HAWAIIAN SHORELINE AND NEARSHORE ECOSYSTEMS

Written and edited by

AECOS, Inc.

WORKING PAPER NO. 50

May 1982

University of Hawaii
Sea Grant College Program
Honolulu, Hawaii

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PREFACE

This working paper on Hawaiian shoreline and nearshore ecosystems is intended as an introduction for readers interested in the natural marine resources and processes. Pertinent information was compiled for the preparation of the Hawaii Areawide Wastewater Treatment Management Plan (also called the "208" Plan) by the state Department of Health. One of the primary efforts in "208" planning was development of an ecological approach to water quality standards. Classification and short descriptions of Hawaiian coastal ecosystems were published in Technical Report 1 (Stahl et al., 1977) of the Technical Committee on Water Quality Standards, chaired by Dr. J.E. Maragos.

Much of the material presented in this working paper draws on the work of the Technical Committee and were published as a series of articles in the *Hawai'i Coastal Zone News*, a monthly newsletter formerly prepared by the University of Hawaii Sea Grant College Marine Advisory Program and funded by the Hawaii Coastal Zone Management Program (the newsletter was terminated in October 1981). The material published in the newsletter was extensively reorganized for this working paper and an emphasis placed on both natural processes and the interactions between physical and biological phenomena, including human interactions with the natural environment. Readers interested in more detailed descriptions of the plants and animals inhabiting Hawaiian reef and shore environments should consult E.A. Kay's (1977) introduction to the revised edition of *Reef and Shore Fauna of Hawaii*. Additionally, pertinent scientific articles can be found in *A Natural History of the Hawaiian Islands* (1972), edited by E.A. Kay.

We wish to acknowledge the support of the Hawaii Office of the Marine Affairs Coordinator (writing/editing); the Office of Coastal Zone Management and the Hawaii Department of Planning and Economic Development (funding of the *Hawai'i Coastal Zone News* project which developed material and artwork for the original articles); and Urban and Regional Planning Program of the University of Hawaii (artwork).

Messrs. Eric Guinther and Paul Bartram of AECOS, Inc. wrote the manuscript, coordinated the review and revision processes, and suggested the use of specific illustrations in this publication. Ms. Ann Fielding, formerly with the Waikiki Aquarium, participated in editing of the manuscript.

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Raymond S. Tabata
UH Sea Grant Advisory Service

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HAWAII—A STUDY IN ISLAND BIOGEOGRAPHY

The Hawaiian Islands are a chain of mid-ocean volcanos built up from the sea floor some two miles deep by inumerable eruptions. Over a period spanning many millions of years, the center of volcanic activity shifted from the northwest to southeast. Thus, the oldest volcanos are the submerged mountain peaks which form the base of the small Northwestern Hawaiian Islands (also known as the Leeward Islands), and the youngest are those on the island of Hawaii where the land building process is still occurring. Ten to 20 million years ago the Leeward Islands probably existed as high islands. Since then these ancient islands have eroded and sunk into the sea and today only coral reefs remain. However, measured against the age of the earth (over 4.5 billion years), the formation of the Hawaiian Islands chain has been relatively "recent."

The study of the formation of the Hawaiian Islands is more than an exercise in geology, for it is important for understanding the origins of shallow-water marine life in these islands. Because there has never been a land connection between Hawaii and the continents, the earliest colonizers of both nearshore and terrestrial areas had to cross the vast expanses of the Pacific Ocean to reach the islands. A comparison of the species of organisms found in Hawaii with the biota found elsewhere in and around the Pacific basin reveals that the Hawaiian biota more closely resembles that found in the southwestern Pacific and Indian Oceans than that found in the eastern Pacific. Although most marine species spend a portion of their life cycle as small larvae drifting with ocean currents before settling in suitable bottom environments, the great distance from even the nearest island groups has served as a barrier excluding many species and limiting the number of arrivals to Hawaii.

Isolation of the Hawaiian Islands from other land masses is the reason for two significant characteristics: (1) a high degree of endemism--that is, the development of species found nowhere else in the world; and (2) ecological fragility resulting from the long evolution of species in a setting not subjected to constant "testing" by new species arriving from outside the islands. The first characteristic confers value on the Hawaiian biota for its uniqueness. The biota has value to man as an object of study and appreciation. The second characteristic explains in part why the introduction of new species to the islands has destroyed much of the unique Hawaiian land biota and caused serious problems in aquatic environments.

SHORELINE ECOSYSTEMS

Physical Setting

A visit to the Puna and Ka'u districts on the island of Hawaii can provide first-hand experience in observing marine environments along a newly formed volcanic coastline. Demonstrated here are a few years to a few centuries of physical change and biological development following the flow of lava into the sea.

Once a flow enters the sea, the processes of erosion and deposition act to reshape the new shoreline. Erosion includes the work of wind and water in breaking down the volcanic material into smaller and smaller particles and removing them from the shoreline. Ultimately, most of this eroded material is moved into deeper water offshore. Deposition involves the accumulation in one place of particles eroded elsewhere. Soon after a flow enters the sea, pounding waves erode the lava and cinder and currents move the eroded material away. Some of the broken volcanic fragments which are deposited in coves or other sheltered locations form unique black sand beaches.

The processes of erosion and deposition are the basis for the classification of shorelines into two general types: (1) solid rock or massive boulders; and (2) beaches of loose boulders, sand, or mud. Solid rock shorelines are basically regions of erosion, whereas beaches are regions of deposition. In Hawaii, rocky shorelines are composed of either volcanic rock or limestone. Beaches vary greatly in the material deposited, from muds and silty-sands in harbors and large bays to boulders in coves along unsheltered coasts.

Recently formed volcanic shorelines on the island of Hawaii are less varied than the much older coastlines of Kauai or Oahu. The greater variety of shoreline features on the older islands arises from additional geological processes which have occurred over long periods of time (such as reef development, so-called "secondary" volcanic eruptions near the coast, additions of land sediments brought to the coast by streams, and changes in sea level). Thus, the stark, low cliffs along the coast where a recent lava flow occurred are replaced by rock outcrops, high cliffs, sand beaches, and shoreline benches after a million years or so of gradual change.

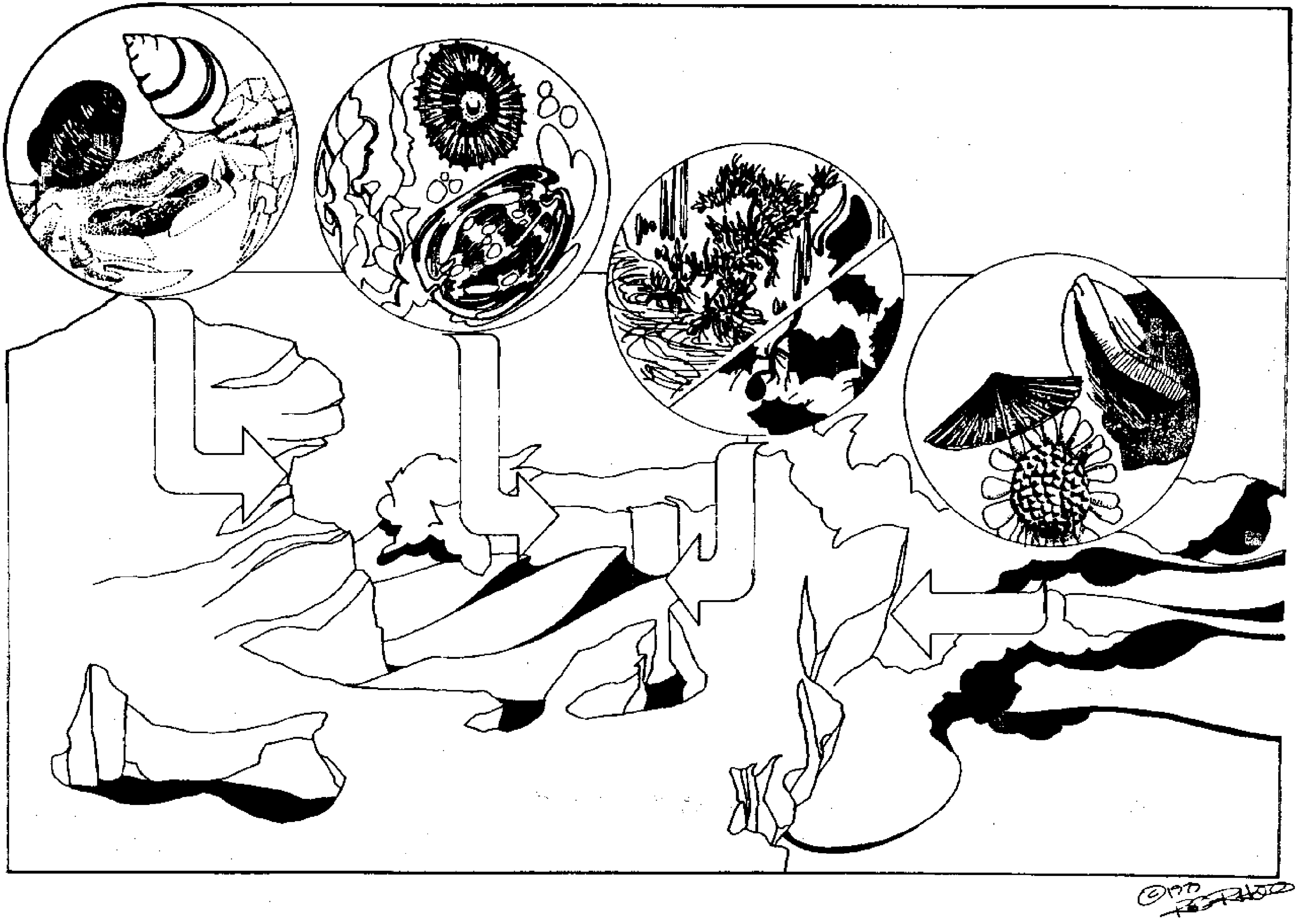
Biological Setting

The plants and animals that live at the shoreline inhabit one of the ocean's most changeable environments. Shore dwellers contend with lack of water at low tide and, on the open coast, with the tremendous force of pounding waves. Out of necessity, they have adapted themselves to withstand both surf and sun.

