

**JOKIEL'S  
ILLUSTRATED  
SCIENTIFIC GUIDE  
TO  
KANE'OHE BAY, O'AHU**

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## **I. The Environment of Kaneohe Bay**

### **A. Kaneohe Bay as an Ecosystem**

The Kaneohe Bay ecosystem (Figure 1) consists of the Kaneohe Bay watershed, the bay itself, the protecting barrier reef, and the nearshore oceanic environment. Kaneohe Bay is directly influenced by runoff from the surrounding watershed as well as by exchange of sea water from the ocean. The semi-enclosed nature of the bay and relatively large freshwater inputs have created diverse marine habitats. These same characteristics make Kaneohe Bay more vulnerable to damage by factors associated with urbanization and agricultural development than an open coastline.

Past, present, and future changes in the bay are closely related to changes in the adjacent watershed. The relationship between the land and the sea was understood by the ancient Hawaiians. Their basic concept of land division was the ahupua'a which extended from the uplands to the sea. Inhabitants of each ahupua'a had "accessibility of all the resources provided by nature" (Devaney et al., 1976). They considered themselves "part of the total environment" and knew that while they could modify it, the resulting benefits or afflictions directly affected farmers, fishermen, and their families. The Hawaiians' principle of malama aina or respect, conserving, and caring for their resources, was expressed in the practice of taking only what was needed from the land or sea.

The terrestrial boundary of the Kaneohe Bay watershed is the ridgeline of the Ko'olau Mountain Range extending from Kualoa to Mokapu. The land surrounding Kaneohe Bay was divided by the Hawaiians into nine ahupua'a (Figure 2) that were in turn subdivided into resource areas known as Ili. The bay itself was similarly divided as fishery areas. The ocean adjoining an ahupua'a was considered to be an extension of that ahupua'a. The Hawaiians saw the ocean as an integral part of their resources not to be separated from the land.

Currently, it is known that chemical, hydrological, and biological conditions in the bay are influenced by land runoff. Streams and ground water runoff transport sediment, nutrients, and other materials from the land into the bay. Water input associated with urbanization transports pollutants and increased amounts of sediments into the ecosystem.

Kaneohe Bay also exchanges water with the nearshore oceanic environment. Tide, surf, and wind drive its current systems. These flush the bay of wastes and allow the dispersal stages of marine plants and animals to enter and leave.

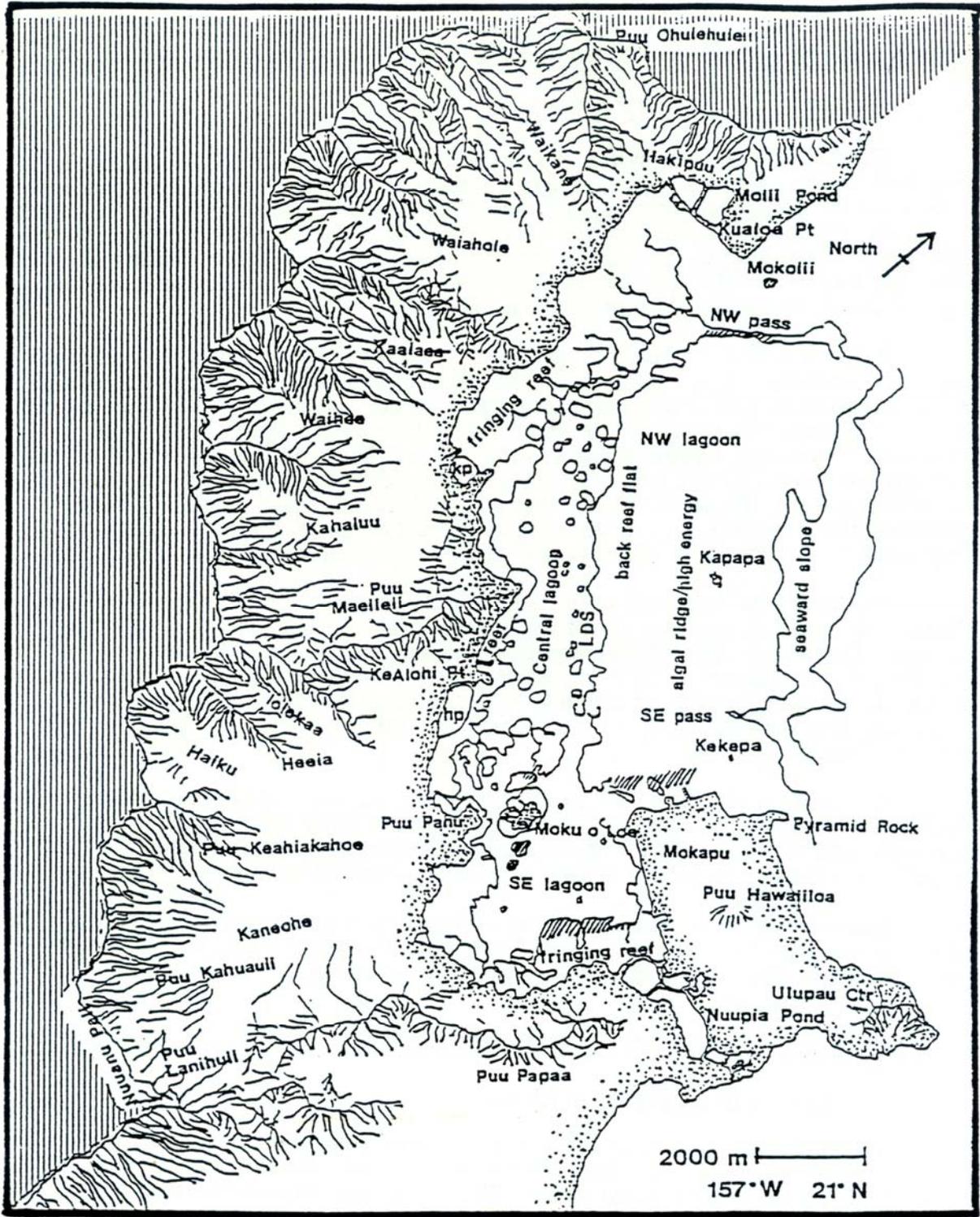


Figure 1: Kaneohe Bay ecosystem including watersheds, major topographical features, and marine physiographic zones. hp= Heeia Pond; kp= Kahaluu Pond, LDS=Lagoon depositional slope

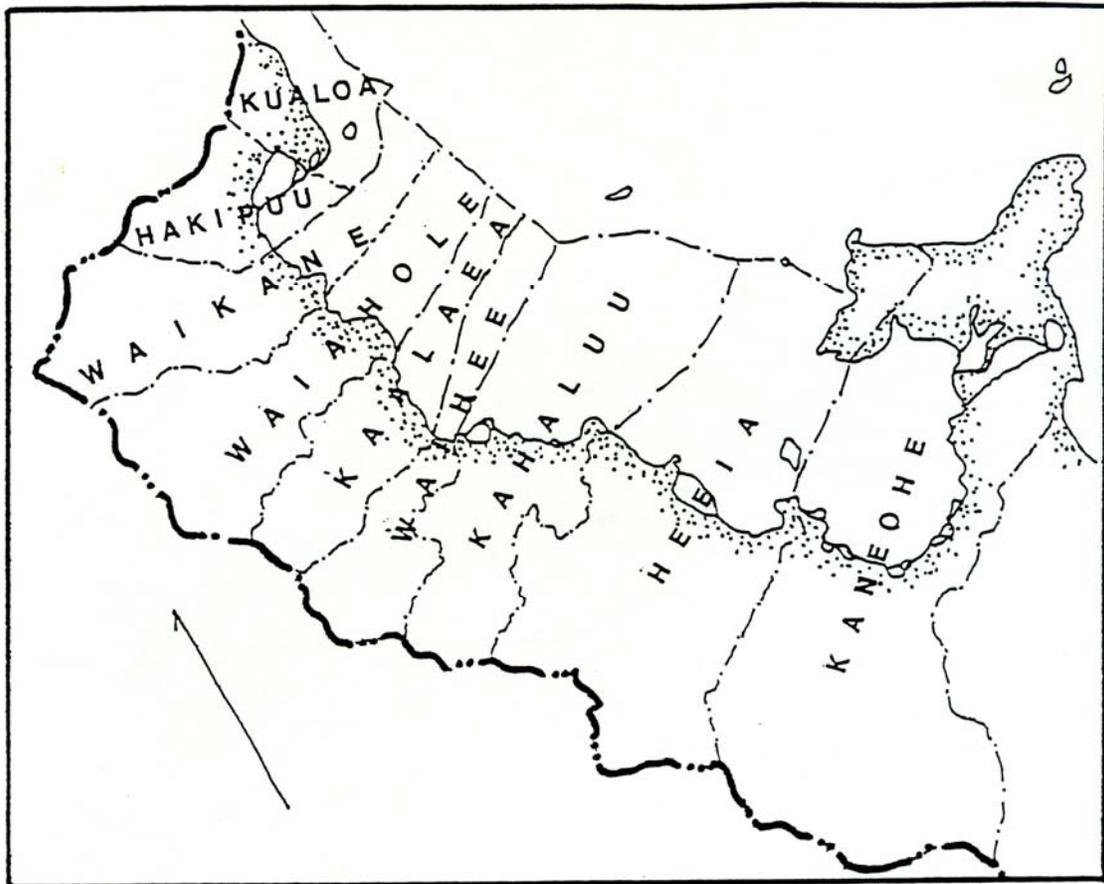
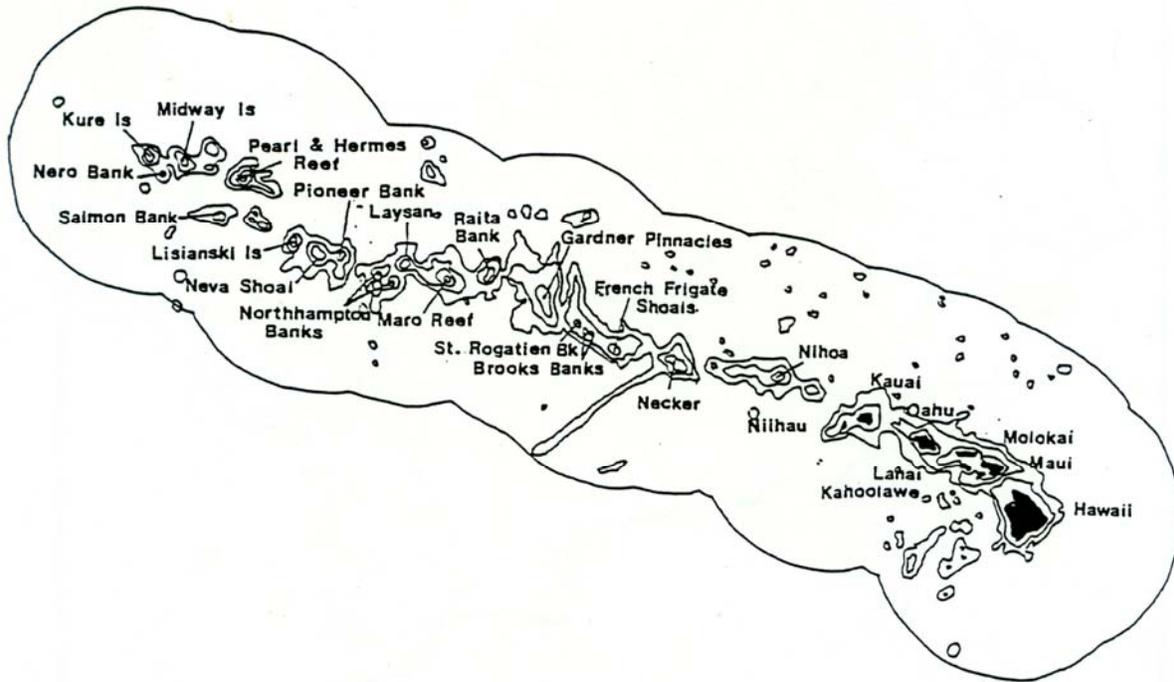


Figure 2: The nine ahupua'a of Kaneohe Bay. (After Devaney et al., 1976)

## B. Geological History of Kaneohe Bay

### 1. Formation of the Hawaiian Islands

The Hawaiian Archipelago (Figure 3) is the most isolated major island group in the world, lying 4000 km (2485 mi) from the nearest continent (North America) and 1600 km (1000 mi) from the nearest island groups. The archipelago contains habitats ranging from the deep sea to 4200 m (13,800 ft) elevation, and have some of the most dramatic rainfall gradients in the world. Along the Archipelago we find everything from deep ocean trenches to coral reefs, rocky intertidal areas, mangrove swamps, sandy beaches, mudflats, and estuaries such as Kaneohe Bay.



**Figure 3: The Hawaiian Archipelago**

The linear arrangement of the Hawaiian chain resulted from the formation of a series of islands as the Pacific tectonic plate moved northwestward over a volcanic hot spot. The island of Hawaii is located over this hot spot, and is still forming. The active volcanoes of Mauna Loa and Kilauea are found here. A new sea mount, Loihi, discovered in the 1950's, is forming to the south of the island of Hawaii. Eventually, Loihi will build to the surface and emerge as the next Hawaiian Island.

The Island of Hawaii is only about a half a million years old. Its volcanoes are still active and enlarging the island. Very little erosion of the volcanoes has taken place so that the island's generally rounded appearance indicates its youth. The islands to the northwest are older. They show the characteristic signs of erosion - deep valleys, broad canyons, and deep soils.

To the northwest of Hawaii Island lie four islands - Maui, Molokai, Lanai and Kaho'olawe. They are situated on a common shallow water platform. Oahu (with approximately 80% of the state's human population) lies farther northwest of the Molokai channel, followed by Kauai and Ni'i'hau. These two northernmost high islands are approximately five million years old. The sharp knife-edged ridges of these highly eroded older islands are a dramatic contrast to the low-sloping domes of the volcanoes on the island of Hawaii.

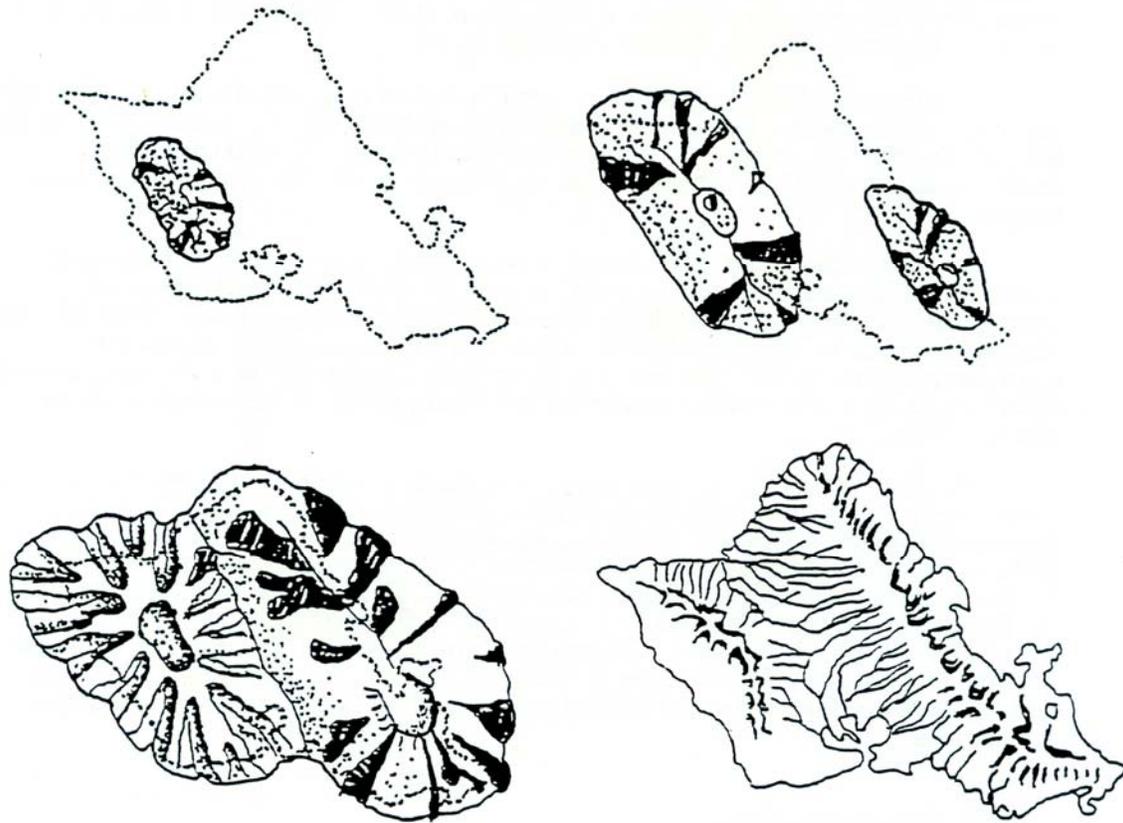
To the northwest of the eight major high islands the chain continues with a string of lower islands, atolls, reefs, and shoals. All of these are of volcanic origin with various degrees of coralline additions. As the chain progresses northwestward, the islands and atolls submerge to become seamounts. North of Midway Island, about 3000 km (1850 mi) northeast of the island of Hawaii, the chain bends sharply to the north and continues as the Emperor Seamounts. Twenty-four hundred km (1500 mi) farther north, these seamounts are sequentially subducted into the Kuril-Kamchatka Trench. This conveyor belt-like progression of islands raises the possibility that islands now eroded and sunken could have at one time supported life and provided colonists for newly arising islands to the southeast.

## **2. Formation of Oahu**

The island of Oahu was formed by two volcanoes, the Waianae and the Ko'olau. They are joined together by a plateau that slopes gently toward the sea. These have become highly eroded and at first glance do not resemble the young dome-shaped shield volcanoes found on the island of Hawaii. Their once-rounded tops have been deeply cut by streams and the material carried away. The wearing away of these peaks has been going on for several million years.

Volcanic activity that eventually created Oahu first broke out along a swelling on the floor of the Pacific Ocean about 25 million years ago, in a period known to geologists as mid-Tertiary (Macdonald and Kyselka, 1967). Basaltic lava poured from the cracks, spread rapidly, and slowly built gigantic shield volcanoes. The top of the Waianae volcano broke the surface of the Pacific about ten million years ago. Lava flowed from three sets of cracks that eventually intersected to form a central vent near the present Kolekole Pass (Figure 4). Lava flows were frequent and erosion made little headway. Rain sank into the porous lava instead of cutting streams.

The Ko'olau volcano appeared a few million years later as a separate island a few miles to the east of the Waianae. The two volcanoes continued building, gradually filling in the ocean between them to form a single island (Figure 4). Finally, the Waianae volcano became extinct, and lava flows from the Ko'olau volcano banked against its side to form the present Schofield Plateau.



**Figure 4: Formation of Oahu by coalescence of the Waianae and Koolau volcanoes. (After Carlquist, 1970)**

The Ko'olau erupted along vertical cracks that extended from beyond Kahuku in the north to past Makapu'u in the south. A central vent and summit depression, or caldera, formed near the present region of Kaneohe and Kailua. The major volcanic activity stopped here about three million years ago.

The Ko'olau volcano was also partially built by lava rising to the surface through thousands of cracks in preexisting flows. Lava cooled in these cracks and formed nearly vertical sheets of dense basaltic rock called dikes. Many such dikes, each about one meter (3 ft) in width, can be seen in the high cuts made for the Pali Highway near Castle Junction and along the Kaneohe - Kailua section of the H-3 highway near Mokapu Blvd. These dikes retained infiltrating rainwater and created a storage area as well as the artesian springs at lower elevations.

The top of the Ko'olau volcano was about 1.8 km (1 mile) above sea level when it ceased building. The old crater region covers the area from Waimanalo to Kaneohe. Also located in the site of the old crater is Olomana Peak, an isolated mountain that sweeps up into a sharp 500 m (1,643 ft) peak.

### 3. Geological History of Windward Oahu

The difference between the leeward and windward sides of the Ko'olau Range is striking. The long, gentle slopes of the leeward Honolulu side terminate in vertical cliffs 0.8 km (0.5 mi) high on the windward side. This cliff line, or Pali, extends for 32 km (20 mi) along the windward side of Oahu (Figure 5). The character of the cliff changes northward along the Pali due to two different agents of erosion. Massive sea cliffs in some places are formed by wave erosion. Vertical walls in other places are formed by stream erosion.

