CHAPTER 1: GENERAL INTRODUCTION AND BACKGROUND.

Evelyn F. Cox and Paul L. Jokiel, Hawaii Institute of Marine Biology

Abstract

Kahoolawe has been closed to the general public for many years. There is little information about the status of the nearshore coral reef environments, particularly associated with extensive sedimentation following overgrazing of the island primarily by goats. The south coast has steep cliffs that are exposed to oceanic conditions in the Alenuihh Channel. The eastern end of the island has large calcareous sand beaches. The northern coastline has been subjected to the highest levels of sedimentation, frequently visible as plumes of sediments in the nearshore waters. The eastern end includes the remnants of the large caldera formed when the summit of the volcano that created the island collapsed. This coastline is directly impacted by waves coming through the Alenuihh Channel. Kahoolawe has average rainfall of 63 cm yr^{-1} and no permanent freshwater streams. An artificial anchialine pond formed in a bomb crater is located at the southwest end of the island in Sailor's Hat Crater. During this 1993 survey, data on coral coverage, fish communities and sediment types were collected from eighteen geographic locations.

Background and Need

Unlike the other main Hawaiian islands, Kahoolawe has never had a large permanent population or modern large-scale agriculture. The nearshore environment has not be subjected to the multiple antropogenic factors impinging on fringing reefs around the other major islands. Since World War II, Kahoolawe was closed to the general public and was not studied by reef scientists. This resulted in a critical need for information about the nearshore marine environments of Kahoolawe.

The United States has a legislated mandate to determine the possible status as a sanctuary of Kahoolawe, Hawaii. This island is reverting to control by the State of Hawaii after many years of use as a bombing range under the administration of the United States Navy. In the final report of the Kahoolawe Island Conveyance Commission (1993), Recommendation 2.12 states that "The State of Hawaii shall recognize the waters surrounding Kahoolawe for their pristine nature - and their importance in maintaining numerous marine species populations - and designate these waters with special status under the law". Many questions concerning the potential for a marine sanctuary or shoreline conservation district remain unanswered.

The purpose of this study was to visit typical sites around Kahoolawe to describe the marine communities and to assess the extent of previous sedimentation and the potential for recovery from this damage.

Geographic Description of Kahoolawe

Location and Size

The island of Kahoolawe (156°35'W Longitude and 20°35'N Latitude) is located in the Hawaiian Archipelago, about 11 km (7 miles) southwest of Maui and 18 km (18 miles) southeast of Lnai (Figure 1.1). The island is approximately 18 km (11 miles) long and 10 km (7 miles) wide and 116.5 km² (45 square miles) in area, the smallest of the eight main Hawaiian Islands. The highest point on Kahoolawe is Puu Moaulanui, with an elevation of 450 m (1477 feet) above sea level.

Physical Description

Kahoolawe was formed by rapid extrusions of thin pahoehoe lava flows from a small summit crater, near the current summit at Puu Moaulanui, and three rift zones. At the end of the initial volcanic phase, Kahoolawe was part of a single large island that included Maui, Lnai, and Molokai. Subsequent erosion and changes in sea level separated this island from its neighbors. Rainfall and waves continue to erode the northern slopes, while wave erosion formed steep sea cliffs on the western and southern coasts (Sterns, 1940).

Prior to the first Western contact, the island was covered with thick layers of lateritic soils. Overgrazing during the historical period destroyed protective vegetation, and strong winds and rain erosion removed vast quantities of soil (Sterns, 1946; Kahoolawe Island Conveyance Commission, 1991, 1993). Total annual soil loss has been estimated at close to 1.8×10^9 kg (2 million tons) of soil per year (Kahoolawe Island Conveyance Commission, 1991; Table 1.1). In 1971 a series of revegetation efforts by the State of Hawaii, the Protect Kahoolawe Ohana and other conservation organizations began. Reductions in the area of exposed soil is already evident (Jones, 1992; Figure 1.2). The U.S. Navy completely eliminated the goats on the island by 1992 (Lt. Michael Nahoopii, U.S. Navy, Kahoolawe Project Coordinator, pers. comm.; Figure 1.3). The Soil Conservation Service has overseen the construction of small check dams on Kahoolawe to reduce soil losses (U.S. Dept. Agriculture, Soil Conservation Service, 1992).

The southern coast consists of steep cliffs with two large bays and several hanging valleys. The sea floor is littered with large boulders and slopes quite steeply away from the shoreline. There is some terrestrial sedimentation from the hanging valleys along the coastline (Figure 1.4) Although this coastline receives the impact of strong waves moving through the Alenuihaha Channel, there are some protected habitats with high coral coverage within the two large bays, Kamohio and Waikahalulu (Figure 1.5).

The western end of the island has two large beaches, Hana Kanaia (Smuggler's Cove) and Keana a ke Keiki (Twin Sands), separated by Lae o Kealaikahiki, "The Way to Tahiti", a point of departure for sailing voyages to distant lands. A wide shelf containing remnants of Black Rock and Kuia Shoal extends offshore from Lae o Kealaikahiki. This portion of the island is subjected to strong southern swell, and coral coverage is low. Coral communities are dominated by *Pocillopora meandrina* (Figure 1.6). Commercial dive operations are known to use this area as a dive site for recreational divers because of the clear water and abundance of fishes (Tabata, 1992; Appendix C).

The northern coast is characterized by gentler slopes and low rocky cliffs, interspersed with numerous small sandy and silty pocket beaches (Figure 1.7). A relatively shallow shelf extends offshore. Numerous gulches along this coast bring soil down from the slopes and continue underwater as deep beds of terrestrial sediments. Turbidity is particularly high after periods of rain and during periods of waves that disturb the sediment bottom (Figure 1.8). Normal trade winds and currents mobilize inshore sediment deposits. As the trade winds increase during the day, inshore turbidity increases. Sediment plumes move out of the bays and along the coast. Along the western shore of these underwater valleys, coral coverage is low and sediment damage is evident. There is a sharp demarcation between the turbid waters of the sediment plumes and the clearer waters along the eastern shores of the underwater valleys, and in the clearer waters, corals typical of less disturbed habitats, *Porites compressa* and several species of *Montipora*, are common and coral coverage is high (Figure 1.9).

The northeastern coast has a steeper shoreline. Turbidity can be high nearshore after rains or disturbance of bottom sediments. Coral coverage and diversity in this zone are high. (Figure 1.10).

The eastern end of Kahoolawe includes remnants of the large caldera formed after the summit collapsed. The presence of faults in this region led to the formation of a large bay, Kanapou, and evidence of post-caldera volcanic eruptions is visible on these cliffs. This bay is exposed to waves moving through the Alenuihaha Channel and into the Alalakeiki Channel, and much water-borne debris collects on the beaches (Figure 1.11). Although wave disturbance is high, coral communities in deeper water are relatively diverse and coverage is moderate (Figure 1.12). Several sites in this area are used by commercial dive operators when weather conditions are good (Tabata, 1992; Appendix C).

Meteorological Conditions

Wind Patterns

Wind patterns in the Hawaiian Islands are dominated by the northeast trade winds produced by the Pacific High northeast of Hawaii (University of Hawaii, Geography Department, 1983). The trade winds are most prevalent (80 to 95%) during the "summer", from May through October. During the "winter", from October through April, trade winds still dominate the wind patterns but are present less frequently (50 to 80%). Haleakal on the island of Maui deflects and funnels trade winds to the east across Kahoolawe at speeds of 8.2 - 9.3 m sec^{-1} (16 to 18 knots). The strong and persistent trade winds have contributed to severe erosion of the island in the last 150 years, particularly after grazing by introduced livestock destroyed most of the covering vegetation. Numerous reports describe large dust clouds blowing off the island (Judd, 1917; Environmental Impact Study Corp., 1979).

Rainfall Patterns

The island of Kahoolawe is relatively dry. Rainfall data were sporadically collected between 1920 and 1971, and a remote weather station has been in place only 4 years (National Climatic Data Center, pers. comm.). Few data from the historical period exist, but average annual rainfall is about 63 cm (25 in) (Environmental Impact Study Corp., 1979). The island is in the rain shadow of Maui during the predominant trade wind conditions. Most of the rainfall on Kahoolawe occurs during winter storms, when winds blow from the south. Rainfall produces great plumes of eroded sediment in the nearshore waters around the island (see Figure 1.10).

