070	350.0	60.0	9	<3	<3
"	Jul 75	--	---	1.6	--	1.10	--	1.020	0.080	0.940			320.0	48.9	350	<3	--
"	Aug 75	--	---	>1.0	--	0.70	1400	0.819	0.009	0.810	0.093	0.085	310.0	ND	--	--	--
"	Oct 75	--	---	---	--	--	--	---	---	---	---	---	---	--	<3	<3	<3
Kuuali'i Spring	Oct 74	3994	748	32.6	8.2	15.00	5400	0.737	0.334	0.403	0.063	0.058	1816.0	93.6	--		
"	Mar 75	--	---	---	--	--	--	---	---	---	---	---	---	--	23(Mar)	<3	<3
"	May 75	7942	---	2.4	--	0.27	4000	0.600	0.020	0.580	0.080	0.050	3949.0	200.0	23	<3	<3
"	Jul 75	--	---	4.0	--	1.50	--	0.830	0.160	0.670	---	0.090	2650.0	--	9	<3	--
"	Aug 75	--	---	76.4	--	28.00	5500	1.287	0.013	1.274	0.088	0.080	2200.0	35.5	--	--	--
"	Oct 75	--	---	---	--	--	--	---	---	---	---	---	---	--	<3	<3	<3
Wainali'i Lagoon	Oct 74	7408	---	9.2	--	<1	9900	1.030	0.386	0.644	0.068	0.048	3615.9	97.5	--		
"	Jul 75	--	---	6.6	--	1.20	--	0.570	0.000	0.570	---	0.170	770.0	--	140	<3	--
"	Aug 75	--	---	1.8	--	1.5	22000	1.217	0.008	1.209	0.083	0.077	9450.0	--	--	--	--
Kīholo Lava Tube	Oct 74	2248	328	1.8	ND	<1	3340	0.903	0.236	0.667	0.055	0.055	972.7	80.7	--		
"	Feb 75	2502	355	0.6	0.6	0.80	2220	0.460	0.000	0.460	0.050	0.040	1160.0	35.6	240(Mar)	4	6
"	May 75	2304	---	0.6	--	0.74	1800	0.790	0.050	0.740	0.100	0.060	1100.0	90.0	150	<3	4
"	Jul 75	--	---	1.4	--	1.50	--	0.890	0.120	0.770	---	0.120	1050.0	67.7	2400	<3	--
"	Aug 75	--	---	>1.0	--	0.70	3400	0.478	0.099	0.379	0.092	0.064	1050.0	8.9	--	--	--
"	Oct 75	--	---	---	--	--	--	---	---	---	---	---	---	--	400	23	150
Waiulua Bay Spring	Oct 74	5172	970	4.2	--	<1	6860	0.790	0.269	0.521	0.047	0.038	2322.7	106.1	--	--	--
"	Feb 75	6376	1142	6.5	2.5	1.10	4450	0.480	0.000	0.480	0.050	0.050	2744.0	--	--	--	--
"	Aug 75	--	---	>1.0	--	0.90	10000	0.687	0.012	0.675	0.070	0.064	3700.0	23.7	--	--	--
Waiulua Pond	Oct 74	3582	664	2.6	ND	<1	5200	0.737	0.184	0.553	0.045	0.045	1625.8	74.0	--	--	--
"	Aug 75	--	---	0.4	--	1.20	5500	0.711	0.025	0.686	0.097	0.077	1700.0	16.0	--	--	--
Ocean Water off Waiulua Bay	Feb 75	36633	4445	27.6	1.2	4.60	14000	0.160	0.000	0.160			18176.0	--	--	--	--

ND = nondetectable.
*Drilled Hole.

APPENDIX TABLE A.2. TRITIUM ACTIVITIES OF WELL WATER SAMPLES

	Date of Collection	Tritium Content in T.U.
Parker Well 1	02-17-75	0.0 ± 0.3
Parker Well 5	02-17-75	1.1 ± 0.4
Parker Well 5	05-28-75	0.1 ± 0.2
Parker Well 6	02-15-75	1.8 ± 0.5
Parker Well 6	05-28-75	0.7 ± 0.3
Puu Waawaa Well	03-24-75	0.4 ± 0.2

APPENDIX TABLE A.3. AVERAGE ISOTOPIC AND CHEMICAL DATA FOR WATER FROM PARKER 5 AND PARKER 1

Source	^{14}C % NBS	^{13}C ‰ PDB	Cl^- mg/ℓ	HCO_3^- mg/ℓ
Parker Well 5	66.51	-14.70	23*	109*
Parker Well 1	52.20	-7.74*	567*	150*

*Separate sample collected on 10-27-76.

APPENDIX TABLE A.4. RADIOCARBON AGES FOR WATER SAMPLES COLLECTED IN THE SOUTH KOHALA COASTAL AREA, HAWAII

Sample	Collection Date	Lab I.D.	^{14}C % NBS	$\delta^{13}C$ ‰PDB	^{14}C Age* (yr)	(adj)
Parker Well 5	May 1976	76-E	63.67	-15.00	3473	2350
Parker Well 5	06-28-76	76-J	69.35	-14.39	2787	1300
Parker Well 1	07-08-76	76-K	52.20	-7.7†	5070	+1700

*For methods of calculation see T.H. Hufen (1974, pp. 66, 86, 89);
Values assumed for water at time of recharge: A_r = 98.1%, $\delta^{13}C_r$ = -17.2 ‰ PDB;
Values assumed for sources of (radiocarbon-free) bicarbonates:
A_1 = 1.9%, $\delta^{13}C_1$ = -0.8‰ PDB.
†Separate sample collected on 10-27-76.

CORAL COMMUNITIES OF PUAKŌ, 'ANAEHO'OMALU, AND KĪHOLO BAYS[1]

Introduction

Most research on coral reef ecology has been limited to qualitative descriptions of geomorphical and biological zonation patterns; few studies have attempted to show what factors are responsible for these patterns. Recently open ocean coral communities have been quantitatively examined in Panama (Porter 1972*a*, *b*, *c*), in the Red Sea (Loya 1972), at Fanning Island (Maragos 1974*a*, *b*), and at South Kona, Hawaii (Dollar 1975).

The purpose of this investigation is to gain an understanding of the factors that control the composition and distribution of coral communities in three open ocean bays on the west coast of Hawaii Island. By relating species assemblage characteristics to gradients of environmental factors and ecological theory, it may be possible to identify some indicator species that may serve to quantify the degree of stress to which an environment may be subject.

The environmental variables that seem to affect coral community structure most directly are wave energy (breakage and abrasion), available light energy (associated with photosynthetic and calcification processes), sedimentation, available solid substrata (associated with settling), and interspecific competition between corals. By examining changes in species number relationships along depth gradients within each study site and comparing data between the three bays that differ in bathymetry, geological structure and origin, and current, wave and wind patterns, it may be possible to gain some insight into exactly how the environmental variables affect community structure.

Methods

All field work for this project was carried out using SCUBA equipment during a series of dives conducted from an anchored 5-m (17-ft) skiff. Samples of the benthic communities at Puakō, 'Anaeho'omalu, and Kīholo bays were surveyed using a contiguous photographic transect technique. This method appears to be more efficient with respect to time spent underwater and area surveyed than either a chain transect or conventional quadrat

[1]S.J. Dollar

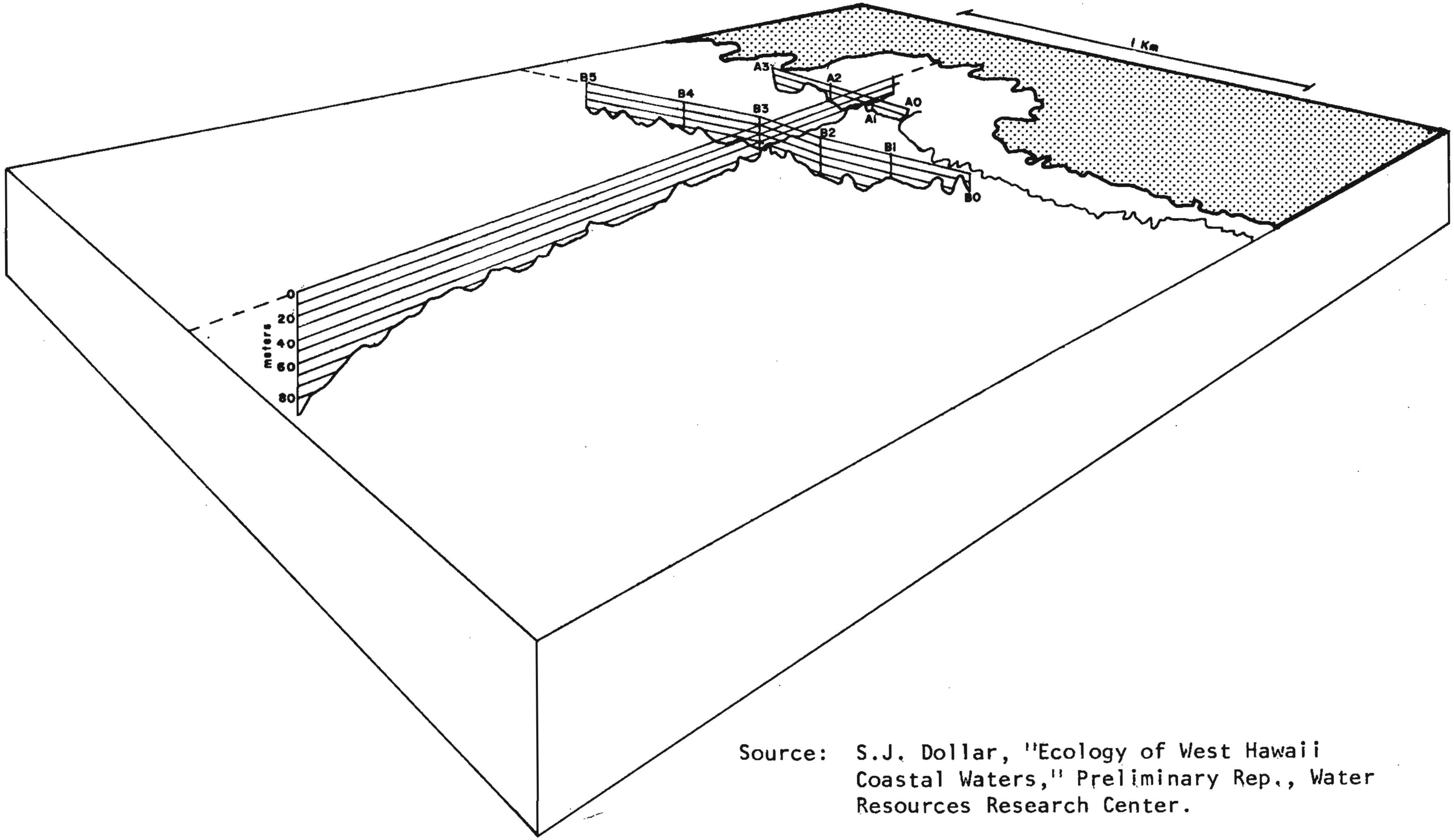
method. In this study each transect was 30 m long at 3-m depth intervals ranging from 3 to 18 m. Two sets of these transects were run in each of the three bays, one in the northern half and one in the southern half (Figs. 14, 15, 16). Two transects were run at each site so that within bay differences, associated with factors such as wave energy and bottom topography, could be evaluated.

The photographic transect technique involves mounting a Nikonos II camera (loaded with 36-exposure color slide film) and a Subsea Mark 50 electronic strobe light on a supporting frame approximately 1.25 m above a 100-cm by 70-cm quadrat (Fig. 17). This entire frame and quadrat is constructed of ½-in. brass tubing and the camera is mounted on a Plexiglas plate attached to the four supporting arms of the frame.

At each transect location a 30-m polypropylene line was laid across the bottom parallel to the shoreline by two divers. The camera-quadrat frame was then placed on the bottom so that the first meter of transect line touched the entire length of a 1-m side of the quadrat. A color slide was taken of the 1 by 0.7-m area within the quadrat, and the camera frame was moved to the second meter of transect line where another picture was taken. This process was repeated until the entire 30 m were photographed. Transect locations and depths were written in large letters on an underwater slate and photographed with the remaining film for later identification. Because small and rare colonies may not show up in the transect photographs, a diver with a species checklist on a clipboard recorded the presence of all coral and echinoderm species in each quadrat of all transects.

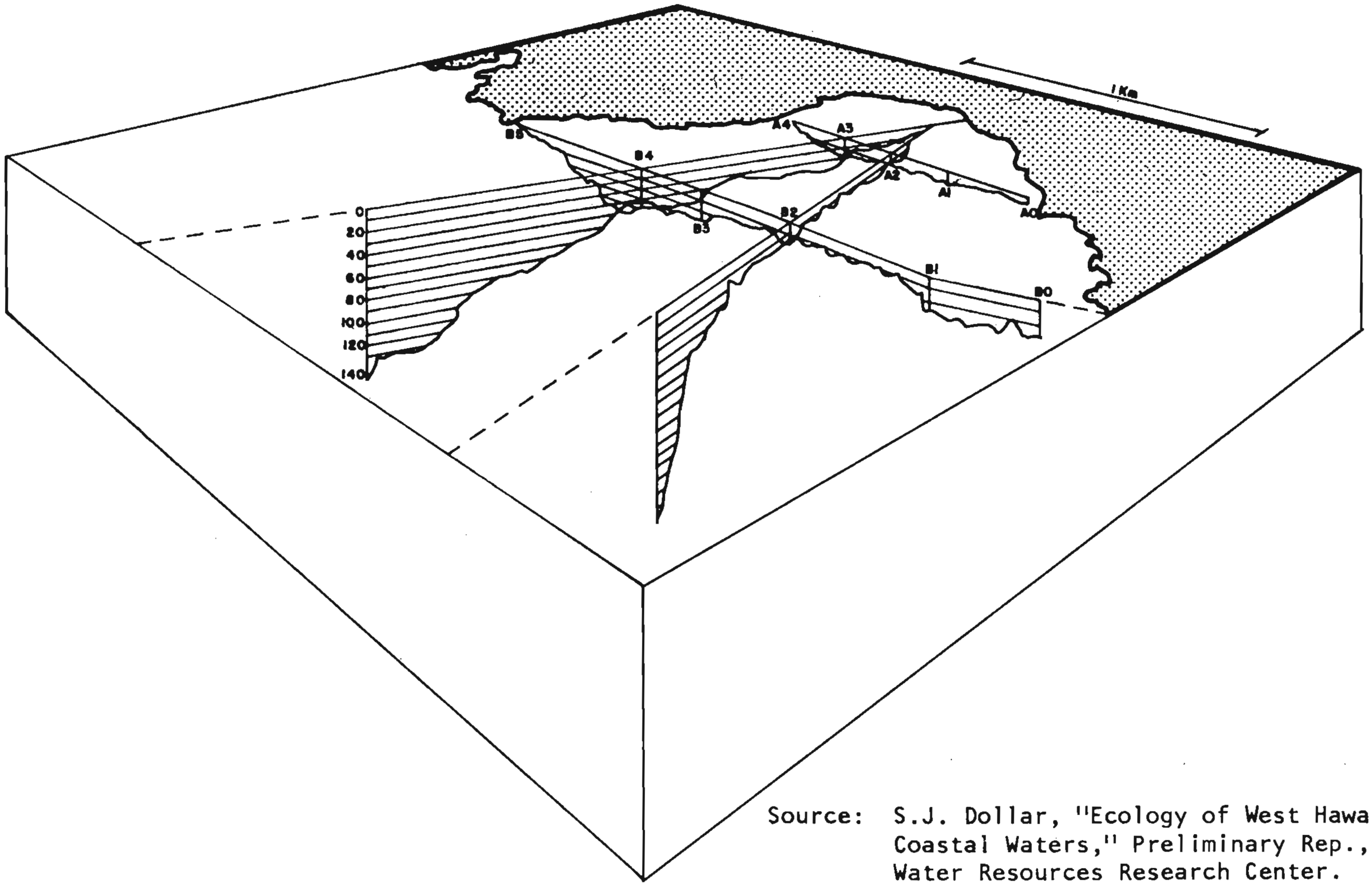
The developed slides were projected onto a grid with the same dimensions as the quadrat and the abundance of corals and noncoral substrata estimated by counting the number of cm^2 occupied by each coral colony or bare area. From these counts estimates of percent cover, colony size, and species cover diversity can be determined.

There are several drawbacks to this method. The use of horizontal coral coverage to estimate abundance of corals is biased in favor of flat or encrusting forms such as *Porites*, *Montipora*, and *Leptastrea* (Maragos 1974). This method is also disadvantageous in areas where the bottom topography is irregular or where corals are found growing on the dead basal parts of other colonies. In these cases, corals may be hidden from the view of the camera and estimates of coral cover will not be totally accurate.



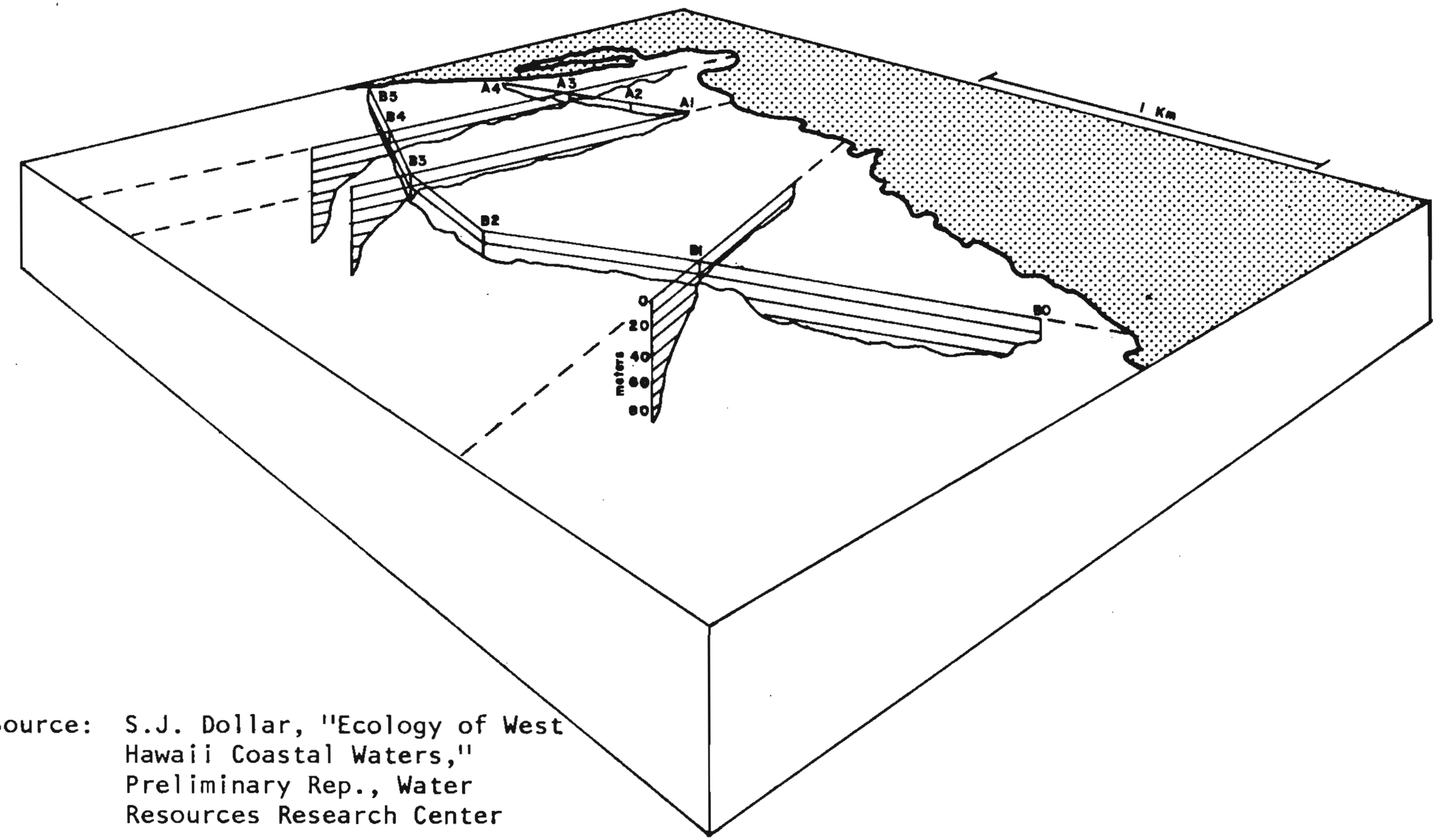
Source: S.J. Dollar, "Ecology of West Hawaii Coastal Waters," Preliminary Rep., Water Resources Research Center.

Figure 14. PUAKO BAY. DEPTH CONTOURS ALONG SELECTED TRANSECT LINES. DEPTHS IN FEET



Source: S.J. Dollar, "Ecology of West Hawaii Coastal Waters," Preliminary Rep., Water Resources Research Center.