Vertical zonation on rocky shorelines

Perhaps the most striking aspect of shoreline ecology is the vertical zonation (distribution in bands) of the organisms found there. As the water ebbs with the outgoing tide, the different bands of life forms, arranged one above the other, are gradually exposed. Zonation occurs in many ecosystems, but nowhere is it more apparent than on a rocky shoreline. The distribution pattern is related to frequency of wetting; higher parts of the shoreline have shorter periods of submersion and dampening by waves. Individuals of particular species will colonize as far up the shore as they can tolerate the potentially damaging exposure to air and heat during low tide. This upper limit is different for each species.

ROCKY SHORELINE



Shore-dwelling species also have seaward limits, usually determined by the presence of predatory animals (which are more active lower down at the ocean edge) or by competition with other organisms.

That portion of the rocky shoreline above the reach of normal waves and tides, but regularly dampened by wave spray, is called the littoral fringe, or splash zone. It is populated by dull gray periwinkles, or pupu kolea (*Littorina pintado, Nodilittorina picta*), which can withstand long periods of exposure to air, hot sun, and drying winds. Black rock crabs, or aama (*Grapsus tenuicrustatus*), scurry about just above the reach of the waves. Seaward of the pupu kolea, but remaining exposed much of the time, are found black snails, or pipipi (*Nerita picea*). Few other animals inhabit this part of the shoreline, and the littoral fringe appears nearly devoid of life. Despite the barren appearance, a thin coating of organic particles, bacteria, minute animals, and algae covers the surface of wet rocks. The algal film serves as food for the pipipi and pupu kolea which feed by scraping the film from the rock surface with small, rasping teeth.

The littoral zone, located below the littoral fringe, is a region alternately covered and exposed by waves and the tide. The upper littoral zone, the highest area always kept wet by waves, is populated by species which can withstand intermittent exposure to the air. Nonetheless, injury and death can result from unusual circumstances of a very low tide on a sunny day with a calm sea. The damage to littoral zone organisms resulting from prolonged exposure demonstrates their need for regular wetting. On basalt surfaces in the upper littoral zone, crisp, yellowish alga, limu akiaki (*Ahnfeltia concinna*), is present; it appears never to occur on limestone or tuff surfaces, however. Opihi (*Cellana exarata*), a limpet, sometimes occurs in this zone. More often found, however, is the smaller, false opihi (*Siphonaria normalis*).

On wave-battered coasts, rocks in the mid-littoral zone are covered with a thin coating of a pinkish calcareous alga (*Porolithon onkodes*). Organisms living here include the yellow-foot opihi (*Cellana sandwicensis*), several species of heavy-shelled snails, and a variety of fleshy algae. In addition to attached or slow-moving forms, fishes live in pools in the littoral zone.

Zonation along the shoreline

The pattern of life just described differs from place to place along the shoreline depending on the steepness of the littoral surface, the type of rock, and wave exposure. Where rock surfaces descend steeply into the sea, fleshy seaweeds usually are not found. The pupu kolea and pipipi merge directly into the zone of encrusting *Porolithon*. The type of rock, especially its surface texture and suitability for housing boring organisms, adds to the variety of habitats found along rocky shorelines. Lava rock is not easily penetrable by borers. Limestone and volcanic ash hardened into tuff are softer than lava rock; hence, a greater variety of organisms are usually associated with shorelines composed of these softer types of substrates.

Because of the small tidal range in Hawaii--less than 1 m (3 ft)--and the much greater range of wave wash--from about 0.3 m (1 ft) in sheltered bays to more than 3 m (10 ft) on the open coast--the degree of wave exposure is primarily responsible for determining zonation patterns at the shoreline. Striking differences are seen from place to place depending on the size of waves normally breaking on the shore. In wave-sheltered bays and coves, especially where there is freshwater seepage, the native Hawaiian oyster (*Ostrea sandwicensis*) encrusts vertical surfaces above the low tide mark, and another oyster (*Isognomon californicum*) and green sea lettuce (*Ulva fasciata* and *U. lactuca*) may form dense mats on horizontal surfaces. Barnacles (*Balanus* spp.) are frequently conspicuous in the upper littoral zone, although they are more often seen on piers and pilings than on rocks.

Shorelines of Erosion

Wave-cut notches and ramps, sea cliffs, and massive boulders are prominent features where lava flows have recently entered the sea or where waves have exposed volcanic rock at the shoreline. Erosion on these shorelines depends upon the type of rock under wave attack. Where hard basalt is present, erosion is primarily by abrasion; waves roll smaller rocks and sand across the surface, gradually wearing it down producing a sloping or ramp-like shoreline. Special erosion forms created in tuff (consolidated volcanic ash) and limestone are described below.

Water-leveled benches

Along surf-swept coasts of tuff, level platforms called water-leveled benches have resulted from the physical disintegration of rock in the zone of constant wetting by wave splash and spray. A bench may range from several square feet up to hundreds of square feet in area. In some places, a bench extends nearly unbroken along the coast for many miles; in other places, a bench is broken into shorter segments separated by cliffs, caves, or small coves. A bench may occur between 0.6 and 6 m (2 and 20 ft) above sea level, being high on shores exposed to large waves.

The water on a bench comes from wave splash and spray, although rainfall and groundwater also contribute in some cases. Benches are awash during rough weather or high tide. However, at low tide or during calm seas, they are mostly dry with only the seaward edge kept continuously wet by waves. Depressions without drains collect wave splash or spray to form pools.

Seawater flooding a bench lessens the intensity or extremes of temperature and salinity, removes sand and other debris, and provides connections between isolated pools. In short, flooding by waves provides sporadic contact with the sea. Nonetheless, the bench surface is essentially a littoral fringe environment inhabited by only a few hardy organisms.

Along the seaward front of most water-leveled benches is a rugged, deeply etched rim known as a rampart. The height of the rampart above the level of the bench may vary from a scarcely noticeable ridge 2.5 to 5 cm (1 to 2 in) high to a massive formation 0.6 to 1 m (2 to 3 ft) high.

Seaward of the rampart is a steep frontal slope against which waves beat ceaselessly. In this constantly wetted zone, shore life blends gradually into ocean life. The surface of the frontal slope is often riddled with cup-shaped holes scraped out by generations of the sea urchin, ina (*Echinometra mathaei*). This honeycomb of small holes and borings supports a dense growth of algae, with the introduced species, *Acanthophora spicifera*, being dominant in many places.

Solution benches

Solution benches, features of limestone coastlines, are characterized by a platform (the bench) which is more or less continuously awash with ocean water. There are three essential differences between a solution bench and a water-leveled bench: (1) they differ in the type of rock being eroded; (2) different processes are at work in forming each type; and (3) a solution bench is lower than a water-leveled bench.

The formation of a solution bench is the result of fresh water dissolving a limestone mass. The fresh water comes from rainfall and groundwater seepage. The limestone mass may represent either an old reef exposed by a drop in sea level, or calcareous beach and dune sands deposited above sea level by wind and waves and naturally cemented into solid rock. The ongoing process can be observed not on the bench itself, but in the pitted zone, an area directly landward of the bench platform.

The pitted zone has a very rugged surface of pits and small, sharp peaks and ridges. A distinct "nip" or under-cut notch is sometimes found at the back of the bench just below the pitted zone. The portion of this zone nearest the bench, called the frayed margin, may be 3 to 9 m (10 to 30 ft) wide. Here, pits may be 1 to 1.3 m (3 to 4 ft) deep and partially merged with one another so that only "spikes" remain.

Farther inland, the pits are shallower and more widely spaced. Interconnections between pits are few. Because of their isolation, pools in this region are renewed infrequently by wave splash. During long periods of calm seas, the water in these isolated pits may evaporate, leaving crystallized salt behind.

The general level of the pitted zone is several feet above the bench. As groundwater and rainwater dissolve the limestone, enlarging the pits and lowering the level of the pitted zone, the bench is gradually extended landward. The whole process of pitted zone erosion by solution stops when the bottoms of the pits in the frayed margin reach the level of the bench. At that point, seawater, which is ineffective in dissolving limestone, constantly floods the pools. Small remnants of the pit walls remaining on the bench are removed by abrasion.

It is only during periods of extreme low tides, combined with a calm sea, that the solution bench surface is exposed for any length of time. Most of the time, conditions of temperature and salinity differ little from those in the sea. The surface of the solution bench is densely matted with fleshy seaweeds, and it is this thick mat that distinguished a solution bench from most other rocky shoreline types.

The creatures which inhabit a solution bench are strictly marine. Within the seaweed mat is found a variety of shell life (for example, cones, miters, cowries). The bench limestone is perforated by burrows of numerous polychaete and sipunculid worms. The front of the bench generally rises steeply from the offshore bottom and may be conspicuously pocked with holes made by the ina (*Echinometra mathaei*). Calcareous algae, and to a much lesser extent corals, may grow here and add to the solid limestone structure.