The low rainfall has played a role in the lack of permanent freshwater on the island (Sterns, 1940). An early survey identified catchment areas for rainwater, but due to the high rates of erosion, these areas were rapidly filled with silt (Sterns, 1940; Anonymous, 1989). Of seven ancient and historical wells located by Sterns in 1940, only two were functional. Sterns (1940) reported these two were brackish and suggested two possible causes of the intrusion of salt water into the underground aquifer. First, introduced kiawe trees have spread extensively and cause high water loss via evapotranspiration. Second, percolation has been reduced due to erosion of the porous topsoil.

Surface runoff on Kahoolawe is estimated at 7×10^7 m^3(19 billion gallons) per year (County of Maui, 1990). At present, this surface water has an extremely high sediment load due to the lack of vegetation and consequent high rates of erosion. Runoff can be up to 90% sediment under these conditions, so water catchment structures rapidly fill with sediment. The survey also revealed the possible existence of a dike impounded groundwater system than may hold between 8×10^7 to 33×10^7 m^3 (21-86 billion gallons) of water (County of Maui, 1990). This water is probably brackish, and surface recharge of this aquifer is minimal due to the lack of percolation into the ground.

Oceanographic Information

Channel and Tidal Currents

Kahoolawe lies along the edge of the Alenuihaha Channel between Maui and Hawaii. Prevailing trade winds and water are funneled into the Alalakeiki Channel between Maui and Kahoolawe. In addition, the dominant North Equatorial current in this region of the Pacific flows in the same general direction. The eastern edge of Kahoolawe, including Kanapou, is frequently subjected to strong wind-driven waves and currents. Evidence of the predominant water direction lies in the debris that collects along the beaches in Kanapou (Clark, 1980; Figure 1.11).

Flood tidal currents follow the patterns of the prevailing trade wind currents, diverging around the eastern end of the island and converging off the southwest coast at Lae o Kealaikahiki. At ebb tide the direction of the tidal current reverses, although the net effect due to the over-riding importance of the wind-driven surface current is flow southward along the coast (Environment Impact Study Corp., 1979).

This water flow pattern was known as "The Way to Tahiti" and has historically been used by Hawaiian voyagers. Starting from Lae o Kealaikahiki, the wind and current patterns favored long journeys to the south.

Wave Patterns

Two beaches are known locally as excellent surfing sites, Kaukaukapapa, east of Lae o Kealaikahiki and Kanapou (Clark, 1980). Kaukaukapapa has a moderately steep slope and powerful currents from north to south. Kanapou is exposed to strong waves from the Alalakeiki Channel.

The southern coastline of Kahoolawe frequently experiences strong waves impacting the shore due to refraction of the currents around the eastern edge of the island.

Evidence of the impact of storm waves is evident in berms along the southwest coastline, e.g. the berm of boulders at O awa palua (Figure 1.13). The damaging force of storm waves is also apparent on the reefs as evidenced by large fields of coral fragments and tumbled coral heads (Figure 1.14).

Historical Background

Some historical information about the island of Kahoolawe can be obtained from Hawaiian legends and early historical accounts. Both sources indicate that prior to the mid 1800s, there was a small but permanent population on the island, with Hawaiians using the island for agriculture and fishing (Neller, 1981; Kahoolawe Island Conveyance Commission, 1993). An early report on the island written by W.F. Allen in 1851 (in Stearns, 1940) described the fertile loamy soil found at Lua Makika, cultivated by natives for a variety of crops.

Post-western contact, the island was used as a penal colony for the Kingdom of Hawaii (1830-1843) (MacDonald, 1972). Surveys in the 1850s were undertaken by representatives of the King of Hawaii and suggested that the island had economic potential. The first lease of Kahoolawe to Robert Wyllie was signed in 1858. Wyllie introduced sheep to Kahoolawe, and subsequent lessees of Kahoolawe brought in additional sheep and goats.

The heavy over-grazing of Kahoolawe led to severe erosion problems, and in 1910 the island was declared a Territorial Forest Reserve (MacDonald, 1972). Between 1912 and 1918 sheep were moved to Maui and approximately 5,000 goats were destroyed. However, the erosion problems continued, and the Territory leased the island to Angus MacPhee in 1918, with the stipulation that all sheep and goats be eliminated by 1922. MacPhee was able to greatly reduce, but not eliminate, the sheep and goat populations, and he made strong efforts to control erosion by installing fences and planting grasses, Australian salt-bush, and kiawe (Ashdown, 1947, 1979).

In partnership with Harry Baldwin, MacPhee formed Kahoolawe Ranch, running cattle on the island. The ranch was beginning to turn a small annual profit by 1941, when the U.S. Army commandeered the ranch’s sampan and subleased a portion of the island for World War II training. By 1944 MacPhee had subleased the entire island to the Army, and in 1945 the Army turned over the sublease to the Navy. In 1947 the Territory of Hawaii attempted to retrieve control of the island, recommending termination of both MacPhee and Navy leases. After 1952 this effort was dropped, and a territorial commission recommended that the Department of Defense take control of the island (Kahoolawe Island Conveyance Commission, 1993).

In 1953, Executive Order 10436 placed the island under the jurisdiction of the Navy, with stipulations that the Navy would embark on a program of soil conservation, eliminate or control the animal population, and return the island to the Territory in a condition "reasonably safe for human habitation, without cost to the territory" (Federal Reporter, 1953).

By the 1970s, civilian opposition to the military’s use of Kahoolawe was strong. The Mayor of Maui, Elmer Cravalho, and the environmental organization Life of the Land filed suit against the Navy in 1971 to require the preparation of an Environmental Impact Statement for use of Kahoolawe by the military. An Environmental Impact Statement was prepared and issued in 1979 (Environmental Impact Study Corp., 1979). Native Hawaiians proposed the return of the island to the state, and in 1976 Protect Kahoolawe Ohana was formed. In 1977 George Helm, a member of the Protect Kahoolawe Ohana, addressed the State Legislature on the issue. Subsequently the House and Senate passed resolutions requesting a solution to the problem of continued federal control and bombing of the island. An interim Committee on Kahoolawe was formed to collect information on Kahoolawe, resulting in the publication of "Kahoolawe: Aloha no, A legislative study of the island of Kahoolawe" (State of Hawaii, 1978), that summarized the information available on the history and use of the island.

Protect Kahoolawe Ohana members were allowed access to the island by court decree in 1980 and currently use the island for cultural activities, religious practices, and subsistence fishing. Archeological studies have documented the importance of the island to native Hawaiians as a fishing site, as evidenced by the numerous fishing shines around the coastline of the island (Aluli and McGregor, 1992).

As part of the state interest in the resources of the island, the State Department of Land and Natural Resources, Division of Fish and Game, has made several surveys of fish and other fishery resources on the island (State of Hawaii, Department of Land and Natural Resources, 1969, 1972, 1993). The Marine Options Program of the University of Hawaii at Hilo conducted a fish survey at six locations on the northern coast of Kahoolawe in 1976, noting high diversity among the fish species (Akaka et al., 1976). In 1981, the University of Hawaii at Manoa Marine Option Program, with financial assistance from the National Science Foundation, made a quantitative survey of the impacts of siltation on the biota at six locations along the northern coast (Kawamoto et al., 1981), finding major impacts of sediments on nearshore reefs.

In 1990 President George Bush ordered the cessation of bombing of the island. The United States Congress suspended training exercises and established the Kahoolawe Island Conveyance Commission to study the transition of the island from military use back to the state of Hawaii. The Kahoolawe Island Conveyance Commission has recommended that the island be returned to the State of Hawaii. Further, special legislation mandates removal of ordnance and funds for the restoration of the island, including soil conservation, water resource development, erosion abatement and stabilization of archeological sites. The commission also recommended controlled access to the island under the jurisdiction of the State of Hawaii (Kahoolawe Island Conveyance Commission, 1993).