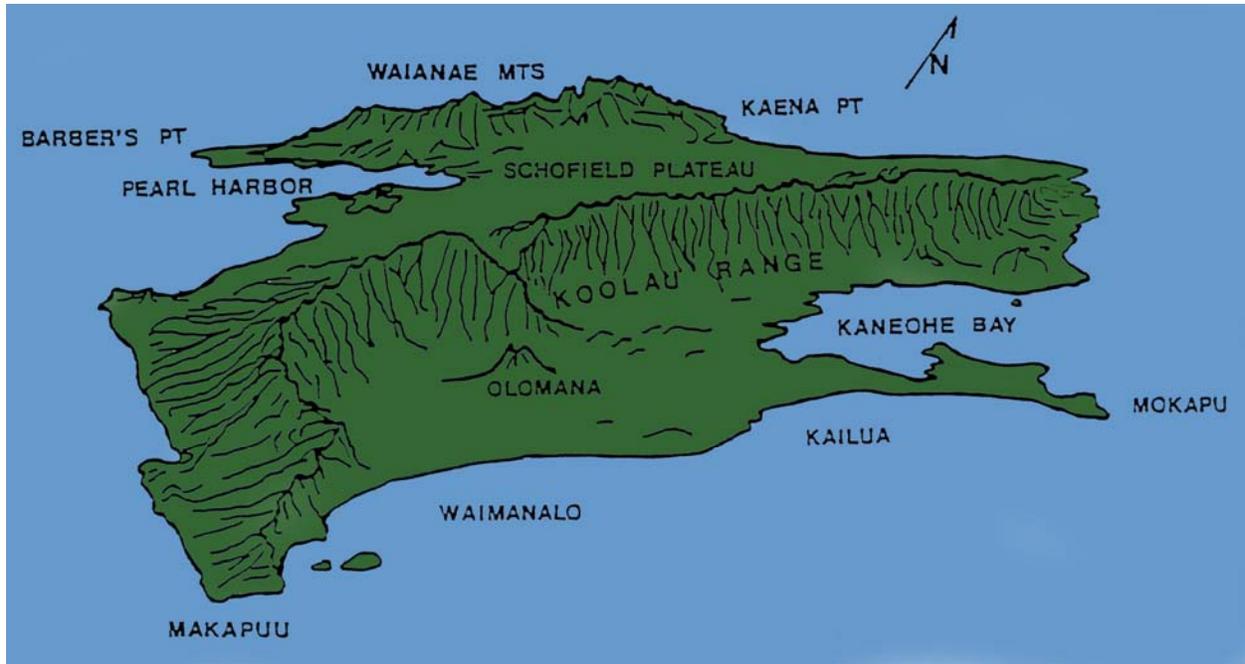


Figure 5: Vertical cliff-line or Pali along the windward side of the Koolau Range. (After MacDonald and Kyselka, 1967).

Early geologists wondered how the Pali was formed. Some thought it was carved when the sea stood at a higher level. Others thought that the Ko'olau volcano cracked and the eastern portion slipped into the sea, leaving a fault scarp, or cliff. Both processes appeared to have played a role.

Extensive recent studies of the deep ocean off windward Oahu revealed that an enormous piece had broken off the island. This type of prodigious avalanche occurred on all the major Hawaiian Islands at least 17 times over the past 5 million years (Moore et al. 1989). The most massive of these was the Kaneohe Bay slide or the "Nu'uuanu debris avalanche".

This landslide occurred along the windward side of Oahu over one million years ago. A massive earthquake caused the windward side of the Ko'olau volcano to break

away and slide down the side of the volcano and into the deep sea. Approximately 290 cubic kilometers (390 cubic miles) of rock pulled away from Oahu, slid for 5 km (3 mi) down the steep-sided of the volcano and into the deep trench that surrounds the islands. The slide deposited a thick layer of rubble outward to a distance of 230 km (140 mi) from Oahu (Figure 6).

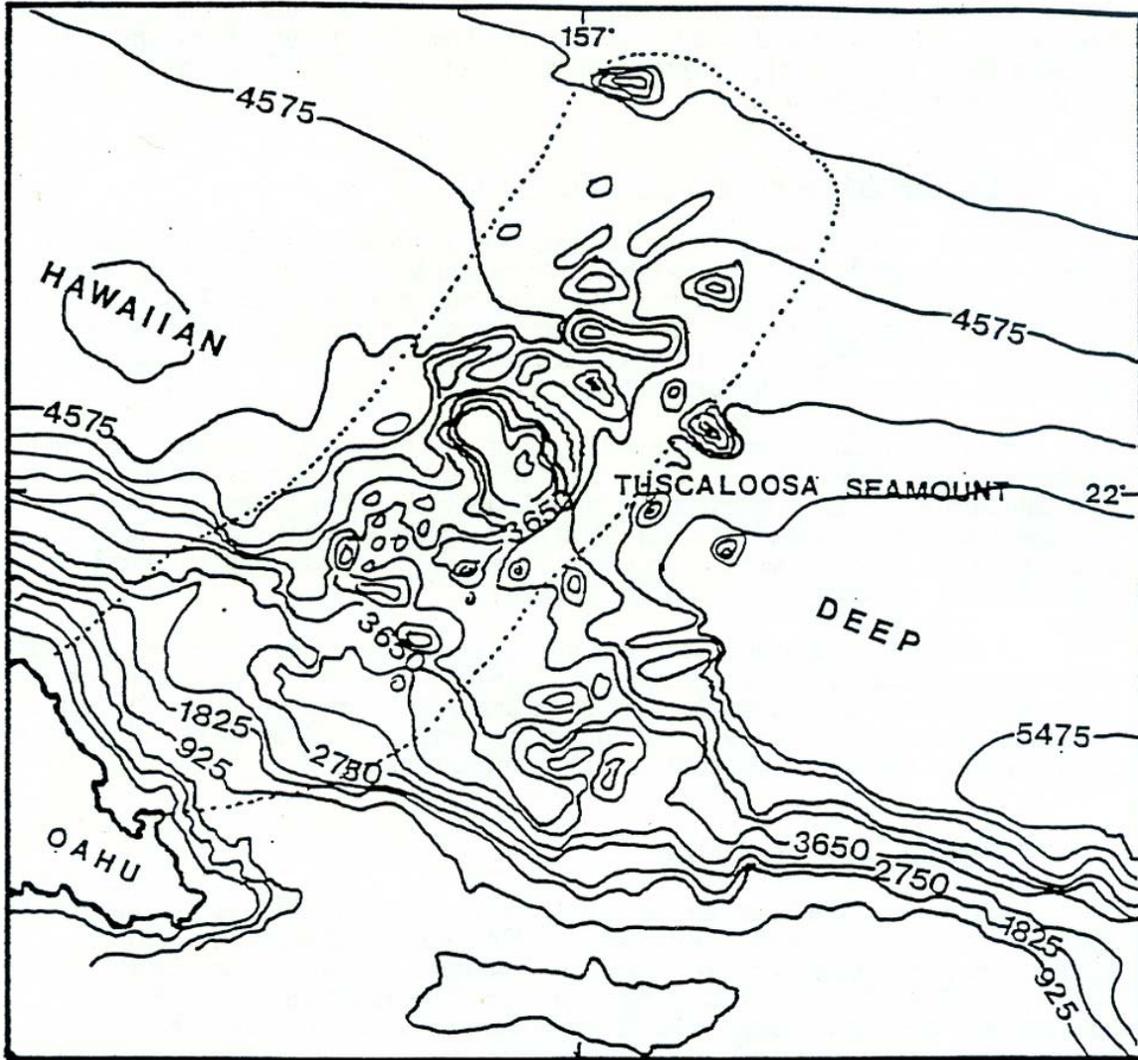


Figure 6: Map showing submarine topography along the windward side of Oahu. Area bounded by dotted line is believed to be debris from the Nuuanu debris avalanche. Contours in meters. (After MacDonald and Abbott, 1970)

Many pieces of rock were 0.8 km (0.5 mi) or more in diameter. One fragment of the Ko'olau volcano, now known as the Tuscaloosa Seamount is 32 km (20 mi) long, 18 km (11 mi) wide and over 1.8 km (1 mi) thick. This fragment of Oahu was carried a

distance of 96 km (60 mi) to the northeast of the Nu'uuanu Pali and now is located at a depth of 2680 m (8800 ft).

#### **4. The Honolulu Series of Volcanic Eruptions**

Approximately a quarter of a million years ago, a new set of cracks opened in a roughly north-south direction across the deeply eroded Ko'olau, and molten rock again rose to the surface in a second burst of volcanic activity (Macdonald and Kyselka, 1967). This period of secondary activity was called the Honolulu Series. Most of the vents of this series appear to lie northeast to southwest, at almost right angles to the principle rift zones of the Ko'olau volcano (McDonald & Abbott, 1970).

Eruptions flattened some of the valley floors and built a series of cones around the southeastern end of the Ko'olau. These cones were some of the earliest eruptions of the Honolulu Series. Located on Mokapu Peninsula, they include the volcanic vent of Pyramid Rock, Ulupau Head, and Pu'u Hawai'iloa (Figure 7). Elsewhere on Oahu, other eruptions of this series broke out near the sea and built the famous landmarks of Diamond Head, Punchbowl, Koko Crater, and Salt Lake.

All of these volcanic landmarks are tuff cones with the exception of Pu'u Hawai'iloa which is a cinder cone (Macdonald and Abbott, 1970). These tuff cones formed from fine brown ash blown up in steam explosions. These explosions were created by molten lava coming in contact with water. These eruptions frequently blasted through coral plains, so some tuff cones contain broken coral as well as volcanic material.

#### **5. Formation of Kaneohe Bay**

Basic geological events that resulted in the formation of Kaneohe Bay include the Kailua and Ko'olau volcanic series, erosion, the Honolulu volcanic series, reef building, changing sea level, and continuing erosion and sediment deposition (Sunn, Low, Tom & Hara, Inc., 1976). The Ko'olau series rift zone formed the northern and western boundaries of the Bay drainage basin. The southern boundary was formed by a coarse breccia ridge, a remnant of the main volcanic vent.

In the million years since the Nu'uuanu debris avalanche, the island moved further away from the "hot spot" and gradually subsided by approximately 1.8 km (1 mi). Erosion continued to shape the Kaneohe Bay watershed. The fluted columns of the Pali were formed by streams that cut into the vertical cliffs left along the Ko'olau volcano after the avalanche. Fed by rain from trade-wind clouds, the streams enlarged and their beds deepened the gullies, leaving high, sharp ridges between. Extensive alluvial deposits were formed. Windward valleys continued to wear down faster at their heads than at their seaward ends due to greater rainfall at higher altitudes.

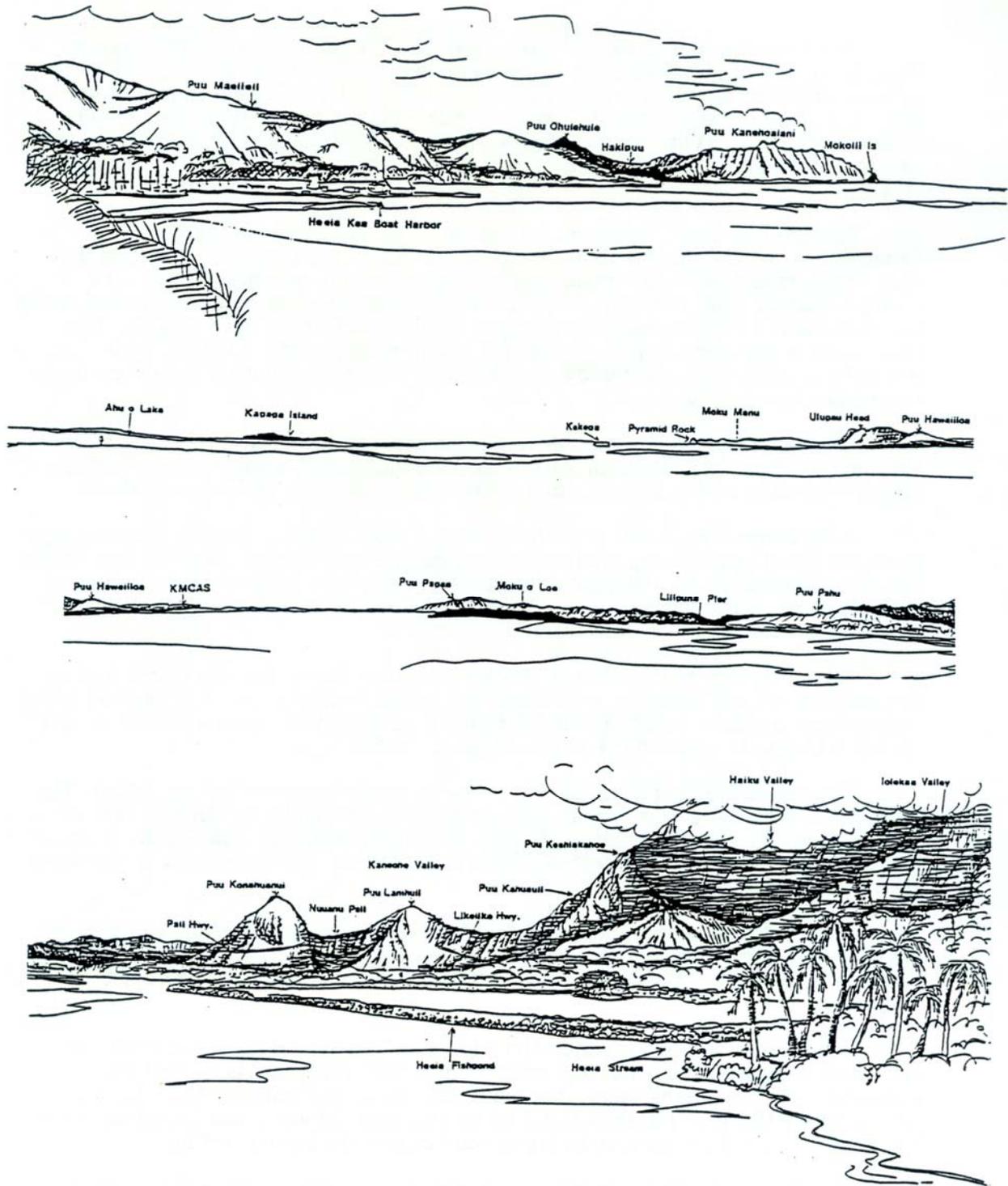


Figure 7: Kaneohe Bay as viewed from Kealohi Point at Heeia State Park, Kaneohe.

The original basalt ridges separating stream valleys became so eroded that currently only three reach the shore (Cox et al., 1973). These are: the ridges between Waiahole and Ka'alaea, between Kahalu'u and He'eia, and between He'eia and Kaneohe. The latter juts into the Bay as Pohakea headland and extends out to Moku o Loe (Coconut Island).

## 6. Changing Sea Levels

The principle cause of the changing sea level during the Pleistocene and Holocene epoch (approximately the last million years) was the formation and consequent melting of large glaciers. At its extremes, the sea level had stood as much as 76 m (250 ft) higher and 91 m (300 ft) lower than its present level. Sea level fluctuations resulted in periods when Kaneohe Bay dried out and reflooded (Stearns, 1974) (Figure 8).

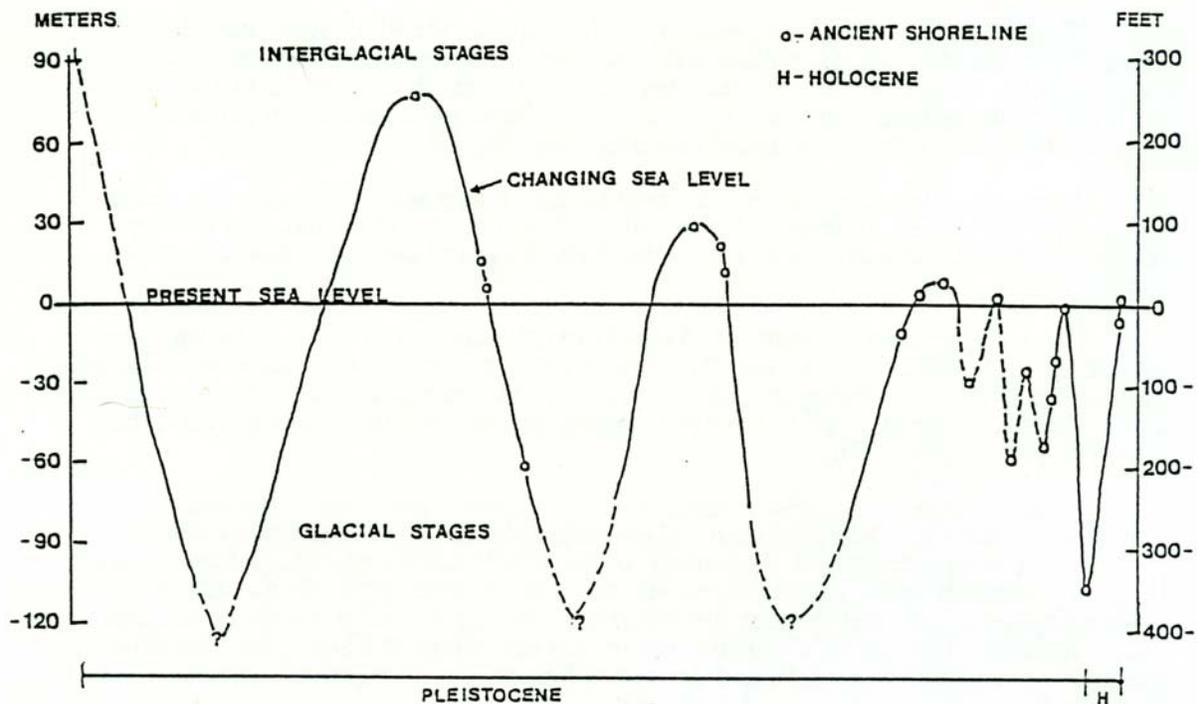


Figure 8: Sea level fluctuations during the Pleistocene and Holocene epochs. (After Sunn, Low, Tom, & Hara, Inc., 1976)

During high sea levels shorelines crept inland. Rising seas swept away old beaches, submerged tide pools, and drowned river valleys. New beaches were built, the barrier reef, fringing reef, wave cuts along mountain slopes, and sand and coral rubble deposits were formed.

Wave cut terraces at depths of 55 and 91 m (180 and 300 ft) in Kaneohe Bay were formed during low stands of the sea. The 55 m terrace was estimated to have been formed around 12,000 years ago (Shepard and Curry, 1967). The barrier reef also has terraces cut into the reef complex at 55 and 91 m deep suggesting that it was in existence prior to both these low stands (Roy, 1970).

Submerged, winding, stream cut channels in Kaneohe Bay were also formed during low stands of the sea. The bay's basin and two channels across the barrier reef were probably cut by stream erosion. According to Roy (1970), there appeared to have been a river valley heading in the present He'eia stream valley, a drainage divide running out toward Kapapa Island, and another stream system draining into what is now the channel next to Mokolii. This system also had tributaries in the valleys of Kahalu'u and Waiahole streams. As sea level raised, reefs, reef-derived sediments, and terrigenous materials filled Kaneohe Bay to its present general configuration.

## **7. Kaneohe Bay as Viewed from He'eia**

From the correct viewing platform such as KeAlohi Point on He'eia Ahupua'a, Kaneohe Bay presents a breath-taking panoramic vista (Figure 7). Here it is possible to view the entire He'eia Ahupua'a from Iolekaa and Haiku Valleys all the way to the tip of Mokapu Peninsula. The following discussion points out some of the major landmarks that can be seen along the bay in a panorama from the northwest to southeast end. A brief geological history of the bay and its surrounding watershed can be described by taking advantage of this panoramic view.

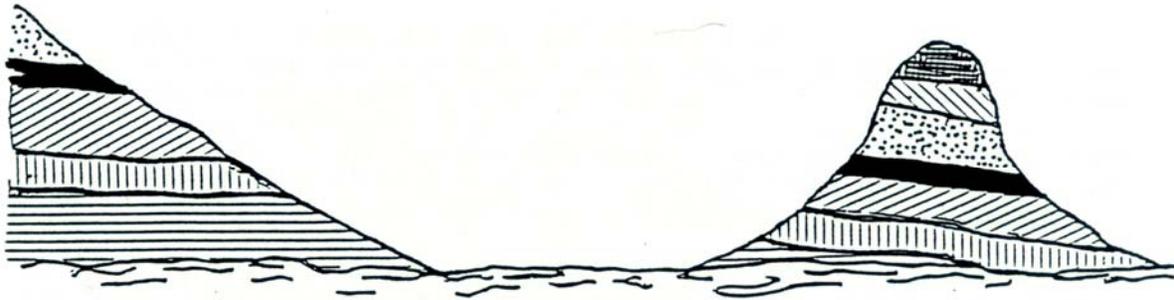
Immediately off KeAlohi Point to the northwest is He'eia Kea Boat Harbor. It is the only public marina with direct access to the bay. Other access is extremely limited, provided mostly by private yacht clubs and piers in private lots.

In the background of He'eia Kea is Pu'u Maelieli through which the rift zone of the old Koolau volcano extends (Gill, 1989). At about the middle of this northern extension of the rift zone is the triangular peak of 690 m (2265 ft) high Puu Ohulehule. At the base of this ridge is Puu Pueo (view blocked by Puu Maelieli), a small hill with red scars and massive dike formations.

At its northwest end, Kaneohe Bay ends in an abrupt wall 580 m (1900 ft) high. Here, in the face of Pu'u Kanehoalani, it is possible to see lava beds sloping down northeasterly from the old Ko'olau rift zone. At the foot of Pu'u Kanehoalani is Moli'i Pond, one of the only functional fishponds remaining in Kaneohe Bay. Between Pu'u Kanehoalani and Pu'u Ohulehule is Hakipu'u Valley. Hakipu'u contains lands that were once set aside solely for the kahunas or priests by Hawaiian ruling chiefs (Devaney et al., 1976).