FIGURE 15. VERTICAL PROFILE AND TRANSECT STATIONS, 'ANAEHO'OMALU BAY



Source: S.J. Dollar, "Ecology of West Hawaii Coastal Waters," Preliminary Rep., Water Resources Research Center

FIGURE 16. VERTICAL PROFILE AND TRANSECT STATIONS, KĪHOLO BAY

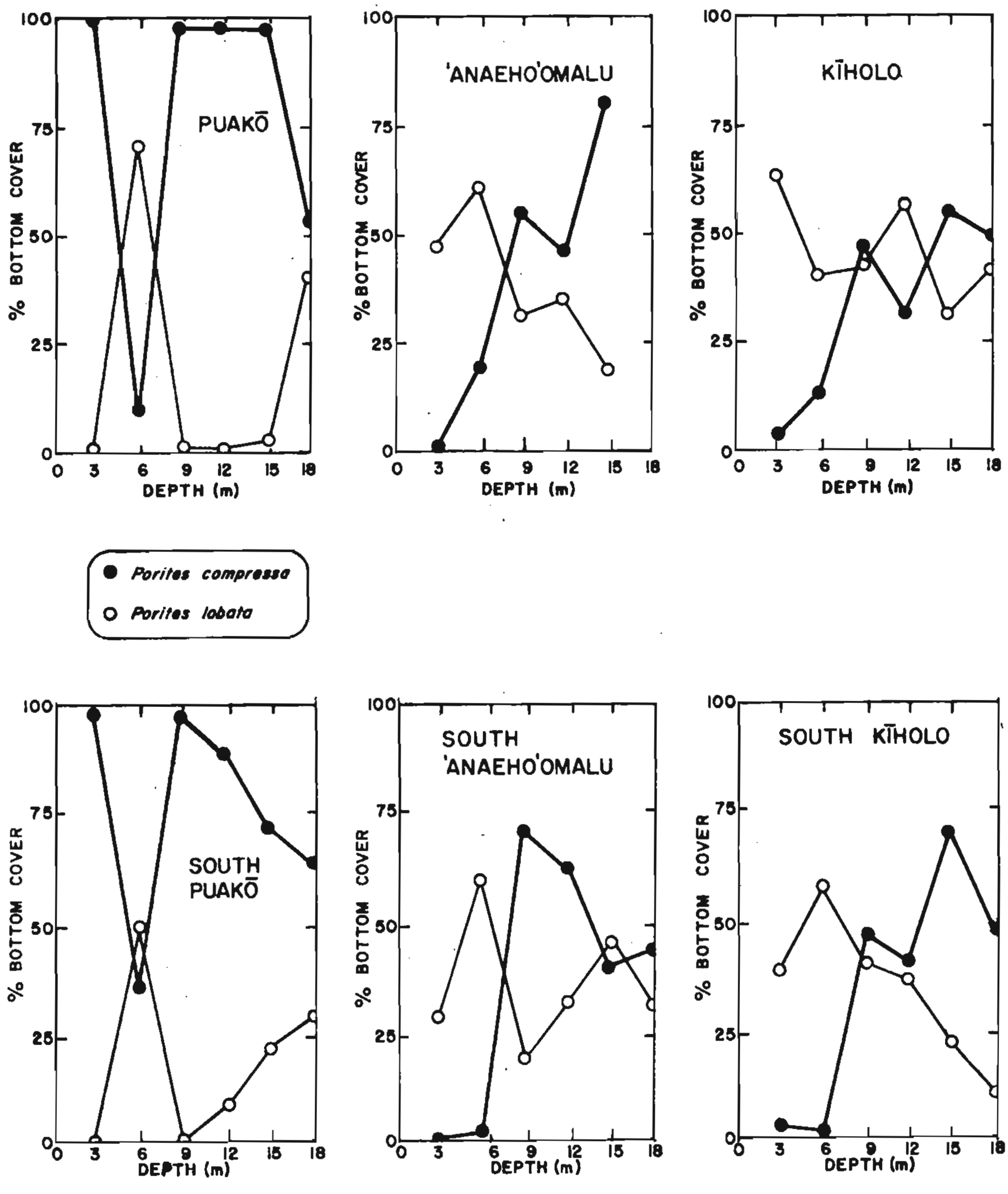


FIGURE 17. CORAL COVER FOR *Porites compressa* AND *P. lobata*

Results

The percent of coral and noncoral bottom cover at each of the 35 transects is shown in Table 8 and as mean percent cover in Table 9. Table 10 shows percent coral cover and percent total bottom cover for each species and noncoral bottom type for all transects. Thirteen coral species were encountered, but the 2 most abundant species, *Porites compressa* and *P. lobata*, comprise 95.73% of all coral cover and 81.7% of total bottom cover. *Porites* dominance is typical of many reef areas in Hawaii. *Porites* comprises approximately 80% of coral cover in reef communities off South Kona, Hawaii at depths ranging from 3 to 35 m (Dollar 1975); *P. compressa* comprises an average of 90% of coral cover in Kāne'ohe Bay, Oahu (Margos 1972).

Figures 17 and 18 show plots of the percent bottom cover of the four most abundant coral species, *P. compressa, P. Lobata, Pocillopora meandrina*, and *Montipora* spp. versus the depth on each transect. Trends in vertical zonation of corals are apparent in these graphs.

For large collections, from which random samples can be drawn and the number of species can be found, the Shannon-Wiener index (1948) can be used to estimate species diversity. Diversity is equated with the amount of uncertainty that exists regarding the species of an individual (colony) selected from a population. The Shannon-Wiener index is sensitive to both the number of species (species richness) and to the degree of equal apportionment of the individuals among the species (equitability). The formula for this index is $H'_c = \sum_{i=1}^{s} p_i \ln p_i$ where p_i is the proportion of cover for the ith species in the population and s is the number of species. Figure 19 shows plots of the Shannon-Wiener diversity index versus the depth of each transect, computed in terms of both coral cover and total bottom cover.

Puakō Bay

At Puakō patterns of coral abundance are strikingly different from those at 'Anaeho'omalu and Kīholo. The shallowest transects (3-m) at both north and south Puakō are covered almost entirely with thickets of *Porites compressa* (99.38% at north, 98.87% at south; Fig. 17). These dense stands of *P. compressa* appear to be growing on, and forming, a structural reef platform. Fissures in this reef platform that open on sand patches show that this reef is 2 to 3 m thick. Although this is not a typical situation on Hawaiian

TABLE 8. CORAL AND NONCORAL BOTTOM COVER FROM TRANSECTS AT PUAKO, ANAEHO'OMANU AND KĪHOLO BAYS

Site	Depth (m)	*P. compressa*	*P. lobata*	*P. meandrina*	*M. verrucosa*	*M. patula*	*P. varians*	*L. purpurea*	Misc.	Basalt	Limestone	Sand	H'c (coral)	H'c (total)
North Puako	3	208,715	785	375	--	--	125	--	--	--	--	---	0.0426	0.0426
	6	20,695	147,650	995	3,520	2,850	---	--	--	--	16,005	16,710	0.6694	1.0195
	9	204,250	3,440	95	410	775	390	--	FS-150	--	550	---	0.1276	0.1626
	12	204,905	1,850	535	100	520	50	--	--	--	2,040	---	0.0923	0.1460
	15	201,820	6,145	170	225	170	170	--	--	--	1,300	---	0.1606	0.1974
	18	110,380	83,175	120	1,880	210	80	--	FS-65	--	6,815	7,340	0.7424	0.9919
South Puako	3	207,640	1,585	240	85	130	320	--	--	--	--	---	0.0733	0.0733
	6	75,355	105,225	615	1,985	1,220	230	--	--	--	13,440	4,930	0.8019	1.076
	9	204,615	4,120	100	685	350	130	--	PSC-100	--	--	---	0.141	0.141
	12	187,125	19,065	260	1,755	1,360	165	--	--	--	280	---	0.4060	0.4156
	15	151,495	46,395	40	2,525	420	---	--	--	--	9,125	---	0.5527	0.7723
	18	136,880	61,020	1,085	5,630	1,175	30	20	FS-30	--	4,180	---	0.7902	0.8722
North Anaeho'-omalu	3	3,140	97,535	3,990	870	6,135	50	70	CO-30	32,015	56,685	150	0.7142	1.4195
	6	42,430	126,750	4,190	1,700	4,450	220	60	--	3,320	11,953	2,210	0.8696	1.0731
	9	115,924	64,015	1,090	2,400	5,335	460	--	--	50	16,030	---	0.8281	1.1123
	12	95,171	72,870	1,235	1,780	855	265	85	FS-50	4,600	18,625	---	0.8279	1.1306
	15	167,550	39,660	1,220	270	620	80	--	--	--	8,710	---	0.5333	0.6787
South Anaeho'-omalu	3	340	51,485	16,855	90	1,615	70	--	PX-12665	7,040	115,161	940	1.0172	1.4890
	6	6,651	126,585	8,755	1,887	2,156	80	--	PX-12744	13,122	36,315	---	0.7925	1.4207
	9	148,480	41,740	1,140	1,200	2,730	110	--	--	1,290	13,230	---	0.6634	0.8887
	12	131,680	67,655	400	1,630	1,520	180	--	--	--	7,030	---	0.7406	1.0877
	15	84,070	97,140	620	2,300	600	30	--	PALY-40	--	20,150	2,000	1.092	1.2592
	18	93,580	66,000	410	1,640	60	---	--	--	--	47,870	1,940	0.7443	1.1577
North Kīholo	3	9,500	130,565	9,215	1,175	1,940	10	--	PX-13095	12,500	31,820	180	0.8620	1.3585
	6	26,940	82,530	5,560	3,400	820	60	--	PALY-20	670	89,860	200	0.8758	1.206
	9	97,122	88,240	520	5,360	700	20	--	--	270	17,025	1,010	0.8388	1.086
	12	65,115	117,920	360	1,840	715	130	--	--	4,750	17,560	1,640	0.7404	1.198
	15	112,000	63,385	160	5,720	510	95	--	PALY-1080	--	27,050	--	0.8324	1.108
	18	100,531	85,008	1,015	1,055	460	165	--	--	--	18,434	3,330	0.7717	1.069
South Kīholo	3	9,565	82,195	10,600	265	1,265	700	50	PX-2100	37,175	99,500	330	0.8571	1.440
	6	6,230	121,600	14,540	1,530	3,520	270	--	--	26,470	35,560	1,750	0.875	1.62
	9	98,822	85,185	550	2,165	320	20	--	CO-20	5,820	13,220	4,015	0.7764	1.144
	12	86,300	75,205	580	2,953	1,117	---	--	PD-40	1,251	42,682	785	0.8748	1.213
	15	147,100	47,635	40	3,830	625	240	--	--	--	7,740	860	0.6731	0.8295
	18	99,600	22,985	160	4,890	360	65	20	--	--	84,050	790	0.6332	1.0903

CO = *Cyphastrea ocelina.*
PALY = *Palythoa* sp.
PX = *Pavona explanulata.*
FS = *Fungia scutaria.*
PD = *Pocillopora damicornis.*
PSC = *Porites (Synaraea) convexa.*

TABLE 9. PERCENT CORAL AND NON-CORAL BOTTOM COVER AT EACH TRANSECT

Site	Depth (m)	*P. compressa*	*P. lobata*	*P. meandrina*	*M. verrucosa*	*N. patula*	*P. varians*	*L. purpurea*	Misc.	Basalt	Limestone	Sand	H'c(coral)	H'c(total)
N. Puako	3	99.38	0.37	0.18	--	--	0.06	--	--	--	--	--	0.0426	0.042
	6	9.85	70.30	0.47	1.67	1.35	--	--	--	--	7.62	7.95	0.669	1.019
	9	97.26	1.63	0.454	0.19	0.36	0.18	--	FS 0.07	--	0.26	--	0.1276	0.163
	12	97.57	0.88	0.25	0.05	0.25	0.02	--	--	--	0.97	--	0.0923	0.146
	15	96.10	2.92	0.80	0.11	0.08	0.08	--	--	--	0.61	--	0.1606	0.197
	18	52.56	39.60	0.06	0.89	0.10	0.03	--	--	--	3.24	3.49	0.7424	0.992
S. Puako	3	98.87	0.75	0.11	0.04	0.06	0.15	--	FS 0.03	--	--	--	0.0733	0.073
	6	35.88	50.10	0.29	0.95	0.58	0.11	--	--	--	6.40	2.34	0.802	1.076
	9	97.43	1.96	0.05	0.28	0.16	0.06	--	--	--	--	--	0.1410	0.141
	12	89.10	9.07	0.12	0.83	0.64	0.08	--	PSC 0.05	--	0.13	--	0.4060	0.416
	15	72.14	22.09	0.01	1.20	0.20	--	--	--	--	4.34	--	0.5527	0.772
	18	65.18	29.05	0.51	2.68	0.56	0.01	0.009	FS 0.01	--	1.99	--	0.7902	0.872
N. Anaeho'-omalu	3	1.49	46.44	6.66	0.41	2.92	0.02	0.03	CO 0.01	15.24	26.99	0.07	0.7142	1.419
	6	20.20	60.35	1.99	0.81	2.12	0.10	0.03	--	1.58	5.69	1.05	0.8281	1.12
	9	55.20	30.48	0.55	1.14	2.54	0.22	--	--	0.02	7.63	--	0.8966	1.073
	12	45.31	34.70	0.59	0.85	0.41	0.13	0.04	FS 0.02	2.19	8.86	--	0.8279	1.131
	15	79.78	18.88	0.58	0.12	0.29	0.04	--	--	--	4.15	--	0.533	0.678
	18	--	--	--	--	--	--	--	--	--	--	--	--	--
S. Anaeho'-omalu	3	0.16	24.51	8.02	0.04	0.76	0.03	--	PX 6.03	3.35	54.83	0.45	1.017	1.489
	6	3.16	60.27	4.16	0.89	1.02	0.04	--	PX 6.06	6.24	17.29	--	0.792	1.421
	9	70.70	19.87	0.54	0.57	1.30	0.05	--	--	0.61	6.30	--	0.663	0.8897
	12	62.70	32.21	0.19	0.77	0.72	0.08	--	--	--	3.34	--	0.740	1.088
	15	40.03	46.25	0.29	1.09	0.28	0.01	--	PALY 0.02	--	9.59	0.95	1.092	1.259
	18	44.56	31.42	0.19	0.78	0.03	--	--	--	--	22.79	0.92	0.744	1.157
N. Kīholo	3	4.52	62.17	4.38	0.55	0.92	0.004	--	PX 6.23	5.95	15.15	0.085	0.862	1.358
	6	12.82	39.3	2.65	1.62	0.39	0.02	--	PALY 0.09	0.32	42.79	0.09	0.876	1.206
	9	46.24	42.01	0.24	2.55	0.33	0.009	--	--	0.13	8.10	0.48	0.838	1.086
	12	31.00	56.15	0.17	0.87	0.34	0.06	--	--	2.26	8.36	0.78	0.740	1.198
	15	53.33	30.18	0.07	2.72	0.24	0.04	--	PALY 0.51	--	12.88	--	0.832	1.108
	18	47.87	40.48	0.48	0.50	0.22	0.08	--	--	--	8.77	1.58	0.771	1.069
S. Kīholo	3	4.55	39.14	5.05	0.13	0.60	0.33	0.02	PX 1.0	17.70	47.38	0.26	0.839	1.440
	6	2.96	57.90	6.92	0.73	1.67	0.13	--	--	12.60	15.93	0.83	0.875	1.620
	9	47.05	40.56	0.26	1.03	0.15	0.01	--	CO 0.009	2.77	6.29	1.91	0.776	1.144
	12	41.00	35.81	0.27	1.41	0.53	--	--	PD 0.01	0.59	20.32	0.37	0.825	1.213
	15	70.04	22.68	0.01	1.82	0.29	0.11	--	--	--	3.68	0.40	0.673	0.829
	18	47.42	10.94	0.07	2.32	0.17	0.03	0.009	--	--	40.02	0.37	0.633	1.090

Misc. = corals.
CO = *Cyphastrea ocellina*
PALY = *Palythoa* sp.
PX = *Pavona explanulata*
FS = *Fungia scutaria*
PD = *Pocillopora damicornis*
PSC = *Porites (Synaraea) convexa*.

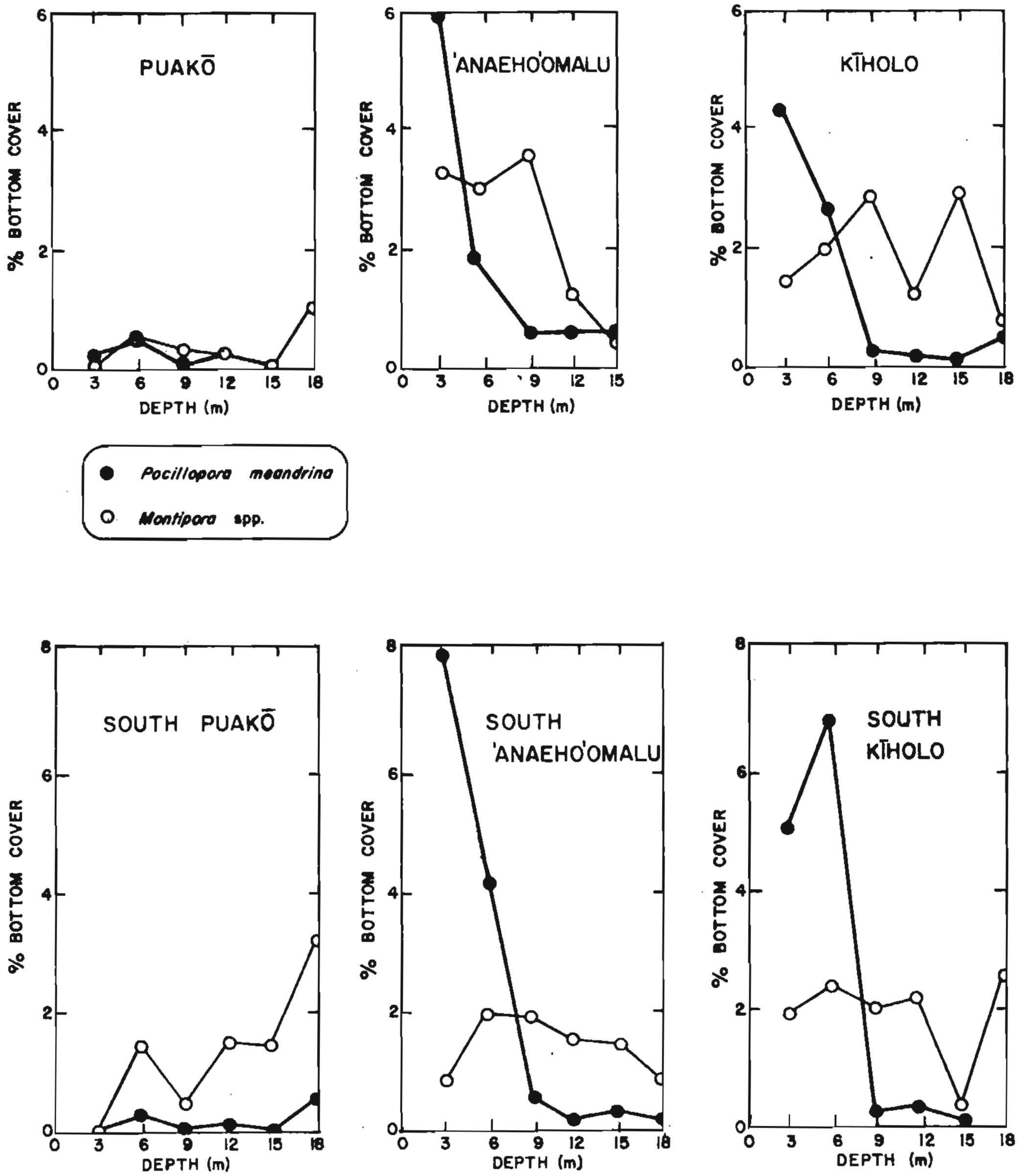


FIGURE 18. CORAL COVER FOR *Montipora* sp. AND *Pocillopora meandrina*

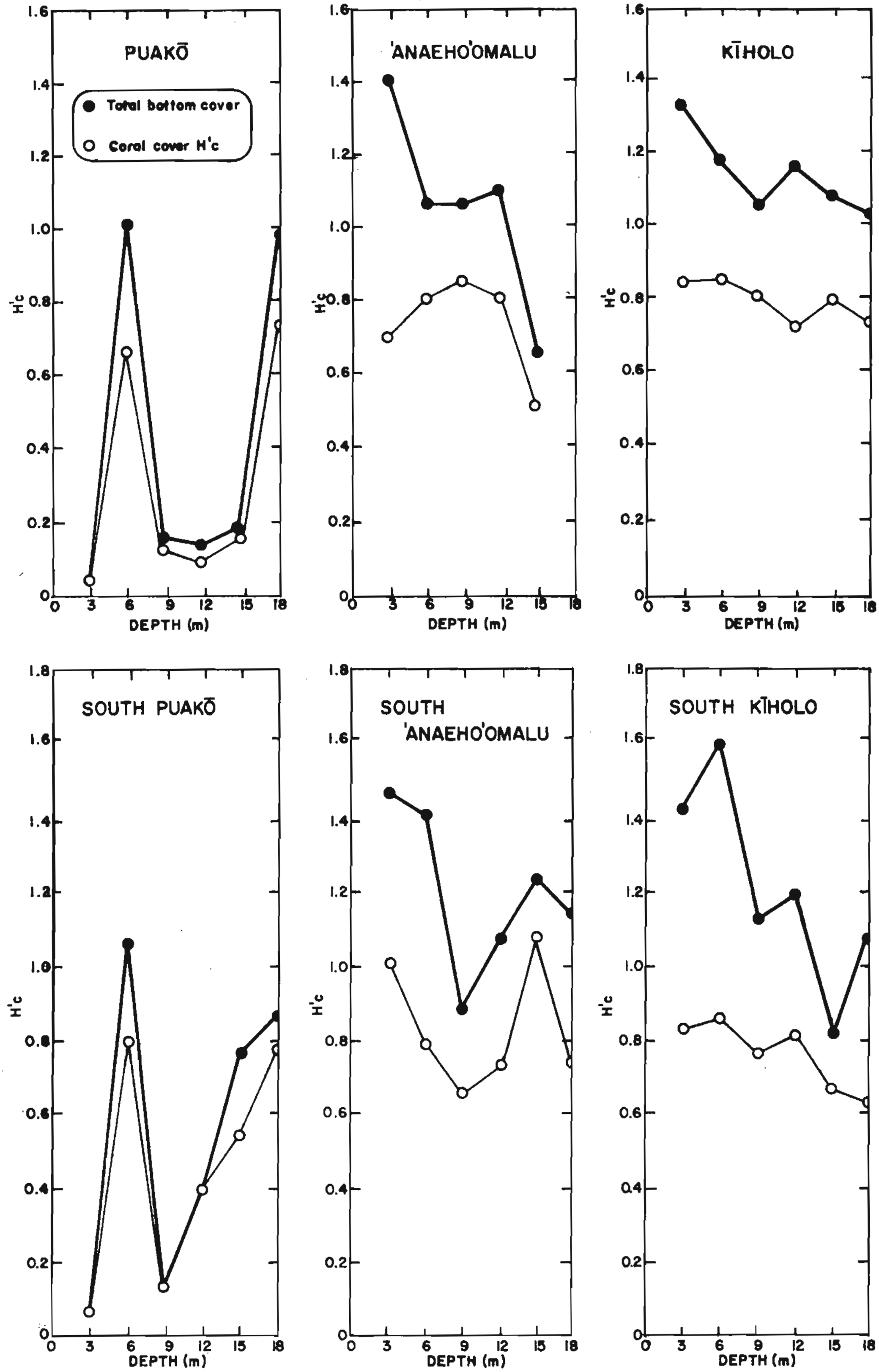


FIGURE 19. SPECIES-COVER DIVERSITY OF CORAL AND TOTAL BOTTOM COVER

TABLE 10. PERCENT TOTAL BOTTOM COVER AND PERCENT OF LIVING CORAL COVER FOR 35 TRANSECTS

Species/ Bottom Cover	% Total Bottom Cover	% Living Coral Cover
Porites compressa	49.75	58.20
P. lobata	32.02	37.53
P. (Synaraea) convexa	0.001	0.002
Pocillopora meandrina	1.37	1.64
P. damicornis	0.002	0.003
Montipora verrucosa	0.94	1.10
M. patula	0.67	0.80
Pavona varians	0.07	0.08
P. explanulata	0.56	0.65
Leptastrea purpurea	0.003	0.004
Cyphastrea ocellina	0.001	0.001
Palythoa spp.	0.02	0.03
Fungia scutaria	0.04	0.05
Basalt	2.06	--
Limestone	11.98	--
Sand	0.47	--