General Methodology

Three site visits were made during 1993. The first visit occurred during March (Table 1.2, Figure 1.15). Survey trip members made daily trips from Maui to sites on Kahoolawe. Survey personnel on the first trip included P. Jokiel, E. Cox, F. Te, and J. Rooney of the Hawaii Institute of Marine Biology, J. Naughton of the National Marine Fisheries Service, and F. Stanton of the University of Hawaii Department of Zoology. At ten sites, one team collected quantitative data on coral coverage and fish abundance (Chapter 2). This team also collected bulk sediment samples along the fish/coral transect lines (Chapter 3). Simultaneously, a second team produced an overall profile of the site, noting depths, general substrate and biological characteristics, presence of unique organisms such as green sea turtles, estimates of ordnance, and percent of area impacted by sediment (Chapter 4).

Two visits occurred during May 1993. Permission was obtained to study the aquatic biota of Sailor's Hat crater, which was formed by a massive explosive test near the U. S. Navy base at Hana Kanaia (Chapter 5). The second trip also included an aerial survey for marine mammals and turtles and to observe general sediment movements (Chapter 4).

A second shoreline survey was conducted in late May. Survey personnel included P. Jokiel, E. Cox, F. Te and F. Stanton. Eight sites were visited and quantitative data on coral coverage and fish abundance were collected (Chapter 2). In addition, beach profiles and core sediment samples were collected at Honokoa, Lae Paki, Kaukamoku, Ahupu, and Papakaiki (Chapter 3). Samples of beach sands from selected sites have been deposited with Dr. Carol Hopper, Waikiki Aquarium, Honolulu, Hawaii.

Acknowledgements

We wish to thank the personnel of the U.S. Navy who assisted in setting up these surveys, in particular Lt. Cmdr. S. Dehart, Capt. Roth, and Lt. M. Nahoopii. We also thank Lt. Ken Robell and the U.S. Navy Explosive Ordnance Disposal teams who accompanied us in the field. Rob Hubbard supplied the vessel for our day trips from Maui.

We would like to thank Scott Henderson, Jim Maragos, and Chris Evans for many informal discussions about the island. Brian Kanenaka and Francis Onishi of the Department of Land and

Natural Resources shared their impressions of the nearshore biota with us. Gail Chun of The Nature Conservancy showed us detailed aerial photos of the island and provided us with information about the terrestrial biota. Hardy Spoehr and the Kahoolawe Island Conveyance Committee furnished much information.

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Table 1.1: Estimates of annual soil loss from selected watersheds on Kahoolawe. Data from Kahoolawe Island Conveyance Commission (1991).

Watershed	Area $m^2 \times 10^6$	Rate kg m^{-2}	Total kg $\times 10^8$
Hakioawa	3.1	95	1.1
Waaiki	0.9	64	0.6
Papakaiki	2.2	68	1.5
Kaulana	2.8	39	1.1
Kheia	0.9	56	0.5
Ahupu	6.6	47	3.7
Kaukamoku	3.1	28	0.9
Wai Honu	5.1	13	0.7
Kanaloa	4.3	47	2.0
Kaukamaka	4.1	125	5.1

Table 1.2: Sites visited on Kahoolawe during 1993. Data collected include quantitative coral (C) and fish (F) transects, bulk sediment samples from transects (B), beach profiles (P), and core sediment samples from transects perpendicular to the beach (S).

date	site	site abbreviation	data collected
22 Mar	Kamohio (west side)	KM	C F B
	Wai Kahalulu (east)	WK	C F B
	Wai Kahalulu (west)	WK	qualitative snorkel
23 Mar	Keoneuli (Beck Cove)	BC	C F B
	Papakanui	PA	C F B
24 Mar	Hakioawa (south)	HK	C F B
	Kaheia (west)	KH	C F B
25 Mar	Hana Kanaia (Smuggler's Cove)	SM	C F B
	Twin Sands (east)	TW	C F B
26 Mar	Makaalae	MK	qualitative snorkel
	Ahupu (east)	AH	C F B
	O awa palua	OP	C F B
14 May	Sailor's Hat	SH	survey of anchialine pond
25 May	Honokoa (east)	HN	C F B P S
26 May	Kaukamoku (east)	KUC	C F B
	Kaukamoku (into beach)	KUS	C F B P S
	Ahupu	AH	P S
27 May	east of Waaiki	WA	C F B
	Papakaiki	PI	C F B P S
28 May	Black Rock	BK	C F B
	Lae Paki (east)	LP	C F B P S
29 May	North Kanapou	NK	C F B
	Lae o Halona	HL	C F B
	O awa wahie	OA	qualitative SCUBA

Chapter 2: Community structure of corals and reef fish.

Evelyn F. Cox[1], Paul L. Jokiel[1], Franklyn T. Te[1], and Frank G. Stanton[2]

1. Hawaii Institute of Marine Biology
2. University of Hawaii, Department of Zoology

Abstract

Coral and fish community structure was characterized at 19 sites around the island of Kahoolawe. Visual counts of fishes along 3 replicate 25 m transect lines were recorded. Coral cover was estimated in 5 contiguous 1 m² quadrats haphazardly taken along the 25 m fish transect lines. Size and spatial distributions of coral colonies at the base of the reef structure were measured at Honokoa, Kaukamoku, Papakaiki and Waaiki as a means of estimated the rate of uncovering of previously buried reef substratum.

Twenty four species of corals were recorded, and coral diversity (Shannon-Weaver H¢$_c$) ranged from 0.38 to 1.78. One hundred and sixteen species of fish were recorded, with diversities (H¢ $_c$) ranging from 0.74 to 3.05. Coral communities could be clustered into five groups. Group I included the stations with the highest coral cover, primarily *Porites compressa* and *Montipora* spp., and high coral diversity. These stations were located in calmer water. Group II had similar coral species as Group I but lower coral coverage. Group III stations had low coral coverage and were dominated by *Porites lobata* and *Pocillopora meandrina*. Group IV stations were dominated by *P. meandrina* and had the coral cover and diversity. The final group included four stations with the lowest coral coverage, but relatively high diversity or high abundance of generally uncommon coral species such as *Pavona duerdeni*.

Fish communities were primarily grouped into shallow and deep stations. The abundance of coral feeding butterflyfishes was positively correlated with the percent total coral coverage.

Introduction

Feral goats were introduced to the island of Kahoolawe, Hawaii shortly after they were brought to the Hawaiian islands by Captain Vancouver to serve as a source of fresh meat for sailing vessels. Overgrazing of vegetation by large populations of goats, and later sheep and cattle, on Kahoolawe lead to severe terrestrial erosion and subsequent sedimentation of the nearshore marine environments. Sporatic attempts to eradicate feral animals began in the 1920s, and in 1971 revegetation operations commenced. Terrestrial ground cover has increased. The last goat was eliminated from Kahoolawe in 1992 (Chapter 1). Kahoolawe has been under the control of the U.S. military, from 1941 until the present, and has been closed to most nearshore marine reacreational activities.

This study was undertaken to characterize the coral and fish community structure around the perimeter of the island of Kahoolawe. A major focus of this study was to assess the impact of sedimentation on coral and fish community structure and the ability of these communities to recover from sedimentation.

Methods

Sampling Methods

Sites visited by the survey team and general methods are given in Chapter 1. At each site, visual inspections of the entire area by skin diving were first conducted. Stations for quanititative censusing were selected as areas with typical coral reef structure. Most sites included two stations, one at 10 m and one at 3 m depth.

Quantitative transects for fish abundance were conducted at each station by a single diver (EFC). The procedure involved a modification of the Brock (1954) visual census technique. Although visual census techniques have deficiencies (Brock, 1982; Green and Alevison, 1989), this technique provides a reasonable estimate for the common, diurnal, reef-associated species. Using SCUBA, the diver swam approximately 1m above the substratum and counted large mobile species (particularly *Scarus* spp., *Melichthys* spp. and *Naso* spp.) in a belt 1 m to each side and 5 m up from the substratum. Each transect was 25 m in length. The diver then returned along one side of the transect line, swimming close to the bottom and counting the smaller and more sedentary species. The opposite side of the transect line was counted while returning to the end point of the transect. At each depth, three transects were sampled.