Mokolii Island or Chinaman's Hat, the most picturesque of all the islands in Kaneohe Bay, lies 0.8 km (0.5 mi) off the northern shore. It is cone-shaped, and at first glance appears to have been formed by some kind of secondary eruption. It is not a

separate volcanic cone, however, but part of the old Ko'olau volcano that was isolated from the main mass by erosion and left standing as a little island, or sea stack (Figure 9). This small island is approximately 0.15 sq. km (37 acres) in area and 65 m (213 ft) high. The seaward side of Mokolii is exposed to considerable wave energy and has a wave cut bench and basaltic boulder talus.



**Figure 9: Mokolii Island showing lava flows corresponding to those on Oahu. The area between the two islands eroded away leaving Mokolii isolated. (After Carlquist, 1970)**

Kualoa, the ahupua'a where Mokolii is located, literally means "long back". This refers to the ridge extending from the Ko'olau Mountain range. Kualoa has a prominent place in Hawaiian tradition and is listed in the National Register of Historical Places.

A Hawaiian legend tells of the formation of Mokolii island. Hiiaka, Pele's younger sister, was traveling along the windward coast when she encountered the great moo dragon Mokolii. Hiiaka did battle with the giant lizard and killed the monster. She disposed of the body so that it formed part of the road-bed in Hakipu'u. Mokoli'i's tail landed in the ocean and the islet is the tip of its flukes.

On the horizon to the south of Mokolii is Kapapa Island. Kapapa Island is on an elevated area of hard limestone on the seaward margin of the barrier reef. Both the island and platform are composed of lithified dune material which was deposited when sea level was much lower. It is now in the process of being eroded.

The seaward side of the island has two wave eroded benches (Stearns, 1978). The lower bench is usually awash. It was cut at present sea level and is similar to limestone benches found on coasts throughout Hawaii. The higher bench is 1-2 m (3.3-6.6 ft) above sea level and was cut when the sea was higher than present. The lagoon side of the island has a wave-eroded notch.

Kapapa Island was once the site of both a Hawaiian heiau or temple and a fishing shrine or koa. Signs of human habitation and a burial ground were found there in 1952 (Devaney et al., 1976). Today, the island is still used by fishermen as an overnight campsite.

Landward of Kapapa Island is Ahu o Laka or "The Sand Bar". It is a small sand islet which is exposed at low tide and awash at high tide. It appears as a long light greenish-yellow band in the water. The main sand wedge that includes Ahu o Laka is approximately 18.5 m (60 ft) thick and 2 km (1.2 mi) long (Moberly and Campbell, 1969). It is about 1.7 (1 mi) offshore, at the lagoonward edge of the barrier reef flat.

This area of the lagoon receives sand carried across the barrier reef by currents. The sand spills down into the main lagoon and accumulates there. The sand wedge is growing landward and appears to be engulfing nearby patch reefs (Roy, 1970). Unique as a "beach in the middle of the ocean", Ahu o Laka is a favorite gathering spot for boaters and other recreational users of the bay.

Further southeast is Kekepa Island, or Turtle Back Rock. It is located on the seaward margin of the fringing reef off the end of the Mokapu Peninsula rather than on the barrier reef. It is also a lithified dune structure. Like Kapapa Island, it is exposed to severe wave erosion and has a prominent notch cut into its base.

The southwestern end of Kaneohe Bay is semi-enclosed by the Mokapu Peninsula. An area rich in Hawaiian cultural and religious traditions, both of land and sea, the peninsula extends about 5 km (3 mi) into the ocean. Although generally consisting of coastal lowlands, this peninsula has a volcanic cone, Pu'u Papaa, which was formed during the Honolulu series of eruptions about 250,000 years ago. Three prominent volcanic vents can be seen on this otherwise flat coral peninsula: Pyramid Rock, the Pu'u Hawai'iloa cinder cone, and the 210 m (683 ft) tuff cone of Ulupau Head.

Ulupau Head erupted off-shore in a series of steam explosions (Macdonald and Kyselka, 1967). It is an off-shore tuff cone. It may have once looked much like Manana Island (Rabbit Island) on Oahu does today. The water between the mainland of Oahu and Ulupau Head was shallow at the time of eruption. When the sea level dropped, the coral reef that makes up most of Mokapu was exposed, connecting the island to Oahu as a peninsula.

Ulupau Head was formed later than Pu'u Hawai'iloa and sits on a thick lava flow from the Pu'u Hawai'iloa cinder cone. Nearby is Pyramid Rock which appears to be a deeply eroded vent in which the dike feeder has been exposed (McDonald and Abbott, 1970). It probably erupted even earlier than Pu'u Hawai'iloa.

Hidden from view about 2 km (1.2 mi) beyond Ulupau Head is a small island known as Moku Manu. It is the remnant of an eroded tuff cone. It was also formed during the Honolulu series. Today, Moku Manu, which means "bird island", is a bird refuge and an important nesting site for sea birds. These include three species of boobies, the Great Frigate or iwa bird, four species of terns, two shearwater species, and Bulwer's Petrel.

A large island can be seen in the southern portion of the bay. Moku o Loe is a remnant of the basalt ridge that forms Pohakea headland. The fringing reef surrounding

the island is quite similar in structure to the patch reefs in the bay. Originally 0.05 sq. km (12 acres) in size, it has been extensively dredged and filled to extend the island to its present 0.11 sq. km (28 acres).

Originally, Moku o Loe was owned by Hawaiian royalty. Later it came under the ownership of Bishop Estate. It was purchased in 1933 by Chris Holmes, a Fleishman yeast heir. It was he who enlarged the island, built the ponds, harbors, and seawall surrounding the island. He also planted large numbers of coconut palms which gave rise to the popular name, "Coconut Island".

After Chris Holmes passed away in 1944 Coconut Island was used for an Army Rest & Recreation center until it was bought by five investors. Eventually Edwin Pauley became principal owner. He gave the University of Hawaii land and a large research grant to establish Hawaii Institute of Marine Biology. Currently Coconut Island is owned by a Japanese investor Katsuhiko Kawaguchi. HIMB has become known worldwide as a leading marine biological research institute.

Surrounding Kaneohe Bay landward are, again, the Ko'olau Mountains. Seen to the right of Mokapu Peninsula's Pu'u Papaa and in the foreground is Pu'u Pahu, a hill on the mainland overlooking Moku o Loe. Lilipuna Pier, which provides access by boat to Moku o Loe, is located here. This headland is known as Pohakea.

To the right and continuing southwest are the peaks of Pu'u Konahuanui, Pu'u Lanihuli, Pu'u Kahuauli, and Pu'u Keahiakahoe. These surround the large valley of Kaneohe. A Hawaiian legend includes many of these place names and makes them easier to remember.

Three brothers, Kahoe, Kahuauli, and Pahu, and their sister, Loe, were sent from Ewa to live in Kaneohe. Loe lived on Moku o Loe (Loe's island). Kahuauli was a farmer at Lulukū (in the area of Pu'u Kahuauli). Kahoe was a farmer near Haiku and Kea'ahala, and Pahu was a fisherman in Pohakea (in the area of Pu'u Pahu).

When Pahu went to visit Kahoe he always received poi from him. In return, he gave Kahoe small leftover baitfish instead of good large ulua that he caught daily. Kahoe eventually learned of Pahu's deceit from Loe who came over from her island to visit him.

Several months later there was a famine and everyone hid the smoke from their cooking fires to avoid having to share their food with others. Kahoe was able to conceal his smoke in his valley. It traveled one to two kilometers before appearing on the summit of the cliff. One evening Loe caught Pahu looking longingly at Kea'ahala and said, "So, standing with eyes looking at Keahiakahoe (Kahoe's fire)." To this day the peak carries this name (Gill, 1989).

On the face of Pu'u Konahuanui, Pali Highway is visible leading up to the famed Nu'uaniu Pali Pass. The pass was formed by two amphitheater-headed valleys eroding

into each other - Kaneohe from the windward side and Nu'uaniu from the leeward side (Gill, 1989). The ridge between the two valleys has been slowly eroded away.

The same thing is happening at the heads of Kaneohe and Kalihi valleys and also at the heads of Haiku and Moanalua valleys. Likelike Highway is visible on the face of Pu'u Lanihuli where Kaneohe and Kalihi valleys are merging. The Haiku and Moanalua valley heads are also the site of the now under construction H-3 freeway.

Pu'u Keahiakahoe is the tallest peak on the mountain range above Kaneohe Valley. On its close side is the deep amphitheater-headed valley of Haiku. In the foreground of both is the valley of Iolekaa which is directly mountainside of He'eia.

This panoramic view ends with He'eia Fishpond immediately off the right side of the viewing platform. He'eia Fishpond is one of the five remaining walled fishponds in Kaneohe Bay and is eligible to be an historic site on the National Register. It is also one of the more structurally unique ponds in the bay.

He'eia Pond's wall is one of the longest, extending for nearly 2 km (1.2 mi) and completely surrounding the pond. Other ponds have the shoreline as its inner wall. He'eia Fishpond is 0.36 sq. km (88 acres) in area. Built in the late 1800's by possibly 10,000 or more men (Devaney et al., 1976), it is no longer functional. The flood of May 1965 caused a 40 m (130 ft) breach in the seaward wall.

### **C. Bathymetry of Kaneohe Bay**

Kaneohe Bay is the largest sheltered body of water in the Hawaiian Islands. It is about 12.7 km (7.9 mi) along the NW to SE axis and about 4.3 km (2.7 mi) wide. Total surface area at mean sea level is 61 x 10<sup>6</sup> m<sup>2</sup> (16 sq. mi. or 15,000 acres) (Holthus, 1986a).

Although the lagoon has a mean depth of 10 m (33 ft), there are two depth zones (Roy, 1970). The shallower zone of 1.5-6.1 m (5-20 ft) is associated with disposal of dredge spoils and stream delta formation. The deeper zone of 12-14 m (40-45 ft) is associated with the flat lagoon bottom. The total volume of the bay, out to the outer margin of the barrier reef is about 381 x 10<sup>6</sup> m<sup>3</sup> (100 x 10<sup>6</sup> yd<sup>3</sup>).

Bathen (1968), in describing the bay's bathymetry, divides it into inshore and offshore portions (Figure 10a and b). The bay is also divided longitudinally into three sections: NW, central, and SE (Figure 10a, c and d). This division is based on circulation, physiography, and oceanic influence (Bathen, 1968; Smith et al., 1981).

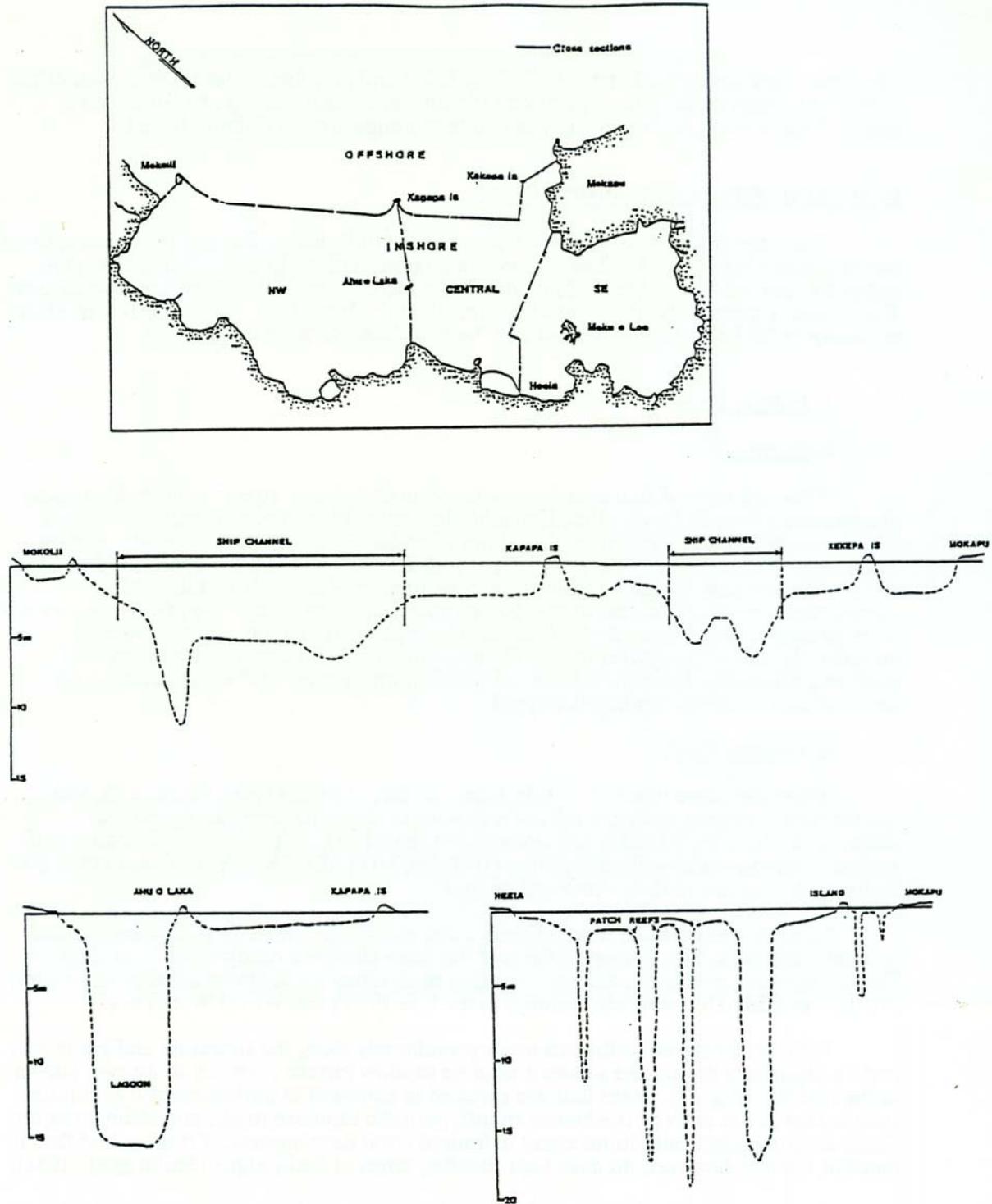


Figure 10: Kaneohe Bay cross section at "division" boundaries. (a) Bay showing "boundary" lines. (b) Longitudinal cross section through the bay. (c) Section between NW and Central sectors. (d) Section between Central and SE sectors. (After Sunn, Low, Tom, & Hara, Inc., 1976)

The inshore portion comprises 66% of the total bay area and has an average depth of 6.1 m (20 ft). It is characterized by numerous patch reefs rising to within less than a meter (3 ft) of the surface. The entire shoreline, except parts of Mokapu Peninsula, is ringed by shallow fringing reef .3-.9 m (1-3 ft) deep and extending 300-750 m (1000-2500 ft) (Cox et al., 1973).

The inshore portion contains the greatest depth found in the Bay at 19 m (62 ft). Both the surface area and average depth decrease towards the northwest although the number of patch reefs increase. The bottom is predominately coral rubble, gray coral muds, and fine coral sands. Close to the shoreline, especially near stream mouths, fine brown silts and clays are found. The inner bay is largely protected from ocean and storm swells. The SE basin is protected and semi-enclosed by the Mokapu Peninsula and Moku o Loe (Coconut Island). A barrier reef with a depth of .3-1.2 m (1-4 ft) fronts the exposed portion of the bay.

Moku o Loe (Coconut Island) and Mokolii (Chinaman's Hat), in the inshore area, are the only basaltic islands in the bay. They are remnants of the eroded volcano. Moku o Loe is a remnant of the ridge that forms Pohakea headland, while Mokolii is a dike of harder volcanic basalt that was more resistant to erosion than the surrounding material.

The offshore portion comprises 34% of the total Bay area. It consists almost entirely of an extensive shallow coral and sand reef .3-1.2 m (1-4 ft) in depth. In the central section, live coral, small-sized coral rubble, coarse coral sand, and volcanic rock are found.

Two natural navigable channels 6 km (3.8 mi) apart (Cox et al., 1973) cross the barrier reef and lead straight into the Bay (Figure 10b). The NW (Mokolii) channel has been dredged to a depth of about 10 m (33 ft) to accommodate larger ships. Large amounts of coarse sand are actively being transported into the Mokolii channel. The SE (Sampan) channel has not been dredged and has a depth of about 2 m (6.6 ft). Larger coral rubble predominates in this channel. A small channel was also dredged adjacent to the Mokapu Peninsula that feeds into the Sampan Channel. Another channel dredged to a minimum of 12 m (40 ft) runs the entire length of the Bay.

Kapapa Island on the barrier reef and Kekepa Island (Turtle Back Rock) near the Mokapu Peninsula are sand dunes that have changed to stone. (Submerged lithified dunes Figure 10) Cross sections of Kaneohe Bay also form a portion of the barrier reef (Roy, 1970) and may form extensive portions of the barrier reef ridge area. The two exposed islands are currently being eroded by wave action. This is very clearly shown by the undercut edge around Kekepa Island.

#### **D. Physiographic Zones**

The three major physiographic marine zones of Kaneohe Bay are the inshore, inner bay, and outer bay (Figure 11). The inshore zone consists of the intertidal zone

along the shoreline, and the fringing reef. The inner bay zone consists of the lagoon and patch reefs. The lagoon is generally divided into SE, central, and NW sectors. The outer bay consists primarily of the barrier reef complex and the two channels bisecting the reef.

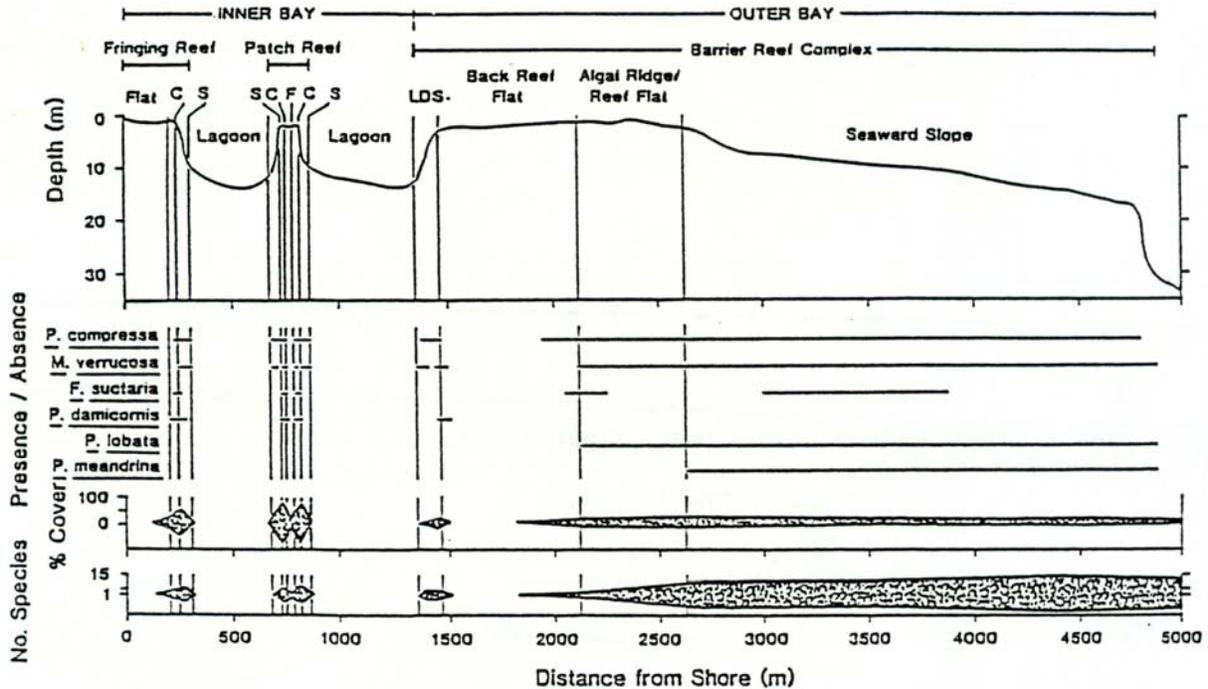


Figure 11: Generalized profile of Kaneohe Bay showing physiographic zones and coral distribution, abundance, and diversity. (After Holthus, 1986b; and Maragos, 1973) c=reef crest; s=reef slope; f=reef flat; LDS=lagoon depositional slope

1. Inshore Zone  
 1. Shoreline

Although natural shoreline areas consisting of beaches, stream mouth deltas, and promontories are still found along Kaneohe Bay, much of the bay's shoreline has been heavily modified. The earliest modifications were fishponds constructed by the ancient Hawaiians. Fishponds may have covered as much as 30% of the bay's shoreline (AECOS, 1981). More recent modifications include construction of seawalls and land fills. Agriculture, urbanization, and stream bed channelization have increased freshwater runoff rates causing sedimentation and pollution. The introduction of mangroves has also modified the shoreline environment. The shoreline is the area most affected by land practices, especially the semi-enclosed SE portion where most of the urbanization has occurred and where circulation is sluggish.