reefs, *P. compressa* is also found dominating bottom cover in very shallow, nearshore areas at 'Āhihi Bay, Maui and at Kealakekua Bay, Hawai'i. As in the innermost areas of Puakō Bay, these areas appear to be well protected from open ocean wave energy.

Several species of small encrusting corals, *Montipora patula, M. verrucosa,* and *Porites lobata* are occasionally found in this zone, growing on dead portions of the *P. compressa* branches. *Pocillopora meandrina,* the coral that is usually the most abundant species in near-shore Hawaiian habitats, comprises only 0.18% and 0.11%, respectively, of the bottom cover on the north and south 3-m transects. Diversity is lower on these transects than on any other in this survey.

Heterocentrotus mammillatus is the most abundant sea urchin in the shallow zone. Numerous *Echinometra mathaei* are found within the *P. compressa* framework and *Tripneustes gratilla* and *Diadema paucispinum* occur occasionally on the reef surface.

The *P. compressa* platform extends approximately 10 to 15 m seaward to a depth of 3 to 4 m at which point bottom topography begins to grade into a flat basaltic pavement covered with a limestone veneer of both living and dead corals. *P. compressa* abundance is greatly reduced on the 6-m transects compared to both shallower and deeper areas (Fig. 17).

Porites lobata is the dominant coral and covers from 50 to 70% of the bottom in large, massive colonies. The other species that are found in this zone include the braching coral, *P. meandrina*, and the flat encrusting species of *Montipora, Leptastrea,* and *Pavona*. Species cover diversity is higher on the 6-m transect than at any other at Puakō. The topographical structure of the bottom and the species composition indicate that this area is absorbing most of the wave energy to which the bay is subject. Sea urchin populations in this zone are greatly reduced compared to shallower transects and consist mainly of *Tripneustes gratilla* on the reef surface and *Echinometra mathaei* occupying indentations in the limestone and basaltic substratum.

The reef shelf zone extends to a depth of approximately 8 m and to a distance of approximately 40 to 50 m from shore. Seaward of this area the bottom topography and community structure are quite different in the north and south regions of Puakō.

At depths of from 8 to 15 m in the northern half of the bay, bottom structure is characterized by a series of coral-covered ridges that run perpendicular to shore and are separated by broad channels of fine white sand. These ridges may be up to 50 m long and are generally 10 to 15 m wide. Transects at 9, 12, and 15 m were made in this ridge and channel area. When viewed in cross section, they are dome shaped with a height of up to 5 m and appear to be formed from accumulated coral skeletal growth. *Porites compressa* covers the tops and upper flanks of these ridges; overlapping plate-like colonies of *P. lobata, P. (synaraea) convexa,* and *Montipora* occupy the vertical lower ridge walls. *P. compressa* branches are noticeably longer and thinner in this region compared to the shorter, thicker branches found on the shallow nearshore platform. *Tripneustes gratilla* and *Echinothrix* spp. are the predominant echinoids found on the coral ridges, but overall urchin abundance is reduced compared to the shallower areas.

At depths of approximately 16 m and 200 to 300 m from shore, the ridge and channel zone grade into a flat, gently sloping shelf that is largely covered with *Porites* spp. It can be seen in Figure 14 that the distribution of *P. compressa* (52.56%) and *P. lobata* (39.60%) is more equitable at the 18-m transect than at any other transect, resulting in a relatively high level of diversity. Numerous colonies of *Montipora* are also found in this region, often growing up the shafts of living *P. compressa* branches. Colonies of the small, deep water corals, *Leptastrea* and *Coscinaraea* occur on scattered rubble chunks. Beyond a depth of approximately 25 m, corals and solid bottom become increasingly rare.

The bottom topography at south Puakō differs from the north in that the ridge channel zone does not occur. Instead, the near-shore basaltic shelf slopes gradually to a depth of 9 m, at which point the slope angle increases sharply to approximately 30°. Coral cover on the shelf break (9-m transect) is almost entirely *P. compressa* thickets (97.4%), similar to the thickets found on the tops of the ridges. Downslope *P. compressa* dominance declines, possibly as a result of suboptimal light conditions. *P. lobata* and *Montipora* abundances increase down the slope causing diversity values to steadily increase with depth. At a depth of approximately 20 m, the coral-covered slope merges with a flat sandy bottom that is barren of all coral cover. As in the deep transects at north Puako, the urchin populations consist mainly of *Tripneustes gratilla* and *Echinometra mathaei*.

'Anaeho'omalu Bay

At 'Anaeho'omalu white sand covers the bay floor for a distance of 30 to 50 m offshore and to depths of 3 to 4 m. Isolated large colonies of *Porites lobata* occur scattered across the sandy expanse and occasionally the tops of these coral heads grow to within 0.30 m of the sea surface.

At approximately 20 m offshore and at depths of 3 to 5 m, white sand occurs only in isolated pockets and bottom topography consists of a flat basaltic shelf that is largely covered with a limestone veneer. It can be seen in Figures 14 and 15 that the coral assemblages of 'Anaeho'omalu and Kīholo bays differ most from Puakō in this shallow 3-m region. While *P. compressa* dominates bottom cover up to the shoreline at Puakō, this species occurs very rarely at both the north and south 3-m transects at 'Anaeho'omalu. *Pocillopora meandrina* colonies are more abundant in this area than on any other transect in this study, composing 6.6% of bottom cover in the north and 8.02% in the south. Encrusting colonies of *P. lobata* are the most abundant coral in this area, and *Montipora* spp., *Leptastrea purpurea, Pavona varians,* and *Cyphastreae ocellina* are also found. Several large patches of *Pavona explanulata* were encountered on the 3- and 6-m transects in the southern sector of 'Anaeho'omalu Bay. This coral seems to be limited to shallow, high wave stress areas on the Kona coast.

Urchin populations in this area consist mainly of *Echinometra mathaei* which occur in the crevices on the shelf. *Heterocentrotus mammillatus*, *Tripneustes gratilla*, and *Echinothrix* spp. are also found occasionally in this region.

Moving seaward across this gently sloping shelf coral cover increases, due to primarily to an increase in *P. compressa* cover, which peaks at 55.2% and 70.7% of the bottom cover at the 9-m transects at north and south 'Anaeho'omalu. *P. meandrina* abundance drops sharply with increasing depth, apparently due to this species' inability to successfully compete for available substratum with the faster growing *Porites* spp. in areas of low wave stress.

It can be seen in Figure 14 that as the level of *P. compressa* domination increases, diversity correspondingly decreases. *Montipora* spp. abundance also decreases and colonies appear more often on the living *Porites* colonies rather than on the noncoral substrata as they are at shallower depths. Occasional patches of white sand as well as lava boulders and fissures occur on the reef shelf. At a depth of approximately 10 m, the shelf angle increases sharply in the same manner as at south Puakō. It can be seen in Figure 14 that while *P. compressa* cover drops with increasing depth on the deep slope at south 'Anaeho'omalu, the peak *P. compressa* cover at north 'Anaeho'omalu occurs at the deepest (15-m) transect. Since no corals occurred below 15 m at this site, it may be that the bottom is too unconsolidated to allow settlement of any corals other than *P. compressa*. It may be that an adaptive advantage of the *P. compressa* lattice structure enables these colonies to increase their range by spreading horizontally over the sandy bottom. With time and consolidation of the substratum due to the accumulation of *P. compressa* fragments, other corals may be able to settle and compete against *P. compressa* for space. Very few living coral fragments occurred on the sandy slope, indicating that storm activity may not be an important factor in expanding the range and depth limits of corals.

Urchin populations in this area are much the same as described for the deep transects at Puakō Bay.

Kīholo Bay

At Kīholo Bay the nearshore shallow shelf area consists of patches of black sand over a flat, basaltic shelf. Water turbulence appears to be higher and water clarity lower at Kīholo relative to the other two sites. While large and apparently very old colonies of *P. lobata* occurred in the sandy shallows at 'Anaeho'omalu, very few corals occurred on the solid bottom at Kiholo at depths of from 3 to 4 m and at a distance of 30 to 40 m from shore. The corals that do occur are *P. meandrina*, *P. damicornis*, *P. lobata*, and *Montipora* spp. These colonies, usually very small in size and often found in fissures in the lava shelf, are as numerous as are the sea urchin, *Echinometra mathaei*.

At depths of 3 to 4 m, coral assemblages resemble those described at 'Anaeho'omalu Bay, the main difference being that the colonies are smaller and more bare basalt is present. As at 'Anaeho'omalu, *Pavona explanulata* is abundant in the shallow 3-m transect at both north (6.23% of bottom cover) and south (1.0% bottom cover) Kīholo.

Porites compressa cover increases seaward, except at the 12-m transects which show a drop in *P. compressa* cover. This drop may be due to the presence of numerous lava caves, arches, and boulders that provide irregular surfaces that may be better locations for settlement and growth of encrusting species rather than the branching *P. compressa*. On the reef slope where bottom structure is flat and not as consolidated, *P. compressa* abundance parks on the 15-m transect. Bare limestone on the deepest transects is considerably higher at the south end of Kīholo (40.02% bottom cover) than at the northern end (8.77%), indicating that wave stress and the resulting coral damage may be greater at the southern end of Kīholo Bay.

Discussion and Conclusions

> Hawaiian reefs may represent physically controlled communities in which species tend to be generalists with broad niches tolerant to relatively large ranges of physical factors, but tend also to be relatively poor competitors unable to resist resource monopolization. (Grigg and Maragos 1974)

Because *Porites compressa* and *P. lobata* comprise almost 82% of bottom cover and 96% of coral cover, these two species appear to be the best coral competitors on Hawaiian reefs and their relative distributions should be important in drawing conclusions on environmental effects and community structure.

The significantly negative correlations between *P. compressa* cover and diversity (Table 11) and between *P. compressa* and other species' cover (Table 12) indicate that *P. compressa* tends to dominate bottom cover in areas where it occurs. The high values of r^2 indicate that it is not necessary to look much beyond the percentage of *P. compressa* cover to predict the diversity of any reef area. *P. compressa* occurs as branching colonies that form connected platforms or thickets that may stretch for hundreds of square meters. Because branching corals effectively occupy space more quickly than massive types, they have a distinct advantage in environments favorable to their growth (Maragos 1972). Because of this rapid growth rate, *P. compressa* successfully interferes with other corals by growing over them, depriving these corals of necessary water circulation and light. Because the branching thickets also spread rapidly in a horizontal direction, they may preempt other corals from settling by covering available substrata. The thin branching structure, however, causes *P. compressa* thickets to be very susceptible to breakage by strong water movement. These two characteristics of *P. compressa*, competitive superiority and a fragile skeletal structure, appear to be very important in explaining the patterns of coral growth in the three bays in this study and on Hawaiian reefs in general.

Because energy from wave stress appears to be on an increasing gradient from north to south on the Kona Coast, *P. compressa* may be expected to become increasingly more abundant at the more northern sites. Plots in Figure 14 and the mean coral cover values in Table 13 support this assumption: the highest peak and mean of *P. compressa* cover is at Puakō, the least at Kīholo Bay. Dominance should decrease with greater wave stress and species cover diversity should increase south. It can be seen in Figure 16 that, indeed, that is the case, with diversity higher in the southern areas. It is also apparent that there is a greater gap between total bottom cover diversity and coral cover diversity with increasingly southern location. The widening gap between the diversity curves may verify the increase in wave stress moving south because it would be expected that greater wave action would be responsible for greater amounts of noncoral bottom cover.

With increasing wave stress at more southerly sites, it may also be expected to find greater proportions of *P. compressa* in the northern sectors of the study bays relative to the southern sectors. However, this trend is not apparent from coral abundance data. This may be due to the variations in physical structure of the three areas. In order to quantify the differences within the bays, it will be necessary to correlate the physical parameters of each individual bay with the coral assemblages.

TABLE 11. CORRELATION COEFFICIENTS BETWEEN PERCENT CORAL COVER AND SPECIES-COVER DIVERSITY

	Porites compressa	*Porites lobata*	*Pocillopora meandrina*	*Montipora verrucosa*	*Montipora patula*
H'_c (coral cover)	-0.794*	0.765*	0.360	0.442*	0.350
r^2 (%)	63.04	58.52	12.96	19.53	12.25
H'_c (total cover)	-0.916*	0.813*	0.556*	0.314	0.438*
r^2 (%)	83.90	66.09	30.91	9.85	19.18

NOTE: H'_c is the species diversity; r^2 is the percentage of variance of diversity to its linear regression on % coral cover.

TABLE 12. CORRELATION MATRIX FOR PERCENT COVER OF FIVE MOST ABUNDANT CORAL SPECIES ON ALL TRANSECTS

	Porites compressa	*Porites lobata*	*Pocillopora meandrina*	*Montipora verrucosa*	*Montipora patula*
Porites compressa	--	-0.856*	-0.701*	-0.171	-0.499*
P. lobata	-0.856*	--	0.368	0.269	0.456*
Pocillopora meandrina	-0.702*	0.367	--	-0.287	0.502*
Montipora verrucosa	-0.171	0.296	-0.287	--	0.051
M. patula	-0.499*	0.456*	0.502*	0.051	--

*Significant correlation at the 0.01 level.

TABLE 13. MEAN PERCENT COVER FOR *Porites compressa, P. lobata, Pocillopora meandrina,* BASALT, AND LIMESTONE FOR ALL TRANSECTS AT EACH SITE

Site	*Porites compressa*	*Porites lobata*	*Pocillopora meandrina*	Basalt	Limestone
	(Mean, %)				
No. Puakō	75.45	19.28	0.38	0.00	2.11
So. Puakō	76.43	18.83	0.18	0.00	2.14
No. 'Anaeho'omalu	40.39	38.17	2.04	3.17	10.66
So. 'Anaeho'omalu	36.88	35.75	2.23	1.70	19.01
No. Kīholo	32.63	45.00	1.33	1.44	16.00
So. Kīholo	35.50	34.50	2.09	5.61	22.27

The relationship between *P. compressa* cover and degree of wave stress is apparent when each site is examined separately. It can be seen that at Puakō, *P. compressa* dominates all bottom cover except at the 6-m transect. While Puakō appears to sustain relatively low levels of wave stress, most of this energy seems to be absorbed at the 6-m depth and not at the shoreline regions as is the case at 'Anaeho'omalu and Kīholo bays. Since the outer reef shelf acts as a wave absorber, conditions in the 3-m nearshore area at Puakō are both optimal and predictable with respect to wave and light conditions. In this situation *P. compressa* is able to effectively exclude other corals from settling and growing in much the same manner that it dominates protected shallow lagoon slopes in Kāne'ohe Bay.

At the 6-m transect at Puakō, breaking waves and scour cause unpredictable and suboptimal conditions which seem to prevent resource domination and results in the coexistence of a variety of other corals. It can be seen in Figure 14 that *P. lobata* is the most abundant of these corals. This species is found occupying a variety of habitats in Hawai'i from very shallow areas to depths of up to 50 m, and is able to successfully populate almost any area by modifying its growth form in response to the physical conditions of the particular environment. By being such a generalist, *P. lobata* can fill any niche that *P. compressa* leaves vacant. It can be seen in Table 6 that there is a positive and significant correlation between *P. lobata* cover and diversity, and that diversity is highly predictable with respect to *P. lobata* cover.

Wave and possibly storm activity at shallow depths and reduced sunlight at deeper areas may prevent *P. compressa* dominance in the zones where *P. lobata* is the most abundant species. However, diversity is also relatively high in these areas. *P. lobata* does not dominate bottom cover to the point of complete exclusion of other forms, as does *P. compressa*. This may be for several reasons. The rigorous wave conditions in shallow areas, such as the 3-m transects at 'Anaeho'omalu and Kīholo and the 6-m transect at Puakō, may constantly disrupt community succession and create new bare substrata that a variety of encrusting corals can settle with a minimum of competition for space. In these shallow zones there is usually an abundance of massive dead *P. lobata* skeletons that are probably the result of intense scour from storm waves. Small colonies are often found settling on these bare surfaces so that *P. lobata* may create a complex of new settling environments as well as adding to the structural deposition of the reef. The positive correlation between both *P. lobata* and diversity, and *P. lobata* and *P. meandrina, M. verrucosa,* and *M. patula* (Table 7), also indicate that more corals coexist more equitably in the regions where *P. lobata* is the dominant species.

At intermediate depths of 9 to 15 m, the environment may be both stable with respect to wave action and optimal with respect to light. At north Puakō the ridge channel system falls into this depth range as does the lower reef shelf and upper reef flat at all other sites. *Porites compressa* dominates coral growth on the ridges except on the lower vertical ridge walls where overlapping colonies of *P. lobata* and *P. (Synaraea) convexa* are better adapted to settle and grow. At south Puakō, where the bottom is a steep slope, it can be seen that *P. compressa* cover peaks at the 9-m transect and gradually decreases with depth. It may be that as depth increases, decreasing light energy may reduce *P. compressa* growth rates to the point where this species can no longer totally outcompete the plate-like growth forms which expose the maximum amount of coral surface area to incident radiation. Thus, *P. lobata* and several specialized forms may coexist with *P. compressa* on sloping bottoms, causing diversity to be higher than at intermediate depths in flat areas. This may also be the case at the 18-m transect at north Puakō, which occurred on a sloping bottom rather than on the ridge and channel area.

Maragos (1972) suggests that *Montipora* establishes itself as a major reef component after communities have been settled by *Pocillopora* and *Porites*. If this is the case, it would be expected that there would be more *Montipora* at Puakō than at either 'Anaeho'omalu or Kīholo since Puakō appears to be a more stable area and may be at later stages of community succession. Qualitative observations indicate that more *Montipora* did occur at Puakō even though transect data does not substantiate this. Much of the *Montipora* at Puakō occurs on the nonliving parts of the *P. compressa* lattice and is, therefore, not easily visible in the transect photographs. It can be seen in Table 12 that *M. verrucosa* does not correlate significantly with any other coral indicating that competitive interference may not have a controlling effect on *M. verrucosa* abundance. *Montipora patula* correlates positively and significantly with *P. lobata* and *P. meandrina* and negatively with *P. compressa*, indicating that this species is found in areas where *P. compressa* does not occur. Observations show that *M. patula* occurs mostly on the near shore reef flat, where *P. compressa* is restricted because of rigorous wave action.