A list of the common reef species, based on Randall (1985), was printed on underwater paper. Fishes observed were talled on the sheets. Cryptic or nocturnal species are not accurately censused by this method, so these species were not included in the community analyses. When sighted, however, these species were noted on the census sheets. The focus of this survey was the diurnal, relatively sedentary, reef-associated species. Qualitative measures of the more mobile species are reported by Naughton (Chapter 4).

Many of the scarids seen on these transects were juveniles or females, difficult to identify to species. Hence, in analyses, all scarids were lumped as *Scarus sp.*

Coral cover was estimated in 5 contiguous 1 m^2 quadrats haphazardly taken along the 25 m fish transect lines (Jokiel and Maragos, 1978; Maragos and Jokiel, 1986; Jokiel and Tyler, 1992). Visual estimates of percent cover of each species within the quadrat was recorded by one observer (PLJ), and notations of additional species observed outside of the sampled area were recorded. Species identifications were based on Maragos (1977). Visual estimates are more reproducable and more accurate than random-point sampling (Dethier et al., 1993).

At several stations (Honokoa, Kaukamoku, Papakaiki, and Waaiki), data on the size distribution of small colonies located on vertical faces at the base of the reef structure were collected. At some sites, colony size was directly measured in bands 1 m by 0.5 m up from the bottom of the reef. At other sites, photographs of the quadrat frame were taken and subsequently analyzed. Colony sizes were estimated using the 10 cm grid of the quadrat frame for scale.

An index of rugosity of the substratum was measured at 18 stations on the first survey trip to Kahoolawe. This index is the comparison of the amount of length of chain draped over the topography of the substratum to the straight line distance covered by the transect line (Luckhurst and Luckhurst, 1978). Sediment samples were collected at each site (Chapter 3).

An index of relative water motion and potential for impacts from major storm conditions was developed using summarized data on typical current patterns, wind speed records and wave patterns (Environmental Impact Study Corp., 1979; University of Hawaii, Geography Department, 1983).

Data Analysis

Coral community diversity was calculated using the modified (Loya, 1972) Shannon-Weaver diversity index ($H¢_c$ = - S pi ln pi) of the mean percent cover each species on the three transect lines. Fish community diversity was caculated using the average number of each species from the three transect lines. Similarity of communities from the 33 sites sampled was assessed using a modified Sørensen Similarity index, after transformation of the data (angular transformation of percent data and square root transformation of average counts):

$Iab = S\ 2Ma\ (Ma + Mb)^{-1}$;

where I_{ab} is the index for two sites (a and b) for each species (i = 1, 2, ...S); M_a is the lower cover or density for the i^{th} species in the two site pair and M_b is the higher cover or density for that species. Cluster analysis was performed on the resulting matrix of similarity values using SAS procedures (SAS 1988).

A principal components analysis was run in SAS using coral coverage and diversity information, fish density and diversity data, an index for exposure to storm events and normal wave energy, and percent silt composition. Rugosity index was not included in this analysis because it was not measured at all stations.

Results

Coral diversity ($H¢_c$) ranged from 0.38 to 1.78 (Table 2.1), with 24 species recorded (Appendix A). Diversity was highest at Papakanui and Hakioawa, where the coral coverage was relatively high and the coral community included *Porites compressa* and *Montipora spp*. Diversity was lowest at Smuggler's Cove, Black Rock, Twin Sands, and North Kanapou, where coral coverage was relatively low and the coral community was dominated by *Pocillopora meandrina*.

Fish diversity ranged from 0.74 to 3.05 (Table 2.1). 116 species were observed over all sites, with an average of 27 spp. per station (Appendix B). Fish diversity was highest at Twin Sands and Beck Cove, with moderate numbers of both fish species and individuals. Diversity was lowest at Kaukamoku, where high abundance of a single species, *Chromis vanderbilti*, was recorded.

Cluster analysis of coral coverage data produced five major groups (Figure 2.1). Group I included stations with the highest coral coverage, high relative coverage of *Porites compressa* and *Montipora spp.*, and generally the highest coral diversity. Group II included stations with lower coral coverage than Group I but still relatively high diversity of corals. Like Group I, Group II also had high relative abundance of *P. compressa* and *Montipora spp*. Group III stations had lower coral coverage than Groups I and II and were dominated by *Porites lobata*, followed by *Pocillopora meandrina*. Coral diversity values were variable in this group and overlapped values for Groups I and II. Group IV were stations dominated by *Pocillopora meandrina*, followed by *Porites lobata*. These stations had low coral diversity and relatively low coral coverage compared to the first 3 groups. Group IV included the stations exposed to largest storm waves. The final group included the four stations with the lowest coral coverage (<6%), but coral diversities ranged from 0.8 to 1.5. Kaukamoku S had the lowest coral coverage as well as low coral diversity. Twin Sands 3 m had the second lowest coverage but high relative abundance of *Pavona duerdeni*. Wai Kahalulu 3 m and 10 m stations had low coverage but relatively high coral diversities.

There was an inverse correlation between the relative coverage of *Porites compressa* and *Pocillopora meandrina* (Pearson correlation coefficient $r = -0.818$, $P < 0.01$, $df = 31$). Stations with high relative coverage of *Porites compressa* had relatively low coverage of *Pocillopora meandrina* (Figure 2.2) and represented the stations in cluster analysis Groups I and II. There was no significant correlation between relative coverage of *P. meandrina* and *Porites lobata* (r =

0.087, $P > 0.05$, df = 31). Group III had high relative coverage of *P. lobata*, followed by *P. meandrina*, and Group IV stations had those proportions reversed.

Unlike the coral communities, fish abundance data clustered stations into two major groups, one including mostly shallow stations and the other deep stations (Figure 2.3). Two stations, Smuggler's Cove 10 m and Kaukamoku S were different from all other stations. Kaukamoku S had the lowest number of species and individuals. Smuggler's Cove 10 m had fairly high diversity and uniform abundance of species.

Twelve variables weighed heavily on scoring for the first axis in principal component analysis (Figure 2.4). They included relative percent silt, coral diversity, total coral coverage, relative percent coverage of five coral species (*Pocillopora meandrina*, *Porites compressa*, *Montipora verrucosa* and *M. patula*, and *Pavona varians*) and relative abundance of four fish species (two coral feeding chaetodontids, *Chaetodon multicincitus* and *Chaetodon trifasciatus*, and two plantivorous pomacentrids, *Chromis hanui* and *Chromis agilis*). The second axis weighed heavily the indices of water motion and wave damage, depth, fish diversity and the relative abundance of 4 fish species (*Gomphosus varius*, *Dacyllus albisella*, *Acanthurus olivaceous* and *Sufflamen bursa*). There were two groups of shallow stations and two groups of deep stations. The smaller group of deep stations (O awa palua, Honokoa, Waaiki, and Kheia) were stations with relatively high silt, coral coverage and fish and coral diversity, whereas the second group had lower diversity and coverage. Likewise, the shallow station group including Hakioawa, O awa palua, Papakanui, Kheia, Waaiki, and Papakaiki, represented stations with relatively high coral coverage, relatively high coral and fish diversity, and relatively low silt, while the larger group of shallow stations had lower coral coverage and diversity. Three stations did not appear to fall neatly into any of these groups. Beck Cove 3 m was unusual in that, although it had relatively high coral coverage and coral and fish diversity, it had much higher percentage of silt than the other shallow stations. Likewise, Kamohio 3 m, with relatively low diversity and coral coverage, had higher percentage of silt than the other group of shallow stations. Papakaiki 10 m had moderate fish and coral diversity, but with high relative abundance of *Pavona maldivensis*.

There were few strong correlations between the environmental variables we measured and the diversity and coverage of coral species (Table 2.2). The ranked indices of wave damage and water motion were not sufficiently precise to show strong correlations between these physical factors that are typically associated with coral community structure. Total coral coverage was positively correlated with coral diversity ($r = 0.432$, $p < 0.01$, $df = 31$).