Marine pools

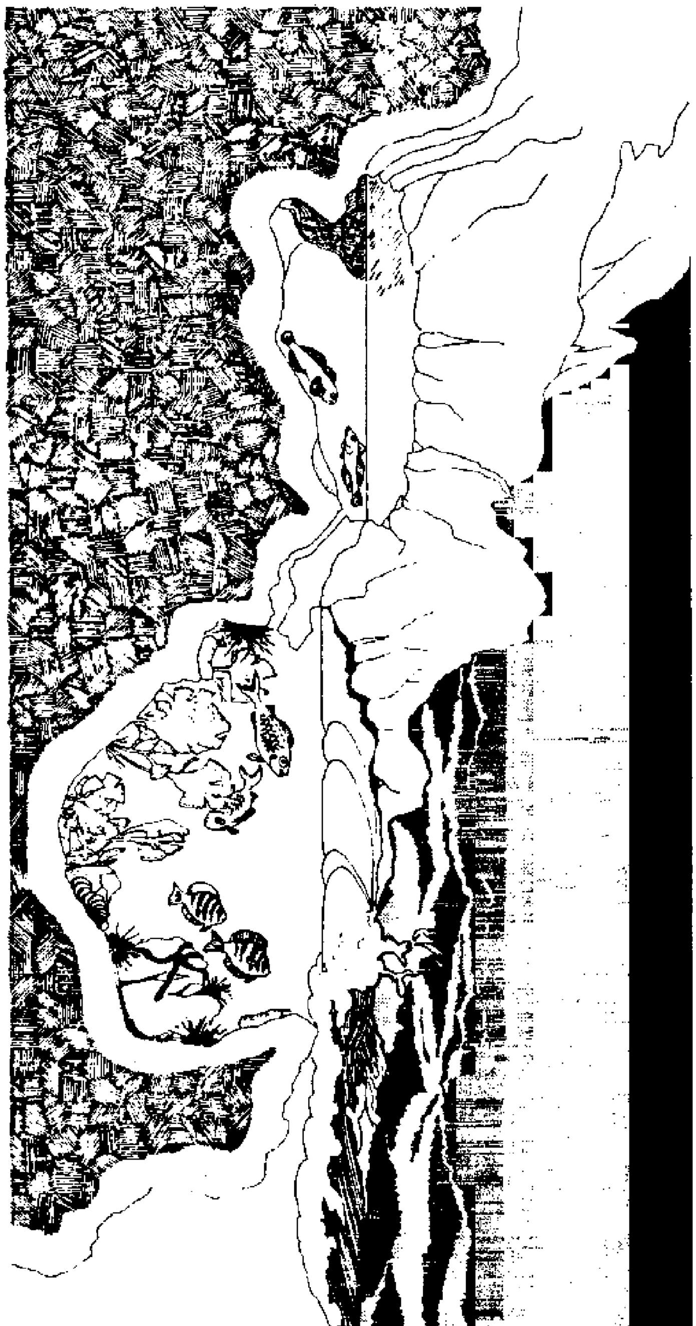
Marine pools in crevices and depressions of rock surfaces along the shoreline form from water splashed by waves or left behind as the tide recedes. They occur on both volcanic and limestone shorelines. Many of the organisms inhabiting the shoreline can survive hours of exposure, ceasing their activities until waves once again wash over them. Others are more sensitive to dehydration and high temperatures and seek shelter in, or always inhabit, pools of water along the rocky shoreline.

Because wave height and tidal range change from day to day, the alternating periods of seawater flushing and isolation vary in a complex manner for each pool. Pools located high up on the shore will be isolated more often and for longer periods of time than those located near the sea. The longer the period of isolation, the more likely physical conditions in a pool will vary. Small, shallow pools are more sensitive to the influence of sunlight, air temperature, and rainfall than larger ones. Deep pools exhibit more stable physical conditions and provide shelter from direct sunlight and high water temperatures at the surface. These pools are preferred by fishes over shallow, more isolated ones. Some of the larger pools exposed to rainfall, runoff, or seepage from the land develop an upper brackish layer floating on a layer of seawater.

In some marine pools environmental conditions fluctuate considerably and present unique problems of survival for the inhabitants. Three factors which fluctuate much more in marine pools than in adjacent ocean environments are temperature, oxygen, and salinity.

During the day, the water temperature in an isolated pool can rise substantially above that of the nearby ocean. When the water is heated, dissolved oxygen which is needed by the plants and animals for respiration is driven off. During the day, lack of oxygen is not a problem in a deep pool which has substantial growth of attached algae since through the process of photosynthesis the water becomes saturated with oxygen. With nightfall, however, photosynthesis stops and plants and animals use up (respire) the dissolved oxygen, reducing its concentration to low levels.

Heavy rains decrease the concentration of salt in seawater, whereas evaporation increases its concentration. In isolated pools these effects are greatly magnified. For example, 2.5 cm (1 in) of rain falling into an isolated pool 2.5 cm deep will dilute the salt content by 50 percent, while having almost no effect on the adjacent ocean environment. If the salt content in a pool becomes too diluted, marine organisms will die. By the same token, excessive salt will cause body fluids of the organisms to be lost, also leading to death.



TIDEPOOLS

The stability of the physical environment in a marine pool is reflected in the number of different kinds of inhabitants. In general, pools which are closest to the sea are richer in plant and animal life than pools farther from shore. In many cases, marine pools near the ocean are not clearly different from surge channels which are always connected to the sea. They may be inhabited by corals, seaweeds, and large mollusks and crustaceans also found farther offshore. However, most marine pools occupy somewhat protected depressions behind the shore face, where the main force of the waves is broken. Further, the only fishes consistently found in isolated marine pools are the zebra blenny, paoo lehei (*Istiblennius zebra*), and the rock skipper, oopu ohune (*Bathygobius fuscus*). Larger fishes usually find marine pools too difficult to get into and too small for permanent residence. Pools located close to the sea serve as nurseries for the young of fishes found offshore as adults (for example, the manini, *Acanthurus triostegus*, and the aholehole, *Kuhlia sandvicensis*).

Although many pools are strictly marine environments, a special type occurs where large quantities of fresh or brackish water seep through the rock and dilute the seawater (common on the island of Hawaii). Certain organisms are able to withstand brackish water for long periods of time.

Human interactions with rocky shoreline environments

Along rocky shorelines, a number of human activities take place, including pole fishing, opihi and pipipi collecting, and limu gathering. Solution benches are popular places for the study of littoral environments. Depressions in the upper portions of the pitted zone are good places for gathering Hawaiian salt and extensive water-leveled benches for shoreline hiking during calm seas.

Rugged volcanic shorelines are subject to less pressure from human activities than most other types of coastal ecosystems. The terrain can be difficult to walk across, limiting public access and discouraging shoreline development. The coastal area behind limestone shorelines is generally lower and flatter than that behind volcanic rock shorelines, and the calcareous material is easier to excavate. Consequently, shorelines of emerged reefs and old dunes are more likely to be developed than headlands or outcrops of volcanic rock.

Pollution can occur from both the land and sea. Chemicals carried by underground water from higher elevations may seep through rocks at the shoreline. Flotsam from sewage discharge or oil from offshore spills may be washed onto rocks, destroying shore life.

Marine pools provide opportunities for nature study, picture taking, fishing, limu collecting, and swimming. Overcollecting of marine life and disturbances related to collecting are the major human pressures on rocky shorelines. Marine pools are miniature worlds that enable teaching and research of ecological processes operating on a small scale. Their small size makes them vulnerable to disturbances, particularly from waste discharge, overcollection of marine organisms, trampling, and overturning of rocks.

Shorelines of Deposition

Sand beaches

Sand in most tropical areas is composed of the calcareous fragments of coralline algae, shells, and skeletons of marine animals. These fragments are washed ashore by waves and accumulate to form beaches. Land material may contribute varying quantities of particles, but most of the sediment on Hawaiian beaches is marine in origin. Exceptions are sediments on black sand beaches which consist of volcanic material, usually cinder and ash. Also, a few Hawaiian beaches have sediments which are greenish in color due to an abundance of olivine, or reddish-brown due to land-derived silt.

Waves move sand particles on and off beaches. The swash (run-up) and backwash (draining) of each wave shape the beach by either adding sand or removing it. Generally, short-period (frequent) waves, characteristic of winter months, erode beaches, whereas long-period waves, characteristic of summer months, build them.

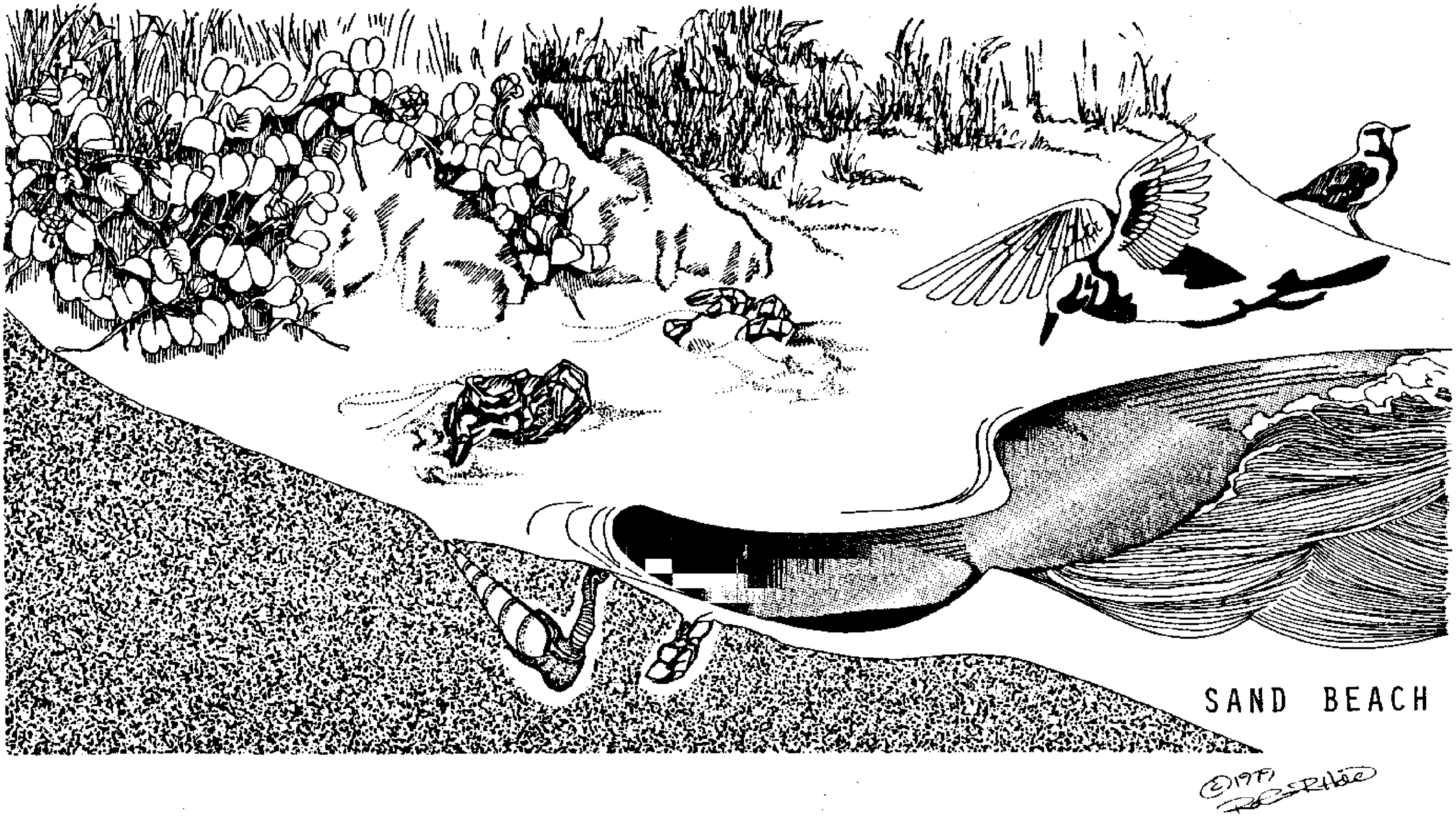
The sandy shorelines of the main Hawaiian islands are usually low, sloping beaches backed by a wave-built berm (sand ridge) or wave-cut wall of limestone or volcanic rock; long stretches of beach are the exception. Short stretches of sand between headlands or rocky outcrops, called pocket beaches, are more typical.