Pocillopora is a major coral on the shallow reef flats at 'Anaeho'omalu and Kīholo. It appears that *P. meandrina* can successfully settle and grow in areas where strong water movement prevents attachment, or causes mortality of other species. It has been suggested that *P. meandrina* is a fugitive species that is the first to settle new substrata and, unless it is in areas too harsh for other species to populate, it appears to be gradually eliminated from the community by competitive interactions with other corals. The significantly negative correlation between *P. meandrina* and *P. compressa* indicates that *P. meandrina* occurs predominantly in areas where *P. compressa* cannot dominate. The low levels of *P. meandrina* at Puakō substantiate the hypothesis that this area is subjected to less stress and that conditions have not been disturbed for a relatively long time. The low levels of *P. meandrina* indicate that Puakō may be at a later stage of succession than the other two bays and *P. compressa* has had time to successfully eliminate this species by successful competitive interactions.

MOLLUSCAN ASSEMBLAGES[1]

Introduction

Mollusks are ubiquitous inhabitants of marine environments throughout the Hawaiian Islands, found from the vegetation line marking the upper limit of the littoral fringe to depths of more than 1,080 m (600 fathoms). In this report, molluscan assemblages of the intertidal zone and subtidal reaches of bays to depths of 18 m (60 ft) are described. Two types of assemblages are distinguished: those characterized as macromollusks, that is, mollusks with shells greater than 10 mm (3/8$^+$ in.) in greatest dimension, and those termed micromollusks, mollusks with shells less than 10 mm in greatest dimension (Kay 1973). Macromollusks are the dominant components of the intertidal zone, micromollusks of subtidal reaches. Because micromollusks represent a variety of trophic and spatial habits, their assemblages are assumed to reflect the structure of the communities of which they are a part. The shells of micromollusks are assumed to be deposited in situ. This latter assumption is based on observations throught the islands which indicate that distinctive assemblages are associated with different depth regimes and different environments (Kay 1973).

Methods

Samples for the analysis of benthic molluscan assemblages were obtained by a variety of methods between August 1973 and March 1976. Stations, methods of collection, and dates of collection are listed in Table 14, and the sampling stations used in the quantitative analysis are shown in Figures 20, 23, 24, and 25.

The stations at Puakō, 'Anaeho'omalu, and Kīholo bays include three depth groups: shoreline stations encompassing tidepools and inshore waters at depths of less than 1 m; mid-bay stations located on transects across the mid-sections of each bay at depths of 3 to 15 m; and outer bay stations located on transects running across the mouths of bays at depths of 6.5 to 20 m. Sampling at Waiulua Bay was at depths of less than 1 m.

Observations on the macromollusks, those species more than 10 mm in greatest dimension, are qualitative, and the macromollusks observed are

[1]E. Alison Kay, Project Associate Investigator.

TABLE 14. STATION NUMBERS, DEPTHS, DATES, AND METHODS OF COLLECTION

Station Numbers	Collection		
	Depth (m)	Date	Method
Puakō:			
01C-04	12-15	Mar. 1975	SCUBA
In1-In3B	3-6	Mar. 1975	SCUBA
ShA-C	1	Oct. 1974	Snorkelling
SB, SC, M2	Shoreline	Mar. 1976	Shoreline
Waiulua Bay:			
In1-3	Shoreline	Mar. 1975	Snorkelling
1-3	Shoreline	Mar. 1975	Snorkelling
'Anaeho'omalu:			
01-04	7-18	Mar. 1975	SCUBA
In1-In3	5-7	Mar. 1975	SCUBA
ShA-B	Shoreline	Oct. 1974	Snorkelling
TP	Shoreline	Mar. 1976	Shoreline
Kīholo:			
01-05	6-9	Oct. 1975	SCUBA
In1-3	2-5	Oct. 1975	SCUBA
10.2-10.20	0.3-1	Aug. 1973	Snorkelling/ SCUBA
12.20-12.25	Shoreline	Aug. 1973	Shoreline

merely reported.

Micromollusks, those species less than 10 mm in greatest dimension, were obtained quantitatively from sediment samples retrieved at each of the intertidal and subtidal stations. Sediments were washed in fresh water and air-dried in the laboratory. Micromollusks were picked from the sediments under a binocular dissecting microscope from volumes of 10 to 25 cm^3. Standing crops were determined by dividing the number of shells in each sample by sediment volumes. Species diversity was calculated from the Shannon-Wiener diversity function, $H' = -\Sigma p_i \log_2 p_i$ (Pielou 1969). Species composition represents relative abundance values determined by calculating the percentage composition of each assemblage.

Similarity indices were computed for all sample pairs using a modified Sorenson similarity index (Maragos 1976). The resulting similarity matrix is reduced to dendrographs (Figs. 21, 25, 26, 27, 28), where similarity within groups or clusters is represented as distance along the vertical scale and distance between any two adjacent samples on the horizontal axis is proportional to their dissimilarity.

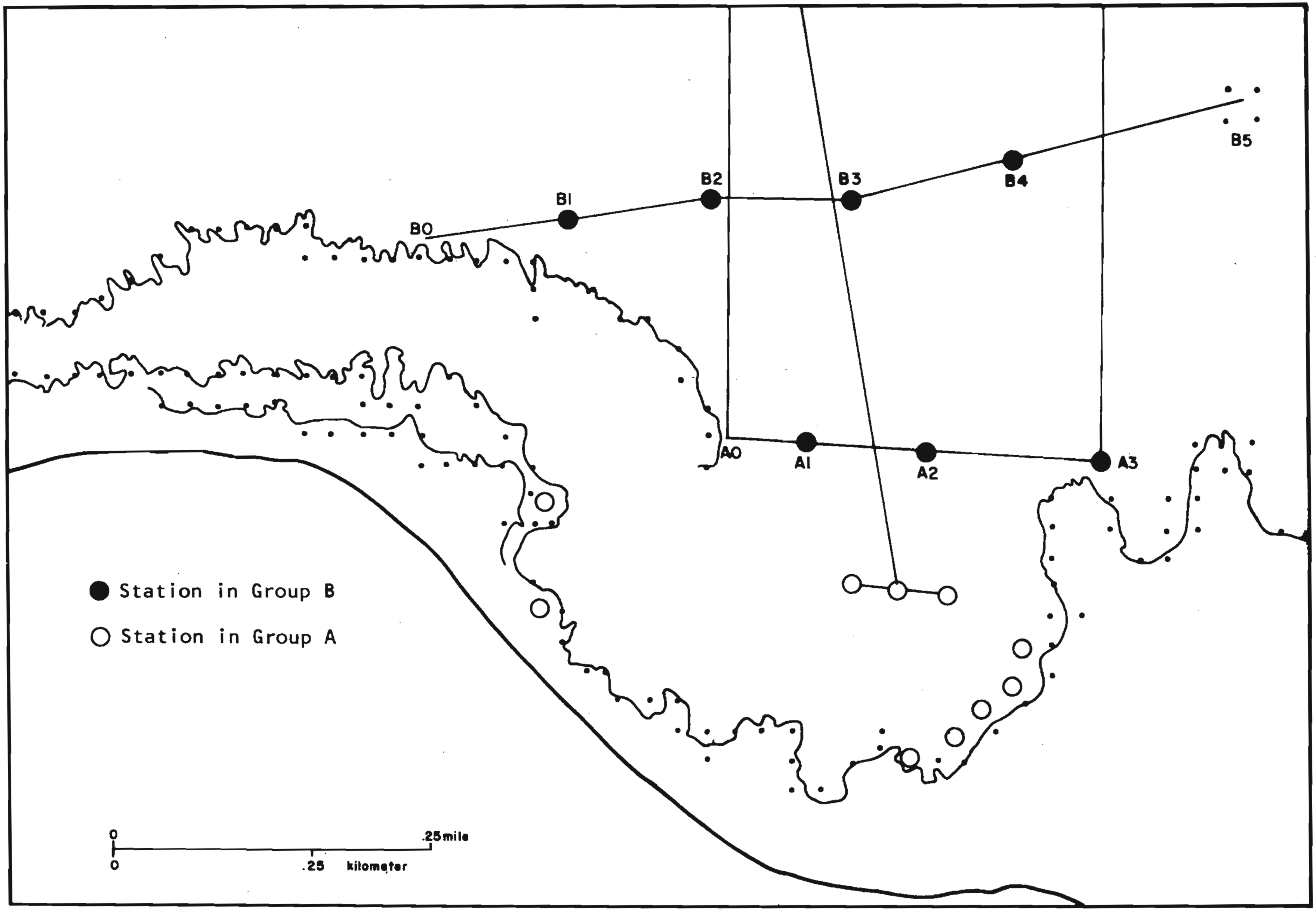


FIGURE 20. STATIONS IN PUAKŌ BAY, KONA COAST

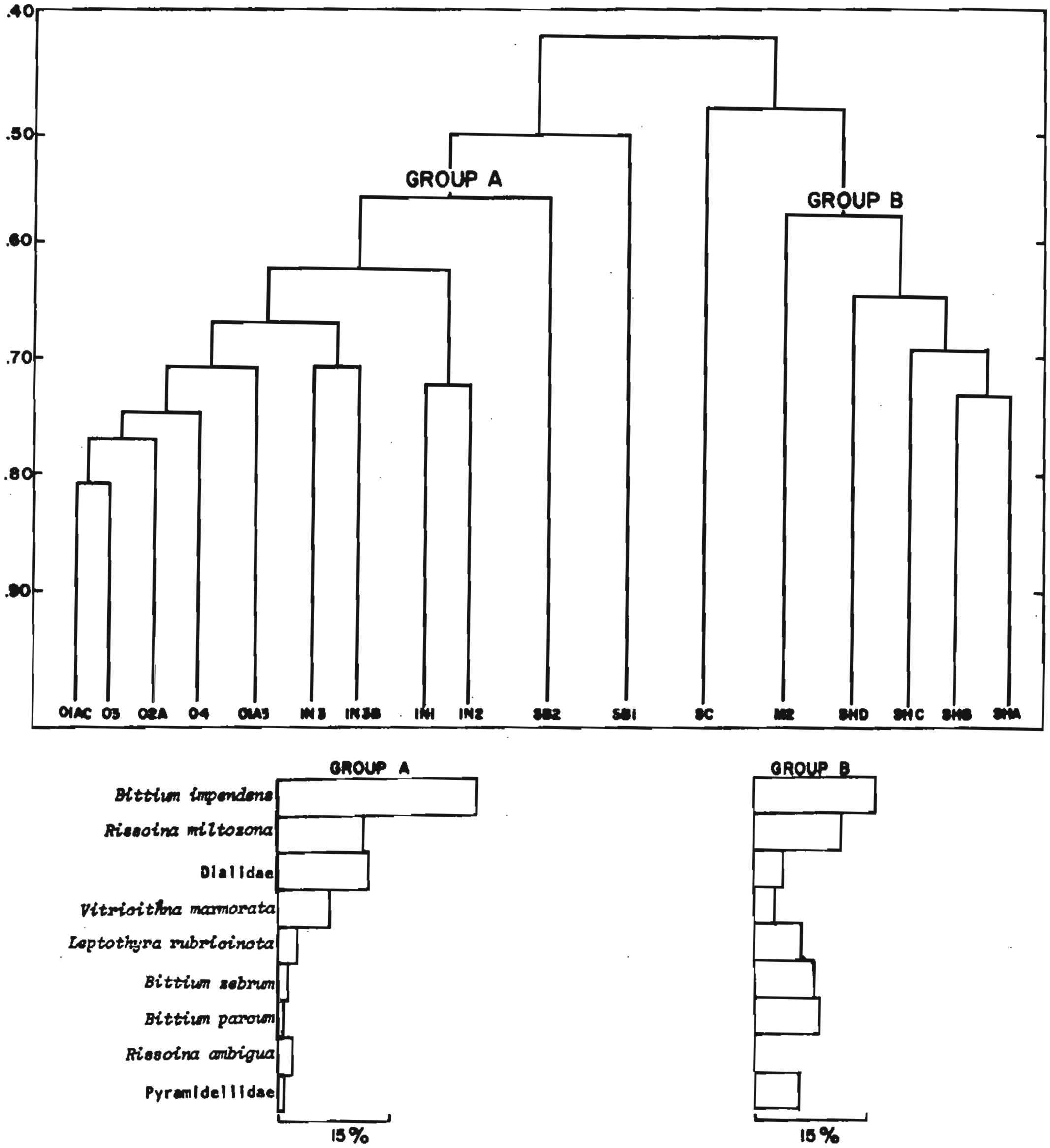


FIGURE 21. DENDROGRAPH SHOWING INDICES OF AFFINITY BETWEEN STATIONS AT PUAKŌ BAY

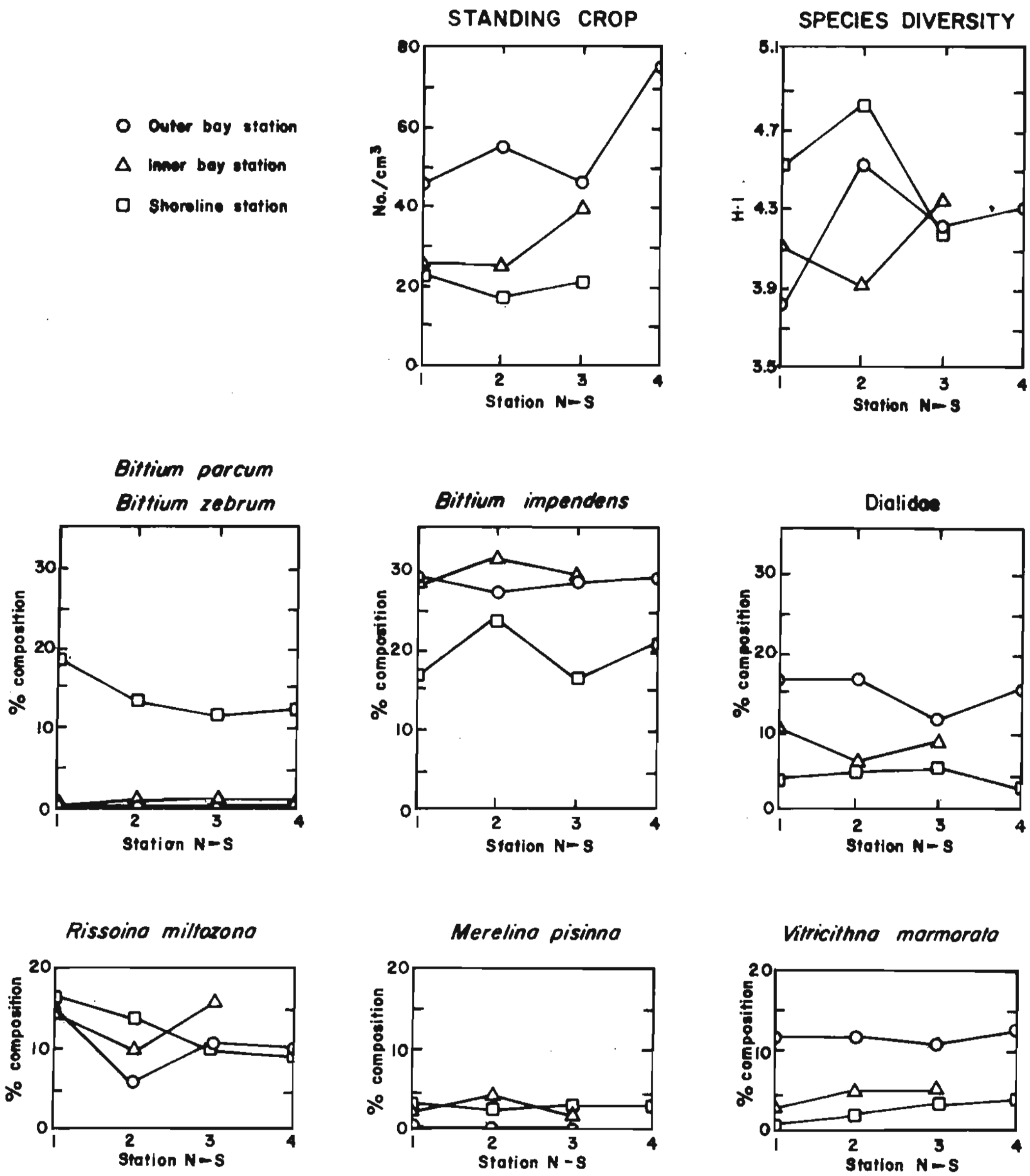


FIGURE 22. DISTRIBUTION OF STANDING CROP, SPECIES DIVERSITY, AND DOMINANT SPECIES IN THE MICROMOLLUSCAN ASSEMBLAGES AT PUAKŌ BAY