Colony size of *M. verrucosa* and *P. compressa* increased on vertical walls with increased distance above the mud and sand in the channels (ANOVA: *M. verrucosa* $F = 4.92$, $df = 3, 29$, $p < 0.01$; *P. compressa* $F = 11.5$, $df = 3, 31$, $p < 0.01$; Table 2.3). The bottom of the reef structures are being uncovered, and coral recruitment has been occurring on the newly exposed substratum. This does not appear to be a "scouring effect" (Dollar and Tribble, 1993) due to movement of large boulders, as no evidence of boulders or their impacts were noted in these fine sediment areas. Too few colonies of *Pocillopora meandrina* and *Montipora patula* were recorded in these quadrats to notice a trend in pattern of settlement. *Porites lobata* was only observed above the second zone from the bottom but with too few colonies to substantiate a trend in colony size. When all coral colonies are grouped, there is an increasing trend in average colony size with distance from the bottom of the reef structure (Figure 2.5).

There was a positive correlation between abundance of coral feeding butterflyfishes and percent total coral coverage (Figure 2.6, $r = 0.522$, $P < 0.01$, $df = 31$). However when the abundances of individual species of butterflyfishes and the coverage values for preferred food species of corals (*Pocillopora spp.* and *Montipora spp.* were considered, positive correlations reflected the overall trend of increased numbers of butterflyfishes with higher coral coverage (Table 2.4).

Discussion

The nearshore marine habitats of Kahoolawe include a variety of reef types, from low coverage reefs dominated by *Pocillopora meandrina* to high coverage reefs with a good diversity of coral species. Although evidence of major sediment impacts in the past was still visible, the overall effects of sediments appear to be diminishing, associated with increased revegetation and decreased sediment inputs. There were many areas of habitat that represent near pristine conditions with high coral and fish diversity, and these areas were already being visited by commercial dive operations when weather conditions permit (Chapter 1).

Coral diversity at sites around the perimeter of Kahoolawe overlaped previously reported diversity indices for Hawaii (Table 2.5). Because Hawaii is relatively isolated within the Pacific Ocean basin, the depauperate nature of the fauna alone resulted in lower diversity values than reported for other locations within the Pacific. Hawaii is also near the northern limit for reef development (Grigg, 1982). Although at a similar latitude, the reefs of Miyake-jima, Japan (Tribble and Randall, 1986) have higher diversity than Hawaiian reefs. Recruits to the Japanese reefs are obtained from the currents flowing northward from more diverse areas near the equator. South of the Hawaiian island chain, coral diversity at Johnston Atoll (Jokiel and Tyler, 1992) is in the same range as diversity indices reported in this study. Although environmental conditions are optimal for coral reef development at Johnston Atoll, its geographic isolation is responsible for low diversity. Other, less isolated, atolls in the central Pacific, such as Fanning (Maragos, 1974) and Canton (Jokiel and Maragos, 1978), have higher coral diversities than were recorded in this study.

The composition of the coral communities surveyed agrees with surveys of the northern coast of Kahoolawe conducted by Kawamoto et al. (1981). They reported lower values for total coral coverage, but their species list and relative abundance of coral species overlapped results from this survey. They found heaviest sedimentation at Kheia, Ahupu and Ahupu iki and described large plumes of silt moving with the currents. The State of Hawaii Department of Land and Natural Resources (1993) survey of the entire island also recorded similar coral coverage and species composition to the results reported in this study.

Many factors affect the diversity and abundance of corals. Physical factors such as water motion, wave damage, light, salinity and depth play a role, but these factors are clearly correlated with one another (Jokiel and Tyler, 1992). An argument can be advanced, however, that water motion plays an overriding role. Water motion controls water transparency, removes sediments, and can lead to coral fragmentation. At stations on Kahoolawe exposed to strong storm waves, coral coverage was low due to occasional storm damage, and the coral community was dominated by *P. meandrina*, a species that requires extremely high water motion for growth (Jokiel, 1978). Good examples of this type of community on Kahoolawe are Smuggler's Cove and Black Rock, both exposed to southern storm swell and episodic hurricanes (Chapter 1). The other end of the spectrum includes areas with calmer water, protected from both southern swell and storms from the North Pacific. These areas had high coral coverage, with the more fragile species, *P. compressa* and *Montipora spp.*, as the dominant corals. *Montipora verrucosa* grows well in calm water (Jokiel, 1978), and *P. compressa* has been described as the climax species in Hawaiian waters protected from wave disturbance such as the deep waters of the leeward coasts or protected bays (Dollar, 1982; Maragos, 1972). We did not find any communities dominated solely by *P. compressa*, as are found in areas such as deep waters off the Kona coast of Hawaii (Dollar, 1982) and Kaneohe Bay, Oahu (Maragos, 1972). Papakaiki 10 m had 65% relative abundance of *P.compressa* but also reasonably abundant coverage of a variety of other species. Perhaps even the most protected sites at Kahoolawe are still exposed to stronger water motion than would be experienced by deep reefs of Kona or in enclosed bays. An alternate hypothesis is that the process of succession in these protected sites on Kahoolawe has been set back due to sedimentation.

Grigg (1985) studied several bays along the Hamakua coastline of Hawaii when sediment discharges by sugar mills were decreased. He estimated recolonization of these areas could take up to 17 years. The Hamakua coastline is continually impacted by large waves, and Grigg (1985) found that recovery began immediately following cessation of discharge with the removal of the sediment deposits. The process of recolonization of Kahoolawe's reefs is on-going, with sediment loads into the nearshore environments apparently decreasing during the last 10 years, and small coral colonies are appearing at the bases of recently uncovered reef structures. The recolonization of nearshore coral reefs on Kahoolawe appears linked with continued recovery of the terrestrial vegetation and further decreases in sediment input (Chapter 3).

Fish community diversity has also been linked to physical factors such as substratum, amount of topographic relief, depth, wave exposure and water motion, and number of refuges (Chave and

Eckert, 1974; Jones and Chase, 1975; Alevizon et al., 1985; Sale, 1991). In communities around Kahoolawe, the most important factor defining clusters of fish communities was depth. The 3 m stations included more species commonly associated with shallow water or surge zones such as *Stegastes fasciolatus*, *Acanthurus achilles* and *Acanthurus guttatus*. Many of the species recorded were found at almost all stations, including *Paracirrhites arcatus*, *Parapenues multifasciatus*, *Chaetodon multicinctus*, *Chromis vanderbilti*, *Thalassoma duperrey*, *Gomphosus varius*, *Acanthurus nigroris*, *Acanthurus nigrofuscus*, *Ctenochaetus strigosus*, and *Sufflamen bursa*. Species such as *Centropyge potteri* and *Dacyllus albisella* were found primarily at the deeper stations.

Similar lists of species and abundances for Kahoolawe were reported by Kawamoto et al. (1981) and the State of Hawaii, Department of Land and Natural Resources (1993). Kawamoto et al. (1981) listed five species as most common: two acanthurids, *Acanturus nigrofuscus* and *Ctenochaetous strigosus*, the pomacentrids *Chromis vanderbilti* and *Stegastes fasciolatus*, and the labrid *Thalasomma duperrey*. The damselfish *Chromis vanderbilti* was the most abundant numerically at almost every site surveyed by the Department of Land and Natural Resources (1993). In addition, surgeonfishes, particularly *Acanthurus nigofuscus*, *A. nigroris*, and *Ctenochaetus strigosus*, were also very abundant, as was the endemic wrasse, *Thalasoma duperreyi*.

Abundance of butterflyfishess has been previously associated with overall coral coverage, as this group includes important coral feeding fishes (Harmelin-Vivien and Bouchon-Navaro, 1983; Bell *et al*., 1985; Bouchon-Navaro, 1986; Roberts and Ormond, 1987; Hourigan *et al.*, 1988; Roberts *et al.*, 1988; Bouchon-Navaro and Bouchon, 1989; Cox, 1994). That trend was also noted in this study, as there was a positive correlation between the total coral coverage and the total number of corallivorous butterflyfishes at these stations. The negative correlations between coverage of *Pocillopora meandrina*, the preferred coral food for most corallivorous butterflyfishes (Hourigan et al., 1988), and abundance of butterflyfishes were related to the positive correlation between butterflyfish abundance and total coral coverage. Where *P. meandrina* was abundant, overall coral coverage and number of coral feeding butterflyfishes were low. The positive correlation found for *Chaetodon quadrimaculatus* and *P. meandrina* probably reflected the ability of this species to utilize algae as an additional food source (Hourigan, 1987; Cox, 1994). The positive correlations for other coral species and butterflyfish abundance, particularly the strong association between *C. trifasciatus* and *P. compressa* and *M. patula*, also reflected the general pattern between overall coral coverage and number of coral feeding butterflyfishes.