The size of sand grains, the composition of the material (proportion of marine fragments to land particles), and the volume of sand vary at each beach. Beaches behind broad, shallow reefs are narrow because the normally small waves do not transport and deposit much sand. Beaches in bays often contain land-derived silt mixed with the sand. Coastlines unprotected by shallow reefs generally have broad sand beaches which undergo large variations in width when eroded by large storm waves.

Life on a sand beach

Survival for inhabitants of sand beaches requires adaptation to a shifting surface. Because of the lack of firm footholds and the scouring action of moving grains, sand beaches do not support abundant seaweeds or animals attached to rocks. The zonation of life which is so distinct on a rocky shoreline is less obvious on a sandy one. Nevertheless, it is possible to subdivide a beach into three general zones: an upper beach or littoral fringe which extends from the high wave line up to the vegetation line; a mid-beach which is found between the high wave line and the low water line; and a lower beach or sub-beach which is nearly always submerged.

Waves seldom reach the upper beach and the water table lies too far below to wet the surface sand; the upper beach is occasionally wetted by storm waves, however. Sand on the highest parts of the beach may form dunes if prevailing winds blow onshore. The best known occupants of this zone are males of one species of ghost crab (*Ocypode laevis*), whose burrows and mounds of excavated sand are a conspicuous feature. Sea turtles leave the ocean to bury their eggs in the sand of the upper beach, although


SAND BEACH

this is rare in the high islands of Hawaii. The presence of salt-tolerant vegetation marks the end of the beach environment and the start of the terrestrial one.

Above the notch formed at the base of the beach by breaking waves, but below the littoral fringe, is a sloping mid-beach which is uncovered at low tide each day. Its width varies with beach slope, the rise and fall of the tide, and wave conditions. The deeper sand layers retain considerable moisture and are well oxygenated. The surface layers drain quickly and may dry out to a depth of several inches between the falling and rising of tides. On shorelines behind sheltering reefs, the mid-beach tends to be stable. On shorelines under strong wave attack, the wave break point may reach well up into the mid-beach and replace the firmly compacted sand with coarse, shifting sand.

The upper part of the mid-beach is occupied by female *Ocypode laevis* and a larger ghost crab, the ohiki (*Ocypode ceratophthalmus*), which can be seen running nimbly over the sand avoiding the edge of the water. At night these crabs forage for food cast onto the beach by waves. During the day they remain in plugged burrows--most likely due to the presence of people rather than to the sun's heat. Although still tied to the sea in which their eggs are hatched and their larvae undergo development, ghost crabs live much like land animals.

At the waterline lives the mole crab, elekuma (*Hippa pacifica*), which follows the tide back and forth, staying where the breakers constantly wash up food. As the waterline moves up the beach with the incoming tide, the elekuma emerge from the sand and are carried up the beach by the wave swash. They rebury themselves before the water recedes. As the tide ebbs, they display the opposite behavior using the backwash to travel down the beach. Elekuma prefer the clean sand at the edge of the water and are not common along beaches where the waters are always calm.

Seaward of the wave-cut notch, the sand deposit is permanently water-logged and only briefly exposed during extreme low tides. This lower beach is usually part of an offshore sand deposit and may be contiguous with either a back-reef sand flat or a deeper, soft-bottom environment. Living in the lower beach are species of tube-dwelling polychaete worms, the acorn worm (*Ptychodera flava*), and auger shells (*Terebra* spp.) which prey on the worms. The sand diver (*Crystallodytes cookei*), a small fish which burrows into the sand, inhabits the base of the beach along with the snake eel (*Caecula platyrhyncha*) which has similar habits.

Boulder beaches

A deposit of loose boulders is often found at or below the waterline along rocky shorelines. Boulder beaches occur in coves along coastlines lacking offshore reefs and characterized by eroding basalt headlands. The boulders are smooth and round as a result of being rolled about by strong waves.

Shorelines of small to large boulders of volcanic origin are not nearly as rich in marine life as solid rock areas. Large waves can move the boulders, crushing most organisms living on or under them.

Human interactions with beach environments

Beaches are exceptionally valuable for many kinds of recreation. They provide the easiest access to the water for swimming and diving, as well as for launching and landing small boats. Beaches serve as natural buffer zones protecting property from wave attack and as a possible source of construction material.

Unless located where there is natural sand loss, sand mining from a beach may interfere with its stability and result in shoreline retreat. Attempts at stabilizing a naturally unstable beach by construction of protective structures (for example, seawalls and jetties) often result in loss of sand from nearby beaches or even from the beach intended for protection. Such unpredictable consequences demonstrate that the interactions between sources of sand, its transport by water motion, and its accumulation along the shoreline are indeed complex.

NEARSHORE ECOSYSTEMS

Physical Setting

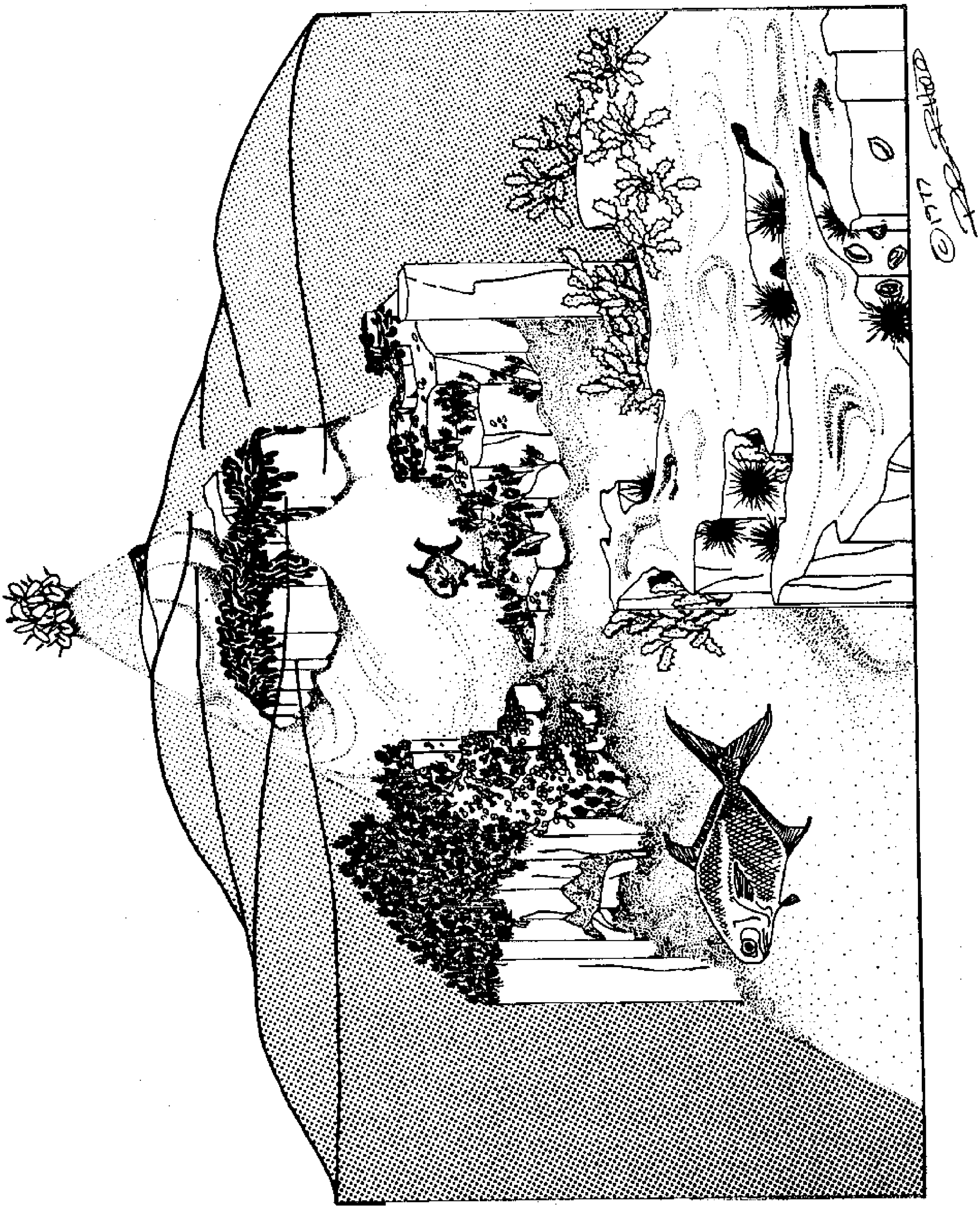
Sublittoral means "below the shore" or, in essence, "always submerged." Sublittoral environments are not subject to the constantly changing conditions typical of littoral areas. The primary physical influence in this environment is water motion.