## 2. Fringing reefs

There are three types of reefs in Kaneohe Bay: fringing reefs, patch reefs, and the barrier reef. Fringing reefs are shallow quiet-water reefs that occur along most of Kaneohe Bay's land perimeter and average less than 1 m (3.3 ft) in depth. Fringing reefs generally extend outward for 300-750 m (1000-2500 ft) (AECOS, 1981). Those in the NW sector of the bay are slightly wider and deeper.

Natural breaks in the fringing reefs occur where freshwater streams have cut and maintain channels. Some areas of the reef flat have also been dredged for boat channels. This is especially true in the SE bay. Fringing reefs along the south basin were extensively dredged and filled for seaplane runways in the late 1930's and World War II era.

Fine, land-derived sediments occur prominently along the shoreline and grade into marine sediments toward the seaward edge on shallow surface portions of the reef known as the reef flat (Figure 12). Reef flats are exposed to extremes of environmental conditions such as changes in salinity, freshwater runoff, periodic exposure to air, and sedimentation. These environmental conditions result in limited coral development. Fringing reef flats in much of the bay, however, do have high standing crops of fleshy algae (Smith et al., 1981).

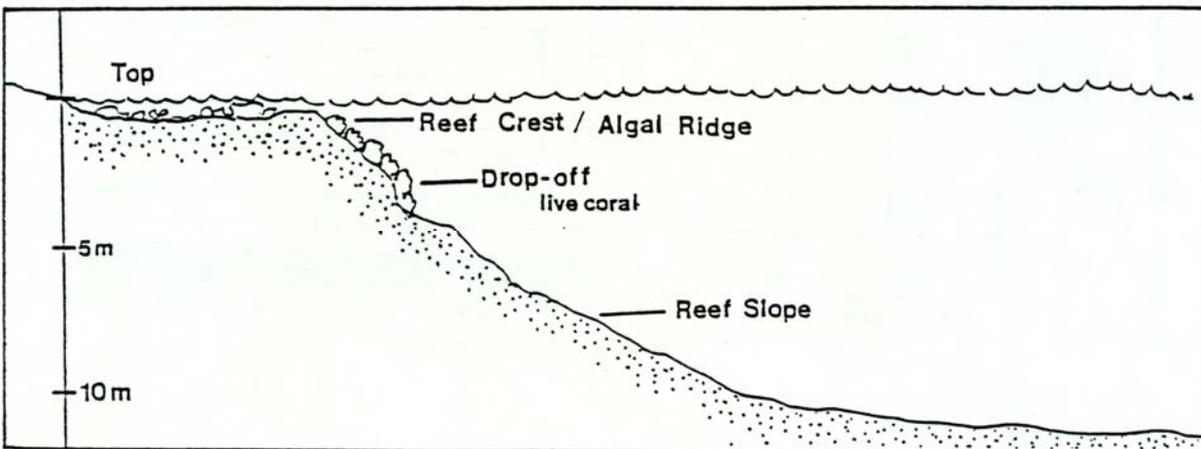


Figure 12: Generalized profile of a fringing reef in Kaneohe Bay.

At the seaward end of the reef flat is a hard-bottomed wave-resistant algal ridge or reef crest. This crest is the highest part of the reef. It is often exposed during low tides.

Beyond the crest a near vertical coral covered drop-off extends about a meter (3.3 ft) down to the reef slope, which continues to the lagoon floor. Coral cover as well

as abundance and diversity of reef fish tend to be high on the reef slope. Fine muddy sediments surround the corals. Although sediments below the actively growing coral generally get finer with depth, large blocks of slumped off coral rock frequently occur in the upper sections of the slope.

Live coral coverage on the fringing reef varies according to environmental conditions. In the NW portion, where water circulation and mixing are good, corals are abundant and occur at greatest depths. In the SE portion, where urbanization, runoff, and sedimentation is greatest and circulation is sluggish, coral development is poor. The SE bay may have had some of Hawaii's finest coral gardens at one time (Banner, 1974; Devaney et al., 1976).

## **2. Inner Bay Zone**

The inner bay zone lies between the fringing reef slope and the lagoon side of the barrier reef. It includes the lagoon and patch reefs. The inner bay is usually divided into three physiographic sectors on a SE to NW axis. This division is based on circulation and relative degree of oceanic influence (Bathen, 1968; Smith et al., 1981).

### **1. Lagoon**

The semi-enclosed SE basin has very restricted circulation and limited exchange with the rest of the bay and oceanic waters. Three major streams empty into the SE Basin, often resulting in lower salinities than other areas of the inner bay. The central portion of the lagoon receives both a moderate influx of freshwater from the surrounding watershed and substantial oceanic water across the barrier reef. It is more oceanic than the SE basin. The NW portion of the lagoon is the most oceanic in character due to a large influx of water over the barrier reef and through the NW channel.

The lagoon waters support a relatively large standing crop of phytoplankton and zooplankton (Smith et al., 1981). Abundant pelagic fishes range from planktivores to top carnivores (sharks). The associated fisheries are of local importance to commercial, subsistence, and sport fishermen.

The lagoon bottom, excluding patch reef areas, has two depth zones. Most of the lagoon bottom slopes from the fringing reef to the barrier reef and has a depth of approximately 10-14 m (33-46 ft). Stream deltas and places where dredge materials have been dumped have a depth range of 1.5-6 m (5-20 ft).

About 50% of the sandy mud on the lagoon bottom is calcium carbonate that was washed into the lagoon from the barrier reef (Smith and Kam, 1973). This material is concentrated near the sandbar. Land-derived volcanic soils become more abundant with proximity to shore. Natural deposition rates of terrigenous material have been increased by agriculture and urbanization along shore and in the watershed. Roy (1970) estimated that the lagoon bottom shoaled by 1.65 m (5.4 ft) between 1927 and 1969. Biota of the lagoon bottom are sparse (Smith et al., 1981).

## 2. Patch reefs

Patch reefs are round to irregular in shape and resemble underwater smokestacks that rise from the bay bottom to near sea level. There are seventy nine patch reefs in Kaneohe Bay, although twenty five were partially or wholly dredged. The remaining patch reefs range in size from 21 m-850 m (70 ft-2800 ft) in diameter, and have a collective surface area of  $2.02 \times 10^6 \text{ m}^2$  ( $2.42 \times 10^6 \text{ yd}^2$  or 500 acres) (Roy, 1970). Most are within 0.6-0.9 m (2-3 ft) of mean sea level although some are as deep as 1.5-3 m (5-10 ft).

Patch reefs were formed by upward coral growth during periods of rising sea level (Roy, 1970). Although it is not known what effect subaerial erosion during low sea level stands had on the formation, modification, and distribution of patch reefs, it is likely that they were eroded down to knolls. During resubmergence, reef growth was able to begin again on the nubs of the relict reefs. New, previously unoccupied substrate was also available for new coral growth and the start of new patch reefs. The youngest of the patch reefs probably began to grow about 12,000 to 8,000 years ago at which time sea level rise began to stabilize and the lagoon bottom rapidly became muddy, preventing formation of more reefs.

The patch reefs in Kaneohe Bay tend to be concentrated near the two channels across the barrier reef. This nonrandom distribution indicates that their development and maintenance may be related to the strong currents and water activity in the vicinity of the passes (Roy, 1970). There seems to be no correlation between the patch reefs and the bay's substratum.

Patch reefs in Kaneohe Bay are simple, small, round-to-oval structures, or larger multilobate structures. The latter are probably compound reefs formed by the joining of simple patch reefs. Compound patch reefs tend to form where simple reefs developed close together.

The most active growth occurs on the side facing the wind and/or current direction. This results in a tendency for reefs to elongate (Figure 13). The actively growing end can also slump, thereby providing new surfaces for coral growth. The down-current end of the reef accumulates both sediments formed by the reef and those carried to the reef by currents.

Most of the coral and coralline algae development is on the sides of patch reefs, with the upper slopes generally supporting the most luxurious coral growth. The flat tops of patch reefs, especially those greater than 30 m (98 ft) in diameter (Roy, 1970; Smith and Kam, 1973), tend to have little live coral growth. They tend to be covered by sand, gravel, dead coral, rubble, and algal nodules. This is probably due to the shallow depth of the reef tops. Small patch reefs, especially those that are not as shallow, tend to have better coral coverage on the top.

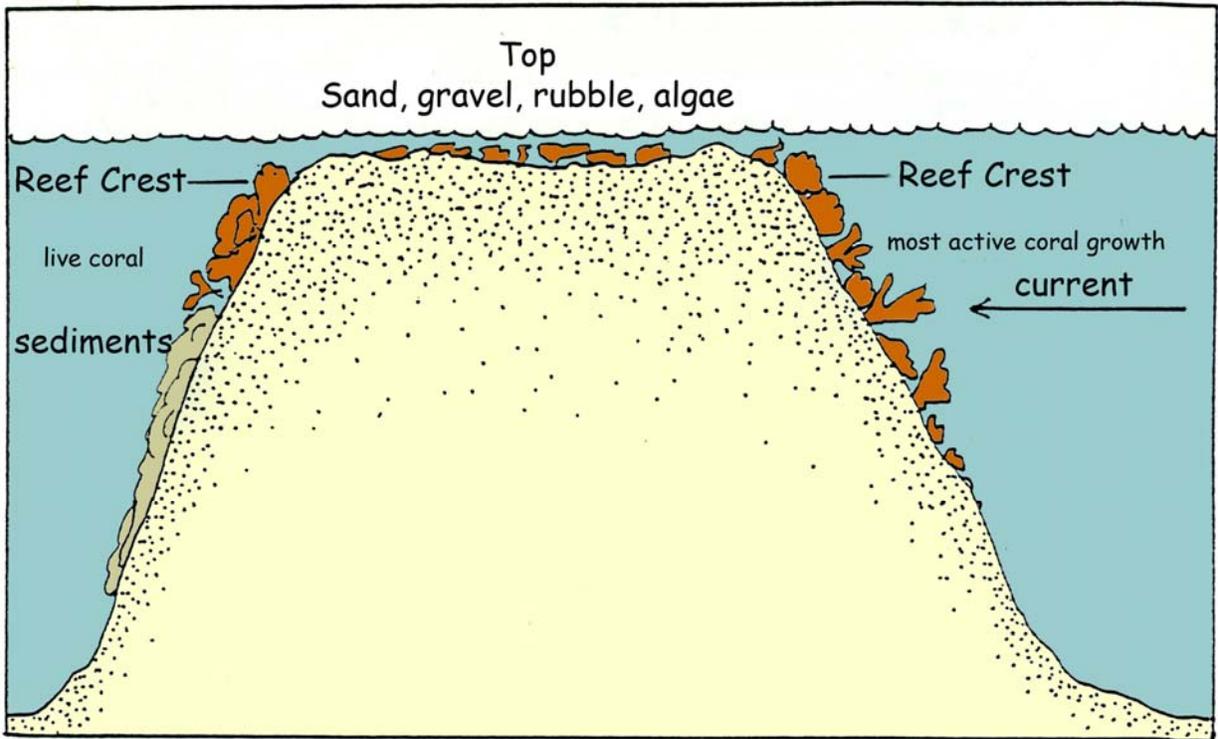


Figure 13: Generalized profile of patch reef in Kaneohe Bay.

### 3. Barrier Reef Complex

Kaneohe Bay probably does not have a true barrier reef composed entirely of limestone. True barrier reefs are formed by calcium carbonate depositing, light requiring organisms that are able to grow at a rate equal to the rate at which a land mass is subsiding or sea level is rising. The Kaneohe Bay barrier-type reef (henceforth called a barrier reef), is probably a basaltic structure that is overlaid with calcium carbonate. It, therefore, has the structure of a barrier reef, but probably a different developmental history.

The barrier reef complex, including the two channels located at the north and south ends, is about 2 km (1.2 mi) wide and more than 5 km (3 mi) long (AECOS, 1981). It consists of four physiographic zones extending from the lagoon to oceanic waters (Figure 14). The zones are the: lagoonward depositional slope, back reef flat, algal ridge/reef flat, and the seaward reef slope. These zones show considerable variation along the length of the barrier reef as a result of different environmental conditions (wave exposure, currents, etc.). The barrier reef complex has not been greatly altered by human activity in the Kaneohe region, although the NW channel was dredged to accommodate large ships.

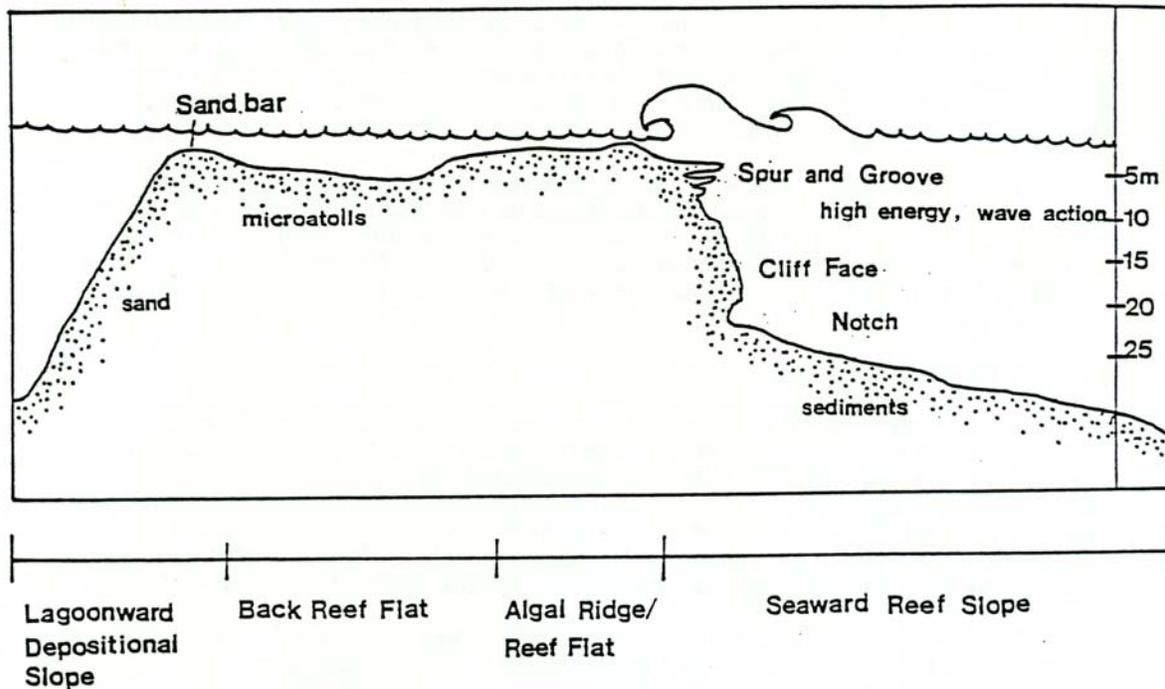


Figure 14: Generalized profile of the barrier reef complex in Kaneohe Bay.

## 1. Lagoonward depositional slope

Located on the lagoonward side of the barrier reef, this steeply sloping depositional face rises from the lagoon floor and extends to the back reef sand flat (Figure 14). Calcareous sands and rubble generated on the barrier reef are carried lagoonward by wave action and currents and deposited on the back reef flat and depositional slope. The resulting sand wedge at the juncture of the lagoonward depositional slope and back reef flat is 18.5 m (61 ft) thick (Moberly and Campbell, 1969; Smith and Kam, 1973) and composed of well sorted calcareous sediments. Some algae and sea grass are present on the upper portion of the depositional slope (Smith et al., 1981).

## 2. Back reef flat

The back reef flat is a 1-2 km (0.6-1.2 mi) wide expanse of unconsolidated calcium carbonate material that was generated on the seaward reef slope and reef flat. It is composed of silt, sand, and rubble that is gradually transported lagoonward to be deposited on the lagoonward depositional slope. The deposits form a sand wedge with a maximum thickness of about 18.5 m (61 ft) and volume of at least  $9.84 \times 10^6 \text{ m}^3$  ( $1.29 \times 10^7 \text{ yd}^3$ ) (Moberly and Campbell, 1969). This sand wedge is growing landward and appears to be engulfing nearby patch reefs (Roy, 1970). Its inner margin is marked by

a large sand bar or island (Ahu o Laka) which is exposed to varying degrees depending on the tidal level.

Much of the back reef flat has a water depth of less than 1-2 m (3.3-6.6 ft). It has a limited amount of coral development in the form of small patches. Microatolls, or coral wheels, also form where periodic exposure at low tide restricts upward coral growth. Various types of seaweeds which occur on the back reef flat help stabilize the sediments.

### **3. Algal ridge/reef flat**

The back reef flat rises precipitously as much as 1.5 m (5 ft) to the 1-2 m (3.3-6.6 ft) deep 65 m (215 ft) wide algal reef flat. This seaward, top portion of the barrier reef complex is predominantly hard-bottomed with abundant corals, algae, and other reef organisms. In this high energy zone, ocean waves are absorbed, protecting reefs in the lagoon and producing a landward flow of water. This landward flow redistributes organic material and calcareous sedimentary material to the back reef flat and lagoonward depositional slope.

The shallowest portion of the reef flat is an algal ridge that reaches within 0.3 m (1 foot) of the water surface. Seaward of the algal ridge, the reef flat slopes gently toward the seaward reef slope. This area has shallow limestone ridges and sand-filled gullies parallel to the water movement that are the beginning of the spur and groove system.

The wide algal reef flat and gently sloping seaward edge of the Kaneohe Bay barrier reef distinguish it from typical barrier reefs. Roy (1970) suggested that it may be a (Figure 14) barrier reef complex, relict beach or dune ridge that has recently been covered by a veneer of coral and coralline algae. This seems to be substantiated by the differences found along the barrier reef. The NW end is an older, reduced area and the SE apparently the actively growing section (AECOS, 1981).

### **4. Seaward reef slope**

The seaward reef slope consists of a near-surface high energy spur and groove zone, a submarine cliff, and a sediment depositional area (Figure 14). The high energy spur and groove zone dissipates most of the tradewind and storm wave energy that would otherwise enter Kaneohe Bay. Sediments not carried onto the reef flat pass down the grooves to be deposited in deeper water. Wave resistant corals and coralline algae grow on the spurs.

The 3-4 m (10-13 ft) deep spur and groove zone descends gently to the top of an eroded cliff at 18 m (60 ft) depth. The cliff continues down to about 27 m (90 ft). A wave cut notch in the cliff at 24 m (80 ft) suggests that the sea was at this level for some time and is responsible for the caves and overhangs in the cliff face (Stearns, 1974).

Below the cliff is a shelf that extends several kilometers out to sea. This is a depositional area for sediments generated on the reef slope.

## **5. Barrier reef passes**

Two channels, one at each end of the bay, separate the barrier reef from the adjacent fringing reefs. Seismic data indicate that each is a relatively deep valley that has been filled with sediments. The channels were either cut by stream action during lower sea level stands, are the result of reef growth during higher sea levels, or a combination of the two. The two channels transport sand in addition to water into and out of the bay. The depth of the water in the two channels allows relatively unimpeded wave energy to pass into the bay. This influences mixing patterns and circulation (Bathen, 1968).

The NW (Mokolii) channel was dredged in 1939 to a depth of 10-11 m (33-36 ft) to accommodate shipping. Between 1949 and 1977, the channel shoaled about 1 m (3.3 ft) (Hollett, 1977), indicating that it is relatively good at flushing itself. In fact, the majority of the water and sediment transported from the bay pass through the NW channel (Bathen, 1968). The SE (Sampan) channel accommodates only small boats because it is relatively shallow and has not been dredged. It transports much less water and sediment than the NW channel (Bathen, 1968).

## **E. Meteorology and Hydrology of Kaneohe Bay Watershed**

The Kaneohe Bay watershed is about 97 km<sup>2</sup> (37 mi.<sup>2</sup> or 24,000 acres) (Smith et al., 1981) in area. It consists of a portion of the Ko'olau mountains and coastal lowlands surrounding the bay. It is drained by a series of intermittent small streams. Drainage after a rainfall is rapid due to the near vertical cliffs of the Ko'olau.

About sixty percent of the bay's watershed is coastal lowlands. The coastal lowlands consist of alluvial deposits, rolling hills from 5 to 250 m (16 to 820 ft) in height, and three basaltic ridges that bisect the lowlands. Seventy percent of the deposits are older, more consolidated, and less permeable (Figure 15). These extend from sea level to an elevation of about 200 m (660 ft). Younger material overlies the older sediments from sea level to an elevation of 70 m (230 ft). This younger, reworked material is less consolidated and more permeable (Takasaki et al., 1969).