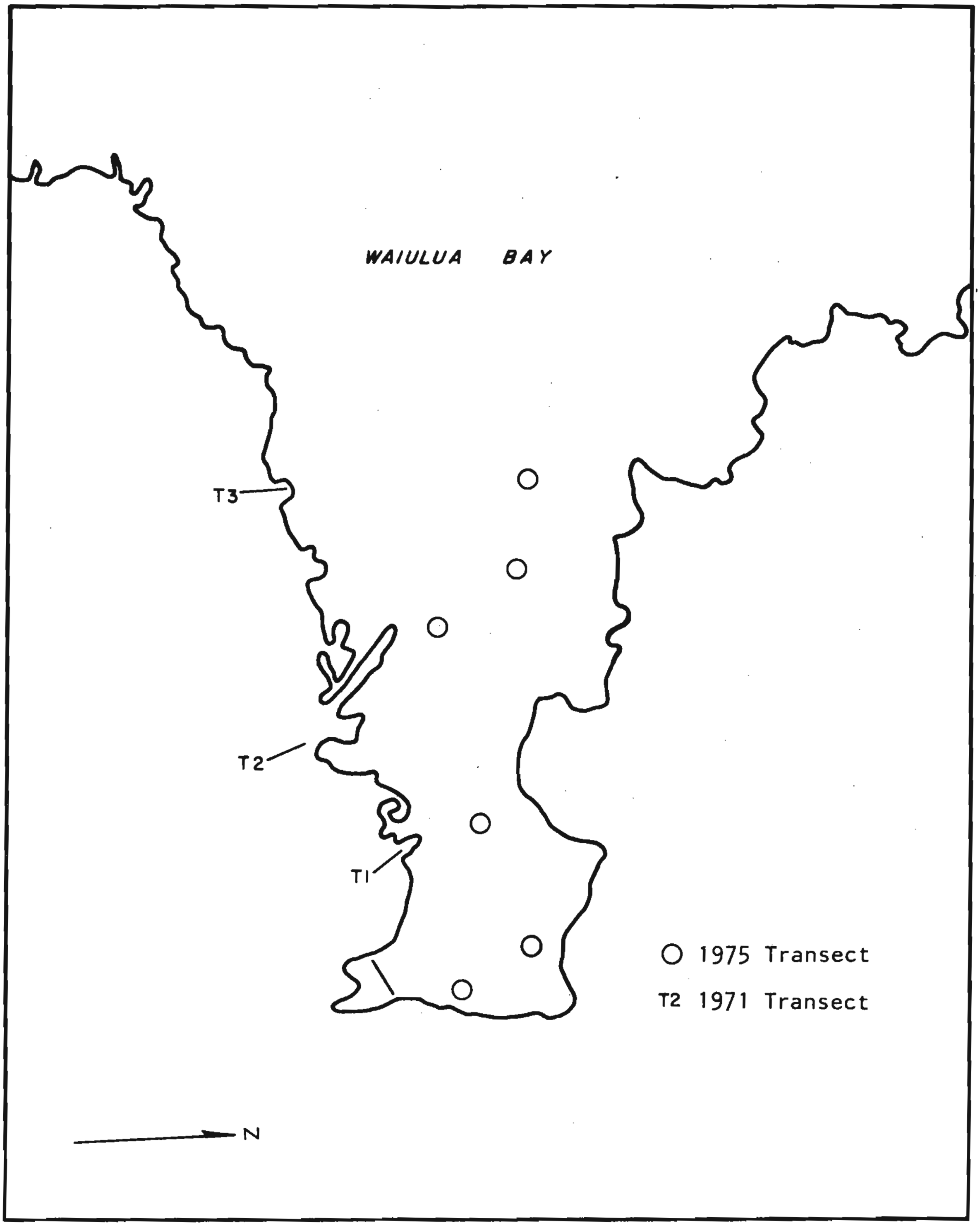


FIGURE 23. STATIONS IN WAIULUA BAY, KONA COAST

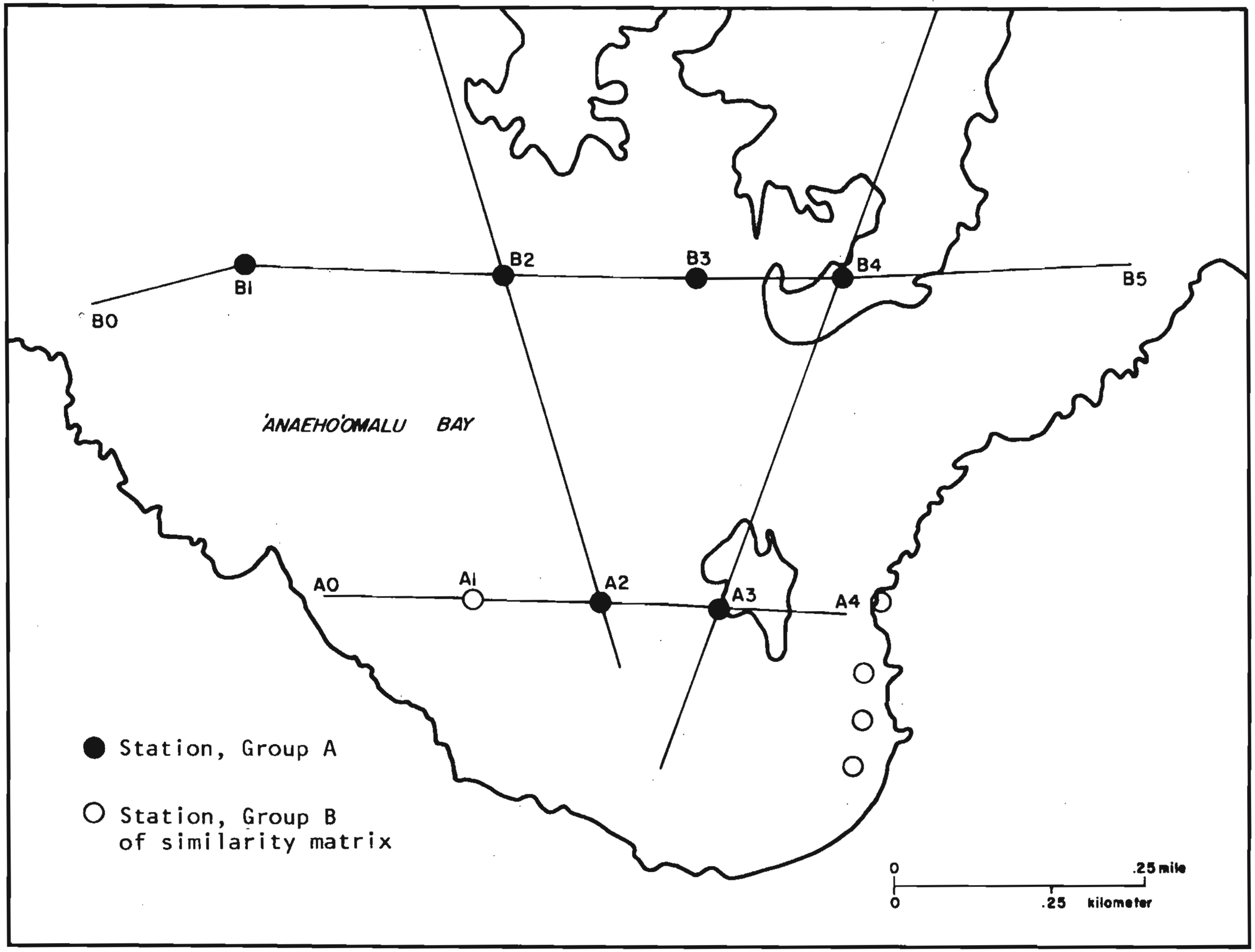


FIGURE 24. STATIONS IN 'ANAEHO'OMALU BAY, KONA COAST

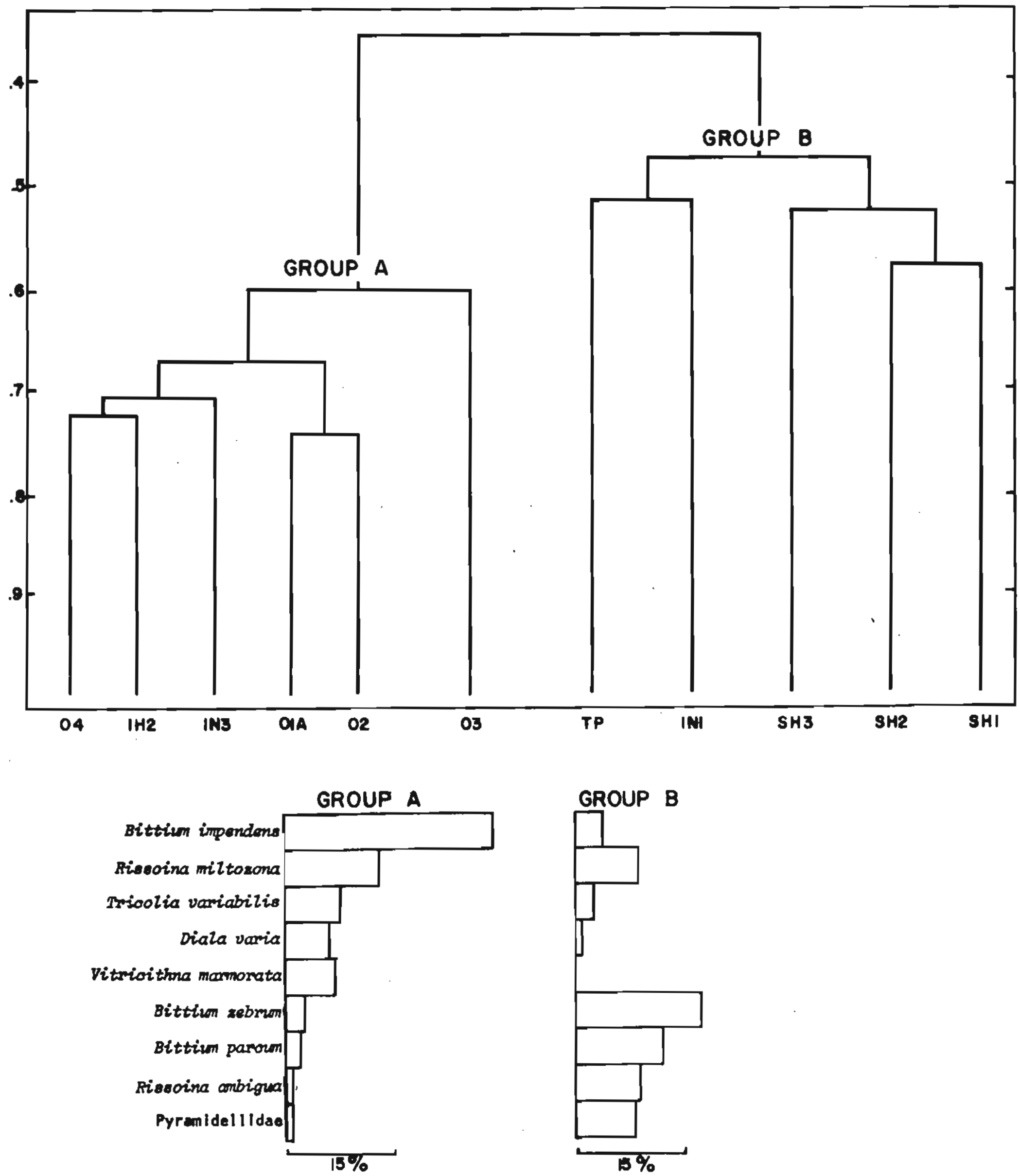


FIGURE 25. DENDROGRAPH SHOWING INDICES OF AFFINITY BETWEEN STATIONS AT 'ANAEHO'OMALU BAY

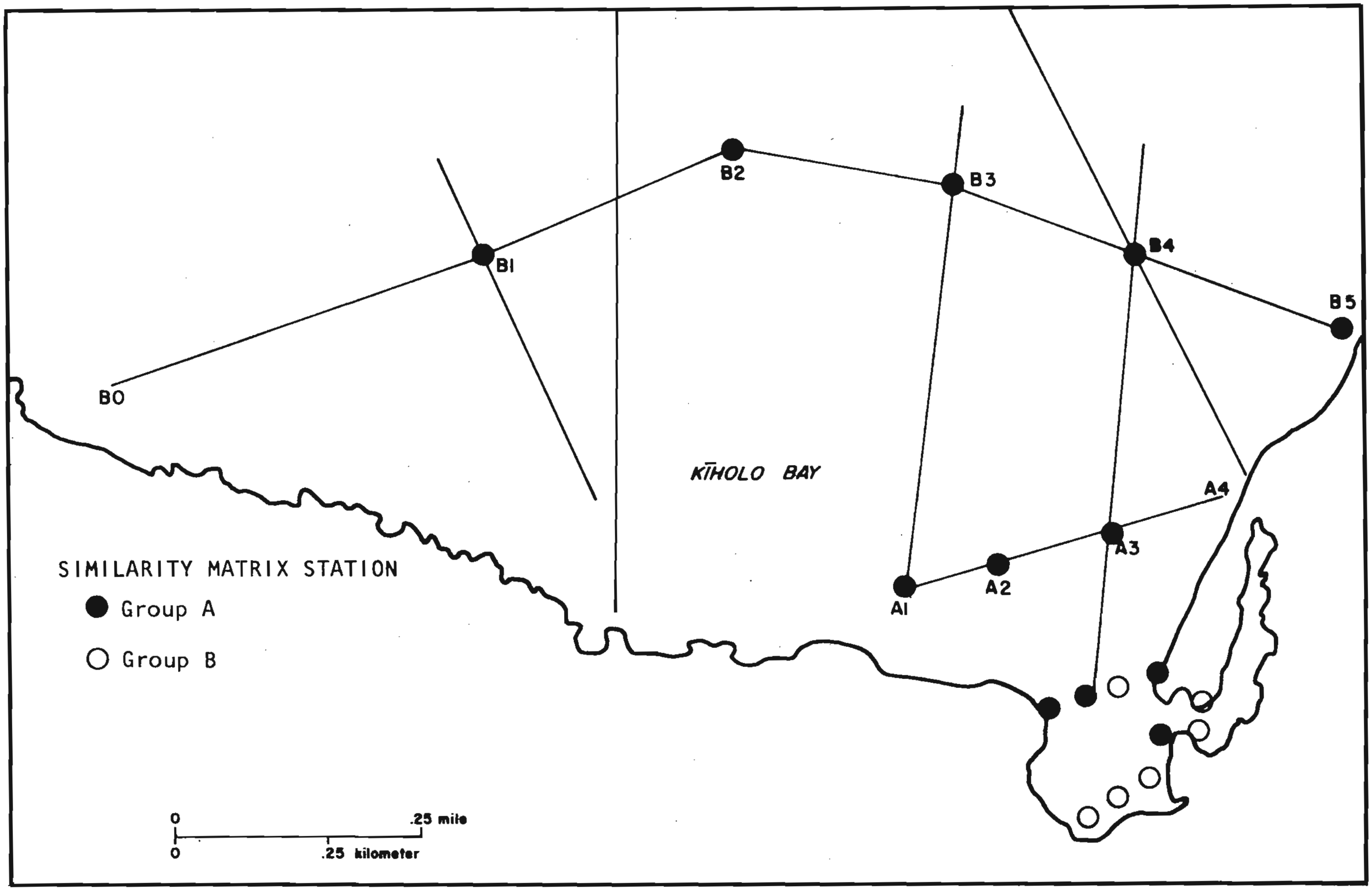


FIGURE 26. STATIONS IN KĪHOLO BAY, KONA COAST

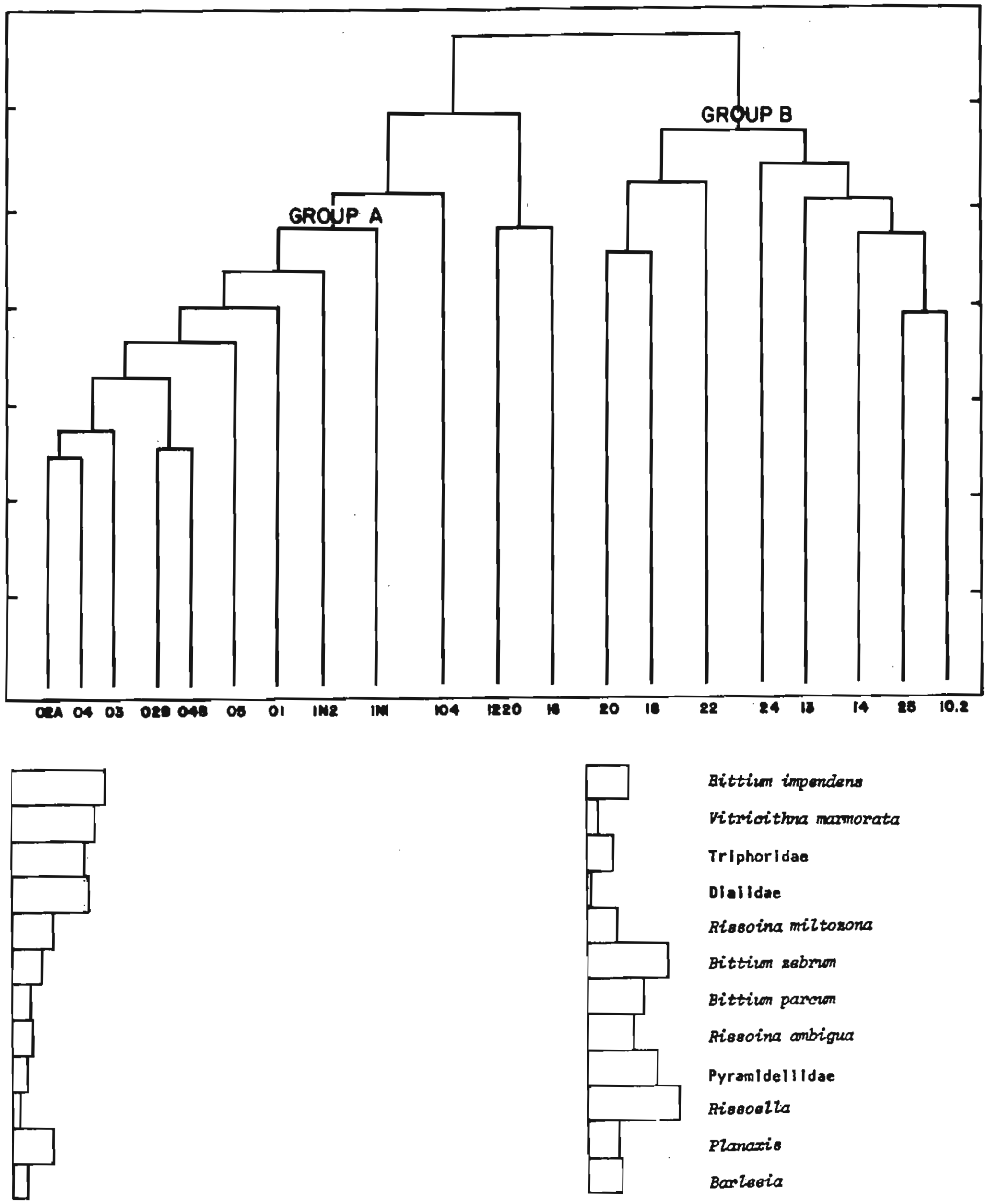


FIGURE 27. DENDROGRAPH SHOWING INDICES OF AFFINITY BETWEEN STATIONS AT KĪHOLO BAY

Puakō Bay

MACROMOLLUSCAN ASSEMBLAGES. The supratidal shoreline at Puakō is comprised of basalt benches which form the northern and southern termini of the bay, and of boulders, rubble, and kiawe trees (*Prosopis pallida*) on the terrigenous beach of the central section. On rocky substrates, the highest level of tidal action is marked by a sparse growth of the crisp red alga, *Ahnfeltia*; below the *Anhfeltia* the substrate is encrusted by a thin cover of the coralline alga, *Porolithon*.

Three species of littorine and one species of nerite occur in the supratidal. The littorine, *Littorina scabra*, is found only on the lowest branches of the kiawe which overhang the waters of the bay. Two other littorines, *Littorina pintado* and *Nodilittorina picta*, and the nerite, *Nerita picea*, occur on basalt substrates. No living macromollusks were found on the terrigenous beach. The macromollusks associated with the intertidal are the gastropods, *Hipponix grayanus*, *Morula granulata*, and *Mitra litterata*, and the bivalve, *Isognomon perna*. An assemblage of brackish-water associated mollusks was found only in one tidepool on the south bench. The dominant brackish-water species in the pool were the macromollusks, *Theodoxus neglectus* and *Melania* sp., and the micromollusk, *Eatoniella* sp. (see below). The marine gastropods, *Hipponix grayanus* and *Morula granulata* were also present.

MICROMOLLUSCAN ASSEMBLAGES. The micromolluscan assemblages are grouped into two major clusters of stations in the similarity matrix (Fig. 21), one series of stations comprising the intertidal and inshore stations, the other composed of the mid- and outer-bay stations (Figs. 20, 21). Standing crop, species diversity, and species composition are recorded in Table 15, and the distribution of dominant species among stations in Figure 22.

The inshore substrates of the bay at depths of less than a meter consist of silty, calcareous sediments studded with occasional heads of the coral *Pocillopora meandrina* and stands of frondose algae, such as *Padina*. The dominant micromollusks are three species of Cerithiidae, *Bittium parcum*, *B. zebrum*, and *B. impendens*; the rissoids *Rissoina miltozona* and *Merelina pisinna*; and the archaeogastropod *Leptothyra rubricintca*. The micromollusks are predominantly epifaunal. Standing crop averages 19.8 shells/cm^3, and the species diversity index H' averages 4.2. The micromolluscan assemblages characterizing the inshore stations are distinguished from those of the mid-

TABLE 15. STANDING CROP, SPECIES DIVERSITY, AND SPECIES COMPOSITION AT PUAKŌ BAY, HAWAII

	Station																
	01C	01S	02A	03	04	In1	In2	In3	In3B	SB2	ShA	ShB	ShC	ShD	M2	SC	SB1
Depth, m	12	15	15	12	12	3	6	6	6	---	---	---	---	---	---	---	---
No. Specimens	460	351	551	473	735	260	261	397	295	356	212	197	203	358	124	345	522
No./cm^3	46	35.1	55	47.3	73.5	26.0	26.1	39.7	29.5	17.8	21.2	19.7	20.3	35.8	5.0	13.8	34.8
H'	3.8	3.8	4.5	4.2	4.3	4.1	3.9	4.3	3.5	4.4	4.6	4.2	4.6	4.6	3.9	3.6	3.6
Percent Composition																	
Archaeogastropods																	
Leptothyra rubricincta	1	5	3	+	3	6	3	5	+	5	5	7	10	5	5	2	3
Tricolia variabilis	+	4	2	+	+	+	1	1	+	+	+	+	+	--	--	--	+
Rissoidae	33	14	23	25	31	21	20	28	26	+	25	22	22	21		5	10
Rissoina ambigua	+	--	+	+	1	--	+	+	+	11	2	+	+	2	--	--	+
R. miltozona	15	8	6	11	10	15	10	16	19	18	16	14	11	11	6	+	7
Merelina pisinna	+	--	1	--	1	+	1	4	2	2	3	3	3	3	6	3	+
Vitricithna marmorata	12	4	12	11	13	3	5	5	3	+	+	2	4	4	2	+	+
Parashiela beetsi	1	1	1	+	1	1	+	--	+	--	--	--	+	--	--	+	+
Cerithiidae	30	36	29	30	29	30	34	30	32	3	31	38	29	40		44	26
Bittium impendens	29	35	27	28	28	28	31	29	32	5	16	24	16	20	11	+	2
B. parcum	+	+	+	--	--	+	+	+	--	1	7	3	5	12	16	27	18
B. zebrum	+	--	1	--	+	--	--	+	--	18	7	9	8	7	11	17	6
Dialidae	16	20	16	11	15	10	6	9	16	--	4	6	5	3	2	+	2
Cerithidium perparvulum	6	10	6	7	6	7	5	2	5	--	2	2	4	+	+	+	1
Diala varia	6	8	8	5	4	--	+	6	11	+	2	4	--	2	2	--	+
Triphoridae	5	2	8	7	4	2	3	5	4	+	5	3	2	2	1	--	1
Pyramidellidae	+	2	+	--	+	+	--	+	4	3	9	6	8	6	7	3	3
Eatoniellidae	--	--	--	--	--	--	--	--	--	2	--	--	+	--	--	--	32

+ = amount too small to be counted.

and outer-bay stations by the high porportion of *Bittium parcum* and *B. zebrum* proportional to *B. impendens* ($\bar{x}$ = 21.4% vs. 14.6%), and the relatively higher proportions of *Leptothyra rubricincta* and lesser proportions of the Dialidae than are found in the offshore stations (Table 16).

TABLE 16. SUPRATIDAL AND INTERTIDAL MOLLUSKS RECORDED IN THE 1971 TRANSECTS

Species	Transect 1	Transect 2 (m^2)	Transect 3
Theodoxus neglectus	886	--	--
Nerita picea	90	165	17
Peasiella tantilla	29	--	--
Littorina pintado	25	70	102
Nerita polita	5	--	--
Planaxis sp.	--	46	--

SOURCE: Key, Guinther, and Miller (1971).

Beginning at a distance of about 20 m from the shoreline and extending to the outer reaches of the bay at depths of more than 30 m, the substrate is covered with coral infiltrated with pockets of calcareous sand (see Coral Communities). Sediment sizes vary from fine sand to coarse fragments of *Halimeda* and coral, but there is a high degree of faunal similarity among the offshore stations, indicated by their inclusion in group A in the dendrograph (Fig. 21). The dominant micromollusks are the cerithid *Bittium impendens*, the rissoids *Rissoina miltozona* and *Vitricithna marmorata*, and the dialids *Cerithidium perparvulum* and *Diala varia* (Table 16). As in the inshore section of the bay, the micromollusks are predominantly epifaunal. Standing crop averages 39.6 shells/cm^3, twice that of the inshore stations, and the species diversity index, H', averages 4.2.

Two stations lie between the two major groups in the similarity matrix, the tidepool station (SB1, Table 15) with the brackish-water associated gastropod *Eatoniella* sp., and the station located in a small cove adjacent to the pier (SC, Table 15). At this latter station, the sediments contain a peculiar association of infaunal mollusks, the gastropod *Caecum* and the small bivalve *Anisodonta*.