Corals are long-lived organisms. As such, they reflect integrated environmental conditions over long periods of time. Zonation patterns based on coral distributions have been described for many reef regions. Fish, in contrast, are highly mobile. Previous work at local scales suggests that there is high overlap in the fish faunas of distinct coral zones (Chave and Eckert, 1974; Jones and Chase, 1975; Bell and Galzin, 1984; Alevizon et al., 1985). Long-term studies of modified habitats have demonstrated changes in the fish fauna to environmental changes, e.g. the impacts of lava flows (Godwin and Kosaki, 1989), intense fishing pressure (Russ and Alcala, 1989), or coral mining (Shepard et al., 1992). To completely describe changes associated with sedimentation and recovery from sediment damage at Kahoolawe would require a long-term study.

Many reef habitats in the nearshore environment of Kahoolawe are in near-pristine conditions. Continued removal of sediments from the nearshore environments will lead to increased settlement of corals to previously damaged reefs. Clearly the nearshore reefs of Kahoolawe have the potential to recover from the sedimentation damage of the past 100 years.

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Table 2.1: Coral coverage (% of substratum), diversity, and number of species and fish diversity and species richness. Site abbreviations are given in Table 1.2 (Chapter 1).

Site	Coral Community			Fish Community	
	% cover	H¢ c	# Spp.	H¢ c	# Spp.
SM10	9.1	1.32	9	2.97	36
SM3	24.6	0.38	5	2.69	40
BK10	20.0	1.01	6	1.64	35
BK3	12.8	0.78	6	2.48	30
TW10	23.9	0.88	9	3.04	35
TW3	3.6	1.00	5	2.61	32
LP10	8.6	1.20	7	2.73	34
LP3	12.3	0.79	7	2.42	29
HN10	10.3	1.47	6	3.01	27
HN3	9.9	1.30	8	2.05	35
OP10	73.0	1.43	7	2.55	28
OP3	54.6	1.52	7	2.48	21
AH3	14.9	0.88	5	2.22	22
KUC	28.9	1.11	12	0.74	24
KUS	2.8	0.82	4	1.55	9
KH10	61.8	1.53	9	1.98	27
KH3	67.8	1.54	8	2.01	24
PA3	56.7	1.78	7	2.15	25
PI10	17.8	1.08	6	2.37	21
PI3	48.9	1.60	7	1.36	23
WA10	83.2	1.33	7	2.87	26
WA3	74.1	1.30	7	1.63	20
HK10	63.2	1.70	7	2.74	20
HK3	51.4	1.33	6	2.55	24
NK10	33.6	0.88	8	2.56	33
NK3	34.0	0.80	8	2.37	26
BC10	25.7	1.40	8	3.05	28
BC3	75.1	1.17	9	2.63	31
HL10	12.4	1.31	6	2.20	32
KM10	37.7	0.94	8	2.72	29
KM3	8.1	1.16	7	2.40	27
WK10	6.2	1.13	8	2.19	27
WK3	4.8	1.48	8	1.76	21

Table 2.2: Matrix of Pearson's Correlation Coefficients with number of total coral cover, number of coral species, coral diversity, depth, water motion index, and wave damage index. (* º critical r = 0.344, p < 0.05, df = 31.)

	# spp	H'c	depth	wat.mot.	wave dam.
Total Cover	0.256	0.432	0.018	0.232 *	-0.168
# spp.		0.239	0.132	0.143	0.088
diversity			0.142	0.121	-0.168
depth				0.121	0.196
wat.motion					0.393 *

Table 2.3: Mean diameter of coral colonies at the bottom of reef structures at Honokoa, Kaukamoku, Papakaiki and Waaiki.

Zone	*M.verrucosa*	*M.patula*	*P.compressa*	*P.lobata*
0-0.5m	2.5 (n=14)	none	2.8 (n=8)	none
0.5-1m	4.1 (n=8)	6.0 (n=3)	3.0 (n=12)	6.0 (n=7)
1-1.5m	9.0 (n=7)	6.0 (n=5)	4.7 (n=7)	11.4 (n=16)
1.5-2m	8.0 (n=4)	none	9.2 (n=8)	10.7 (n=7)

Table 2.4: Pearson correlation coefficients for coral feeding butterflyfishes and total coral abundance and abundance of specific food corals. (* º critical r = 0.344, p < 0.05, df = 31; ** º critical r = 0.443, p < 0.01, df = 31.)

Species	total	*P.meandrina*	*P.lobata*	*P.compressa*	*M.verrucosa*	*M.patula*
C.multicinctus	+.448 **	-.150	+.456 **	+.412 *	+.313	+.357 *
C.ornatissimus	+.428 *	-.195	+.354 *	+.295	+.386 *	+.449 *
C.trifasciatus	+.815 **	-.265	+.288	+.771 **	+.644 **	+.864 **
C.unimaculatus	+.220	-.238	+.122	+.238	+.280	+.304
C.quadrimacultus	-.285	+.541 **	+.081	-.542 **	-.378	-.299

Table 2.5: Coral diversity indices from selected studies in the Hawaiian islands. Reference 1 = Grigg and Maragos (1974), reference 2 = Dollar (1982), reference 3 = Grigg (1983), reference 4 = Cox (1994).

	coverage	diversity	reference
Hawaii			
Kapoho	12%	1.15	1
Wai Ahukini	18%	1.02	1
Kehena	22%	0.89	1
Hookena	25%	0.68	1
Kealakomo	25%	0.70	1
Milolii	70%	0.53	1
Kailua Kona	12-31%	0.78-0.88	2
Kailua Kona	20-64%	0.56-0.97	2
Kailua Kona	8-76%	0.50-0.62	2
Hnaunau and Kealakekua	67%	0.65	3
Puak	70%	0.76	4
Maui			
hihi Knau	19-22%	1.41-1.66	4
Olowalu	21%	1.72	4
Kanapali and Olowalu	49%	0.90	3
Lnai			
Club Lnai	42%	1.68	4
Oahu			
Kahe	6%	1.24	4
Kneohe Bay	87-88%	0.72-0.73	4
Hanauma Bay	54%	0.75	3
Kauai	51%	0.65	3

Chapter 3: Sediment Processes

Franklyn T. Te, Paul L. Jokiel and Evelyn F. Cox, Hawaii Institute of Marine Biology

Abstract

Sediment samples were collected at 19 reef stations along the coast of Kahoolawe. Sediment grain size was determined by wet-sieving; mineralogy of the sediments was defined using x-ray diffraction analysis. The silt fraction of was generally of terrestrial origin while coarser fractions were generally carbonates formed by marine organisms. Sediment deposits in shallow water (< 3 m) are winnowed by wave action and contained less silt compared to sediment deposits from deeper water (3-10 m). Deposits in deeper water generally showed a thin (<10 cm) layer of wave-reworked sediment with low silt fraction that was underlain by sediment with a higher silt content.

Local topography, vegetative cover of watersheds, and the soil condition of Kahoolawe controls terrigenous input of sediment loads along the coast. Offshore bathymetry, especially steepness of the seaward slope, is a major factor in determining weather or not sediments will accumulate. Prevailing patterns of waves and currents prevent sediments from settling on the reef and can resuspend old deposits. Water motion thereby influences localized turbidity, sedimentation and sediment removal.

Our observations suggest that sediment deposits on the coral reefs of Kahoolawe are dynamic features that are constantly being replenished by terrestrial runoff as well as by biogenic carbonate material from the reef. These deposits are, in turn, being altered and depleted by resuspension of fine fractions during periods of strong surf and currents. There is a continual movement of materials down-slope that is enhanced by physical disturbance (waves and currents). Our observations suggest that sediment deposits on the reefs of Kahoolawe are presently being removed more rapidly than being replenished. This conclusion is consistent with data showing a gradual increase over the past 20 years of vegetation covering the island. We noted uncovering of old buried reef structures at many locations previously subjected to high sediment loading. We found no evidence of corals being buried under newly deposited material. Rapid recruitment of new coral colonies onto newly uncovered reef surfaces was noted at all locations, leading us to conclude that the reefs are presently undergoing recovery as sediment input diminishes. Further revegetation will diminish sediment inputs to even lower levels and lead to acceleration of the reef recovery process.