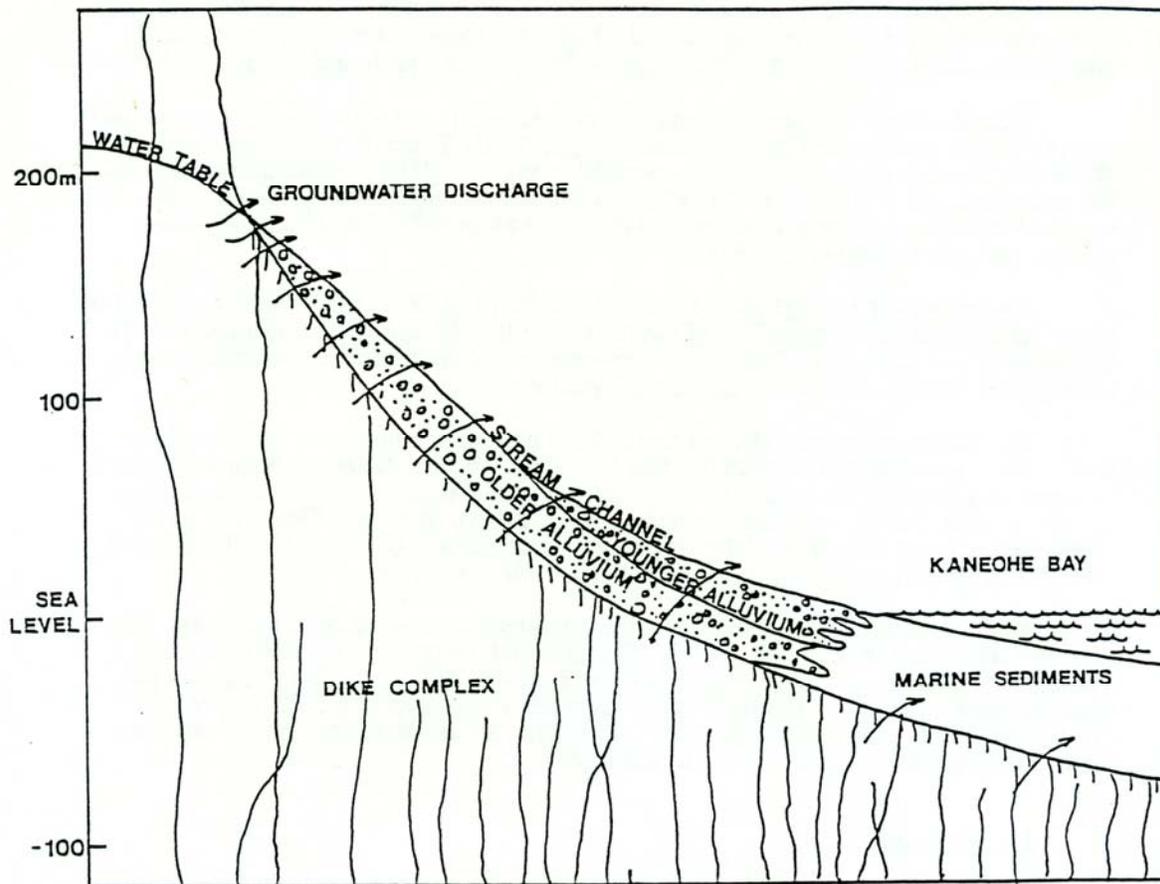


Figure 15: Distribution of alluvial deposits in the Kaneohe Bay watershed . (After Sunn, Low, Tom, & Hara, Inc., 1976)

## 1. Climate

Hawaii lies in the northeast tradewind belt. The climate of Kaneohe Bay is semitropical (Chave, 1973). The wet season extends from October to May, with August having the highest monthly average rainfall (Holthus, 1986a). Maximum daily rainfall, however, usually takes place in winter during storms which counteract the tradewind flow.

Rainfall averages about 2400 mm (94 in) per year in the watershed and about 1400 mm (55 in) per year in the inner bay (Smith et al., 1981). Torrential rains are common. Water loss through evaporation and transpiration averages 1100 mm (43 in) per year for the watershed and 1700 mm (67 in) per year for the inner bay (Takasaki et al., 1969). The bay and watershed receive an average net freshwater input of  $117 \times 10^6$  m<sup>3</sup> (31 billion gallons) per year (Smith et al., 1981).

Air temperature ranges between 20 °C (68 °F) and 28 °C (82.4 °F) throughout the year. Tradewinds blow about 70% of the time from the NE and E, and average 18.5-20 km per hour (10-11 knots). Tradewinds are more consistent during the summer months, although the strongest winds develop during winter storms.

The Ko'olau mountain chain forms a sharp cliff perpendicular to the prevailing trades. As the tradewinds encounter this cliff, their moisture-laden air is forced upward suddenly and swiftly. This updraft is so strong near the Nu'uanu Pali where the highway crosses the cliff that it sometimes creates an "upside down waterfall". The wind blows water from existing falls upward during many days of the year (Carlquist, 1980). During rainfall this updraft may even make raindrops appear to fall upward.

As this air rises up the mountain cliff, it suddenly contacts a colder air mass. Its moisture condenses resulting in rainfall. This is called the orographic effect (Figure 16). Though the outer margin of the bay receives only about 75-100 mm (3-4 in) of rain per year, the ridge crest of the Ko'olau Mountains receive 380-500 mm (15-20 in) per year (Taliaferro, 1959). Occasional severe winter storms release large amounts of rain that cause flooding that can severely impact the bay

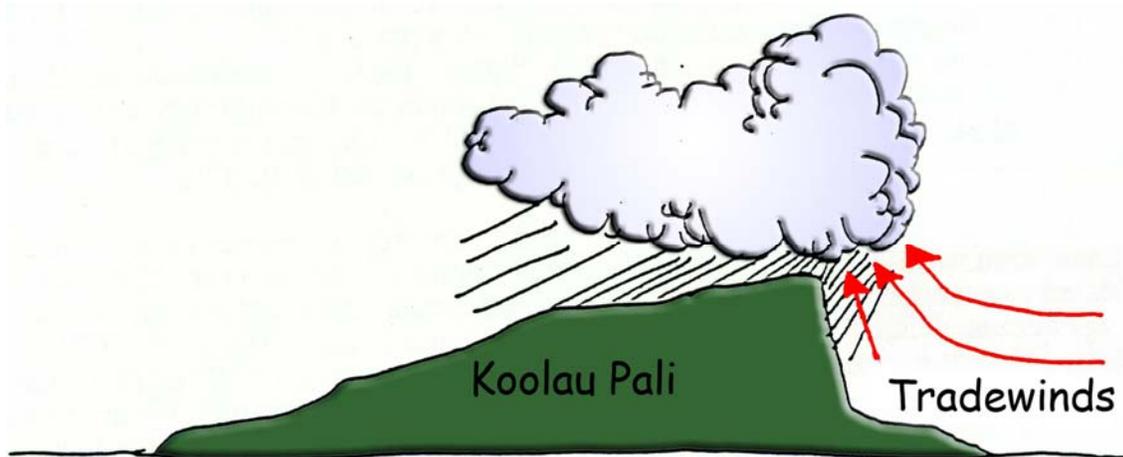


Figure 16: Formation of theographic rain at windward Oahu.

## 2. Hydrology

A continuous water cycle can be described for tropical volcanic islands. Its pattern varies at different times and places according to differences in landforms, soils, and rainfall. The cycle is also modified by human activities, such as diversion of stream water for irrigation, loss of groundwater from wells, alteration of infiltration by resurfacing the land, altering evapotranspiration and runoff patterns by agricultural and urban development, and disposal of sewage effluent into the ocean.

## **I. Sources of Surface Water - Streams**

The landforms of surface water drainage basins reflect the geologic age and rainfall in different parts of the Hawaiian Islands. Watersheds are typically small. Of the streams gauged on Oahu, 80 percent have drainage areas smaller than 13 sq. km (5 sq. mi. or 3200 acres) (Armstrong, 1983). The relief of the watershed land and the stream channel is steep, especially in the headwaters. Stream channels are short and lack storage, and at times of heavy rain they are liable to flash floods.

Many streams are nearly perennial in mountainous areas where orographic rain occurs daily. Streams that traverse dry lowland and coastal plains tend to lose water as it seeps into the porous soil. Stream water is usually tapped by diversion in rainy headwater areas and transported long distances from the watershed. Stream water quality is generally lower than that of groundwater in terms of turbidity, nutrients, and coliform, especially during wet weather periods. Outside of the forest reserve headwater areas, urban and agricultural activities introduce pollutants such as traces of pesticides and heavy metals.

Although freshwater enters Kaneohe Bay directly from rainfall, most comes from runoff from the watershed. The steep slopes and stream channels in the nearly vertical Ko'olau Mountains result in large volumes of runoff. Seven perennial streams carry most of the surface freshwater discharge into the bay. Fifty percent of the net runoff enters the NW region of the bay and 25% enters the SE (Bathen, 1968). Of the estimated  $117 \times 10^6$  m<sup>3</sup> (31 billion gallons) per year of freshwater that enters the Kaneohe Bay watershed and bay (Smith et al., 1981), it was estimated that  $23 \times 10^6$  m<sup>3</sup> (6.1 billion gallons) were annually diverted for domestic and agricultural use (Takasaki et al., 1969).

Large volumes of runoff can also transport very large quantities of sediment. Sediment load varies with the amount and rate of rainfall. The seven streams were estimated to average  $1.8 \times 10^5$  kg (200 tons) of terrigenous sediment per day, with an average annual yield of  $6.6 \times 10^7$  kg (73,000 tons) (Jones et al., 1971). Fan (1973) estimated that one of the larger streams alone in flood carried  $8.9 \times 10^6$  kg (9800 tons) of sediment per day. Channelization of streams and removal of vegetation for urban and agricultural development have increased freshwater runoff and erosion in the bay

## **II. Sources of Ground Water - Aquifers**

The geologic feature that is of greatest hydrologic importance is the presence of thousands of layers of volcanic rock formed from lava flow over lava flow (Armstrong, 1983). These thin-bedded (3 meters or less), gently sloping (3-10°), lava flows comprise the bulk of the island volcanoes. These flows are typically very porous due to an abundance of clinker sections, voids between flow surfaces, shrinkage joints and fractures, lava tubes, and gas vents.

These layers of porous rock are highly permeable to water and thus serve as excellent aquifers. The principal aquifers in Hawaii accumulate fresh water in large lens-shaped bodies near sea level (Figure 17). The lens (commonly known as the Ghyben-Herzberg lens) is maintained through direct recharge by rain water and indirect recharge by seepage of high-level, dike-impounded water (Figure 18).

When an island is newly emerged above the ocean, the only groundwater in the rock is salt water from the ocean and its surface is at sea level. A freshwater lens develops as fresh water percolates down to the salt water and, because of its lower density, floats on the underlying salt water. The freshwater lens gradually expands in thickness and depresses the interface between the fresh water and the salt water to some depth below sea level. At the interface, the salt water and fresh water mix to form a "zone of transition" whose thickness varies from about 3 meters (10 ft) in a relatively undisturbed lens to as much as 300 meters (985 ft) in parts of southern Oahu.

On the older islands, especially Kauai and Oahu, the coastal margins of the volcanic mountains are covered by non-porous material of alluvial and marine origin, (Figure 17) called caprock. These materials act as barriers that retard the seaward escape of groundwater and cause the basal freshwater lens to thicken and to become artesian. The freshwater lenses in southern Oahu are of this type, with heads that are presently 6-8 meters (20-26 ft.) above sea level, and with total thicknesses of about 250-315 meters (820-1,025 ft). In other permeable basalt regions that lack an effective caprock, the lenses are as thin as 15-30 meters (50-100 ft).

The quality of Hawaii's fresh water from basaltic aquifers is excellent: the water is soft (low in mineral content) and free from harmful bacteria and viruses. Sewage-borne coliform bacteria and pathogenic enteric viruses are filtered from water passing through the common soil found on all major islands except the Island of Hawaii. Consequently, the fresh water from basaltic aquifers is free of coliform bacteria and meets U. S. drinking water standards.

The basal groundwater is tapped by pumped wells and infiltration galleries. Infiltration galleries, known as Maui wells throughout the world, are nearly horizontal tunnels of great length drilled just below the water table. Theoretically, they skim the top of the basal lens water.

The only serious source of contamination of the basal freshwater lens is the underlying seawater. Excessive pumping of the freshwater lens causes a rise in the concentration of chloride from the seawater. Another concern is agricultural return-irrigation water, which accumulates in the uppermost layer of the basal water. Agricultural seepage contains high concentrations of chloride, nitrate, and sulfate.

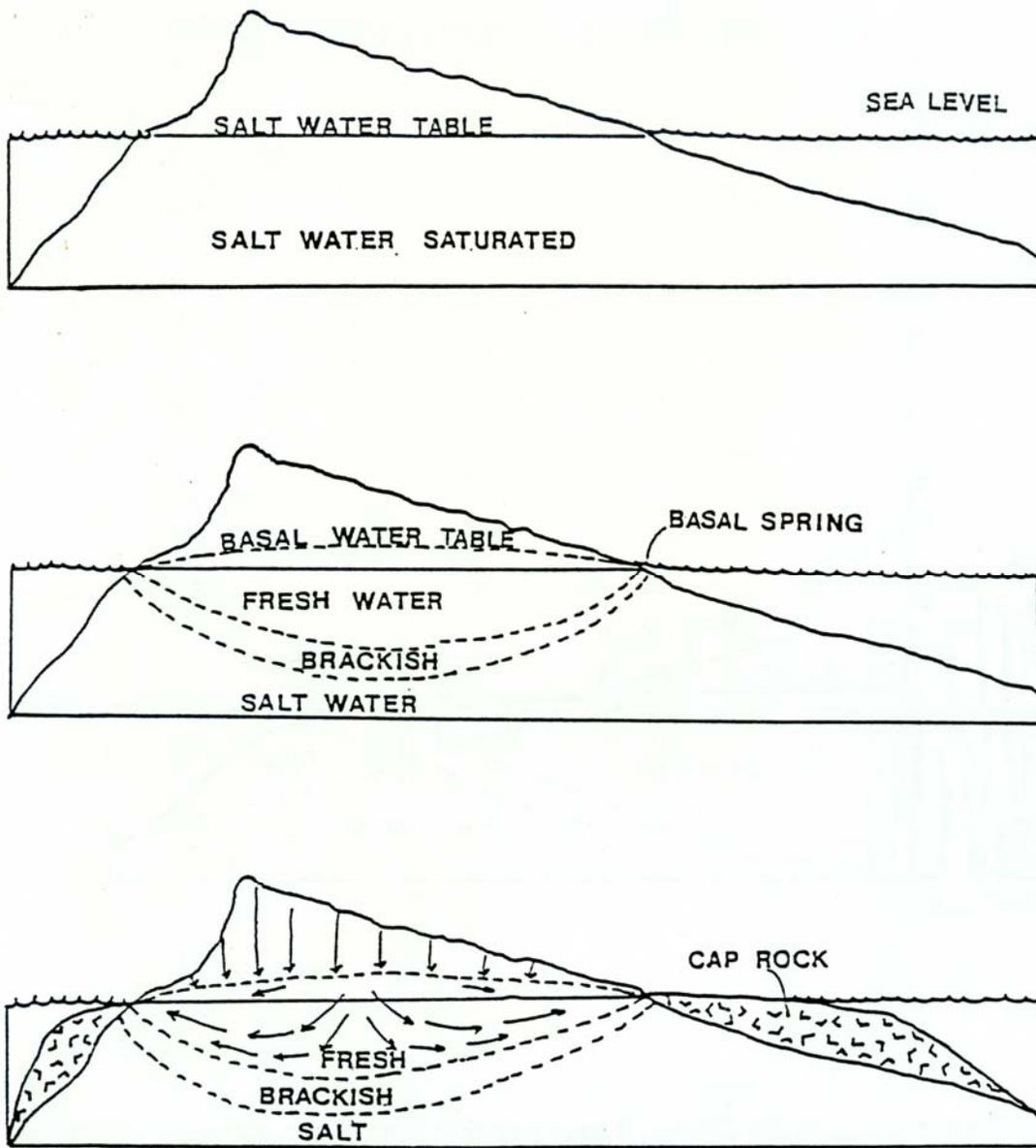


Figure 17: Development of the Ghyben-Herzberg lens of freshwater on Oahu. (a) Oahu without rainfall, saturated up to sealevel with saltwater. (b) Fresh rainwater infiltrates Oahu's porous rocks and forms a lens shaped layer floating on top of the saltwater. (c) Impermeable caprock raises the level of the water table and thickens the freshwater lens. Arrows show the direction of water movement. (After MacDonald and Abbott, 1970)

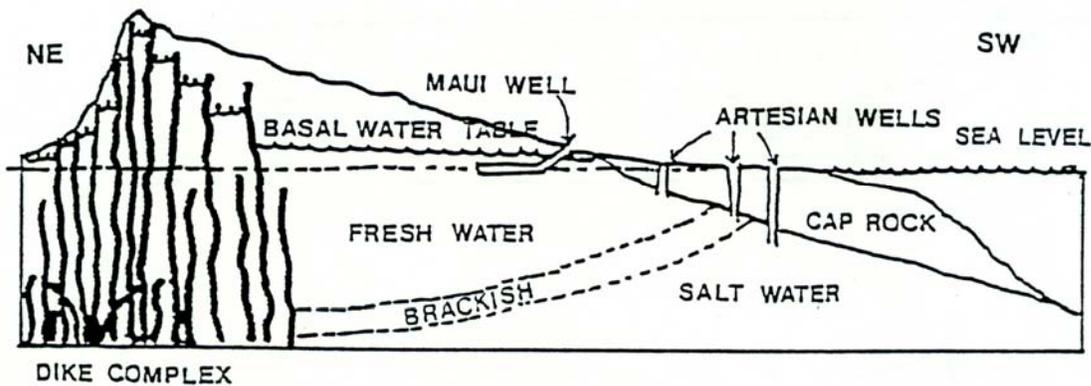


Figure 18: Cross section of the Koolau Range showing general groundwater conditions and the nature of Oahu artesian water. (After MacDonald and Abbott, 1970)

### 3. Dike Impounded Groundwater

In the rift zones on the flanks of Hawaiian volcanoes, molten lava intruded, cooled in the fissures and formed dikes. Unlike permeable flow basalts, dikes are nearly vertical sheets of dense basaltic rock. Where dike complexes cut through the permeable lava flows and make up 10 percent or more of the total rock volume they can form water storage compartments (Armstrong, 1983).

Such dike complexes are generally located at high elevations and impound rain-fed percolating water 60 m to 90 meters (200-300 ft) above sea level. Natural seepage occurs through mountain springs which continuously discharge perched and dike impounded groundwater. Dike water is collected by piercing a tunnel through several dike compartments at high elevations from which the water drains by gravity. Approximately 2.4 cubic meters per second (54 mgd) is drawn from dike compartments on Oahu.

### 4. History of Water use in Hawai'i

The early Hawaiians developed a water supply system based on streams, springs, and hand-dug wells for subsistence and agriculture (Armstrong, 1983). They built low, stone dams in streambeds to raise the level of water. The water was then diverted into ditches for the irrigation of taro fields.

In the second half of the nineteenth century, long ditches were built to carry stream water to dry, leeward areas for large-scale farming on sugar cane plantations. The first irrigation ditch was built for Lihue Plantation on Kauai in 1857. Hawaii's first drilled well, completed in 1897 near Ewa, Oahu, struck artesian water, and the secret of the vast groundwater resources in southern Oahu became quickly known.

Water diversion to the leeward side of Oahu by means of tunnels bored through the Ko'olaus began in 1916 with the Waiahole ditch tunnel system. Involved with the project were 27 connected tunnels with 37 stream intakes and 4 development tunnels. Debris from the main tunnel was hauled to Kaneohe Bay via a railroad system that was constructed for the 6 km (10 mi) haul.

The Waiahole Stream discharge between 1956-1958 was  $2.43 \times 10^7$  m<sup>3</sup> (6.41 million gallons), about two-fifths of the 1912 figure (Devaney et al., 1976). Two valley springs dried up and the Waikane Stream flow decreased. Groundwater storage was also estimated to be reduced by 1.1 cubic meters per second (24.23 mgd) as a result of this project.

Tunnels constructed following this project were the Haiku Tunnel, the Kahalu'u Tunnel, and the Waihe'e Tunnel. They were constructed in 1940, 1946 and 1955 respectively. They resulted in the same general pattern of decreased stream flow, dried springs, and reduced groundwater storage (Devaney et al., 1976). Stream runoff in the bay went from an estimated average of 3.7 cubic meters per second (83.2 mgd) to 2.1 cubic meters per second (48.1 mgd), representing an overall decrease of over 40%.

Fresh water has had an important bearing on both the terrestrial and marine areas of the Kaneohe Bay region. At the end of the 19th and early 20th century, overgrazing by cattle is thought to have denuded some terrestrial areas, possibly resulting in material being washed into the bay and causing "the first deterioration of the inshore environment" (Banner, 1974). Runoff and sedimentation loads due to urbanization have affected the bay since the 1950's. Mass mortality of marine life as a result of extreme flooding, combined with low-tide conditions, is well documented (Banner, 1968). The transport of pollutants, whether as increased nutrient loads of pesticides from sewage or urban runoff, is of major concern and has received considerable attention in recent years (Devaney et al., 1976).

Uses of Hawaii's coastal waters as a waste-water receptacle, if done improperly, can have an adverse impact on recreational waters and beaches. Further, marine conservation and preservation zones, as well as fisheries, are continually affected by coastal land and water uses and management practices. The 1970's have seen considerable research, planning, regulation, and improvement in wastewater management, with the result that coastal waters and marshes are now better protected than formerly.