Most water motion is caused by winds or tides. In general, the tide and local winds produce water flow (or a current) which is weak but definite in direction. Winds blowing over great expanses of open ocean and the strong winds associated with storms give rise to the wave swells which approach Hawaii from many directions. Wave swell produces surge, a type of water motion. Surge currents can be strong if the waves are large, but the motion is oscillatory (travels back and forth) and not continuous. Waves breaking against the shoreline or over a shallow bottom produce turbulent water motion.

At any given place, one type of water motion usually predominates. In protected environments, such as bays and lagoons, wave surge is slight whereas tidal and wind-driven currents are most influential on physical and biological processes. Along the open coast, wave surge predominates over the weaker wind-driven and tidal currents.

In shallow water, the surge and turbulence associated with large waves can damage corals and other organisms living on the bottom. The most violent waves along Hawaiian coasts are those originating with winter storms in the North Pacific. The distribution of corals and other marine life around the islands is largely controlled by these infrequent disturbances. Usually the richest coral growth in water shallower than 9 to 12 m (30 to 40 ft) is found off the leeward rather than the windward side of the islands.

NEARSHORE REEF FLAT



Biological Setting—Coral Communities

Stony corals are frequently the most conspicuous inhabitants of hard-bottom marine environments in the tropics and subtropics. Forty different kinds of reef-building corals are found in Hawaii. Although all forms of life modify their surroundings, few do so as spectacularly as stony corals. Growth of coral is a major determinant of community structure--the property of a biological assemblage which includes the arrangement and variety of organisms present. The irregular surface of a coral-rich bottom results in uneven exposure to light, surge, and sediment accumulation, and provides countless nooks and crannies where a wide variety of organisms can find shelter, feed, and reproduce.

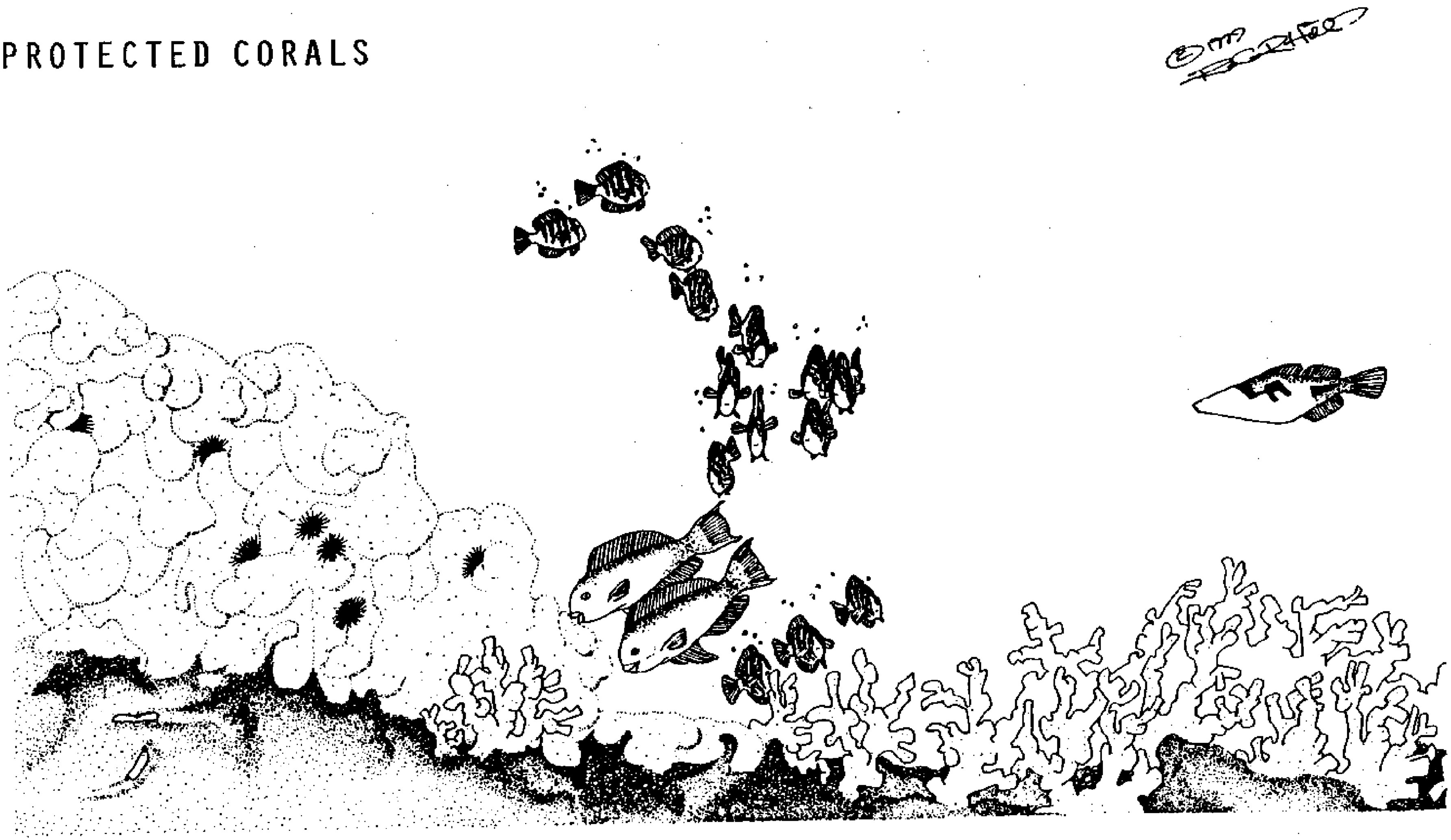
The growth of hermatypic (reef-building) corals in tropical waters is largely due to the symbiotic relationship between coral animals and single-celled algae called zooxanthellae; both organisms mutually benefit from the close association. Living within coral tissues, zooxanthellae impart the subtle brown, yellow, and green colors to coral heads. The corals provide the zooxanthellae a sheltered environment rich in carbon dioxide and excretion which are essential to plants for photosynthesis and growth. Like the cells of other algae, zooxanthellae "leak" soluble sugars which the coral tissues utilize as an energy supplement. The relationship permits internal recycling of nutrients, increasing the efficiency of both organisms in utilizing the nutrients contained in seawater. This is an advantage in tropical waters which generally contain low levels of nutrients. Of even greater importance to the coral, however, is the utilization of dissolved carbon dioxide by the zooxanthellae; this aids the coral in depositing its limestone skeleton. Growth of the skeleton is faster in corals with zooxanthellae than in corals without and growth is more rapid in the light than in the dark. Like all "green" plants, zooxanthellae need sunlight for growth. Therefore, hermatypic corals grow best where there is ample sunlight. Although these corals may occur to depths of 45 m (150 ft), they seldom flourish below a depth of about 9 m (30 ft) in Hawaii.

Quiet water coral communities

Along open coasts, the most vigorous coral growth occurs in quiet waters below the influence of strong wave surge. Well-developed coral communities in shallow waters are generally confined to lagoons behind reefs or inside sheltered bays and coves. In these communities, live coral may cover 90 percent or more of the hard bottom. Sand channels and patches occur in depressions or valleys between coral-rich mounds. On sloping bottoms sediment is swept off the corals by water movement and deposited in adjacent deeper areas; this aids coral growth. On nearly level bottoms, however, sediment accumulation may exclude corals altogether.

Fragile branching and delicate tabular (plate-like) corals predominate in relatively tranquil environments. Corals depend on water passing over their surface to bring food and dissolved oxygen as well as remove wastes. Like their close relatives the sea anemones, coral polyps have tentacles armed with nematocysts (stinging structures) which are used to snare tiny food particles in the water. Branching increases the food-catching surface. On the other hand, encrusting and plate-like growth

PROTECTED CORALS



gives maximum exposure of the coral tissue to light, thereby promoting growth of the zooxanthellae.

The fingercoral, *Porites compressa*, is the dominant coral species in most sheltered water areas in Hawaii. It forms continuous thickets over wide areas. Few other species of corals are present because *P. compressa* grows over the other forms, depriving them of necessary light and water circulation. In parts of Kaneohe Bay, almost pure stands of *P. compressa* cover some fringing and patch reef slopes.

The lobate coral, *Porites lobata*, can be prominent in the quiet water community where it forms large mounds and pinnacles scattered among the fingercoral. In less protected situations, this coral occurs in greater abundance than fingercoral.