Waiulua Bay

MACROMOLLUSCAN ASSEMBLAGES. This is the smallest of the four bays surveyed and consists of little more than an indentation in a prehistoric lava flow which meets the sea. The bay is fringed entirely by basalt, with low, vertical benches at the northern and southern termini, a basaltic flat forming the central section, and a rubble bar dividing the inner section of the bay from the outer section. There is abundant evidence of groundwater intrusions throughout the bay, with noticeable freshets gushing from crevices along the shoreline.

A survey of the macrofauna in 1971 (Key, Guinther, and Miller 1971) describes the distribution and density of macromollusks on three transects (Fig. 22). The dominant species are supratidal and intertidal forms, *Littorina, Nerita,* and *Theodoxus*. These species and their densities on each of the transects are shown in Table 16. Two bivalves were reported at densities of less than 250/m^2, *Isognomon californicum*, associated with fresh water, and its congener, *I. perna*, which is less tolerant of fresh water. The position of these two species on the rocks to which they are attached, one above the other, indicates that conditions of vertical stratification with respect to salinity are probably permanent (Key, Guinther, and Miller 1971).

MICROMOLLUSCAN ASSEMBLAGES. The substrate in Waiulua Bay is composed of pebble and black sand in the inner and outer sections, and occasional heads of the coral *Pocillopora meandrina* stud the floor of the outer section. A freshwater lens several centimeters in thickness lies across the inner section of the bay and extends into the outer section beyond the rubble bar.

Standing crop, species diversity, and species composition of the micromolluscan assemblages are shown in Table 17. Of the 1,203 mollusks counted in the sediment samples, 67% were associated with fresh water. The dominant mollusks of the inner bay are *Theodoxus neglectus*, which comprise about 46% of the mollusks in the sediments, and *Eatoniella* sp., found in two of the three samples in the inner bay and comprising respectively 12% and 31% of the samples. The outer bay sediments are dominated by the cerithids *Bittium zebrum* ($\bar{x}$ = 69%) and the rissoids *Rissoina ambigua* and *R. miltozona*. *Eatoniella* sp. comprised 83% of one of the outer bay samples. Standing crops averaged 24.4 shells/cm^3 in the inner bay and 15.7 shells/cm^3 in the outer bay. The species diversity index, H', averaged 4.1 in the inner bay and 3.0 in the the outer bay.

'Anaeho'omalu Bay

MACROMOLLUSCAN ASSEMBLAGES. The shoreline at 'Anaeho'omalu, like that

TABLE 17. STANDING CROP, SPECIES DIVERSITY, AND SPECIES COMPOSITION OF MICROMOLLUSKS, WAIULUA BAY

	Station					
	In1	In2	In3	O1	O2	O3
No./sample	346	210	177	121	129	220
No./cm³	34.6	21.0	17.7	12.1	12.9	22.0
H'	2.4	1.1	2.1	4.1	3.7	1.3
	% Species Composition					
Archaegastropods						
Tricolia variabilis	1	-	+	2	-	+
Leptothyra rubricincta	-	-	-	4	+	+
Rissoidae	+	-	6	29	15	6
Rissoina ambigua	+	-	1	7	2	2
R. miltozona	+	-	3	12	11	3
Merelina pisinna	-	-	-	7	-	-
Vitricithna marmorata	-	-	-	-	-	-
Cerithiidae	13	2	12	33	30	3
Bittium impendens	+	-	-	-	3	2
B. parcum	+	-	+	15	+	+
B. zebrum	12	2	10	17	26	+
Eatoniellidae	-	-	-	-	-	-
Eatoniella sp.	31	-	12	-	11	83
Neritidae	-	-	-	-	-	-
Theodoxus neglectus	45	96	60	1	-	2

at Puakō, is composed of several distinctive topographic features. The northern and southern boundaries of the bay are defined by sea-level benches interspersed with tidepools which are open to the ocean. The basalt boundaries of the tidepools of the northern terminus are thickly encrusted with the coralline alga, *Porolithon*. The basaltic bench with its associated tidepools which define this section of the shoreline slopes inland, terminates at the *mākāhā* (sluice gate) through which Ku'uali'i Fishpond empties into the bay. The bench is intertidal, covered with a dense mat of the bivalves, *Isognomon californicum* and *Brachidontes crebristriatus*, both of which are tolerant of fresh water. Beyond the *mākāhā* a sandy, arcuate beach is the central feature of the bay. No living mollusks were seen on the beach, but the ghost crab, *Ocypode*, burrows in the upper portion of the beach. To the south the bay is fringed with basaltic boulders and bench. There is a sparse population of *Isognomon californicum* and *Theodoxus neglectus* in crevices of the bench and between the boulders.

MICROMOLLUSCAN ASSEMBLAGES. As at Puakō, the stations sampled for micromollusks at 'Anaeho'omalu cluster in two groups in the similarity analysis

(Figs. 24 and 25), a shoreline and inshore series of stations which also includes one station on the inner bay transect, and an offshore series of stations. Standing crop, species diversity, and species composition are shown in Table 18.

The inshore section of the bay consists of a broad, sandy flat which is succeeded some 30 m from the shore, at depths of 3 to 4 m, by a zone of isolated colonies of the coral, *Porites lobata*. Beyond the zone of *P. lobata*, coral cover increases and is dominated by *P. compressa* (see Coral Communities). Sediments of the bay floor are primarily calcareous.

The inshore stations (including the tidepools) are characterized by high proportions of *Bittium parcum* and *B. zebrum*, and relatively high proportions of the rissoid, *Rissoina ambigua*, and pyramidellids (Fig. 25, Table 19). Standing crop averages 7.1 shells/cm^3 and the species diversity index, H', averages 3.8.

The outer bay stations are clearly distinguished from those of the shoreline stations by high proportions of *Bittium impendens, Rissoina miltozona, Vitricithna marmorata,* and *Tricolia variabilis*. Standing crop is higher than in the shoreline sections of the bay ($\bar{x}$ = 41.8 shells/cm^3), and the species diversity index, H', also averages higher (4.2).

Kīholo Bay

MACROMOLLUSCAN ASSEMBLAGES. The shoreline at Kīholo, like that at Wailua Bay, is formed by a continuous fringe of basalt. The northern terminus is steep, more than 3 m above sea level and there is a short, vertical intertidal zone. The mid-section of the bay consists of pebble beach and benches of smooth pāhoehoe. The southern terminus is formed by a low, flat pāhoehoe bench with a broad, horizontal intertidal zone. A prominent feature of the shoreline is Wainanali'i Pond, which intrudes into the bay on the northeast between the northern terminus of the bay and the central pebble beach. The pond is separated from the bay proper by a rubble shoal.

The dominant supratidal mollusks are the littorine, *Littorina pintado*, the nerite, *Nerita picea*, and, on the horizontal bench, the pulmonate limpet, *Siphonaria normalis*. The dominant mollusks of the intertidal and shallow subtidal waters are the gastropods, *Hipponix grayanus* and *Peristernia chlorostoma*, and the bivalve, *Isognomon perna*.

TABLE 18. STANDING CROP, SPECIES DIVERSITY, AND SPECIES COMPOSITION AT 'ANAEHO'OMALU

	Station										
	01A	02	03	04	In1	In2	In3	ShA	ShB	ShC	TP
Depth, m	8	8	8	18	6	5	8				
No. Specimens	339	373	193	652	61	457	496	80	87	87	112
No./cm^3	33.9	37.3	19.3	65.2	6.1	45.7	49.6	8	8.7	8.7	11.2
H'	4.0	4.5	4.3	4.4	3.3	4.2	4.1		4.1		
Percent Composition											
Archaeogastropods											
Leptothyra rubricincta	7	7	6	10	6	11	10	--	2	5	3
Tricolia variabilis	10	5	11	7	1	7	9	--	--	1	3
Rissoidae	40	34	21	38	33	36	29	11	26	22	
Rissoina ambigua	1	3	+	1	13	2	1	2	7	11	15
R. miltozona	24	15	3	17	11	10	13	7	9	7	12
Merelina pisinna	3	6	--	7	2	10	2	2	9	2	--
Vitricithna marmorata	5	5	9	6	--	7	7	--	--	--	--
Parashiela beetsi	2	+	3	2	--	1	1	--	--	--	--
Cerithiidae	27	33	27	26	42	32	27	24	30	40	
Bittium impendens	23	25	22	20	11	22	25	1	6	1	3
B. parcum	2	2	4	+	--	1	+	6	5	26	--
B. zebrum	2	2	--	2	31	7	+	16	19	10	12
Dialidae	+	3	17	3	--	1	13	--	1	--	--
Cerithidium perparvulum	+	+	11	2	--	+	5	--	+	--	--
Diala varia	--	+	4	+	--	--	3	--	--	--	--
Triphoridae	6	6	3	2	5	1	1	--	--	--	
Pyramidellidae	1	+	--	1	--	2	3				
Eatoniellidae											

+ = amount too small to be counted.

TABLE 19. STANDING CROP, SPECIES DIVERSITY, AND SPECIES COMPOSITION AT KĪHOLO BAY

	Station																			
	01	02A	02B	03	04	04B	05	In1	In2	In3	10.2A	10.4	10.14	10.16	10.18	10.20	12.20	12.22	12.24	12.25
Depth, m	6	6	6	9	9	9	9	5	2	2										
No. Specimens	194	585	344	541	668	359	318	135	305	228	248	640	153	93	225	228	58	87	127	231
No./cm^3	19.4	58.5	34.4	54.1	66.8	35.9	31.8	13.5	30.5	22.8	9.9	32.4	6.1	3.7	9	9.1	2.3	3.5	5.1	9.2
H'	4.0	4.5	4.7	4.9	4.2	4.7	4.0	4.3	4.4	3.7	4.2	4.8	4.2	3.9	3.4	3.8	4.1	3.5	3.5	4.3
Percent Composition																				
Archaeogastropods																				
Leptothyra rubricincta	7	3	5	9	6	4	7	4	7	+	6	3	--	--	--	--	--	--	--	4
Tricolia variabilis	15	11	7	6	13	11	11	3	6	3	4	5	6	3	2	5	5	--	3	1
Rissoidae	22	37	42	37	32	36	13	43	33	29	30	23	23	38	20	17	33	9	13	26
Rissoina ambigua	--	--	3	2	+	1	--	4	4	5	14	4	4	15	2	3	12	--	5	8
R. miltozona	3	5	9	6	4	6	+	15	4	2	11	3	8	12	2	1	3	1	--	5
Merelina pisinna	--	--	--	2	4	4	2	10	9	1	1	4	2	1	2	4	2	--	+	2
Vitricithna marmorata	5	14	15	15	12	14	6	4	5	+	+	2	5	5	--	--	10	--	+	--
Parashiela beetsi	8	10	7	6	7	4	2	1	1	+	--	--	--	--	--	--	--	--	2	--
Cerithiidae	14	11	16	18	19	21	26	21	34	46	28	17	33	14	16	24	24	38	46	42
Bittium impendens	11	8	12	16	14	13	19	15	18	1	--	+	3	4	2	+	10	22	--	3
B. parvum	1	+	+	+	1	2	4	1	3	5	13	9	21	5	6	6	3	2	10	14
B. zebrum	+	2	2	1	2	3	1	3	11	23	12	6	8	3	8	16	9	14	36	24
Dialidae	22	16	10	9	13	7	9	3	1	+	+	1	+	3	3	+	2	2	+	+
Cerithidium perparvulum	15	10	7	7	12	6	8	3	+	--	+	+	--	1	--	+	--	--	--	--
Diala varia	+	1	+	--	+	--	--	--	--	+	--	+	--	--	--	--	--	--	--	--
Triphoridae	2	4	5	4	4	5	6	4	1	+	2	+	1	2	+	1	2	2	--	--
Pyramidellidae	+	--	--	+	+	+	--	2	+	+	2	9	15	5	8	14	2	21	6	6
Eatoniellidae	--	--	+	1	1	--	--	--	5	3	--	9	4	19	44	13	--	13	2	+

+ = amount too small to be counted.

MICROMOLLUSCAN ASSEMBLAGES. Two assemblages of micromollusks are identified at Kīholo in the similarity analysis (Figs. 26, 27), one associated with a predominantly offshore cluster of stations (Group A, Fig. 27), the other characterizing predominantly inshore and shoreline stations (Group B, Fig. 27). Standing crop, species diversity, and species composition are shown in Table 19.

The inshore area at Kīholo is comprised largely of sediments of black sand studded with rubble at distances to 10 m offshore and at depths of less than 1 m. A variety of corals, such as *Porites lobata, Pocillopora meandrina,* and *Montipora verrucosa,* also occurs, although coral cover in the inshore area is sparse. A prominent freshwater lens is present along the northeastern sector of the shoreline, from Wainanali'i Pond to the central rubble beach, and the lens extends well into the mid-section of the bay, at least during the early morning hours. This lens causes considerable turbidity and reduced visibility, resulting in a rather uninviting prospect to a diver interested in clear water and colorful coral communities.

The dominant micromollusks of the inshore stations are *Bittium parcum* and *B. zebrum.* Two species associated with fresh water are also prominent, *Eatoniella* sp. and *Planaxis* sp., which occurred in 87% of the samples. Standing crop averages 9.3 shells/cm^3, and the diversity index, H', averages 3.7.

The dominant micromollusks of the offshore stations are *Bittium impendens, Vitricithna marmorata,* and *Parashiela beetsi.* The offshore stations are distinguished from those at 'Anaeho'omalu and Puakō by consistently lower proportions of *Rissoina miltozona* and higher proportions of *Parashiela* (Table 18). Standing crops average 31.9 shells/cm^3, and the mean of the species diversity index, H', is 4.4.

Three inshore stations occurring in the cluster of offshore stations include mollusks associated with fresh water, *Eatoniella* and *Planaxis*, as well as pyramidellids which may be associated with sessil invertebrates, such as oysters and sponges.

WAINANALI'I POND. Wainanali'i Pond is characterized by strong physicochemical gradients in the water column. These gradients primarily affect the fauna in the upper 0.5 m of the water column where a brackish to freshwater lens operates in conjunction with tidal flow and selects for euryhaline organisms. The dominant macromollusks in the pond are, thus, two species which are primarily associated with fresh water, *Isognomon californicum* and *Ostrea* *sandwicensis*. Details of the molluscan assemblages are described in the section on Wainanali'i Pond.

Discussion

Benthic marine communities are traditionally separated into supratidal, intertidal, and subtidal zones on the basis of discrete faunal communities characterized by the regular occurrence of conspicuous, usually numerically dominant elements of the fauna within each of the zones. No community of organisms is continuous, however, and differences in topography, depth, water chemistry, and the presence or absence of substrates such as coral, algae, and sediment determine the occurrence of local, specialized assemblages of organisms. The Kona Coast of Hawaii is a case in point: in the four bays considered here, localized assemblages of organisms appear to be the rule rather than the exception, and although each of the bays is generally characterized by the traditional zonation pattern, there are also marked differences in assemblages of mollusks (and other organisms) among and within the bays.

At Puakō the shoreline is one in which topographic and biotic features are primarily determined by tides rather than wave action, and marine conditions generally predominate along the shoreline. The overhanging kiawe trees, the sparse intertidal biota restricted to a few boulders and basaltic outcrops, and the presence of a broad, shallow inshore zone with coral growth reaching the tide line reflect both the lack of wave energy and freshwater intrusions in the bay. At 'Anaeho'omalu where the shoreline vegetation is restricted to the berm shoreward of the shoreline, where a wide, calcareous sand beach forms a central feature of the bay, and where tidepools at the northern terminus are surrounded by boulders encrusted with a rich growth of *Porolithon*, the situation suggests that wave energy rather than tides is a predominant determinant of the configuration of the bay. As at Puakō, marine conditions generally predominate. At Waiulua and Kīholo, the basalt shorelines with pebble, rubble, and black sand beaches are suggestive of areas receiving even more wave energy than is effective at 'Anaeho'omalu. Freshwater influxes are noticeable features of the shoreline of both bays, indicated not only by freshets of groundwater which gush from crevices in the basalt but by the freshwater lens present in the inshore areas of both bays.

The assemblage of macromollusks associated with the shoreline and inshore areas of the four bays reflect the conditions cited above. The most consistently encountered assemblage of mollusks is that found in the rocky supratidal, the assemblage characterized by *Littorina pintado*, *Nodilittorina picta*, and *Nerita picea*. This assemblage is characteristic of all rocky supratidal substrates in the windward Hawaiian Islands. One supratidal mollusk, *Littorina scabra*, however, is found only at Puakō, on the kiawe trees overhanging the bay. This gastropod, which is widespread throughout the Indo-West Pacific, is unusual in the Hawaiian Islands, and found only in protected areas such as in bays and harbors (Whipple 1967).

In the intertidal there are two assemblages of macromollusks, a marine assemblage with *Hipponix grayanus*, *Morula granulata*, and *Isognomon perna* most frequently encountered, and a freshwater-associated assemblage of *Theodoxus neglectus*, *Isognomon californicum*, and *Brachidontes crebristriatus*. At Puakō *Theodoxus* was found only in one shoreward tidepool. At 'Anaeho'-omalu *Isognomon* and *Brachidontes* were similarly found in a single area. At Waiulua and Kīholo the four mollusks were consistently encountered the length of the shoreline. That the freshwater intrusions at Waiulua and Kīholo are permanent features of the shoreline is indicated by the distinct zonation exhibitied by these mollusks along the shoreline at Waiulua Bay and in Wainanali'i Pond at Kīholo.

Analysis of the micromolluscan assemblages of the four bays indicates even more subtle differences among and within the bays. Some of the differences are summarized in the similarity matrix which includes all stations sampled at Puakō, 'Anaeho'omalu, and Kīholo (Fig. 28). Two major groups and five subgroups of stations are distinguished. In one major group (Group A) are the offshore stations of Puakō, 'Anaeho'omalu, and Kīholo and the inshore stations at Puako; in the other major group (Group B) are the shoreline stations at 'Anaeho'-omalu and Kīholo. Standing crop and the species diversity index are generally lower at the shoreline and inshore stations than in the offshore stations (except for the high species diversity index calculated for the inshore stations at Puakō).

The distinguishing species of the shoreline stations at 'Anaeho'omalu and Kīholo are *Rissoina ambigua*, *Bittium parcum*, and *B. zebrum*. All three species are ubiquitous shoreline species in the Hawaiian Islands, *B. parcum* associated with frondose algae, *Rissoina ambigua* and *B. zebrum* with rubble. The Kīholo stations (subgroup B2) are distinguished from those at 'Anaeho'-

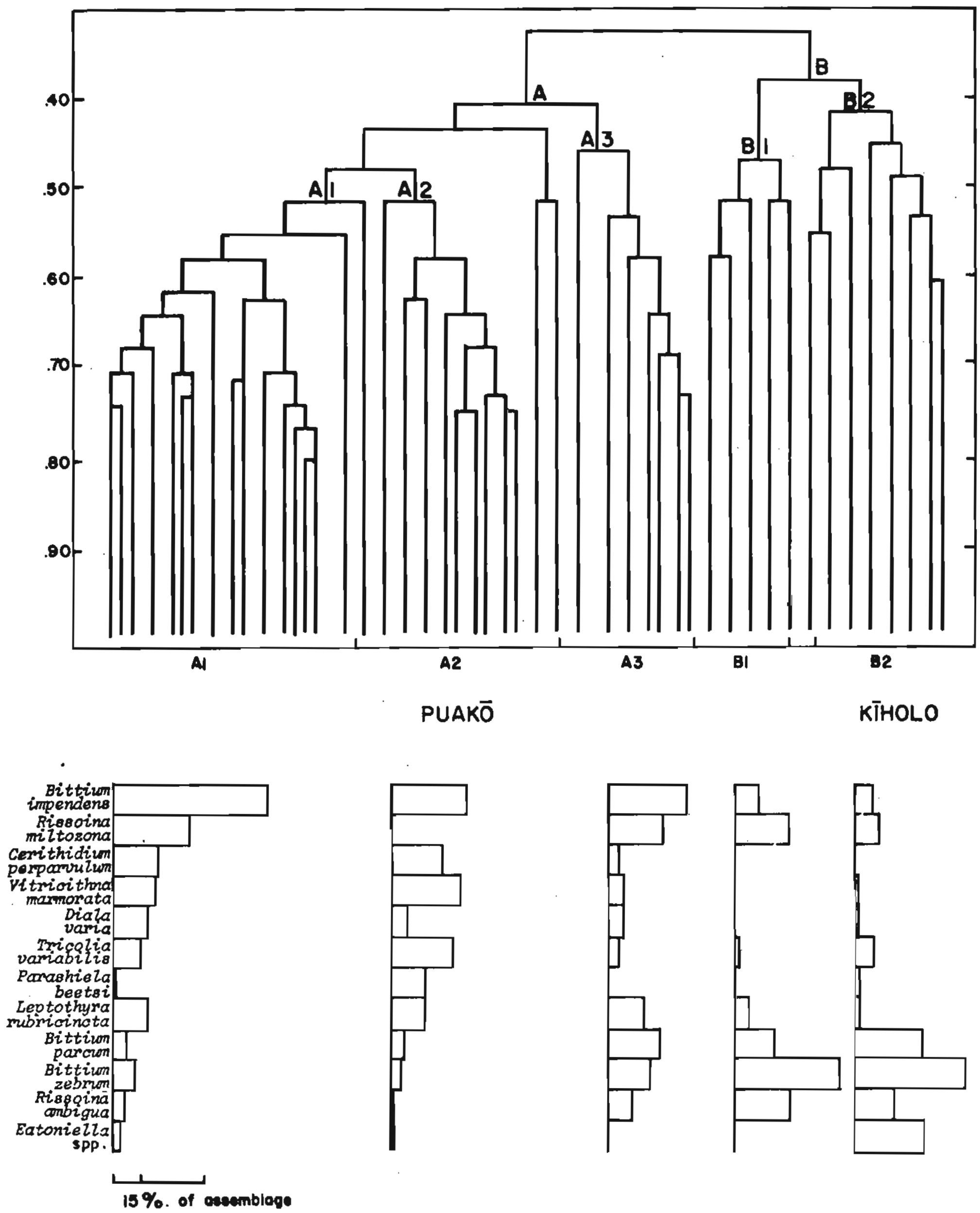


FIGURE 28. DENDROGRAPH SHOWING SIMILARITY INDICES FOR PUAKŌ, 'ANAEHO'OMALU, AND KĪHOLO BAYS

omalu by the occurrence of *Eatoniella* sp. which is associated with fresh water. The effect of the freshwater intrusions on the benthic marine community at distances of some 30 m from shore is also indicated at Kīholo by the presence of *Eatoniella* sp. (and *Planaxis*) at three offshore stations where the freshwater-associated species are admixed with marine species (Table 5). The admixture of species associated with freshwater and typically marine species at these stations suggests that although the freshening effect persists offshore, the low salinity water is mixed with the water mass of the bay.