## **5. Future of Water Use in Hawai'i**

On the island of Oahu in 1975, total use of fresh water amounted to 21 cubic meters per second (470 mgd) (Armstrong, 1983). Of this, 18 cubic meters per second (400 mgd), or 85 percent, was drawn from groundwater sources. Oahu's municipal water supply is virtually 100 percent dependent on groundwater sources.

Water budget estimates for Oahu indicate the rainwater is dispersed as 40 percent evapotranspiration, 24 percent surface water runoff, and 36 percent groundwater recharge. Not all surface water and groundwater is available for human use. The sustainable yield of groundwater for Oahu is estimated to be in the range of 21-28 cubic meters per second (480-630 mgd), which is somewhat less than what is being replaced by groundwater recharge. For the entire island of Oahu, the present 18 cubic meters per second (400 mgd) draft from groundwater approaches the sustainable yield from this source, a situation that indicates a potential water shortage by the year 2000.

Stream water is again regarded as an important alternative source for areas where groundwater sources, such as the Pearl Harbor aquifer, are nearing full exploitation. Surface water flow is seasonally variable and it is easily contaminated. Increased use of surface water and construction of more surface water treatment plants will have to be considered in the near future. Another minor source of water supply is rainwater catchment, which is practiced in rainy areas and especially in rural areas on islands other than Oahu.

Whether there will be an adequate water supply for the island of Oahu beyond the year 2000 is a major and valid concern. By the turn of the century, water demand on Oahu could exceed the total sustainable yield of all the island's water sources developed by conventional methods. Potential and alternative water sources will have to be determined, including greater use of dike and stream waters, use of sewage affluent for irrigation, blending brackish water with fresh water, and desalting brackish water.

## **F. Physical Oceanography of Kaneohe Bay**

### **1. Circulation Patterns**

Circulation patterns in Kaneohe Bay are very consistent, controlled by the bay's bathymetry, and driven by tides and wind (Bathen, 1968). In turn, the flow of water governs the volume of water transported into and out of the bay. Net transport of oceanic water over the barrier reef and into the bay is driven by wave action. Net transport out of the bay is through the NW and Sampan channels. Circulation is active in the NW portion of the bay. The SE area, however, is largely enclosed, experiences rather sluggish circulation, and has a longer water residence time.

Different circulation patterns exist for incoming and outgoing tides (Bathen, 1968). The eastern side of Oahu has an alongshore current that goes from SE to NW. During incoming tides, water enters the Sampan Channel (SE) over its entire depth range. The majority of the water flowing into the bay, however, is surface oceanic water of 0-1.5 m depth (0-5 ft) that flows over the barrier reef. Water deeper than approximately 1.5 m (5 ft) is deflected to the north and enters the deeper NW channel from the surface to a depth of 7 m (23 ft). Below 7 m, water in the bay flows out of the channel. Strong tradewinds increase flow into the bay, which in turn causes the water

below 7 m to flow more rapidly out of the NW channel. General flood tide circulation (Figure 19) was determined by Bathen (1968).

During outgoing tides, the circulation patterns of deeper water in Kaneohe Bay below approximately 5 m (16.5 ft) are approximately the same as for incoming tides. However, surface circulation is quite different, especially in the NW and SE channels. Much of the water entering over the barrier reef due to wind and wave action is diverted to the channels, which are the main exits for water during ebbing tides (Figure 20). Surface waters in the SE basin generally flow out through the Sampan Channel.

Kaneohe Bay, like the rest of Hawaii, generally has mixed tides. The two high and two low tides that occur each day are of different heights. The mean tidal range is rather small; 68 cm/d (27 in/d) with a maximum of about 110 cm/d (43 in/d). These differences (Figure 19) are not great. Tides in Hawaii can vary enough so that, on occasion, there is but one tidal cycle during a twenty-four hour period.

Large areas of Kaneohe Bay are quite shallow. These areas of the Bay are sometimes exposed during low tides. Thus, tidal height has a significant effect on the Bay's circulation. The volume of water exchanged is therefore dependent upon both tidal height and bathymetry. A mean diurnal tidal exchange of about 63.5 cm (25 in) Kaneohe Bay results in an exchange volume of  $35.1 \times 10^6$  m<sup>3</sup> (9.3 billion gallons). A maximum tidal change of 112 cm (44 in) results in transport of  $50.0 \times 10^6$  m<sup>3</sup> (13.2 billion gallons).

The times of high and low tides in Kaneohe Bay usually precede Honolulu tides by 75 to 93 minutes (Bathen, 1968). Kaneohe Bay's average daily tidal height is usually 3 to 8.5 cm (1.2-3.3 in) greater than that of Honolulu tides. The 3 cm difference is probably due to the bathymetry of the Bay. Differences greater than 3 cm are due to the added effect of winds.

Wind speed and direction can affect the tidal height and exchange volumes. Kona winds have the effect of decreasing the daily tidal height in Kaneohe Bay so that it is equal to or less than that of Honolulu. Trade winds can cause as much as 5.5 cm (2.2 in) accumulation over astronomically predicted tides.

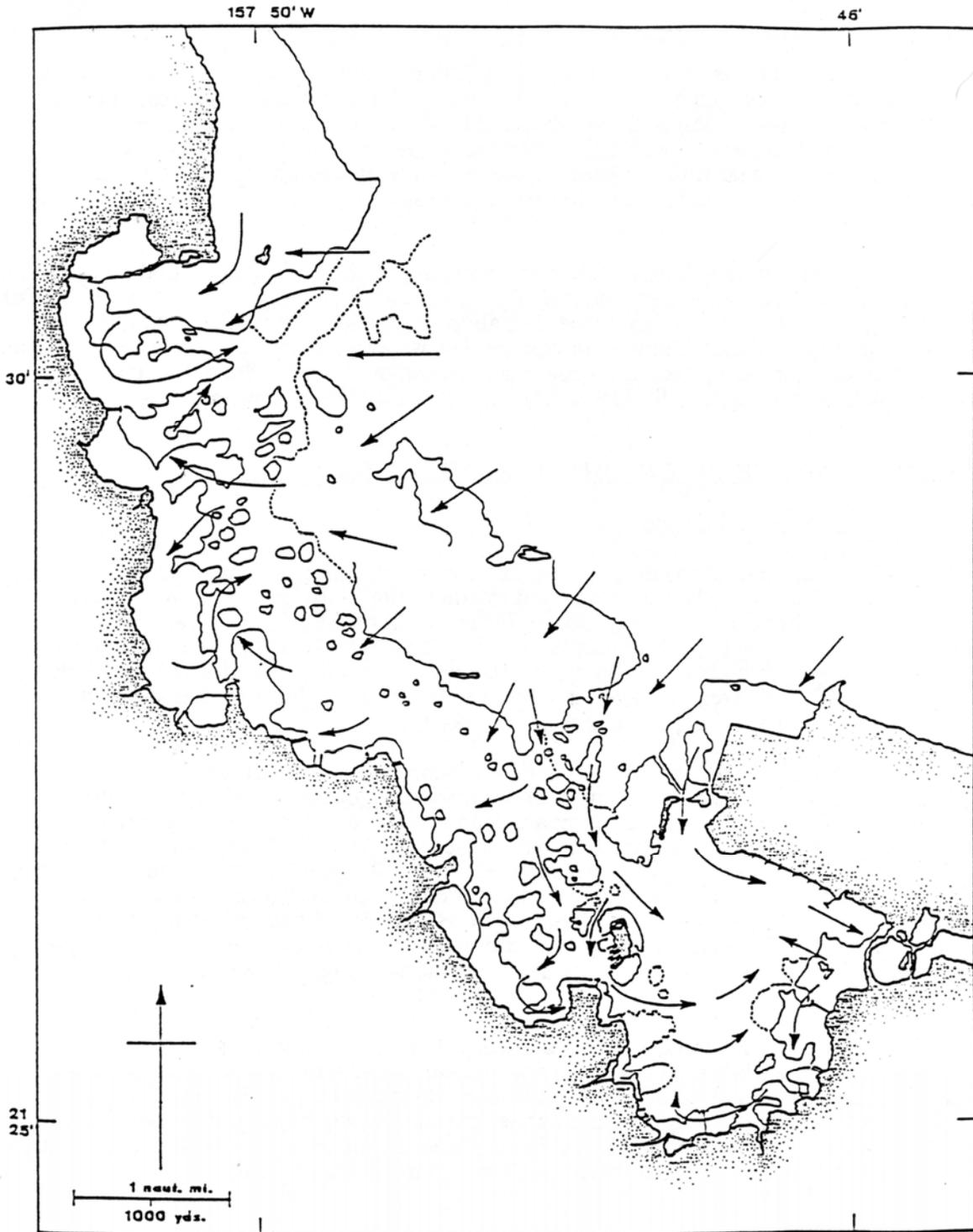


Figure 19: General flood tide circulation in Kaneohe Bay. (After Banner and Bailey, 1970; and Bathen, 1968)

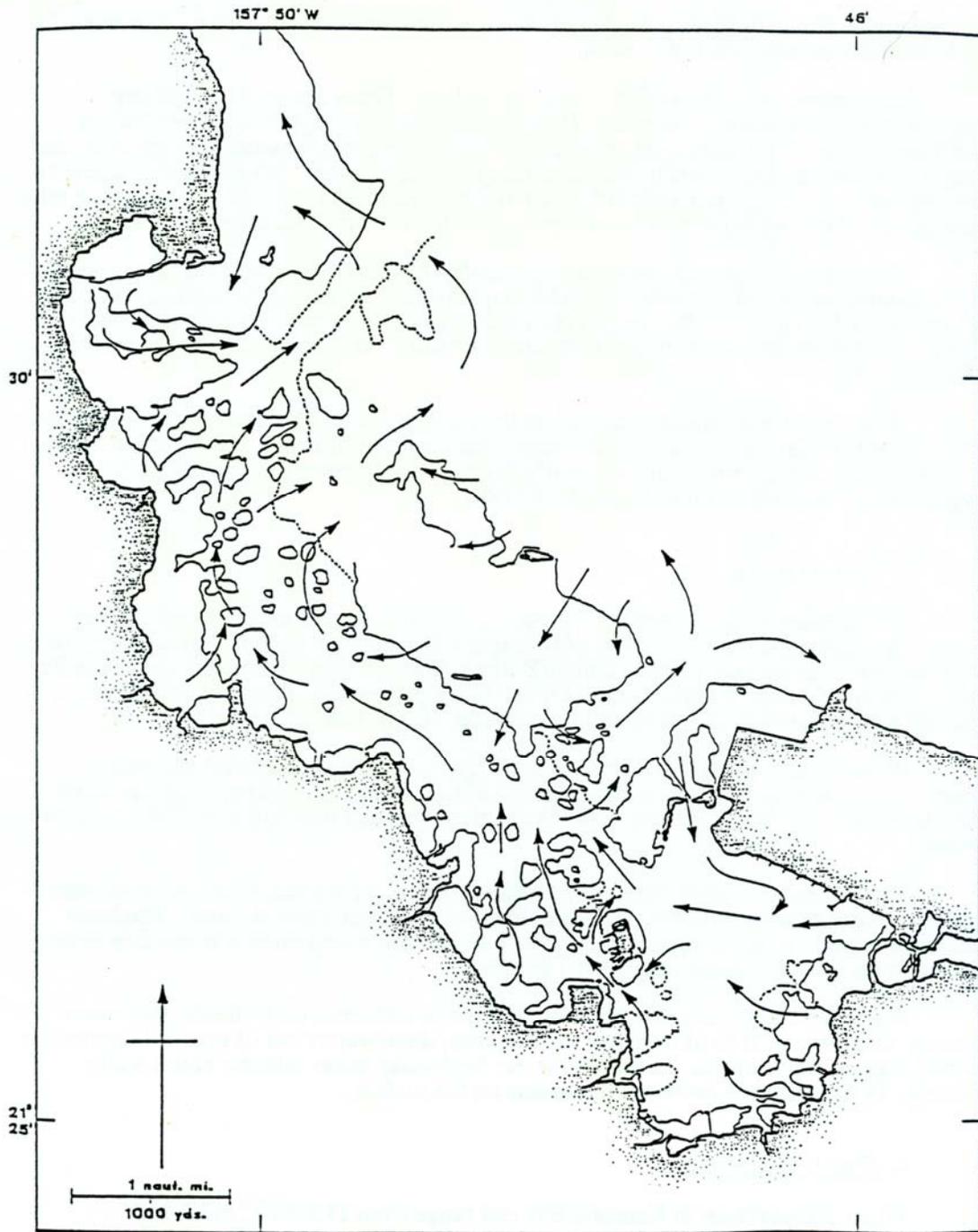


Figure 20: General ebb tide circulation in Kaneohe Bay. (After Banner and Bailey, 1970; and Bathen, 1968)

## **2. Tides**

## **3. Water Quality**

The distribution and variation in water properties such as temperature, salinity, oxygen concentration, and phosphates in Kaneohe Bay depend upon the circulation, runoff into the Bay, heat exchange, and rainfall (Bathen, 1968). Three different areas in the Bay show consistently different variations in these water properties. These areas are: water at the bay entrance, water over reef areas, and water near stream mouths.

Water quality at the bay entrance exhibit typically oceanic conditions. Water properties are less variable here than inside the Bay. Ranges of temperature and salinity variations here can be one-fourth that at stream mouths and one-half that of deep inshore waters.

The extensive shallow reef areas in Kaneohe Bay have a major influence on water quality. Water passing over the reefs mix slowly with deeper inshore water. The large numbers and size of these reefs cause average temperature and salinity in the Bay to be greater than that of oceanic water in the summer.

Water next to stream mouths also has a major influence on Kaneohe Bay water quality. Comprising 15% of total bay surface area, these waters are of especial importance during high rainfall months. In the winter the freshwater mixes into the entire water column. In the summer, however, it remains on the surface.

## **4. Water Temperature**

Water temperature in Kaneohe Bay can range from 19.5-28°C (67.1-82.4°F) (Bathen, 1968). During "winter" months (approx. from November to February) average water temperature is usually less than 25.6°C (78.1°F). During the summer (May to September) average water temperature is usually greater than 27.4°C (81.3°F). In the spring and fall (March to April and September to October) average temperature is between 25.6 and 27.4°C.

Seasonal, monthly, and daily variations in temperature differ depending upon location in the Bay. Shoreline and stream mouth areas have the largest variation ranging from 19 to 28°C (66.2 to 82.4°F). Deeper inshore areas also have a large variation of 20 to 27°C (68 to 80.6°F). Shallow reef areas exhibit the highest temperatures at about 29°C (84.2°F). Shoals and sand flats usually have small variations at 23 to 27°C (73.4 to 80.6°F). Water at the bay entrance is usually very similar to oceanic conditions and has the smallest range at 24 to 27°C (75.2 to 80.6°F). During the winter, two thirds of Kaneohe Bay can be 0.25 to 1°C colder than oceanic water. During the summer the entire bay can be 1.5 to 2°C warmer than the open ocean.

Temperature stratification in the Bay increases during summer months (Bathen, 1968). There is usually a weak thermocline from May to August at about 8.5 m (28 ft.) depth. This may vary 1 to 2 m (3.3 to 6.6 ft.) shallower or deeper during the summer. The upper .5 m (1.5 ft) in the bay is generally isothermal. During the months of September to November and February to April temperature gradient is consistent throughout the water column due to storm mixing, cooling of the surface, and stream runoff.

## **G. Chemical Oceanography of Kaneohe Bay**

### **1. Salinity**

Salinity in Kaneohe Bay can range from 31 to 36 ppt (Bathen, 1968). From about November to February, average salinity is less than 34.8 ppt. During May to September it is usually greater than 35.3 ppt. From September to October and March to April average salinity ranges from 34.8 to 35.3 ppt.

As with temperature, seasonal, monthly, and daily variations depend upon location in the Bay. Shoreline and stream mouth areas again have the largest variation ranging from 31 to 35 ppt. This is due to freshwater runoff into the Bay. Deeper inshore waters have moderate variations with a range of 33 to 35 ppt. Reef areas have the highest salinities at 36 ppt. Shoal and sand flats have a small range of 34 to 35.5 ppt. Waters at the bay entrance exhibit the smallest range at 34 to 35 ppt.

Freshwater cycles in Kaneohe Bay have considerable influence on salinity. Freshwater runoff into the bay mixes with higher salinity waters on shoreline reefs. This generally results in lower average salinity than in the open ocean. Periods of high rainfall can add a layer of very low salinity water on the surface of the bay. This may persist for one to four days. Periods of low rainfall and low cloud cover increases the temperature of waters over shallow reefs and causes higher evaporation rates. The salinity during these periods can be higher than in the open ocean.

### **2. Dissolved Oxygen**

Average dissolved oxygen concentration in Kaneohe Bay at 0 to 3 m (0 to 10 ft) depth is 4.5 ml/l (Bathen, 1968). At 3 to 8 m (10 to 26 ft) depth average oxygen level is 4.3 ml/l. Below 8 m depth average oxygen concentration is 3.9 ml/l.

Bathen (1968) observed that dissolved oxygen content varies considerably with location. High oxygen concentrations of 5 to 6 ml/l are found at the entrance of the bay. This is due to the breaking surf on the barrier reef complex. Dissolved oxygen concentrations along the large areas of shoreline reefs are also relatively high at 4 to 5 ml/l. High oxygen levels are also consistently found over areas of patch reef with luxuriant coral growth. Water circulation around these reefs are weak causing the dissolved oxygen to remain in the area. Waters over areas with extensive growth of fixed benthic algae also have high concentrations of dissolved oxygen.

Shoreline areas along stream mouths have lower concentrations at 3.5 to 4 ml/l. This is due to siltation from stream runoff. Siltation greatly reduces live reef growth and thus oxygen production. During very heavy storms, however, cold freshwater runoff can result in higher oxygen levels of 4.5 to 5 ml/l. Historically, oxygen concentrations as low as 2.5 ml/l have been found in the southeast basin near sewage outfalls.

## **II. Biology of Kaneohe Bay**

Marine organisms can be classified by where they live. Those that drift with the currents in Kaneohe Bay are known as plankton. Those that swim in open waters are nekton. The term demersal is used for fishes that live around a coral reef. This is in contrast to pelagic species that range in open waters between reefs. Organisms that live on the sea floor are benthic and include those that are sessile or live in one place. Sessile animals are fixed or attached to a substrate. Other territorial organisms can move about, but live permanently associated with an area.

Populations of marine organisms are groups of individuals that belong to the same species. Communities are all the populations living in a given limited area. Ecosystems are communities and their physical environment considered together.

Marine organisms are also classified by how they relate to each other. Associations between two different organisms that involve an intimate "living together" are generally referred to as symbiotic relationships. Some of them are so close that the partners are mutually dependent (mutualism). In others, one of the partners exploits the other (parasitism). However, there are other cases of association in which the relationship is less close, the level of dependence is low and the partners can do quite well without one another (commensalism).

Marine organisms are also grouped by trophic relationships or what they eat and what eats them. Three major trophic divisions are producers, consumers, and decomposers. Marine plants and phytoplankton (plant plankton) are self nourishing. These are called primary producers. Other marine organisms ultimately depend upon these primary producers for food. The complex feeding relationships of marine organisms are represented by diagrammatic food webs.

Rates of primary productivity limit the size of consumer populations they support. Consumption and predation rates are regulated through a feedback mechanism. Abundant primary productivity allows consumers to thrive and reproduce rapidly. Eventually, they consume the marine plants faster than they can reproduce themselves. Overgrazing causes food shortages which in turn reduces consumer populations. With decreased consumption the phytoplankton population can recover and the cycle begins again. The ever changing rates of consumption and primary production along with the complexity of food web relationships ensure highly dynamic populations throughout marine communities

### **A. Habitats in Kaneohe Bay**

A habitat is the physical place where an organism lives. Kaneohe Bay offers a diverse array of habitats for marine organisms ranging from inter-tidal to deep sea within only a few kilometers of each other. The interrelated influences of tides, circulation, bathymetry, wave action, and water quality produce an infinitely varied set of vertically and horizontally arranged habitats. Vertical and horizontal distribution of marine organisms reflect corresponding changes in the environment. This distribution is called zonation.

The surface of Kaneohe Bay waters are populated by plankton. Phytoplankton or plant plankton are generally microscopic single celled organisms. They are limited to the upper photic or sunlit portions of the water column. Zooplankton or animal plankton live throughout the water column and range in size from microscopic single celled organisms to large multicelled ones.

Kaneohe Bay has a particularly rich assemblage of plankton. Some of the members of this habitat are the nehu or Hawaiian anchovy (*Stolephorus purpureus*), arrow worms (*Sagitta*), copepods, barnacle, crab, and mollusc larvae, and *Oikopleura longicauda*, a free-swimming tunicate that builds a mucus house around itself. Also in this habitat are members of the "wind drift community" which includes the Portuguese-man-o'-war.

Pelagic organisms in Kaneohe Bay include large fish such as ulua and papio (*Carangidae*), aku (*Katsuwonus pelamis*), hammerhead sharks (*Sphyrna zygaena*), halfbeak and needlenose fish, Hawaiian green sea turtles (*Chelonia mydas*), and occasionally Pacific bottlenose dolphins (*Tursiops truncatus*). Offshore and oceanic waters outside of Kaneohe Bay support large schools of aku and mahimahi (*Coryphaena hippurus*). Occasionally humpback whales (*Megaptera novaeangliae*) are seen during winter months. The first specimen of a previously unknown shark, "Mega mouth", was also captured offshore of Kaneohe Bay at a depth of approximately 150 m (500 ft).