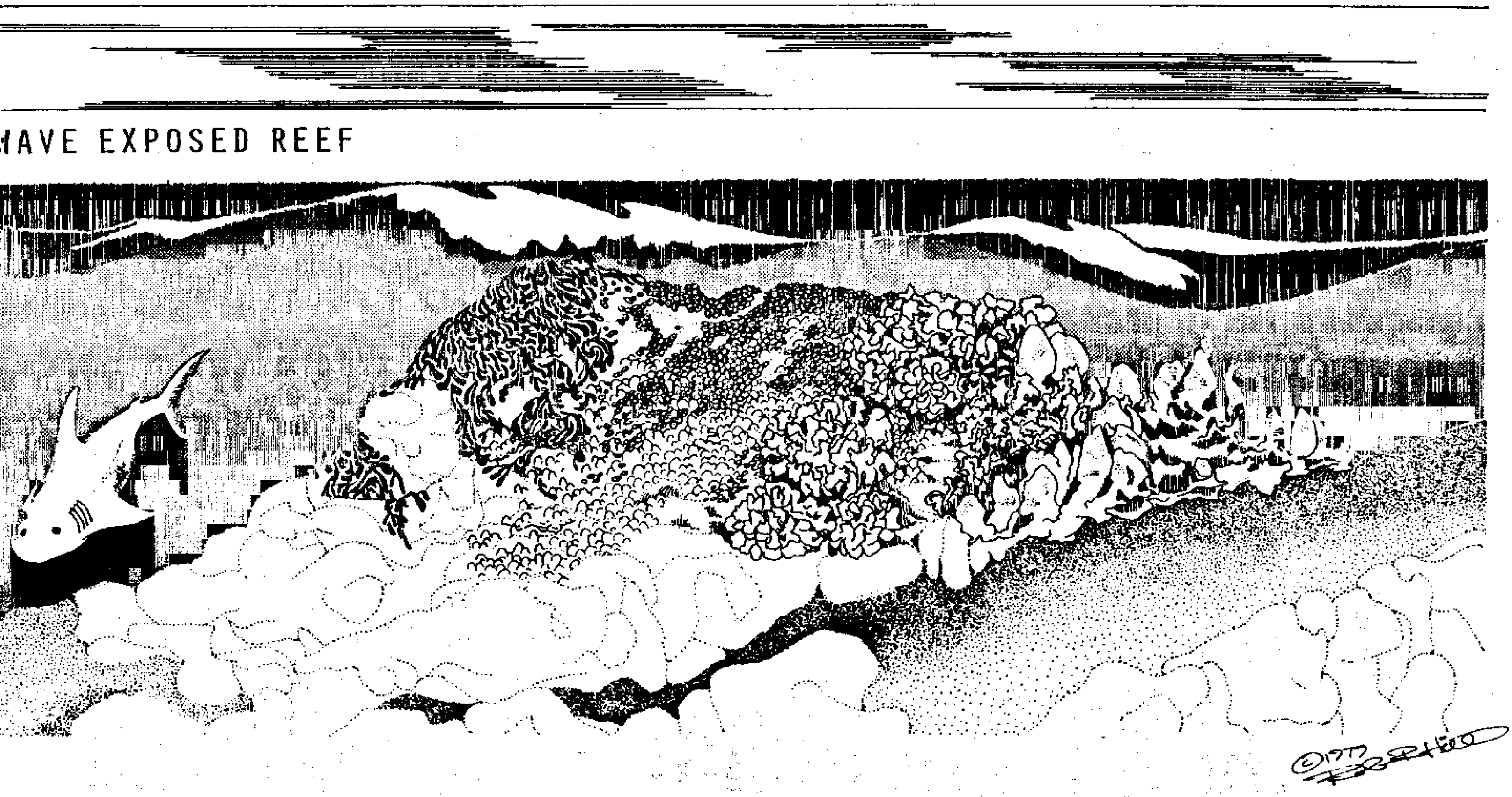
Occasionally, two other corals, *Montipora verrucosa* and *M. patula*, are common in quiet waters in Hawaii. *M. verrucosa* appears to withstand waters slightly diluted by freshwater runoff from the land; *M. patula* can withstand more exposure to turbulence. Both corals are basically encrusting types, although *M. verrucosa* forms plates and irregular branches in quiet waters.

Among the more conspicuous invertebrates found in protected coral bottom areas are the slate pencil urchin, haukeuke (*Heterocentrotus mammillatus*), the pin cushion urchin, hawae (*Tripneustes gratilla*), and the wana or long-spined urchins (*Echinothrix* spp.). A variety of mollusks are common, especially cowries (*Cypraea* spp.). Low-growing algae, encrusting coralline algae, bryozoans, and sponges may compete with corals for space on hard surfaces. These forms are seldom abundant except on the undersides of shelves and in holes where reduced light discourages vigorous coral growth. Most large, fleshy seaweeds are cropped down to a low turf by grazing fishes.

A wide variety of reef fishes swim freely in the vicinity of the corals and take advantage of the irregular bottom for shelter to escape predatory fishes such as the ulua (jack). A typical protected coral community in Hawaii may harbor between 50 and 100 different species of fishes. Examples of the numerous fishes which variously depend on corals are the long-nosed butterflyfish, lauwiliwili-nukunuku-oioi (*Forcipiger flavissimus*), which uses its narrow snout to feed on small invertebrates between coral fingers; the surgeonfishes, palani (*Acanthurus dussumieri*) and manini, which graze on the algal turf; parrotfishes or uhu (*Scarus* spp.) which scrape the surface of limestone and coral with their beak-like teeth; the solitary Jenkin's damselfish (*Stegastes fasciolatus*) which hides in the cracks and crevices between coral fingers, feeding on algae and zooplankton; and the pebble butterflyfish (*Chaetodon multicinctus*), which feeds on coral polyps.

<u>Wave surge coral communities</u>

In shallow water along an open coast, the influence of wave swell can be seen in the character of the coral community. Coral heads are solid and sturdy forms which are able to resist pounding waves and wave surge. They may grow as thin crusts or as squat (boulder-like) masses. Branching


AVE EXPOSED REEF

forms, such as the rose coral (*Pocillopora meandrina*), have stout branches which are not easily breakable.

Wave surge coral communities inhabit hard bottom areas from near sea level to depths of nearly 15 m (50 ft) off coasts regularly exposed to large winter surf. The offshore sloping bottom is often broken by ledges and terraces, and sand tends to collect in depressions or on nearly flat bottom areas.

In shallow water where waves break and sand scours the bottom, only a few fast-growing or abrasion-resistant species can survive. The surface of rocks may be bare except for encrusting coralline algae. Corals, if present, cover a small proportion of the bottom. The rose coral is usually the most conspicuous species. Lobate coral appears as thin crusts rather than as massive heads in deeper water or protected areas. Other coral genera present include *Montipora*, *Pavona*, and *Leptastrea*. The soft coral (*Palythoa tuberculosa*), sea urchins (*Echinothrix* spp. and *Echinometra mathaei*), a sea cucumber (*Actinopyga mauritiana*), and a variety of mollusks are usually conspicuous.

In water 9 to 30 m (30 to 100 ft) deep, seaweeds may predominate, although sand deposits tend to be extensive. Coral cover on available hard bottom is greater than in shallow water because of reduced wave surge and sand abrasion. In addition to *Porites lobata* and *P. compressa*, corals represented in the deeper zone include *Pavona* and encrusting *Montipora*, as well as species seldom seen in shallow water (for example, *Pocillopora eydouxi*). Conspicuous invertebrates include the green starfish (*Linckia diplax*); the cushion star (*Culcita novaeguinea*); the crown-of-thorns starfish (*Acanthaster planci*); two wana (*Diadema paucispinum* and *Echinothrix* spp.); the hawae (*Tripneustes gratilla*); and sometimes a sea cucumber (*Stichopus horrens*). In crevices and caves are found hee (*Octopus* spp.); ula (spiny lobster, *Panulirus* sp.); uu (squirrelfishes, menpachi, *Myripristis* spp.); and puhi (moray eels, *Gymnothorax* spp.).

In addition to the numerous species of typical "reef" fishes, schools of kumu (*Parupeneus porphyreus*), moano (*P. multifasciatus*), and other goatfishes are attracted to large adjacent sand bottom areas. Larger, predatory fishes such as the ulua and papio (*Caranx* spp.) frequent the waters around wave-exposed coral bottoms.

Human interactions with coral bottom environments

Stony corals provide habitats for fishes and shell life having commercial, recreational, and food value. Coral-rich bottoms are valuable for scuba and skin diving, spearfishing, underwater photography, and glass bottom boat tours. Although coral bottoms appear sturdy, they can be easily damaged and are slow to recover. The living tissue of even massive coral heads is only a thin layer over the surface. Damage by anchors and anchor chains and by divers in search of shells and aquarium fishes can lead to disease and death of the coral colony. Stony corals harvested illegally for sale as bleached skeletons provide small economic benefit compared with the economic importance of corals in the ecology of the offshore bottom.

Enrichment of waters over coral reefs by sewage and urban runoff may kill corals indirectly by stimulating the growth of seaweeds and filter-feeding animals. These organisms grow over the corals and deprive them of light and oxygen; furthermore, they quickly colonize on bare surfaces, preventing the settlement of coral larvae.

Dredge and fill operations, erection of underwater structures, and extensive erosion of the watershed are factors which can increase the rate of sediment deposition on coral bottoms. Dredging in coral communities may not only result in dislodging of live coral heads, but also in changing of rock surfaces to level bottom areas where sediment accumulates. The bottom of a dredged basin is usually unsuitable for recolonization by corals. Although corals shed sediment particles by trapping them in mucus and then moving the mucus off the edge of the colony, this cleaning process can be overwhelmed if particles are too heavy or settle too rapidly on the coral surface. Furthermore, sediment on rock surfaces interferes with the settlement of coral larvae. Particles suspended in the water reduce the amount of light reaching the corals and their zooxanthellae, thereby stunting coral growth.

Reef Building and Erosion

Corals are usually thought of as the builders of tropical reefs. Although corals are major contributors, stony or coralline algae usually surpass other organisms as the main frame-builders in shallow, surge-swept areas. In fact, the outermost margin of a reef may harbor few corals. Instead, there may be a ridge of encrusting algae, called the algal ridge, where the greatest force of the waves is concentrated. The encrusting growth of coralline algae binds together the solid and loose fragments of limestone which collect on a reef.

Both stony corals and coralline algae remove dissolved minerals from seawater to form skeletons of limestone. Most live firmly attached to the bottom and their skeletons remain in place after death, adding to the rigid frame of the reef. This frame serves as a surface of attachment for other organisms and provides shelter for motile (capable of moving about) reef dwellers. The framework is not a solid mass, but contains holes, depressions, and cavities in which loose material gradually accumulates. Reef ecosystems produce a great deal of rubble and sediment from the breakdown of corals and coralline algae, as well as from the skeletons and shells of mollusks, sea urchins, and one-celled animals called foraminifera.

Because Hawaii is located in the subtropics and the climate is more extreme than in the tropics where reef-building organisms grow best, reefs here do not normally approach or grow above the low tide level. Reef growth in any particular location depends on such physical factors as depth, turbulence, clarity, sediment movement, temperature, and salinity. Areas scoured by sand, buried under mud, or diluted by freshwater runoff are generally not conducive to reef building.

Even where conditions for growth are most favorable, erosion wears down the reef. Solid reef rock is reduced to small particles by the scraping, boring, and dissolving activities of a number of reef dwellers. Storm waves wrench pieces of rock from the seaward face. Loosened material may drop down the sloping outer face where it contributes to the base on which the reef grows outward, or the material may be carried onto the reef flat. Smaller particles may be transported shoreward and deposited on the backreef flat or on a beach.