Differences in species composition in the subgroups of the other major group (Group A) in the similarity matrix are more difficult to explain than are those of the inshore waters because we know less of the habits of subtidal mollusks than of intertidal forms. *Bittium impendens* which is a dominant component of these assemblages is peculiarly associated with the Kona Coast of Hawaii Island and with the leeward Hawaiian Islands of Midway, Laysan, and the like. It is found on Kauai, Oahu, Maui, but it forms a dominant component of micromolluscan assemblages only on Hawaii and in the leeward islands. The other dominant species include four ubiquitous subtidal species found elsewhere in the islands at depths of 10 to 100 m; *Cerithidium perparvulum, Diala varia, Vitricithna marmorata,* and *Parashiela beetsi*; and three species found from the intertidal to depths of about 50 m: *Leptothyra rubricincta, Tricolia variabilis,* and *Rissoina miltozona.* The Kīholo offshore stations (subgroup A2) are distinguished by higher proportions of *Tricolia, Vitricithna,* and *Parashiela* than occur at Puakō or 'Anaeho'omalu. *Tricolia* feeds and breeds on frondose algae, such as *Padina* (Wertzberger 1967); *Vitricithna* and *Parashiela* appear to be associated with substrates which have more rubble than coral cover (although no statistically significant correlation was found). It is tempting to suggest that their dominance at Kīholo is associated with the lesser coral cover characteristics of this bay than occurs in the others (see Coral Communities). The Puakō inshore stations (subgroup A2), with their admixture of deep and shallow species are consonant with the protected calm waters of the bay and the extensive inshore coral cover.

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WAINĀNĀLI'I POND[1]

Waināāli'i Pond in Kīholo Bay represents a unique shoreline ecosystem among the four bays studied, and perhaps in the Hawaiian Islands, and is here described in detail.

Wainānāli'i Pond (Fig. 29) is an elongate lagoon formed by a cobble-and-sand bar lying along the 1859 pāhoehoe lava flow which constitutes the eastern boundary of Kīholo Bay. The bar connects with the lava at its seaward (northern) end, enclosing the head of the pond. At its landward end, the bar is crossed by two shallow passes which connect the pond with the inner part of Kīholo Bay.

The pond is roughly 457 m (1,500 ft) long by 30 m (100 ft) to 91 m (300 ft) wide, with an area of nearly 2 ha (5 acres). Detailed soundings were not made, but observations indicate steep sides and a relatively flat bottom at depth of 3 m (10 ft) to 4 m (12 ft). There is a partial barrier, about halfway along the pond, formed by a submerged extension of the lava flow. The gap between the end of this shoal and the cobble bar is about 3 m deep, so that while this feature restricts circulation, it does not form a sill behind which the deep water might tend to stagnate.

The main (northern) pass has a "channel" about 6 m (20 ft) wide with a sill depth of about 1 m (3 ft) at mean low water. The sides of the pass shoal very gradually, so that the total width varies with the stage of the tide between approximately 30 m (100 ft) and 61 m (200 ft). The small secondary pass, in which no measurements were made, has a maximum width of about 15 m (50 ft) at high water.

Freshwater springs enter the pond at several points along the edge of the lava flow. The most notable spring was observed at the head (northern end) of the pond.

The measured range of tide in the pond was 0.8 m (2.5 ft) at an extreme spring-tide maximum. More interestingly, a persistent 10- to 13-cm (4- to 5-in.) seiche, with a period of 6 to 8 min, was observed throughout the study period. The seiche was virtually undetectable on the open shoreline, but was easily visible within the quiet pond, and was strikingly evident in the passes over the bar, where the fairly strong current alternated in direction every few minutes. The mechanics of this seiche have not been investigated,

[1]Edward D. Stroup, David P. Fellows, and E. Alison Kay.

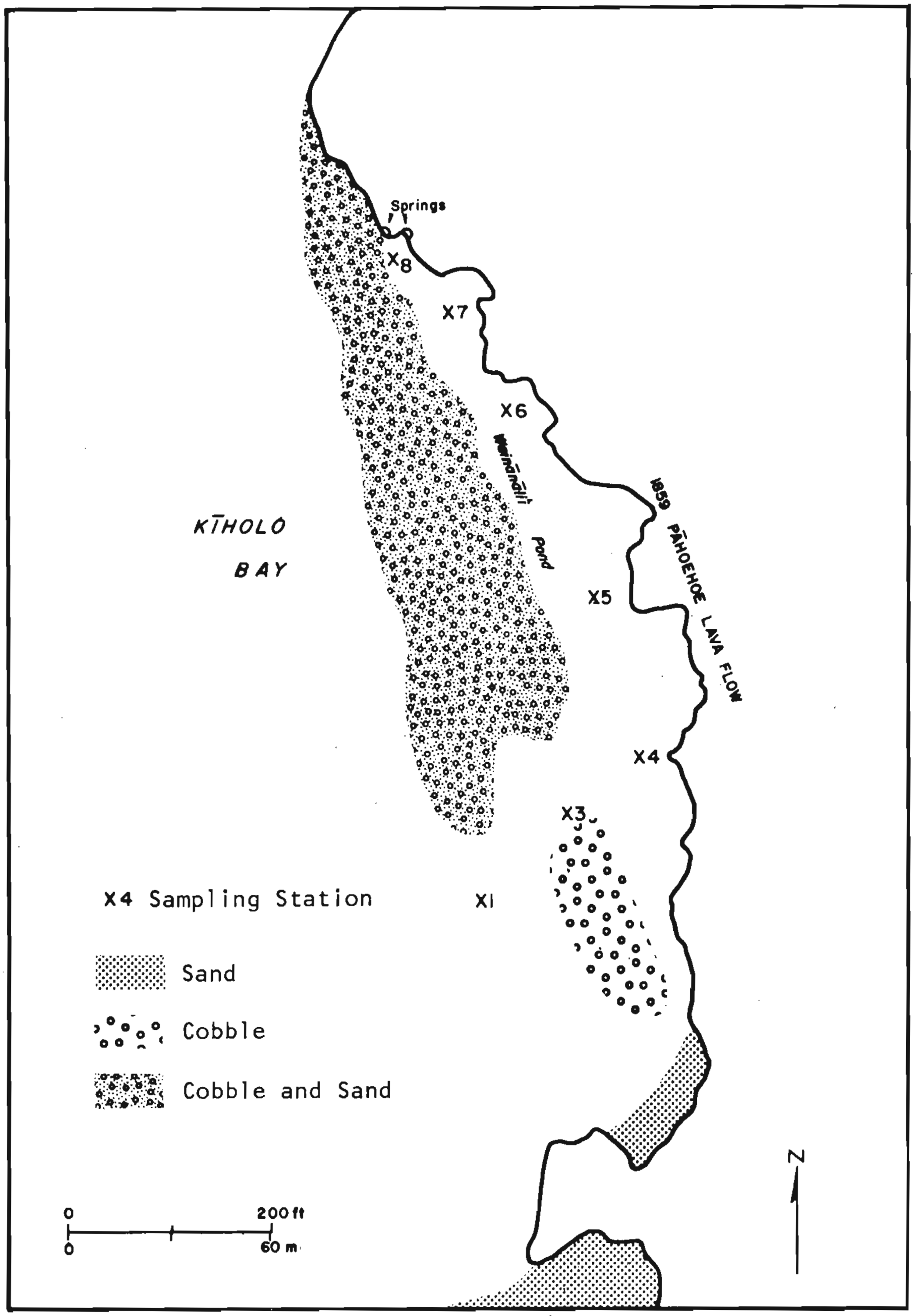

FIGURE 29. MAP OF WAINĀNĀLI'I POND ADJOINING KĪHOLO BAY

but the period would suggest a reflection of wave energy between the east and west sides of Kīholo Bay, that is, greater Kīholo Bay with a breadth of some 2.5 km. Other types of edge-wave effects may also be possible sources of this oscillation.

Physical Measurements

Observations of temperature, electrical conductivity, and dissolved oxygen concentration were made at stations extending the length of the pond, on the entrance bar, and just outside the bar, as shown in Figure 30. At each station within the pond, measurements were made at the surface, 0.6 m (2 ft), 1.5 m (5 ft), and just above the bottom (usually about 3 m). At the station on and outside the bar, observations were made only at the surface and bottom.

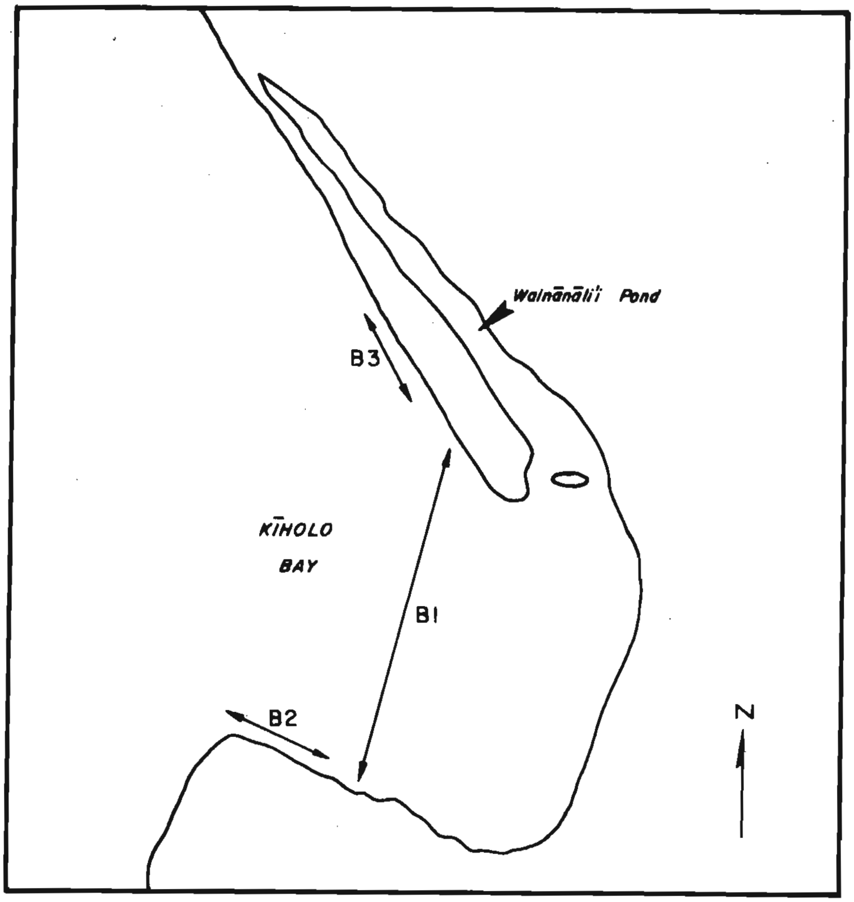

FIGURE 30. APPROXIMATE LOCATIONS OF KĪHOLO BAY TRANSECTS OUTSIDE WAINĀNĀLI'I POND, NORTH KONA

The stations were occupied near low water (0815 to 0950) on 10 August 1973, and again near low water (0930 to 1030) and near high water (1500 to 1540) on 11 August 1973. Only the data from 11 August are illustrated; there were no significant differences between the distributions at low water on this and the previous day.

TEMPERATURE. At low tide (Fig. 31-A) the cold, fresh (see below) outflow from the springs extended over the whole surface of the pond. The development of stratification was aided by calm or very light winds during the night. The cooling seen in the deeper pond near the bar may be caused by mixing generated at the bar by the seiche.

At high tide (Fig. 31-B), and after some hours of a brisk sea breeze from the WNW, the surface of the pond was 3 to 5°C warmer, with stratification very much reduced. The deeper layers have also been warmed by the sun, especially toward the inner end of the pond, where seiche-induced mixing would have least effect. The effect of the freshwater springs can be seen only in the slight cooling near the surafce at the very head of the pond.

SALINITY. Again, at low tide, the freshwater layer shows up clearly (Fig.32-A). Note that this layer mixes away rapidly as it crosses the bar into the bay. The station outside the bar show salinity lower than the usual oceanic value of near 35‰ in Hawaiian waters because there are many springs entering the ocean along this coast.

Salinity in the deeper pond is 28 to 29‰ during the low tide period. At high tide the stratification has nearly vanished, with surface salinities sharply increased and deep salinities somewhat reduced from the earlier values. Evidence of saltier water entering over the sill is indicated in Figure 32-B, since the observation at Station 3 was made during the inflowing phase of the seiche. During the outflowing phase, the bottom salinity on the bar dropped sharply.

OXYTY. The dissolved oxygen concentration (oxyty) distribution (Fig. 33) shows strong photosynthetic-respirational effects. In the early morning, at low tide, the deeper pond has depleted oxyty. The stable stratification has restricted downward mixing from the surface.

At high tide, in the late afternoon, oxyty has increased everywhere in the deeper pond, and also increased markedly in the water outside the bar. At the surface of the inner pond, the oxyty has decreased somewhat from the morning values, probably by a combination of mixing with deeper water and