Benthic habitats in Kaneohe Bay are found in upper, middle, and lower intertidal zones along the coast. Shorelines have small sandy beaches, rocky shores, mud flats, and mangrove swamps. Many of these areas are affected by estuarine conditions.

Subtidally, many organisms live on live coral reefs as well as in dead coral and coral rubble areas. Sandy and muddy areas of the lagoon floor along with hard bottom areas of limestone and lithified sand dunes in the bay also provide habitats. Organisms are found living both in as well as on top of the bottom substrates.

The upper intertidal is also known as the splash zone as it is only wet by high spring tides and splash from waves. Organisms in this habitat in Kaneohe Bay include aama crabs, ghost crabs or ohiki, periwinkle shells, and black nerite shells or pipipi. Middle and lower intertidal zones are frequently inundated by tides and have greater diversity. Inhabitants include hermit crabs, blue pincher crabs, loose colonies of zoanthids, sea anemones, sponges, and solitary and/or colonial tunicates. Algae or

limu in this habitat includes sea lettuce (*Ulva* spp.), and several edible reds (*Gracilaria salicornia*, *Hypnea* spp., *Euचेuma spinosum*).

Kaneohe Bay has extensive areas of mangrove swamp and estuarine mud flats. The dominant mangrove species is *Rhizophora mangle* or red mangrove. These areas are dominated by freshwater from stream runoff during low tides and by seawater during high tides. There are also large fluctuations in dissolved oxygen, pH, and temperature in these habitats. Frequently, these areas are one of deposition and decay. The prop roots of the mangroves accumulate much sedimentary and organic detritus producing a fine silty mud bottom of alkaline pH and containing hydrogen sulfide.

Inhabitants of these areas are tolerant to large changes in salinity. Freshwater species live closer to the landward side of this habitat while brackish and marine species live closer to the seaward edges. Organisms found here include blue pincer crabs, mantis shrimp, little necks clams, pipipi, polychaetes or bristle worms, and marine gobies. Freshwater species include several species of endemic gobies, hihiwai, and a freshwater opae. Many of these areas are breeding grounds and nursery areas for other Kaneohe Bay marine life.

The lagoon floor in the bay has both sandy and hard bottom substrates. Sand dwellers frequently burrow into the substrate. These include acorn worms, auger shells, box crabs, alpheid shrimp, the lampshell *Lingula*, and clams. Schools of goat fish or weke (*Mullidae*) swim over sandy bottoms in search of food. *Halophila* or turtle grass is also found growing in sandy areas of the lagoon, especially on parts of the sand bar. Hard bottom dwellers include serpulid worms.

Kaneohe Bay is famous for its coral reefs. Coral reefs are the largest biologically produces structures on the surface of the earth. Its primary productivity equals or surpasses that of all other natural ecosystems. They provide food and shelter for a greater variety of living things than most other natural areas in the world. One reef alone may support as many as 3,000 species. It would be greatly beyond the scope of this paper to describe all the organisms found on a reef.

Fish commonly found living on Kaneohe Bay reefs include wrasses or hinalea (*Labridae*), parrotfish or uhu (*Scaridae*), butterflyfish (*Chaetodontidae*), damselfish (*Pomacentridae*), surgeonfish and tangs (*Acanthuridae*), and goatfish (*Mullidae*). Algae include members from the greens (*Ulva*, *Halimeda*, *Dictyosphaeria*), browns (*Padina*, *Sargassum*, *Dictyota*), and reds (*Gracilaria*, *Euचेuma*, *Hypnea*, *Acanthophora*, *Porolithon*). Echinoderms include black, brown, and red sea cucumbers, the soft *Opheodesoma spectabilis*, and several sea urchins: short spined boring urchins or ina (*Echinometra mathaei*), long-spined wana (*Echinothrix diadema*), red slate pencil urchins (*Heterocentrotus mammillatus*), and collector urchins (*Tripnuestes gratilla*).

## **B. Kaneohe Bay Corals**

The Hawaiian Islands have few reef corals due to their isolated geographic locality. Most of the 40 known species (Maragos, 1977) occur in Kaneohe Bay, though only a few are abundant. These corals can be separated into two faunas based on wave energy. High energy, wave resistant species occur on the seaward margin of the barrier reef, while more delicate, low energy species occur in the bay proper. However, many of the bay species also occur throughout the Hawaii Islands in deeper, low energy environments.

Corals are most common on the crests and slopes of fringing and patch reefs in the bay, and on the algal ridge/reef flat, crest, and slopes of the barrier reef. They are rare or nonexistent on the soft bottom of the bay, on the reef flat of fringing and patch reefs, and on the lagoonward depositional slope and back reef flat of the barrier reef. In general, corals have to grow on hard substratum in areas with clear, high salinity water; they do not grow well in areas with murky, sediment laden water or low salinity.

The most abundant coral in Kaneohe Bay is the finger coral, *Porites compressa*. It is found in the bay proper and cannot withstand high wave energy; it is also common in other protected habitats around the Hawaiian Islands. This species has a porous skeleton and forms finger-like projections. Large platforms can form when adjacent colonies grow or fuse together. Its rapid grow rate allows it to outcompete other corals and Maragos (1972) estimates that *Porites compressa* comprises as much as 85% of the total coral population in Kaneohe Bay.

*Porites compressa* is quite variable in morphology and at least 16 forms have been described (Maragos, 1977). This variability is expressed by different amounts of branching, fusion of branches, etc. Even with this large degree of variability, the species is considered distinct enough to be separated from all other species in the genus *Porites*, and it is generally recognized as occurring only in the Hawaiian Islands. However, recent studies (S. Coles, personal communication) indicate that *P. compressa* is very similar to, or is the same species, as a *Porites* sp. that occurs in the Arabian Gulf. If they are indeed the same species, this is a remarkable distribution pattern because it has not been found at any locality in between.

The other most common corals in Kaneohe Bay are *Montipora verrucosa*, *Pocillopora damicornis*, *Cyphastrea ocellina*, *Pavona varians*, and *Fungia scutaria*. They occur in varying amounts but are much less abundant than *Porites compressa*.

The most common corals on the seaward portion of the barrier reef are *Porites lobata* and *Pocillopora meandrina*, both of which are high energy species. Lower numbers of "bay" species also occur. In general, coral coverage is lower on the barrier reef than in the bay, with live coverage averaging between 5 to 10 percent.

Historically, Kaneohe Bay has been known for its lush coral gardens, especially in the south bay. However, several man-made and natural impacts have altered parts of the bay to the extent that few corals are currently found. The south bay in particular has been subjected to impacts from agriculture, urbanization, pollution, dredging, and filling

so that large areas have been modified. Perhaps the most extensive impact resulted from discharging large volumes of sewage into the SE basin that resulted in widespread coral mortality. Fortunately, the diversion of the sewage outfall to the ocean side of the Mokapu Peninsula resulted in an almost immediate improvement of environmental conditions, resulting in a widespread recovery of the coral assemblage.

Natural environmental extremes occur in Kaneohe Bay that have limited, and sometimes extensive impacts, on the corals. Extreme low tides occur periodically that expose coral to air, temperature changes, and fresh water (rain). This generally has a limited impact and can cause some mortality, although it can be more serious if it occurs at noon on a very hot day or during a very heavy rain storm. Freshwater "kills" are generally more serious and result from severe storm flooding and runoff from the land. If flooding occurs during an extreme low tide, coral (and other marine organisms) can be killed down to a depth of several feet below the water surface. An extensive freshwater "kill" occurred during the Keapuka Flood of May, 1965, as well as the New Years flood of 1988. Shallow fringing and patch reef corals throughout the bay were killed during these floods. Although these impacted areas do recover, it takes several years.

Other invertebrates include lobsters, 7-11 crabs, box crabs (*Calappa calappa*), octopus, pearl oysters, cowrie, and cone shells, tunicates, sponges, shrimp, feather duster worms.

### **C. Organisms of Kaneohe Bay**

Several of the more interesting or unusual organisms found in Kaneohe Bay are presented here in more detail. This is by no means a complete listing of all the important or fascinating organisms that live in or around the Bay.

#### **1. Octopus**

*Octopus cyanea* is found throughout the Indo-Pacific and in the Hawaii is commonly known as the "day squid" or "hee". The commercial fishery is small, about 3,000 kg (3.3 tons) annually in 1976, according to State Fish and Game Records. Sports fishermen, however, probably take three to four times the commercial catch (Van Heukelem, 1976).

When they are small, they double their weight every 11-13 days. At ten months, they are fully mature and weigh an average of 4 kgs (8.8 lbs.) with a maximum of 6 - 7 kgs (13.2-15.4 lbs.). Growth ceases shortly after sexual maturity. They die of old age at 12-15 months. Females die shortly after their eggs hatch and males die after reaching sexual maturity. Spawning takes place throughout the year. This species feeds on small crabs, shrimp, and other crustaceans. Piles of crab shells are often found outside of their burrows. After spawning, female octopi rarely eat. Eggs require 20-36 days to develop. Females usually die within 10 days after hatching their young.

#### **2. Sharks**

Kaneohe Bay is a pupping ground for the scalloped hammerhead shark *Sphyrna zygaena* or *mano kihikihi* (Clarke, 1971). The pups are most abundant between April and October. While in the bay, the pups stay in the most turbid areas by day and move out at night to reef areas where they feed on reef fishes and crustaceans. The pups spend a maximum of three to four months in the bay and then leave nearshore areas. The total number of pups born in Kaneohe Bay may be as high as 10,000 per year.

Adult hammerheads enter the bay between April and October to bear young and breed. Squid beaks in their stomachs show that the adults have come in from offshore areas. These types of squid do not occur in the bay. Hammerhead sharks live in deep ocean waters during the rest of the year. While in the bay, the hammerheads are largely concerned with breeding and have not been a threat to swimmers and divers. Hammerhead pups are the most abundant large carnivore in the bay, particularly around the reefs. They probably consume a significant portion of the reef's resources.

### **3. Whales**

Humpback whales can be found offshore of Kaneohe Bay. The scientific name of humpback whales is *Megaptera novaeangliae* which means "giant wings of New England." This whale is found throughout the world's oceans (Mobley and Dell, 1985). The North Pacific is one home for the estimated 5,000 to 7,500 that inhabit this planet. The whales arrive in Hawaii during the winter and spring months from the colder, nutrient rich waters of southeast Alaska through the Gulf of Alaska and the Aleutian archipelago. The roundtrip distance of 9,600 km (6,000 mi.) qualifies the trip as the longest traveled by any animal species. The behavior of the humpbacks while in Hawaii contrasts sharply with those in the feeding areas off southeast Alaska. The quick swimming and elusive svelte humpbacks in Hawaii give way to the slow moving, rotund grazing giants in the northern waters.

Prior to the 20th century, as many as 15,000 whales existed in the North Pacific population, but the population has dwindled due to the intensive whaling that has occurred in this century. Although protective measures have been initiated by whaling nations since 1966, current populations are estimated to be from under 1,000 to over 2,000 individuals.

### **4. Turtles**

The Hawaiian Green Turtle, or honu as it is known to the Hawaiians, is another inhabitant of Kaneohe Bay. The scientific name is *Chelonia mydas*. It is the more abundant of the two species of marine turtles native to the Hawaiian chain (Balazs, 1976). Primarily vegetarians, they feed on marine plants that grow in shallow coastal waters. The color portion of the name refers not to the shell or skin color, which ranges from black to dark olive, but rather to the fat that occurs in their body.

In March, the Hawaii Green Turtle travels to the Northwestern Hawaiian Islands, specifically to French Frigate Shoals, which is the largest mating and nesting grounds.

The females lay their eggs there between mid-May and August. Weighing in at only 30 grams (one ounce) at hatching, the turtles will grow to weigh a whopping 90-170 kg (200-375 lbs.) when mature (Balazs, 1976). While most marine turtles never return to the land after leaving their natal beach, the Hawaiian Green Turtles bask regularly on the beaches of these protected refuge islands.

The other species of turtle that is found in the Hawaiian Archipelago is the Hawksbill, known to the Hawaiians as ea and to the scientists as *Eretmochelys imbricata*. It is easily distinguished from the Green Turtle by its pointed hawk-like beak, which allows them to probe into coral and rock crevices. Also, the plates of the juvenile's shell overlap one another (Balazs, 1976).

The adult shell coloration is mottled brown and the underside is yellowish. Due to market demand in more affluent countries, the Hawksbill is hunted for its horny plates or "tortoise shell" for use in such items as jewelry and combs; and more recently for whole stuffed animals, which creates a demand for even small immature animals (Balazs, 1974). The U.S. Department of the Interior and the International Union for the Conservation of Nature have placed the Hawksbill on an Endangered Species List.

## **5. Pearl Oyster**

The commercially valuable black-lipped pearl oyster (*Pinctada margaritifera*) was once abundant in Kaneohe Bay, but has nearly been eliminated by collectors. This species occurs throughout the Pacific and is a valuable source of pearls and mother of pearl. This industry generates approximately 28 million dollars annually. This species is now protected in Kaneohe Bay: it is illegal to remove shellfish from the bay. Nevertheless, ignorant or disreputable individuals still take specimens for ornamental or aquarium use. Pearl oysters were abundant at Pearl and Hermes reef in the Northwest Hawaiian Islands in the 1920's, where it was found at lagoon depths of 2 to 7 m (6.6-23 ft.). Shells weighing upward of 7 kg (15 lbs.) were reported in 1930. Over 9.07 x 10<sup>4</sup> kg (100 tons) of shell was removed from Pearl and Hermes reef between 1927 and 1929. The beds never recovered. Only one or two living oysters have been seen at Pearl and Hermes reef in recent years.

In 1930, 310 oysters were introduced from Pearl and Hermes reef into Kaneohe Bay. Good growth and reproduction was reported. In 1938, over 1.9 x 10<sup>4</sup> kg (21 tons) of pearl oysters were dug from beds in Kaneohe Bay and distributed and resown on different islands (Devaney et al., 1976). It is estimated that only about 200 black-lipped pearl oysters remain in Kaneohe Bay (Sims, unpublished manuscript).

## **6. A Living Fossil**

One of the most unusual species found in Kaneohe Bay is *Lingula reevii* a brachiopod that is endemic to the Hawaiian Islands (Emig, 1987). This species, remaining essentially unmodified for 350-400 million years, is literally a living fossil. Brachiopods (lamp shells) are common marine fossils. They are now rare throughout

the world. There are twelve species currently found throughout the world, seven being endemic, throughout Japan, Northern Australia, the Hawaiian Islands (occurring only in Kaneohe Bay), and the Philippines (Worcester, 1969). Members of this genus are found mostly in shallow marine or brackish waters from the intertidal zone to about 20 meters (66 ft.). Due to the unique nature of these Brachiopods, conservation is very important.

## **7. Portuguese-Man-o'-War**

The Portuguese-man-o'-war (*Physalia physalia*) usually lives far out to sea and is part of the "wind drift" community. Another member is a beautiful and delicate purple snail (*Janthina fragilis*). This snail floats on the surface by secreting a float made of bubbles. The blue nudibranch or sea slug (*Glaucus atlanticus*) also belongs to this community. It floats on the surface by spreading out projections that look like wings. Both these animals are predators of the Portuguese-man-o'-war.

The Portuguese-man-o'-war and its community co-members are often seen blown into Kaneohe Bay by storms and strong north winds. The Portuguese-man-o'-war, like coral, is colonial, formed by many animals called polyps. Unlike coral, the Portuguese-man-o'-war has groups of polyps specialized to perform various functions. Some polyps form the bubble and keep it inflated; some form the tentacles and stinging cells. Other specialties are feeding, reproduction, and food capture.

Portuguese-man-o'-wars are predators that kill their prey with stinging cells or nematocysts located on the tentacles. The tentacles are extended for many meters when actively "fishing". Upon contact, the nematocysts discharge tiny venomous barbs into their prey. The barbs are what causes a person to feel like they are being stung by many dozens of bees when hit by a Portuguese-man-o'-war.

After firing, the nematocysts cannot be reused so are detached from the tentacles and discarded or left stuck in the prey. The venom contains three different toxins which prove fatal to small fish and other prey items. In humans, the histamines in the venom can cause pain, sickness, allergic reactions, and sometimes death to those who are very sensitive to bee and other insect stings.

## **8. Sea Vegetable or Sea Weed?**

*Eucheuma spinosum* or tambalang is a red alga or "seaweed" found in Hawaii almost exclusively in Kaneohe Bay. It was introduced to Hawaii in the 1970's from the Philippines where it is extensively cultivated for food and its high carrageenan content. Carrageenan is a colloid gel that is an important industrial additive used as a stabilizer and emulsifier in dairy and pharmaceutical products. It is commonly used in ice cream, chocolate milk, and toothpaste.

Tambalang was introduced to Hawaii to determine the feasibility of a similar industry here. In 1976 fresh tambalang was made available in Honolulu markets but sales were poor. It has not been on the market since.

Tambalang grows in large masses that can be over 2 meters (6.6 ft.) high and several meters wide. It has thick round succulent stems with "spines" and "branches". Color varies from clear olive green when fresh to rosy and even purple when dried.

Although the experimental growth plots in Kaneohe Bay are now part of a wildlife refuge, huge patches exist elsewhere in the Bay. Some people are concerned that its continued presence in the Bay may interfere with native algae. Nicknamed "Ick-euma" by many, it is considered a pest. Others consider it a delicacy and prized salad vegetable. Limu pickers frequent KeAlohi Point to gather tambalang for pickling or use as a relish.

## **9. Pink Sea Cucumbers**

One of the most prominent yet odd organisms of Kaneohe Bay is *Opheodesoma spectabilis*, a giant, non-burrowing sea cucumber. It is endemic to Hawaii and occurs abundantly and almost exclusively in Kaneohe Bay. Berrill (1965) observed aggregations of 300-1,000 *Opheodesoma* in the vicinity of Coconut Island alone.

*Opheodesoma*'s appearance includes variously patterned stripes and spots of orange, red, violet, and gray. Its retractable tentacle crown has fifteen tentacles. Its body wall projects into five symmetrical rows of "warts" which increase in number and size with body length. Embedded in its skin are numerous plate and anchor ossicles or spicules which give it a "sticky" texture and serve to attach the body to substratum. *Opheodesoma* can grow up to 1.5-1.8 m (5-6 ft.) long when relaxed.

*Opheodesoma* up to about one meter (3.3 ft.) long are found most often living in association with masses of a brown alga, *Sargassum* where there is continual but slow water movement.

*Opheodesoma* is unable to withstand environmental extremes such as wave action, freshwater dilutions, and exposure to sun and air. The *Sargassum* beds not only provide protection from wave action and exposure to sunlight, but also collect a lot of detritus, thus becoming a major source of food supply.

Unlike other sea cucumbers, *Opheodesoma* lack tube feet. Locomotion is achieved through a combination of tentacle movement and peristaltic waves through the body. The flexible nature of the skin makes *Opheodesoma* one of the most active sea cucumbers. *Opheodesoma* are less active during the day and most active in early evening. They feed on detritus and algae by means of the tentacles. Broadcast spawning begins in May and continues until mid to late September.

## **10. Green Bubble Algae**

Kaneohe Bay is known for its growth of large masses of the green bubble alga *Dictyosphaeria cavernosa*. This alga belongs to the Siphonocladales and is bright green in color. The individual "bubbles" may reach 5 mm (.2 in.) or larger in diameter. As these bubbles proliferate and grow, they form larger, hollow, spheres, hence the name "cavernosa".

The bubbles give this seaweed a firm, crisp texture that university students have "likened to certain commercial breakfast foods" (Banner, 1973). Masses may grow as large as 2 m (6.6 ft.) long and 1 m (3.3 ft.) high and wide. It attaches only tenuously to the substrate and is easily dislodged when not on a solid substrate such as coral.

Banner (1973) noted a "cropped" growth form in the middle and northern sections of Kaneohe Bay. The difference was attributed to grazing by fish, especially juvenile parrot fish. Other consumers of this alga may include the garbage collector sea urchin (*Tripneustes gratilla*) although it does not crop the alga to the same extent as do the fish.

In the 1960's green bubble algae was observed growing over portions of reef slopes in the central part of the bay. In areas it reached a biomass of 1 kg/m<sup>2</sup> (.2 lb/ft<sup>2</sup>) (Goodin & Sanderson, 1977). Invasion rate of the "front" of the alga moving into a head of living finger coral was measured as 2 cm (.8 in.) a month (Banner, 1973).

Coral invaded by the alga was observed to be considerably weakened at its base. As a result, the still growing fingers of coral were frequently held in place only by the algal mat. Disturbances, such as wave action, would cause the algal mat to rupture allowing the coral to fall either to the interior of the mat or down the reef slope where it was unable to grow. The resulting hole would be grown over by the alga. In this way, an entire reef front would be taken over by green bubble algae.