Introduction

Accelerated soil erosion due to overgrazing and military use of the island of Kahoolawe as a target range resulted in extreme sediment loading on the coral reefs (Chapter 1). Recently, all grazing animals have been eradicated from the island and military activity has been curtailed. Revegetation is occurring, and the amount of exposed soil has decreased. Presumably, there has been a consequent reduction of sediment input on the reefs, although direct data are lacking.

An estimated 1.7 x 10^9 kg (1.9 million tons) of soil per year is eroded annually from Kahoolawe (Chapter 1), with annual point-discharge rates ranging from 0.6 x 10^8 to 5.1 x 10^8 kg (62,000 to 561,000 tons) at the largest stream mouths. Anthropogenic stress factors often associated with sediment loading (i.e. sewage, fertilizers, agricultural pesticides, industrial pollutants, etc.) are not present. Thus, Kahoolawe offers a unique opportunity to study sediment dynamics on coral reefs in a situation that is free from many confounding influences.

This report presents the following: 1) the distribution of size fractions within sediment deposits at two depths (3m and 10 m) along the coast of Kahoolawe; 2) the mineral composition of these sediments; and 3) factors that influence the distribution of size fractions and mineral composition of these sediments. In addition, qualitative surveys were conducted at each survey site. This information allows for the formulation of a preliminary dynamic model that can be tested in further studies.

Materials and Methods

Sample collection and preparation

Bulk Samples.

Sediments were collected at 19 sites around the island (Chapter 1). When possible, samples were collected from two depths (3 m and 10 m). A hand-held plastic scoop was used to collect samples along the transect lines that were also used in the fish and coral surveys (Chapter 2). About four scoops (roughly 40 - 100 g) of unconsolidated surface sediment were taken at each station and placed into plastic bags (Whirlpak brand). These plastic bags were then sealed and stored in wet condition for later analysis by wet sieving (McManus, 1988).

Core Samples.

Core samples were taken from 5 randomly chosen sites along the northern coastline of Kahoolawe. Observations from the first site visit in March, 1993, suggested that the northern coast was heavily sedimented and an in-depth investigation of the impact sediment loads impacting these areas was undertaken. Core samples were obtained in replicates of two at 50 m intervals, starting at the water line on the beach and moving seaward through the central part of each bay (Figure 3.1). Polyvinylchloride (PVC) pipes of 18 mm in diameter and 300 mm length were used as sampling devices at each station. The PVC core samplers were manually pushed into the sediment and both ends capped tightly in the water before being brought up to the surface. All the core samples were kept frozen prior to

analysis.

A modified core extraction method was used due to the small diameter of the cores (18 mm). Briefly, the core samples were allowed to thaw and then extracted from the PVC samplers by opening the lower end cap first and then slowly opening the top cap. The sediment cores came out slowly from the tubes after the top cap was removed. In a few cases when the cores were too sticky, a small glass-tip plunger was used to slowly push air through the PVC sampler and extrude the remaining sediment core. The length of the extracted cores was then measured, and the number and size of layers per core were noted. The type, texture and the color of each layer per core were also noted.

Sample analysis

Size Fraction Determination.

Sediment samples were wet sieved through standard brass sieves (USA Standard Testing Sieve: A.S.T.M.E.-11 specifications with opening diameters of 500 µm and 63 µm) and categorized into 3 size fractions: silt (< 63µm); fine sand (> 63µm but < 500µm) and coarse sand (> 500µm). The wet samples were individually shaken and manually mixed while still in the plastic bags. The homogeneous mixture was then subsampled (range 30 - 60 grams) for sieving. The subsamples were washed through the 500 µm sieve into the 63 µm sieve with filtered fresh water. Washings were done with a hand-held wash bottle and all the washings through the 63 µm sieve were collected onto a brass pan. The sediment fraction remaining on each sieve was then washed through pre-weighted filter paper and air-dried for about a week. These filtered samples were then weighed and the total weight of the sample per station each transect site was determined. The percent by weight of each fraction was then determined by calculating the ratio of the different size fractions to the total sample weight (McManus, 1988).

Size fraction determinations were also performed on the core samples. Cores with noticeable stratigraphic layers were cross-sectioned at the demarcation point and subsamples from each layer (ranging from 20 - 50 grams) were taken for wet-sieving.

Chemical Composition Determination.

Mineral composition of the sediment samples was determined by X-ray diffraction analysis (XRD) as described by Hardy and Tucker (1988). Analyses was performed by Mr. Clark Sherman of the University of Hawaii School of Ocean and Earth Science and Technology (SOEST). Samples were ground using a mortar and pestle and the powdered sediment was then placed on smear slides. These slides were then loaded into an automatic sample loader and fed to the Scintag Pad V X-ray diffractometer connected to a solid-state Germanium (Ge) detector tuned to Copper (Cu) *K* a radiation. Two runs per sample were performed. First, a general scan was done to determine the overall mineralogy of the sediments. This run was performed with the machine set at a range of 2° 2ø to 70° 2ø with a rate of 5° 2ø per minute. The second run was performed at a much narrower range of 22° 2ø to 32° 2ø with a rate of 1° 2ø per minute to quantitatively determine the carbonate mineralogy of the sediments. Aragonite to calcite ratios were determined using the methods of Sabine (1991) and the mole % Magnesium (Mg) content of the calcite fraction was determined using the procedures established by Bischoff et al. (1983).

The possible sources of calcite in each sample can be ascertained based on the mole % Mg content of the calcite fraction. Specifically, the mole % Mg is the amount of Mg atoms substituting the calcium (Ca) atoms at the Ca binding sites in the crystal structure of $CaCO_3$. Calcareous organisms have distinctive ratios of Mg to Ca substitutions in the calcite produced. Representative groups of organisms and their respective mole % Mg content are presented in Appendix 1 and were based on Table 5.2 of Morse and Mackenzie (1990).

A subset of the total sediment samples collected from Kahoolawe were analyzed by X-ray diffraction. These samples were selected from sites that best represented the different and unique regions along the coast.

Results

Size Fraction Determination

Samples from the northern portion of Kahoolawe had a higher silt percentage than samples from the south and eastern coasts (Figure 3.2, Table 3.1). Beck Cove had the highest silt fraction followed by Kamohio, Wai Kahalulu and Hakioawa. Conversely, the southern and southwestern regions showed higher fine sand and coarse sand fractions with Smuggler's Cove having the highest coarse sand fraction (Table 3.1). The samples ranged from brown to dark brown sand intermixed with silt. The silt fraction of the deeper transect stations was generally higher than the shallower stations except at Honokoa, Papakanui, Papakaiki, Beck Cove, Kamohio and Wai Kahalulu (Figure 3.1). The coarse and fine sand fractions generally constituted larger percentages than the silt fractions in all stations. Several stations did not have sediment deposits in the transect area. Thus, no data are presented for Black Rock 3 m, Lae Paki 3 m, Hakioawa 3 m and one of the Kaukamoku sites.

All cores from the shallower stations were uniformly mixed while the deeper stations had two readily noticeable layers (Figure 3.3). These deeper station core samples contained sticky clay particles that adhered to the outer surfaces of the PVC core collectors (Table 3.2).

Generally, there was a lower percentage of silt in the shallower, nearshore cores as compared to the cores collected from the deeper, offshore stations (Figure 3.3). Cores from the deeper areas at Lae Paki, Ahupu and Papakaiki generally had higher silt fractions in the surface layers compared to the subsurface layers. The other two sites, Honokoa and Kaukamoku, showed more silt in the subsurface layers (Figure 3.3). These exceptions may be influenced by the topography of each site and the dynamics of oceanic currents and sediment deposition rates affecting the area.