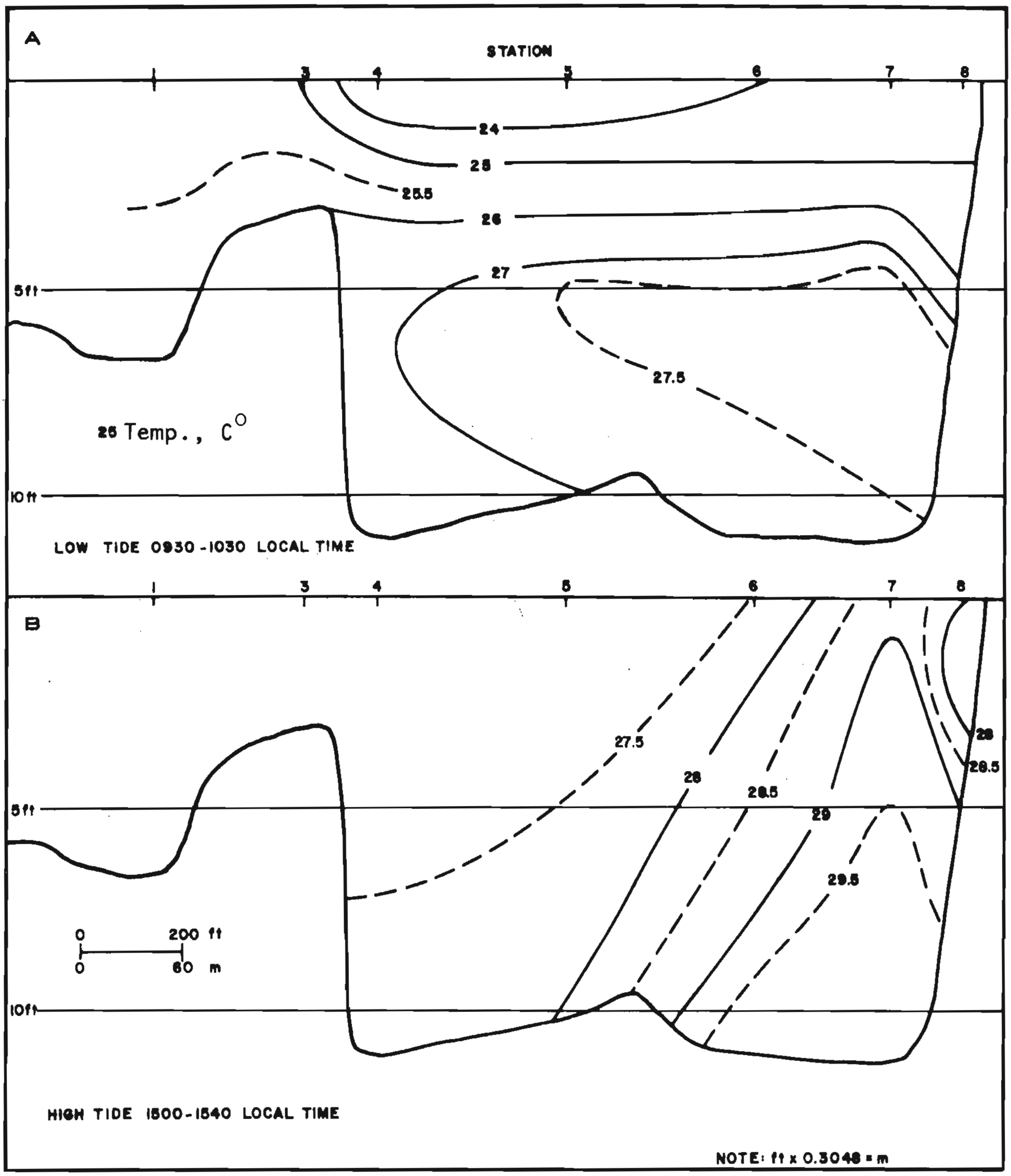

FIGURE 31. TEMPERATURE DURING LOW AND HIGH TIDES, WAINĀNALI'I POND

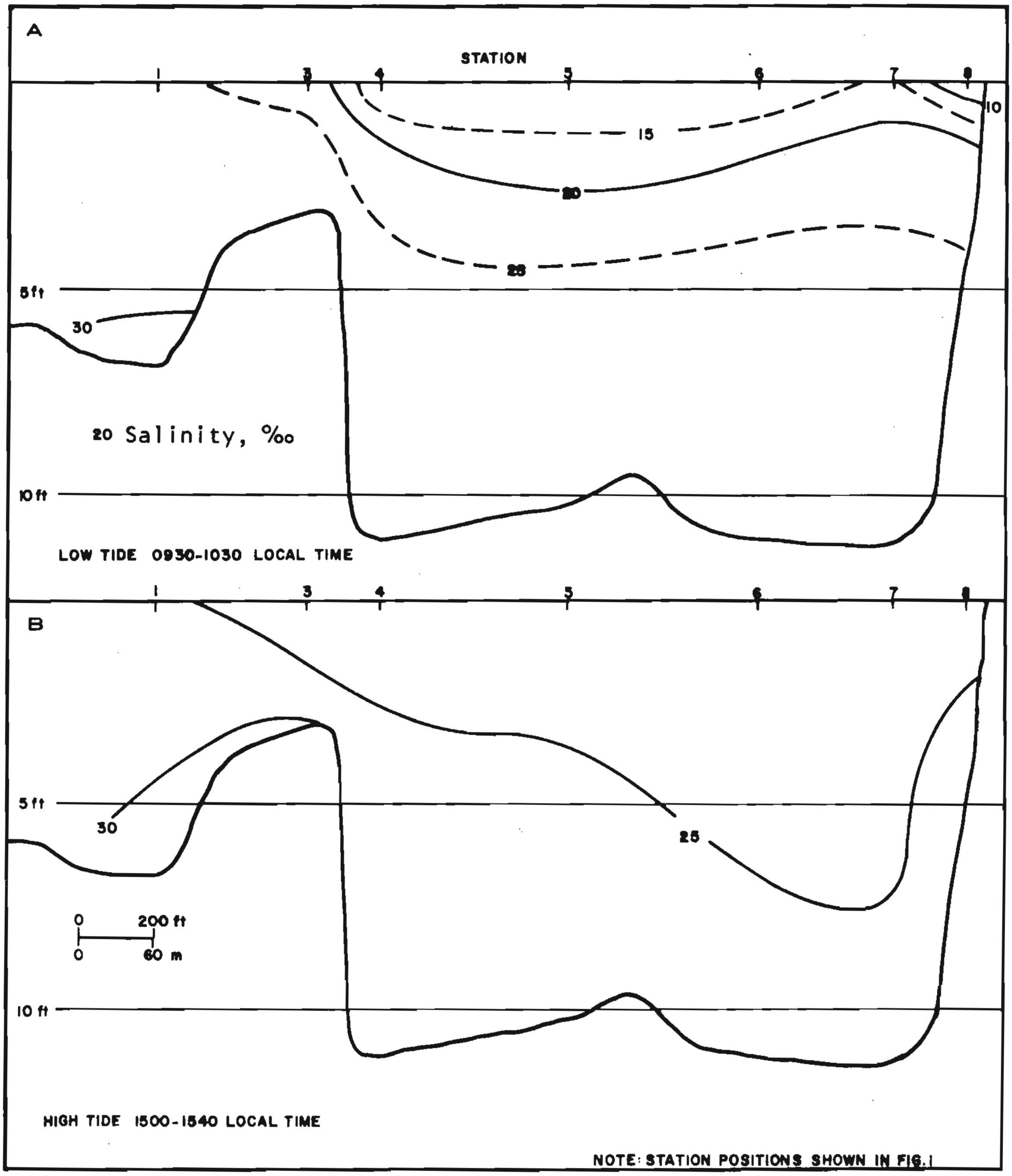

FIGURE 32. SALINITY DURING LOW AND HIGH TIDES, WAINĀNĀLI'I POND

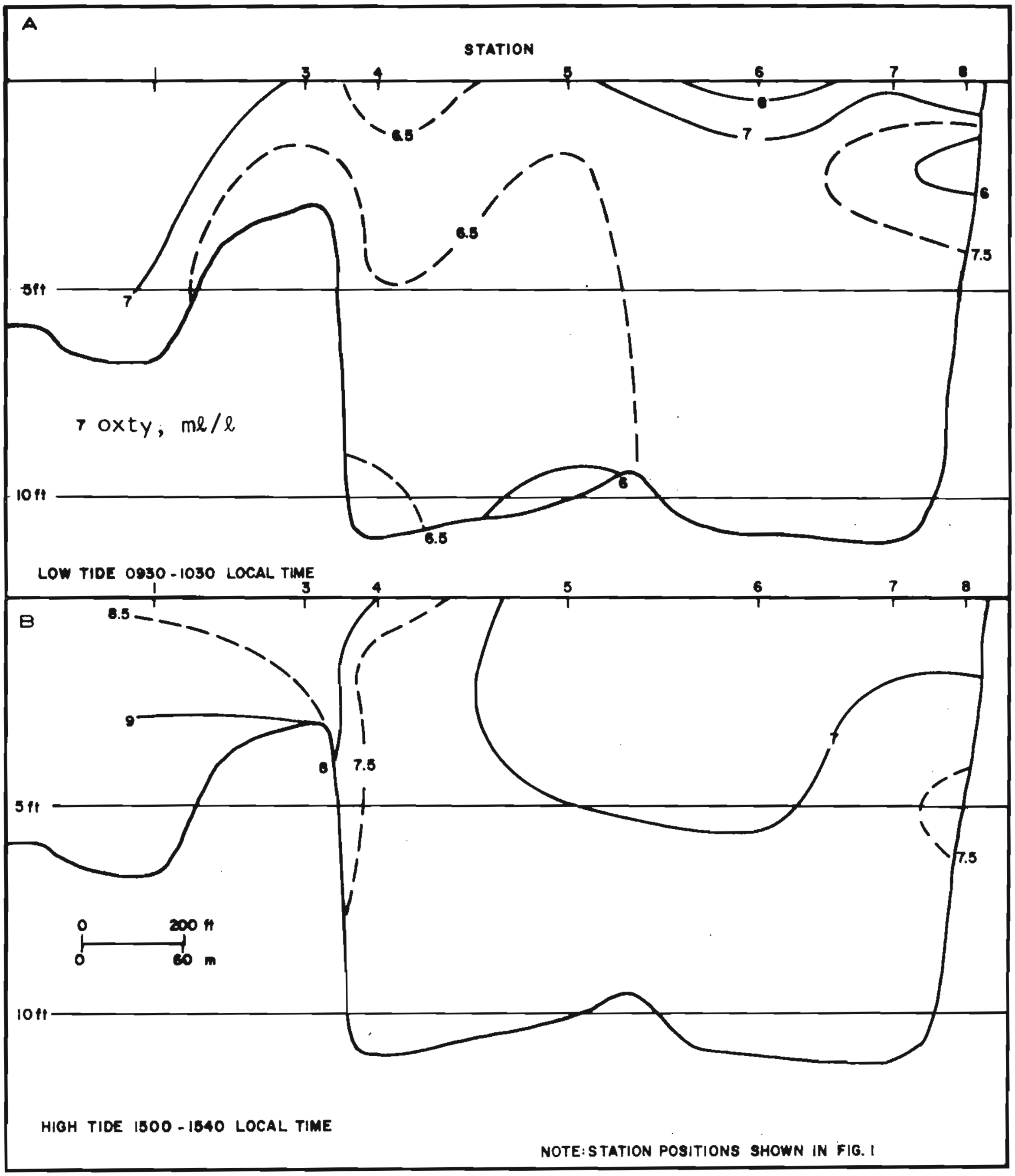

FIGURE 33. DISSOLVED OXYGEN CONCENTRATION DURING LOW AND HIGH TIDES, WAINĀNĀLI'i POND

loss to the atmosphere.

Observations on the Biota

General turbidity in the pond, coupled with extensive silt deposits over most of the substrate surface, permitted only quantitative sampling of the benthic community. Five cross-sectional transects (P1 to P5, Fig. 34) were sampled at random to determine the composition of communities associated with the substrate in the pond. Based on the results obtained from the cross-sectional pond transects, a longitudinal transect was also established. This transect ran the length of the pond approximately 1 m below the low tide mark. Starting approximately 30 m from the pond entrance, samples were taken every 5 m for the first 100 m and thereafter at 10-m intervals. In all, 40 samples were taken over a distance of 300 m. Depending upon substrate composition, four double-handfulls of sand or four rocks (20- to 35-cm diameter) were examined at each sample point and the relative abundance of each organism characteristic of the pond habitat was noted.

Figure 35 illustrates a generalized cross section of the pond as determined by transects P2 and P5. The cross section is generally representative of all areas in the pond except: (1) the entrance, which consists of a shallow, predominantly cobble sill; and (2) a restricted beach area close to the entrance where Zones I and II consist of coarse angular black sand rather than cobble.

General substrate conditions and communities characteristic of each zone are summarized in Table 20. The strong physicochemical gradients reported above appear to have little effect on the fauna except in the uppermost 1.5 m where a brackish to freshwater lens operates in conjunction with tidal flow and strongly selects euryhaline organisms. Elsewhere, throughout the pond, community composition appears relatively consistent within a given substrate despite variations in water quality parameters.

The general, within-substrate faunal consistency noted above was more critically examined in Zone II by means of the longitudinal transect. Based upon a preliminary survey of organisms within this zone, each species encountered at a given sample point was rated either common or rare relative to its general abundance throughout the zone. The results of this survey are shown in Table 21 by groups of five successive sample points. The relative local abundance of each species is indicated and the number of sampling points

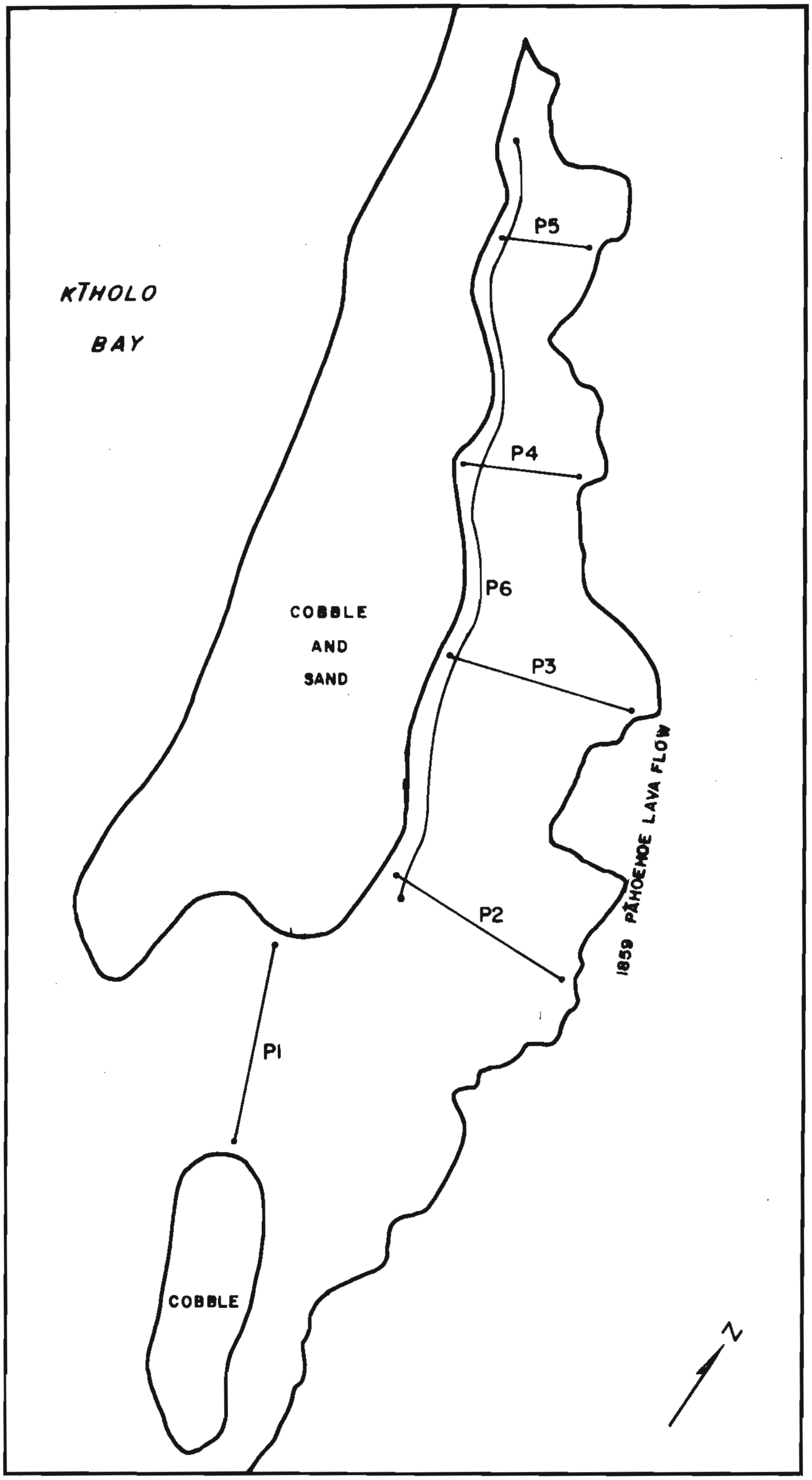

FIGURE 34. CROSS-SECTIONAL AND LONGITUDINAL TRANSECTS, KĪHOLO, NORTH KONA

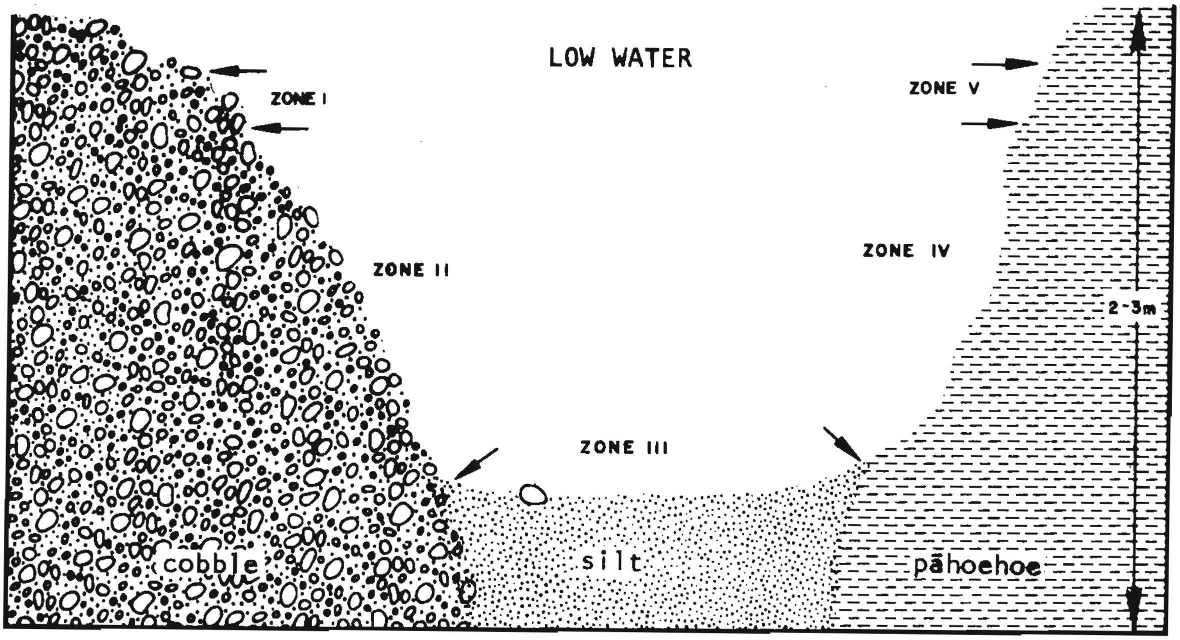

FIGURE 35. GENERALIZED CROSS SECTION OF WAINĀNĀLI'I POND, KĪHOLO, NORTH KONA

on which it occurred is shown for each segment of the transect. Also indicated in Table 21 is the relative abundance of species inhabiting the channel at the mouth of the pond as determined by transect P1.

From Table 21 is apparent that the majority of the Zone II cobble community is distributed throughout the length of the pond wherever suitable substrate occurs. This generalization does not, however, extend to the pond entrance where an ecotone community inhabits a substrate and depth commensurate with the cobble areas surveyed in Zone II. Moreover, within the pond, at least three species (*Eurythoe complanata*, *Isognomon californicum*, and *Ostrea sandvicensis*) and, possibly, a fourth species (*Hipponix* sp.) display longitudinal population gradients indicative of adverse selection in portions of the habitat. Efforts to determine factors limiting these organisms might prove them to be of value as indicator organisms.

Micromollusks

Two distinctive assemblages of micromollusks were identified in the pond, one at the entrance, the other mid-way in the pond itself. In both assemblages, brackish-water or freshwater-associated mollusks predominate. At the entrance of the pond, the dominant species are *Eatoniella* (44.5%) and

TABLE 20. SUBSTRATES AND ASSOCIATED MACROBENTHOS OF WAINĀNĀLI'I POND

Zone	Substrate	Community Composition	Other Observations
I	Bare clean cobble	Sparse pelecypod (*Isognomon perna*)-anthozoan (*Aiptasia*-like) community; infrequent small colonies of two species of demospongiae	Entirely within low salinity lens at low tide
	OR		
	Clean coarse sand	Macrobenthos absent	
II	Vegetated cobble, silt content in-	Diverse pelecypod (*I. perna*; *I. californicum*; *Brachydontes cerebristriatus*; *Ostreaea hawaiiensis*)-gastropod (*Hipponyx* sp.)-anthozoan (*Aiptasia*-like)-polychaete (*Eurythoe complanata*)-holothurian (*Holothuria monocarida*)-poriferan community	*Acanthophora* and filamentous algae cover much exposed surface
	OR		
	Coarse sand, silt content increasing with depth	Enteroptneust (*Ptychodera flava*)-annelid (*Cirratulus* sp.) community; burrows of unidentified Callianasid shrimp common, some of these occupied by gobies	Some filamentous algae present on sand surface, density increases with depth
III	Fine claylike silt	Similar to sandy section of Zone II, but *Ptychodera* less common. *Acanthophora* and *Aiptasia*-like anemone cover scattered rocks	Single specimen of gastropod-feeding crab, *Calappa hepatica* found
IV	Vegetated, lightly silted pāhoehoe lava	Anemone (*Aiptasia*-like) and *Acanthophora* cover virtually entire surface	
V	Bare, clean pāhoehoe lava	Scattered anemones (*Aiptasia*-like) only	Entirely within low saline lens at low tide

TABLE 21. LONGITUDINAL DISTRIBUTION OF ORGANISMS IN ZONE II, WAINĀNĀLI'I POND, KONA COAST

Species	Substrate								
	cobble	sand	sand	cobble	cobble	cobble	cobble	cobble	cobble
	Distance from mouth of pond (m)								
	0-5*	30-50	55-75	80-100	105-125	135-175	185-225	235-275	285-325
Porifera									
Species 1 (red encrusting)	C	---	---	C-5	C-3	C-5	C-2	C-2	C-4
Species 2 (yellow branching)	-	---	---	C-3	C-3	C-1	C-4	C-4	C-3
Coelenterata									
Aiptasia-like	-	---	C-1†	C-5	C-5	C-5	C-5	C-5	C-4
Annelida									
Cerratulus sp.	-	C-1	C-1	---	---	---	---	---	---
Eurythoe complanata	-	---	---	C-5	C-5	C-5	C-3	R-2	R-1
Mollusca									
Planaxis labiosa	C	---	---	---	---	---	---	---	---
Isognomon perna	R	---	---	C-3	C-3	C-2	C-1	C-5	C-4
Isognomon californicum	-	---	---	---	---	---	---	C-2	C-5
Brachydontes cerebristriatus	R	---	C-1†	C-4	C-2	C-2	C-3	C-3	C-2
Ostraea hawaiiensis	-	---	C-1†	C-1	C-1	C-3	C-4	C-5	C-5
Theodoxus neglectus	R	---	---	---	---	---	---	---	---
Hipponyx sp.	-	---	---	C-4	C-4	C-4	C-5	C-1	---
Cypraea caputserpentis	C	---	---	---	---	---	---	---	---
Cypraea mauritiana	R	---	---	---	---	---	---	---	---
Echinodermata									
Holothuria monocaria	C	---	---	C-2	C-5	C-5	C-5	C-3	C-5
Actinopyga mauritiana	R	---	---	---	---	---	---	---	---
Echinometra mathaei	R	---	---	---	---	---	---	---	---
Asterina anomala	-	---	---	---	R-1	R-1	R-2	---	---
Enteroptneusta									
Ptychodera flava	-	C-5	C-5	---	---	C-1‡	C-1‡	---	---

NOTE: See text for details.
*Based on transect across mouth of pond.
†On isolated rock at one station.
‡In isolated sand pocket at one station.
C = common.
R = rare.
Numbers indicate number of sample stations in interval in which species occurred.

Planaxis and *Theodoxus* (10%) which are associated with brackish water, and marine-associated cerithids (*Bittium parcum*, *B. zebrum*), rissoids (*Rissoina ambigua*, *R. miltozona*), and pyramidellids. On the shoaling sill mid-way into the pond, *THeodoxus* and *Melania* which are associated with fresh water comprised 27% of the assemblages, and the remaining micromollusks consist of dead shells of marine species such as rissoids, *Tricolia*, cerithids, and the like. An interesting component of the micromolluscan assemblages in the middle of the pond is the endemic Hawaiian capulid, *Capulus tricarinatus*, which probably lives on the oyster *Ostrea sandvicensis*.

SUMMARY[1]

A study of the topography, hydrology, and marine biota of four open ocean bays along the Kona coast of Hawaii, Puakō, Waiulua, 'Aneho'omalu, and Kīholo, has yielded some distinctive differences that are significant to the future use of those waters and coastal areas.

From hydrologic evaluations, the seaward flux of groundwater is in a range from 3.8 to 15.4 mgd/mile (8,938 to 36,221 m^3/day/km) of coastline, with a probable value of 7.3 mgd/mile (17,170 m^3/day/km) or 116 mgd (450,415 m^3/day) for the entire study area (16.3 miles or 26 km of coastline). This probable value is equivalent to about 17% of the mean annual rainfall for the area.

Associated with this groundwater flux is the terrigenous nitrogen and phosphorus loading. The total nitrogen load is 936 lb/day (flux of 57.4416/day/mile) and the total phosphorus load is 106 lb/day (flux of 6.5416/day/mile).

Wave energy varies from minimum exposure on the north at Puakō to maximum exposure at the south at Kīholo. The offshore groundwater input varies from a minimum at Puakō to maximums at Waiulua and Kīholo.

The distribution and diversity of coral and micromolluscan communities in the bays followed the trends of groundwater flux and wave energy. *Porites compressa* and *Porites lobata* account for almost 96% of coral cover and 82% of all bottom cover. *P. compressa* dominates coral cover in any area where wave stress is not rigorous enough to cause breakage and abrasion and light energy is sufficient for maximum growth rates. *P. lobata* appears to be able to successfully occupy any niche left vacant by *P. compressa*.

In the intertidal zones of the bays, both marine-associated and freshwater-associated assemblages of micromollusks were found, with fewer of the latter at Puakō and 'Anaeho'omalu bays. In the subtidal zones, standing crop and species diversity index are generally lower at the shoreline and inshore stations than in the offshore stations. At Kīholo, freshwater-associated species were found in admixture with typically marine species at offshore stations.

Water uses and development independent of water clarity and a "typically tropical" marine biota would be favored in a situation as at Kīholo or

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[1]Reginald H.F. Young, Project Principal Investigator.

Waiulua bays. However, a use such as a marine park would require excellent water clarity and diverse coral reef communities, i.e., a low wave energy, groundwater influx situation as at Puakō and 'Anaeho'omalu. These are broad generalizations based on a study of the hydrology and communities of these water areas but they together with the results of the study can serve as appropriate guidelines for planning and management of the West Hawaii coastal area. The methodology employed in this study can serve as a basis for field evaluation of other coastal areas in the state that may be under consideration for development or changes in land-use designation.

ACKNOWLEDGMENTS

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