### **III. Cultural and Human Use of Kaneohe Bay**

#### **A. HUMAN INFLUENCE ON KANEOHE BAY**

Man's impact on Kaneohe Bay is a result of practices and modifications made both in the bay and on land. The first Hawaiians fished, built fishponds, and practiced agriculture within the Kaneohe Bay watershed. These practices had far less effect on the environment than modern agriculture and urbanization.

##### **1. Fisheries**

###### **1. Traditional Hawaiian Fisheries Management**

The Hawaiians formed a very wise system of land division boundaries extending from the mountains to the sea. This allowed residents of each ahupua'a to enjoy the products of both the land and the sea (Mauka and Makai). The Great Mahele declared the fisheries outside of the reefs to be common property of everyone, yet still

maintained the ahupua'a boundaries between the reefs and the land. The Hawaiian chiefs (Konohiki) were able to place a kapu on any single variety of fish, and therefore, received the bounty of that particular fish caught by any fisherman (Devaney et al, 1976). The other alternative was that the Konohiki prohibited all fishing on their fisheries during certain months of the year, and declared as their property one-third of all fish taken on their private fishing grounds during the fishing season.

The laws became more complex until 1851 when all fishery rights (except for the fishponds) opened to all the people. By June 14, 1990, the Organic Act opened the remaining fisheries to everyone, repealing on all laws that conferred fishing rights on any one person. Certain individuals, however, were able to gain exclusive rights by filing a petition to circuit court stating their claims.

## **2. Traditional Hawaiian Fishing Techniques**

Traditional Hawaiian fishing techniques included spearing, trapping, netting, and hook and line fishing. One technique of catching fish was to feed the fish two or three times a week to ensure they remain in the area. When they were ready to catch the fish, the fishermen prepared special food of seaweed mixed with crushed kukui nuts (candlenut), a powerful laxative. Fish that ate this mixture expelled all the food matter in their intestines. Two days later the fish were so hungry fishermen had no problem netting or hooking them.

Traditional Hawaiian fishermen also built many fishing shrines. Several have been recognized from Mokapu to Kahalu'u and also out on Kapapa Island. The extension of ahupua'a and Ili boundaries out to the reef edge to show discrete fishery areas as well as numerous fishing legends (Devaney et. al. 1976) also attested to the importance of the sea and fishing to the Hawaiians.

Hawaiians also obtained fish through use of walled or kuapa fishponds. These provided a regular source of food whereas shoreline fishing, susceptible to the vagaries of weather and surf, sometimes yielded an insufficient supply. Mullet and awa or milkfish were the most common species raised. These are key species in the food chain in that they directly consume algae and detritus. This shortens the food chain making protein production more efficient by as much as 10,000% (Devaney et. al., 1976).

The chiefs or Konohiki planned and supervised construction of the fishponds. Construction required the labor of more than 10,000 men. Fish harvested from the ponds were first given to the chiefs and fishermen and the rest divided among the community.

After Western private property and landownership concepts were introduced, fishponds were declared to be part of the ahupua'a to which they were attached. In 1848, they were claimed by the king, the government, and a few powerful chiefs. With the advent of commercial agriculture in Hawaii, landowners ceased to have much

interest in the ponds. Many of them fell into disrepair and the practice of this early type of aquaculture ceased.

## **B. SEACO/SAIC/NOSC KMCAS**

Mokapu Peninsula was first used for military purposes in 1918 when Fort Hase was established at Ulupau Head. This is the site of one of the oldest military bases on Oahu. In 1939 the Navy established an advanced naval base on the peninsula. Later it was expanded to include the administration of the Kaneohe Bay Naval Defense Sea Area and the Kaneohe Naval Air Space Reservation.

On December 7, 1941, the Air Station was the first place to be attacked, even before Pearl Harbor. During World War II, the first Japanese plane was shot down here and the first Medal of Honor was awarded for heroic action to an ordnance man stationed at Mokapu. The Naval Air Station was eventually decommissioned in June 1949.

In 1952 the Kaneohe Marine Corps Air Station was commissioned as a training site for a combined air-ground team. Today KMCAS houses the only such team in the entire Marine Corps. As of 1972 population on KMCAS was 464 military and 442 civilian.

Located on the west side of the Air Station is Naval Ocean Systems Center. NOSC is involved in ocean engineering, marine biosystems, ocean bionics, ocean surveillance, ocean technology, and teleoperator/remote presence systems. Some of their activities include fiber-optic systems testing, undersea surveillance systems testing, environmental monitoring at Naval installations, marine fouling and antifouling research, and hazardous waste monitoring. Their facilities include a research and development lab for design, engineering, and prototype assembly and testing, a Navy certified recompression chamber and dive locker, and a deep-water offshore in situ test facility.

Perhaps the most visible aspect of NOSC research involves the whales, porpoises, and sea lions used for their undersea research. Much of the animal handling and training procedures occur in Kaneohe Bay. Also seen in Kaneohe Bay is the Kaimalino, a small Stable Semisubmerged Platform (SSP) vessel which is designed to be highly stable and to provide smooth operations in rough seas.

Establishment of a military base on Mokapu Peninsula has affected the Kaneohe Bay environment directly and indirectly. From 1952-1978 the KMCAS wastewater plant discharged untreated sewage directly into the southeast basin of Kaneohe Bay. It was later diverted to a deep ocean outfall off Ulupau Crater. Discharge of industrial wastes has been modified to prevent their entry into sewage and storm drainage systems.

Open dump burning of solid wastes was discontinued in 1970 in favor of landfill operations. However, burning of contaminated fuel for firefighting training continues.

The Marine Base claims to be using cleaner burning fuels and reduced burning time and drill frequency. Noise from aircraft operations and maintenance continues as a source of irritation and objections from the surrounding community.

KMCAS has also established a fish and wildlife conservation program. Two wildlife refuges are managed under a multiple-use concept. The main objectives for establishment of these refuges are for "proper management of recreational opportunities, conservation and education, watershed protection, preservation of rare and endangered wildlife species, and coordination of designated wildlife refuge areas with other resource uses."

Nu'upia Pond Wildlife Refuge includes mudflats and marsh areas which are breeding and nesting sites for wetland birds such as the threatened Hawaiian stilt, the black-crowned night heron, cattle egret, and Hawaiian coot. Migratory ducks from North America also use this refuge during winter months. This refuge is also used for amphibious tractor training operations, controlled sport fishing, hiking, and horseback riding.

Ulupau Crater Wildlife Refuge houses the only land-accessible colony of red-footed boobies located on the greater part of a weapons range. This refuge is routinely the recipient of land improvement projects such as clearance of observation areas by the Rod and Gun Club. Firebreaks are also cleared around the entire refuge to prevent accidental small brush fires resulting from live weapons firing. Wildlife refuge boundary signs have also been erected.

### **C. Agriculture**

Ancient Hawaiian agriculture had a limited impact on the environment of Kaneohe Bay. Uplands cultivation involved using a stick to poke a hole for each plant. This would have caused much less erosion than modern plowing techniques. Wetland cultivation involved the construction of irrigation ditches and terracing. This altered surface water flow. The nutrient enriched stream water was frequently diverted into fishponds to promote algae production as fish food.

The introduction of non-Hawaiian agricultural techniques during the mid-nineteenth century began a period of rapid change on the nearshore areas of Kaneohe Bay. Great networks of irrigation ditches were constructed. Land was plowed, flooded, and compressed by farm animals to increase water holding capacity (Devaney et al., 1976). Herds of cattle, horses, and goats caused extensive deforestation in the watershed. This all compounded to cause extensive erosion.

Eroded soils were deposited in the bay. This caused shoaling of the bay floor and impacted shoreline habitats, and possibly impacted coral reef assemblages in various parts of the bay. Siltation had the direct affect of smothering coral and other types of sedentary plants and animals. In addition, the reduced water clarity had an impact on corals, algae, and other organisms that require sunlight for survival.

## **D. Fishponds**

Fishponds were considered to be a part of the land (agriculture) by early Hawaiians, though we now think of them as aquaculture. The ponds were constructed in sheltered areas and the walls, made from basalt and coral, were usually built out from the shoreline to enclose shallow bodies of water of various sizes. Mullet and milk fish were the most important fishes cultured.

Kaneohe Bay's sheltered conditions and freshwater streams made it ideal for fishponds. There were at least 30 ponds in the bay (Devaney et al., 1976), though they gradually fell into disuse or were filled in. By 1901, only 16 ponds were in commercial use in Kaneohe Bay, perhaps half of what were in use thirty years earlier (Cobb, 1902). Devaney et al. (1976) found only 12 recognizable fishponds remaining in Kaneohe Bay.

The number of fishponds built on the fringing reef of Kaneohe Bay would have had some effect on nearshore circulation. This would have altered sedimentation patterns to some degree and had an effect on nearshore habitats. Overall, the changes would have been less than the much more extensive system of shoreline walls and revetments that were built in the 20th century.

## **E. Introduced species**

### **1. Mangroves**

Mangrove trees were introduced into Hawaii in 1921 in an attempt to control erosion. Several species were introduced at different times, but the one that thrived was the red mangrove from Florida. Mangroves continue to spread in Kaneohe Bay, with their best development in He'eia Stream.

Mangroves change the environment as they develop into forests. Their highly developed prop roots are effective sediment traps and cause the deposition of fine materials around the trees. By developing in shallow shoreline areas and depositing sediment, they can effectively build a new shoreline and outcompete native shoreline trees and plants. It is likely that the forest at He'eia Stream traps some of the sediments eroded from the adjacent watershed that would have washed into Kaneohe Bay, but no attempt has been made to measure the volume of sediment trapped.

Mangroves rapidly colonize the walls of ancient Hawaiian fishponds. This has a negative financial impact on the few operational ponds and, perhaps more important, causes the degradation of non-utilized ponds that are not kept free of the trees. These important archaeological structures, which have existed for hundreds of years, are now being rapidly degraded by trees that were introduced less than 70 years ago.

## **F. Dredging, Filling and Sediment - Irreversible Damage**

The most extensive and irreversible changes made to the reef environments of Kaneohe Bay were from dredging and filling. These completely alter the structure upon which the reef grows so that recovery is impossible in many instances. Dredging and filling can also modify the physical regime of an area by changing circulation patterns, salinity, and temperature.

Dredging in Kaneohe Bay was limited prior to 1939 and consisted primarily of dredging boat basins and piers through fringing reefs (Devaney et al., 1976). The most extensive dredging and filling was associated with the construction of the Kaneohe Marine Corps Air Station on Mokapu Peninsula between 1939 and 1945. Patch reefs and fringing reefs were also dredged to accommodate shipping and to construct a seaplane runway. Patch reefs were likewise dredged to clear a ship channel the entire length of the bay, and the NW channel was dredged to a depth of 10 m (33 ft.).

Some of the material dredged for the Marine Corps Air Station was used to double the land area of the Mokapu Peninsula (Roy, 1970; Devaney et al., 1976). The remainder of the material was dumped either in the bay or offshore in deeper water. It is believed that this dredged material is responsible for a significant amount of the shoaling that has occurred in Kaneohe Bay (Roy, 1970; Devaney et al., 1976).

Private dredging and filling has had an effect on Kaneohe Bay. Moku o Loe has been extensively dredged and has had its size doubled by filling. From 1946 to 1976, twelve ancient Hawaiian fishponds were filled for housing developments, in some cases, by dredging the adjacent fringing reefs (Devaney et al., 1976).

In addition to physical destruction of the reefs, dredging produces fine sediments that smother and scour corals. Sediment is unsuitable for coral planulae settlement, preventing reestablishment of the corals. Recovery of dredged areas is very slow and frequently impossible over normal periods of time. Recent surveys in the SE basin indicate that corals have reestablished on some dredged reefs (S. Coles and P. Jokiel, personal observation).

## **G. Urbanization**

Population growth and urbanization in the Kaneohe region grew after 1930, with very rapid expansion after 1940 (Devaney et al., 1976). Clearing of the land, construction of surfaces impervious to water (roads, parking lots, etc.), and channelization of streams resulted in erosion and transport of freshwater and sediments into the bay. Increased land sediment input and material from dredging caused the bay to shoal by about 1.65 m (5.4 ft) between 1927 and 1969 (Roy, 1970).

A major impact of urbanization was the discharge of large volumes of sewage into the SE portion of the bay. This caused a large increase in the nutrients necessary for plant growth. The result was a rapid increase in the amount of phytoplankton and benthic algae. The phytoplankton increase lowered water clarity and light penetration in the water, which had a severe impact on corals. The green "bubble algae"

(*Dictyosphaeria cavernosa*) rapidly spread and grew over the coral causing extensive mortality. Filter feeding organisms multiplied as a result of the increased plankton. Many of these organisms bore into calcium carbonate and their increase accelerated the degradation and breakdown of the coral reef structure. The overall result was the massive mortality of coral and associated organisms in the SE bay. Fortunately, many areas have recovered now that the sewage is being diverted to an offshore discharge site.

## **H. Sewage Discharge**

Prior to the development of sewage collection systems, pit latrines and individually constructed cesspools met the needs of the then small community of Kaneohe (Goodin & Sanderson, 1977). In 1951, Kaneohe Marine Corps Air Station built the first sewage collection system which discharged virtually untreated sewage along the southeastern margin of the bay until early 1972. In 1963, the City & County of Honolulu's Public Works Department built Kaneohe Municipal Plant which began dumping secondarily treated sewage (settled and chlorinated) in the southwest corner of the bay. By 1972 it was discharging an average of .13 cubic meters per second (3.05 mgd).

In 1969 documented changes in the southeast basin included eutrophication, decreasing species diversity, decreasing plankton populations, and altered ecosystem structure. Changes in coral reef communities were gradual in the 1950's and 60's but accelerated in the latter years. Benthic organisms showed an increasing dominance of filter and detrital feeders such as sponges, colonial and solitary tunicates, feather-duster worms, oysters, clams, and a detritus-eating sea cucumber, *Opheodesoma spectabilis*. A further effect of sewage was the displacement of corals on the reef slopes by green bubble algae *Dictyosphaeria cavernosa*. The Department of Health did a detailed study of Kaneohe Bay in 1969 but found no problem.

In 1972 various citizens groups (such as the Outdoor Circle, Kaneohe and Kahalu'u Citizens' Councils, Windward Citizens Planning Conference, and numerous university professors) began to work together and take action by forming a united organization known as "Kaneohe Bay in Crisis" (Tanimura, 1988). This groups blocked construction of a thermal power plant along Kaneohe Bay and drafted a city grading ordinance that was eventually adopted. In 1971, a Kaneohe Bay Task Force headed by the director of the Office of Environmental Quality Control was appointed by the governor. The task force built a case for the diversion of the sewage outfall to the open ocean.

The diversion was eventually constructed and put into effect in 1978. KMCAS continued to discharge sewage for a short time longer. In 1988 a small treatment plant at Ahuimanu continued to discharge sewage in the center of the bay with plans to connect up with the ocean outfall of Mokapu Peninsula. Since diversion, periodic breakdowns in the sewer system continue to dump thousands of gallons of raw sewage

into the bay (the most recent breakdown is occurring as this is being written, 5 Jan. 1991).

Research done by Hawaii Institute of Marine Biology scientists confirmed that sewage and its resulting nutrient loading definitely impose a major stress on bay corals and stimulate green bubble algae growth. Studies also found that after diversion and removal of heavy sedimentation and nutrient loading, corals showed signs of recovery in a surprisingly short time. Reducing sewage, however, also reduces food for fish, clams, and seaweed (i.e. ogo or Gracilaria) which thrive on high nutrient environments.

## **A. HEEIA FISHPOND**

Fishponds were used by early Hawaiians to insure a consistent protein supply. This technological development was necessitated by the large population's need to be reasonably independent of the unpredictability and limited supply of shoreline fisheries.

Marine fishponds were constructed in sheltered areas. Walls made from basalt and coral were usually built out from the shoreline to enclose shallow bodies of water of various sizes. Sluice gates (makaha) were built into the walls to regulate water depth, salinity, and to catch the fish.

Mullet and milk fish were the most important fishes cultured in the fishponds. Their choice by early Hawaiians demonstrated a sophisticated understanding of marine food chain dynamics. The Hawaiians chose two species of fishes that feed directly on plants (algae) and, therefore, utilize a much shorter food chain. This resulted in a much more efficient use of their marine resources.

A typical marine food chain consists of primary producers (plants) that are fed on by small herbivores, which are fed on by small carnivores, which are fed on in turn by larger carnivores. In each stage of this food chain only about 10% of the food material, (biomass), is incorporated into the next higher feeding (trophic) level. Therefore, if human beings are the fifth link in a food chain (plant, herbivore, small fish, large fish, man), 10,000 pounds of plants would be necessary to produce 1 pound of human. By utilizing a three link food chain (algae, fish, man), it would take only 100 pounds of plants to produce and sustain 1 pound of human, which is a 10,000% increase in efficiency over feeding on large carnivores.

Kaneohe Bay's sheltered lagoon fringing reefs and freshwater stream input made it ideal for aquaculture in fishponds. At least 30 fishponds were built in the bay (Devaney et al., 1976) and were utilized through the nineteenth century. However, with development and the prospect for making more money in agriculture, the fishponds gradually fell to disuse or were filled in. By 1901, only 16 ponds were in commercial use in Kaneohe Bay, perhaps half of what were in use thirty years earlier (Cobb, 1902). McAllister (1933) found evidence of 24 fishponds in Kaneohe Bay, but only a few were

being worked at that time. Currently, there are 12 recognizable fishponds in Kaneohe Bay (Devaney et al., 1976).

He'eia Fishpond was in operation until the disastrous Flood of May, 1965. This event caused considerable damage throughout the area, including breaching sections of the He'eia Fishpond wall. Small sections of the landward (mauka) wall adjacent to He'eia stream were damaged, thus letting freshwater into the pond. A larger section of the seaward (makai) wall (approximately 130 feet wide at mean tide level) was knocked down, which exposes the pond to tidal fluctuations. Because He'eia Fishpond was designed to be free from tidal fluctuations and have carefully controlled salinity and depth, the pond was rendered unusable by the flood. Unlike some of the other Kaneohe Bay fishponds that were damaged by the Keapuka Flood (Moli'i, Kahalu'u, and Waikalua fishponds), He'eia was not repaired

He'eia has some design and structural features that are rare in Hawaiian fishponds. As noted by Henry (1976):

a wall was built all around its perimeter,  
the wall was constructed to be "compact,"  
a main water-control gate was built to control the water level, and  
the makai wall was built in straight-line alignment sections.

He'eia Fishpond is unusual because an earthen dike, rather than the shoreline, forms the inner wall of the pond. A rock wall with makahas forms one side of the channel of He'eia stream to allow freshwater to be mixed with the pond water to control salinity. This was necessary because a lot of evaporation occurs in large shallow ponds. The seaward or makai fishpond wall was constructed on top of the fringing reef which borders the shoreline of much of Kaneohe Bay.

The walls of He'eia Fishpond were designed to be as leakproof ("compact") as possible so that water level and salinity could be closely controlled. The seaward (makai) wall consists of two parallel two foot rock walls. The eight foot space separating them was filled with rock, coral rubble and/or earth. Wailupe Fishpond (now Wailupe Peninsula) is the only other Oahu fishpond known to have "compact" walls.

The walls of He'eia pond, as in other Hawaiian fishponds, have 'auwai o ka makaha, which are sluice gates used primarily to capture fish. However, they also help regulate water depth and salinity, which are especially important in a large pond with compact walls. He'eia Fishpond is unusual because it has a makaha nui (main water-control gate) located in the seaward wall. This gate is used strictly to control the flow of seawater into and out of the pond, and thereby control water level and salinity. It is composed of 4 sections and is 21.5 feet in length. The gates could be independently raised or lowered to regulate water flow.

The makaha nui could not be used to catch fish as the auwai o ka makaha were (Henry, 1976). The distance between the gate and the grate is only two and a half

inches. The distance between the gates at auwai o ka makaha vary from six to twelve feet to form a fish trap.

The walls of He'eia Fishpond were constructed in straight-line segments that were lined up with geographical features. This and the overall construction of Hawaiian fishponds without the use of metal tools or modern equipment demonstrated a remarkable engineering knowledge that was seldom seen in other ancient Pacific island communities.

As mentioned, He'eia Fishpond was not repaired after the 1965 Keapuka Flood. Although small sections of the landward (mauka) wall were breached during the flood, the major damage was to the seaward (makai) wall. Henry (1976) estimated that the hole is about 130 feet at mean tide level. These holes render the fishpond unusable in its current condition because neither the water depth nor the salinity can be maintained or regulated.

Henry (1975) addressed the question of restoring He'eia Fishpond and estimated that it would cost about \$700,000 to remove the mangroves, dredge the pond, rebuild and repair the walls, and repair the makahas. However, after determining that the fishpond need not be dredged to become operational, he revised his estimate to about \$100,000. The cost would be considerably higher now. However, there are plans to temporarily patch the walls in an attempt to bring the fishpond back into production to pay for the restoration of the pond (M. Brooks, personal communication).

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## **VI. Measurement Conversions**

ppt - parts per thousand

ml/l - milliliters per liter

mgd - million gallons per day