Replacement of reef material removed by erosive processes is made possible by the continuous growth of corals and coralline algae. Over the long term, the net result may be one of equilibrium--that is, losses from erosion more or less equal gains from skeletal growth. The windward reefs of many of the islands appear to be eroding as fast or faster than they are growing. Where growth exceeds erosion, particularly in leeward and sheltered locations, a reef gradually extends upwards and outwards. The process is a slow one: reefs grow only about 1.3 cm (0.5 in) per year under ideal conditions. The fragility of a reef is apparent with the realization that maintenance and growth depend directly on the health of the corals and coralline algae which make up a relatively thin layer of living tissue on the outer reef flat and reef front.

Reefs begin as coral-rich bottom communities which, over thousands of years, grow upwards to near the sea surface. Eventually a great mass of limestone extending as a shelf from the shoreline, called a fringing reef, results from the accumulation and binding together of the skeletons of corals, coralline algae, and other reef dwellers.

Fringing reefs

Behind the natural breakwater of the reef margin is a shallow platform or reef flat normally between a few centimeters and a few meters deep. Parts may be exposed during minus tides.

Reef flats are a mixture of hard and soft bottom types. The more seaward areas are comprised of solid limestone, with depressions partially filled with sand or rubble. The shoreward, or backreef, areas are usually sand flats, strewn with worn fragments of reef rock. On well-developed reefs the backreef is usually a little deeper than the outer reef flat. The change in character of the bottom and types of organisms inhabiting different parts of a reef flat is related to the gradual reduction in wave surge and currents which occurs between the outer reef margin and the shoreline. Because most marine organisms depend upon the motion of the water to bring food, remove wastes, and renew oxygen, the abundance and diversity of living forms decrease from the seaward margin to the shore.

Seaweeds are usually the most conspicuous occupants on rock and rubble surfaces of reef flats. Inshore, where water circulation is sluggish, fleshy seaweeds are most common. Near the reef edge, where water movement is more vigorous, pastel-colored stony algae (especially *Porolithon* spp.) are characteristic.

Mollusks, sea urchins, worms, and crustaceans are abundant on reef flats, but most live concealed from view. Limestone can be penetrated by

OFFSHORE REEF FLAT

many worms and sponges that dissolve or hollow out the rock to form galleries and tunnels. These animals hasten the breakdown of solid reef rock, and where active growth of corals and calcareous algae ceases, the rock soon becomes crumbly. Where there are sand patches on the reef flat, shelled animals of many varieties lie buried beneath the surface. Examples are the flea cone (*Conus pulicarius*), augers (*Terebra* spp.), and moon snails (*Natica* and *Polinices*). Most free-ranging mollusks and crustaceans seek shelter in holes or burrow into the sand during the day; thus, the diversity of life on a reef flat is far more apparent at night. Although not usually conspicuous on backreefs, a few species of stony corals (*Pocillopora damicornis* and *Cyphastrea ocellina*) are present. The fishes seen on a shallow reef flat are mostly juveniles of species (particularly damselfishes and wrasses) found as adults in deeper waters off the reef face.

High water temperatures, reduced salinity, drifting sand, and mud that pours out from streams during heavy rain all retard the growth of stony corals and coralline algae in shallow waters between the reef edge and shore. Backreef areas are environments of deposition where there are few corals and calcareous algae. The reef margin and reef face, which receive the full force of waves, are wave-surge environments. Stony corals are always present, but calcareous algae predominate in the zone of maximum wave surge. The bottom is generally solid limestone in the form of ridges or fingers projecting seaward and separated by grooves. On well-formed reefs the outer margin is the shallowest part, although this is seldom the case in Hawaii. The deeper margins of most Hawaiian reefs are, in part, responsible for the excellent surfing conditions.

Offshore reefs

In contrast to fringing reefs which extend out from an island shoreline, other kinds of reef platforms rise from the bottom some distance offshore. Three basic types of offshore reefs are barrier reefs, atoll reefs, and patch reefs. Although quite different from one another in form, all three types are associated with a sheltered body of water called a lagoon which is usually greater than 2 m (6 ft) in depth.

Barrier reefs. Barrier reefs are separated from volcanic islands by a wide, deep lagoon. Barrier reefs begin as fringing reefs around the shoreline of a volcanic mountain. Over long periods of time, volcanic islands settle into the crust of the earth. This "sinking" can be so slow that upward growth of the outer margin of a reef can keep pace and therefore always remain near sea level. In addition to islands settling, sea level itself fluctuates. Over the last 20,000 years, sea level has risen more than 90 m (300 ft). Although growth of the outer reef flat and reef margin can keep pace with sea level rising at this rate, in many cases the accumulation of sediments on the backreef flat cannot; if sea level is rising, the shoreline moves inland, away from the growing reef, increasing the area to be filled. The result of an unfilled backreef flat under conditions of rising sea level is a lagoon. The reef itself becomes a barrier type. The best example of this type of reef in Hawaii is found across the front of Kaneohe Bay. The reef off Waimanalo, which deepens midway between the reef margin and shore, resembles a barrier form.

Atolls. Atoll reefs are linear reefs which partially or wholly surround a lagoon in which there is no volcanic land mass.

The gradual settling of a volcanic island, combined with the wearing down of its mountains, eventually results in its disappearance below the surface of the sea. If coral growth has kept pace, the only trace of the island would be its limestone reefs. Because of the recent rise in sea level, the barrier reef of a volcanic island becomes an atoll once all traces of the former volcano are gone. The best examples of atolls in the Hawaiian Islands chain are Kure Atoll and Midway Island. At Midway, a hole drilled downward through the reef passed through some 150 m (500 ft) of limestone before volcanic rock was encountered, demonstrating the volcanic origin of this atoll and the extent of growth which has taken place to maintain the reef near sea level.

Land masses on atoll reefs, properly termed islets, are composed of coral rubble and sand accumulated above sea level by waves and currents, but particularly by storm waves. Islets seldom occur more than a few yards above sea level at their highest point. Characterized by poor soil and limited fresh water, they support relatively few types of plants or animals. Many islets harbor large populations of seabirds which derive their food from the sea.

The biological assemblages on the outer margin and sloping front of atoll and barrier reefs resemble those on fringing reefs. Waves breaking on the seaward face drive water across the reef flat and are responsible for the pronounced physical and biological zonation on offshore reefs. Because this flow is less restricted by a lagoon behind the reef than by an island shoreline (as is the case for fringing reefs), stagnant conditions are unlikely to occur on the backreef flats of barrier reefs. Furthermore, where a lagoon is large, significant wind-driven waves and currents may develop along its margin where rich coral growth would be encouraged.

Patch reefs. Patch reefs are small and isolated and are usually found in lagoons of atolls and inside barrier reefs; they are common features in most atoll lagoons. Patch reefs develop from knolls which rise above the general level of a lagoon floor where coral and algal growth keeps ahead of the sediment deposition which characterizes lagoon environments. The most extensive development of lagoon patch reefs is found immediately inside breaks or channels through atoll or barrier reefs where currents are favorable for reef growth. In Hawaii the best examples of patch reefs are found in Kaneohe Bay. Some offshore patch reefs occur along the windward coast of Oahu (for example, in Kahana Bay) and Kauai (for example, in Hanalei Bay).

The patch reefs in Kaneohe Bay are steep-sided with flat tops at or a little below sea level. Sand and rubble predominate on their inner portions and leeward slopes. Consolidated reef rock supporting coralline algae and corals characterizes their windward margins. The dominant coral species on Kaneohe Bay patch reefs is the fingercoral (*Porites compressa*). Plate coral (*Montipora verrucosa*) and the solitary mushroom coral (*Fungia scutaria*) are conspicuous. Patch reefs serve as biological oases rising from the relatively barren sandy-mud bottom of the lagoon. A large variety of reef fish inhabit patch reefs, particularly along the windward slopes.

Human interactions with coral reef environments

Coral/algal reefs are the largest structures on earth built by plant and animal growth. By causing waves to break offshore, reefs protect beaches and land masses, slowing coastal erosion. In addition, reefs provide recreational sites for surfers, fishermen, and skindivers, as well as sheltered waters for swimmers. The natural breakdown of reef rock and skeletal remains of reef dwellers are the source of white sand beaches which provide Hawaii residents with recreational as well as economic benefits through the visitor industry. Many of the coastal plains on Oahu (and to a lesser extent on Kauai) are the remains of reefs developed thousands of years ago.

Reef flats provide shelter for many organisms which are collected for food, including limu (edible seaweeds), mollusks (such as octopus or hee), wana (long-spined sea urchins), loli (sea cucumbers), and various fishes. Ornamental mollusks (cowries and other shells) and stony corals (especially the rose coral, *Pocillopora meandrina*) are collected for curios. Some organisms (for example, the spaghetti worm, *Lanice conchilega*) have been collected for use in medical research.

Because of easy access and generally calm waters, reef areas are heavily used by collectors, naturalists, and teachers for nature studies. As a result, certain reef flats are adversely affected by human visitors, especially during exceptionally low tides.

Nutrient enrichment from sewage discharge and land runoff into south Kaneohe Bay has enhanced the growth of numerous organisms normally occurring in low abundance on patch and fringing reefs. Sponges, tunicates, sea anemones, the soft corals (*Palythoa psammophilia* and *Zoanthus pacificus*--colonial forms related to corals but lacking a calcareous skeleton), and the rapidly growing bubble algae (*Dictyosphaeria cavernosa*) cover much of the hard bottom of the reef margins excluding corals and coralline algae. The growth of reef destructors--species capable of breaking down limestone rock by their boring activities--is also enhanced by nutrient enrichment of the waters. Although the reefs currently support an abundance of algae, invertebrates, and fishes, these organisms contribute little to the growth of the reef and many hasten the destruction of reef rock. The margins of fringing and patch reefs in the southern basin of Kaneohe Bay are slowly disintegrating. Diversion of sewage to the Mokupu Outfall will alleviate the problem somewhat, but the contribution of increased sediments and pollutants associated with urbanization of the watershed area continues to work against the reestablishment of reef-building organisms.

Soft-Bottom Communities

Sedimentary environments

Sediments accumulate in depressions or sheltered places where currents are absent or too weak to sweep away the particles. Thick deposits are most likely to form in bays and lagoons, in the reef channels, as well as on more or less level terraces. The composition of the sediment with respect to the proportion of terrigenous (land sources, usually volcanic silts and clays) and marine (ocean sources, such as shells and calcareous algae remains) particles depends on erosion sources. Reefs generate marine sediments; streams and easily eroded volcanic rocks at the shoreline contribute terrigenous sediments. The make-up with respect to grain size depends on water motion; the smallest grains (silts and clays) are deposited only where water motion is slight.

Two broad classes of soft-bottom environments may be recognized: (1) bottoms composed of larger, heavier particles (chiefly sand) found on open coasts or in open bays and channels where wave action and currents carry off the finer, lighter particles; and (2) bottoms dominated by small, light particles (chiefly silts and clays), which occur in lagoons and other settings protected from waves or strong currents.

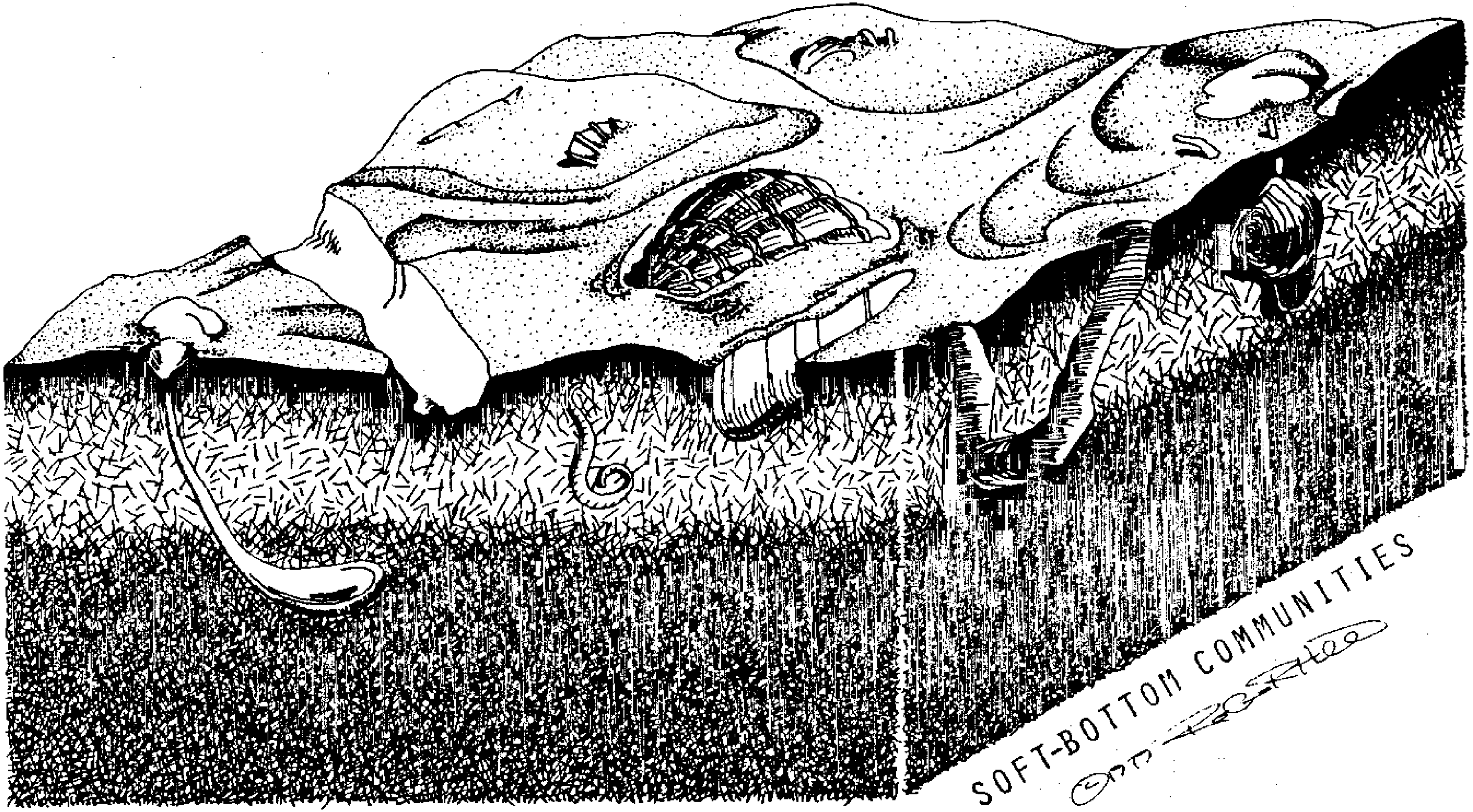
The size of particles in a deposit has a strong influence on the physical and chemical properties of the bottom. Deposits of sand-sized particles are firm underfoot and often marked by small dunes or ripples. Because these formations are usually disturbed only by waves, their stability increases with depth. Deposits of muddy sand are softer underfoot, have a high water content, and are easily agitated by the burrowing activities of resident animals or by disturbances caused by divers or ship propellers.

Soft-bottom life

The biological composition of soft-bottom communities varies with the depth and stability of the sediment deposit, as well as the composition of the sediment. Zonation of life is much less obvious in soft-bottom communities than in hard-bottom ones. The crevices, ledges, and cliffs found on rocky bottoms cause sharp breaks in habitat types over short distances and, furthermore, provide a wider variety of distinct habitats. Habitat differences associated with soft-bottoms are much more subtle.

Because sediments are readily set in motion by wave surge and currents, they provide no firm attachment for bottom-dwelling organisms. Furthermore, soft-bottoms lack the cover sought by many small fishes and invertebrates for protection from large predators. Those animals that live on the bottom can be divided into two categories: infauna (animals that live under the surface) and epifauna (animals that live on the surface). As a rule, infauna are more abundant than epifauna.

Soft-bottoms appear rather barren and lifeless, although close inspection reveals numerous burrows, mounds, trails, and tracks as evidence of the unseen inhabitants. Burrowing is a common way of life for bottom-dwelling animals, including forms (such as crabs) which normally crawl about on the surface and temporarily bury themselves when disturbed. Many inhabitants spend their life hidden from view in burrows which they constantly maintain. Some infaunal organisms move through the sediment without establishing or maintaining a burrow. Others lie secure beneath the surface in mucus-lined tubes. Numerous minute animals (mostly polychaetes) are small enough to live in the system of pores between sand grains. Some attached forms--including anemones, an alga (*Halimeda*),


SOFT-BOTTOM COMMUNITIES

and a flowering plant (*Halophila ovalis*)--can anchor themselves on the soft bottom.

Mud bottom environments

Mud bottom environments are usually associated with quiet waters of embayments and lagoons which receive significant amounts of land-derived sediments from streams. Mud is not as porous as sand; water does not pass freely between the closely packed grains and may become stagnant and depleted of oxygen. Only animals adapted to living under conditions of low oxygen can survive in the mud.

An alpheid shrimp, *Alpheus malabaricus mackayi*, is a conspicuous burrowing animal on muddy bottoms. Several polychaete species and minute marine oligochaete worms burrow through the mud, feeding on organic matter carried from the land. Swimming crabs (*Portunus* spp. and *Podophthalmus vigil*) and the introduced Samoan crab (*Scylla serrata*) may be the only large epifaunal organisms.

The activities of burrowers disturb and destabilize the bottom, whereas mats of one-celled algae grow on the surface, reducing sediment mobility. Grazing by plant-eaters and the activity of burrowers partially destroy this mat and expose bare sediment.

Silty-sand bottom environments

Silty-sand bottom environments occur in open embayments, on protected backreef flats, and on deeper offshore bottoms. Where streams carry sediments from the land, some of the silt may be terrigenous, but in many cases the silt is derived from the breakdown of reef material. Segmented worms are common in silty-sand bottom areas; some types build tubes which they line with mucus and sand grains, or with a parchment-like material.

The organisms associated with silty-sand environments demonstrate the variety of lifestyles found in soft-bottom communities. Some soft-bottom dwellers (such as swimming crabs) capture and eat whole organisms. Others, such as sea cucumbers and burrowing polychaetes, plow through the sediment, taking in particles and extracting whatever organic matter they encounter. Filter feeders, a third feeding type (certain clams and tube worms) remain buried in the sediment and sieve water, removing edible particles.

In deep offshore sand deposits, beds of the pen clam (*Pinna muricata*) may form almost solid patches. Carnivorous mollusks, particularly *Terebra* spp. and *Conus* spp., are also common. Furthermore, populations of garden eels are occasionally observed on deep deposits.

Human interactions with soft-bottom environments

Marine dredging and filling, construction of seawalls and groins, and denuding of adjacent watersheds can result in changing patterns of sediment erosion and deposition. The impact of sediment-generating activities may often be only temporary, having the immediate effect of near-complete destruction of most soft-bottom animal populations, followed by rapid recovery. After burial under a thick layer of new sediment, reestablishment of the soft-bottom biota takes up to one year for fine-grained sediments and up to three years for coarse-grained sediments. Some inhabitants can dig themselves out from under as much as 1 m (3 ft) of a similar sediment (that is, sand deposited on sand or mud deposited on mud), but can be killed by as little as a few inches or an unlike material (that is, sand on mud, or mud on sand).

A small amount of fine sediment introduced to a sand-bottom area may fill the spaces between grains, slow the movement of water through the sediment, and cause stagnation and oxygen depletion just below the surface. The organic content of sediment and potential for storing toxic substances are usually greater in silt-dominated bottoms. If large quantities of organic material such as sewage sludge are added to the bottom, the oxygen supply in the sediment pores may not be sufficient to support the organisms that normally break them down. In the absence of oxygen, microorganisms which do not completely decompose organic matter become established. Such an environment will support only a few species of specially adapted worms and bacteria.

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