Chemical Composition Determination

X-ray diffraction analysis of each size fraction of the station sediment samples showed that land derived minerals comprised most of the silt fraction while aragonite and calcite make up the larger grain size fractions (Table 3.3). The larger grain size fractions were mostly made up of coral pieces, foraminiferans, echinoid debris, ophiuroid parts, crustacean skeletons and calcareous algae material. The silt and clay fractions were mostly terrigenous soils and minerals (Table 3.3, Table 3.4). At many stations, clay and other terrestrial minerals (i.e. magnetite, goethite, gibbsite and plagioclase feldspar) were detected within the larger fractions indicating probable heavy silt/clay loads in these areas. These clay minerals were not readily removed during the wet-sieving process after numerous washings, implying strong adhesion or embedding and accumulation of clay minerals into the small pores and crevices of the aragonite and calcite skeletons.

Discussion

Sedimentation Dynamics in General

At Kahoolawe we were faced with a difficult problem. It was necessary to evaluate complex dynamic sedimentary processes at a series of sites with only a few hours of research time allowed at each site along the coast. Time series were not possible due to logistic problems and costs of operating at Kahoolawe. Therefore, we sampled sediment deposits at each station during our biological assessments and subsequently analyzed the samples. Results of this approach demonstrate that a great deal of information on factors governing sediment deposition and removal can be determined with this relatively cost-effective approach. Our resulting model of sediment dynamics is presented in Figure 3.4. Sediment deposits on coral reefs at Kahoolawe are dynamic features. Analysis of the deposited material (size fractions and chemical composition) allowed us to infer input sources, relative input rates, processes of sediment removal from reefs and related parameters. Deposits on the reefs are constantly changing in response to changes in inputs and outputs.

Sediment Sources.

Analysis of sediment removed from deposits at various sites along the nearshore areas of Kahoolawe provide insights into the dynamic processes occurring in this area (Figure 3.4). Basically there are only two sources of sediments found in the shallow areas: 1) erosion of soils from the island and 2) material derived from calcareous reef organisms.

Kahoolawe is a dry island and does not have perennial streams or rivers. Sediment loading is sporadic and in pulses which are dependent on the intensity and duration of rainfall sufficient to initiate stream flow, the topography of the watershed, the types of soil and amount of vegetative cover (Chapter 1). X-ray diffraction analysis of the silt fraction found clays and other land-derived minerals, indicating their source was terrestrial erosion. Wind generated sediments are also produced at Kahoolawe, but these are probably carried away from the nearshore marine environment.

Flood waters may contain up to 90% sediment by some estimates (Jones et al., 1971; County of Maui, 1990). Given the known erosional and discharge characteristics of such Hawaiian streams, it is reasonable to expect that a single "Kona Storm" period could deposit over 90% of the annual sediment load on a given reef. Although a storm of this type might last for a few days, most of the sediment could conceivably reach the reefs within a period of a few hours during the height of storm activity. The bedload and extremely dense suspended load (i.e. up to 90% solids) presumably would form a turbidity flow that would carry most of the sedimentary material offshore into deeper water. Burial of inshore reef areas is likely during floods and could be very dramatic during major "hundred year" flood events. However, such events are often associated with high winds and waves that might tend to prevent accumulation of sediments in the shallower regions.

Formation of carbonate sediments is a continuous process and is dependent on the health of the coral reef area. Corals, calcareous algae, foraminiferans, mollusks and other organisms that form hard carbonate shells contribute to the overall carbonate deposits found on reefs (Morse and Mackenzie, 1990). Natural breakdown, storm waves and the presence of bioeroders further influence the status and distribution of these deposits.

Silt was generally more prevalent along most of the coasts of Kahoolawe while larger sized carbonate materials were more predominant around the southwest coast of the island. The river gulches around the southwestern region had shallower slopes and traversed large vegetated areas before depositing sediments in the nearshore environments. Furthermore, the southwest coast is exposed to higher wave activity and water turbulence that resuspended the silt fraction and removed it from the nearshore reefs. Many areas of Kahoolawe accumulate silt and fine sediments due to the many small-scale topographical differences (i.e. peninsulas, bends around channels, reef slope structure, etc.) and oceanic factors (i.e. storm waves, seasonal currents, eddy effects, etc.) that influenced the overall sediment deposition rates around the coastal areas of Kahoolawe.

Offshore bathymetry is also an important factor controlling sediment deposition. Extensive sediment deposits cannot form on steep slopes. Deep water in proximity to the reefs serves as a sediment sink. For example, the low-slope along the north shore of Kahoolawe is covered with accumulated sediment deposits to the exclusion of reefs. The steep slope to the south of the island falls off to oceanic depths and is devoid of such deposits in spite of high sediment loading.

Sediment Removal.

Sediments are continually being removed from the reef by waves and currents. Size fractionation occurs as waves impinge and move sediments along the bottom. The fine fractions (suspended load) are carried off by currents. Coarse fractions (bedload) tend to creep downslope with each passing wave disturbance. Overall, less silt was found in the shallower zones than in the deeper areas. Water turbulence resuspends the fine particles in shallow water and promotes their removal by waves and currents.

During infrequent storm events, the removal process may be greatly accelerated. Under extreme conditions, the reef structure itself is pulverized (Dollar and Tribble, 1993). In other areas, sediment deposits that have prevented reef development for decades may suddenly be washed into deeper water, opening the way for coral settlement. For example, waves generated by Hurricane Iniki in 1992 removed extensive sediment deposits off the south coast of Lnai and exposed hard substratum (Dr. Richard Brock, pers. comm.).

Sediments and geographic zonation of coastline

Four geographic areas along the coast were delineated based on sediment size (silt fraction), and mineralogy (XRD) of sediments. Within each of the four zones we observe differences in sediment sources, wave and currents patterns, bathymetry and local topography.

North

Watershed Topography:

The northern coast of Kahoolawe has numerous large watersheds that have low vegetative cover. There are numerous river channels and gulches that drain large areas of the upper slopes of Kahoolawe which have extensive hardpan areas at higher elevations (Figures 1.7, 1.15, Chapter 1). Consequently, sediment laden runoff is high during periods of heavy rainfall.

Bathymetry of Reef Areas:

The reef area is gently sloping compared to the other coastal areas of Kahoolawe. It was observed that the region had a noticeable lack of coral reefs at depths greater than 10 m, possibly due to extensive sediment deposits that buried them.

Patterns of Waves and Currents:

This area experiences good water motion due to wind action resulting from the trade wind patterns. The northern coast area is generally protected from the damaging south swell and hurricane waves from storms passing south of Kahoolawe. This coast is also protected from the damaging north Pacific storm waves and hurricane-generated swells from north by islands of Molokai and Maui.

Silt Fraction:

Sediment loading from gulches in this zone was high with an average of 1.5 x 10^8 kg (163,000 tons) per year (or 50 kg m^{-2} per year) (Chapter 1). Silt and fine sand were the more predominant sediment types found along the northern coasts. Based on mineral composition, these sediments were mostly terrigenous in origin indicating erosion of the upper land area. The overall silt load in the area is moderate due to constant flushing by wind-driven waves and currents influenced by the northeast trade winds. Ahupuis located on the northwestern coast of Kahoolawe which does not get as much water motion and wave exposure as Hakioawa and Beck Cove which are on the eastern side. As such, the reef area of Ahupuis heavily impacted by sediment deposition and there were no corals evident below 5 m. Papakaiki is located on the northern coast and gets a moderate amount of wave exposure and wind driven currents. This was evident in the moderate silt load and good coral cover of the area (Figure 3.2, Table 3.2).

East

Watershed Topography:

The eastern coast of Kahoolawe was generally composed of steep cliffs with numerous river gulches that drain one of the largest watershed areas of Kahoolawe. There was very little vegetation along the upper slopes and sediment loading as a result of river runoff was the highest overall for Kahoolawe (Figure 1.15, Chapter 1).

Bathymetry of Reef Areas:

The reef area was noted to be steeply sloping into deep water with coral communities extending into deep water. Small pockets of sediment deposits were seen scattered all over the steep slopes.

Patterns of Waves and Currents:

The eastern coast of Kahoolawe is exposed to the continued impact of heavy waves generated by strong trade winds and those from destructive north Pacific storms. Strong water movement and continued resuspension of sediments were observed. Access to this area is very limited due to hazardous surf conditions.

Silt fraction:

Kaukamaka (draining into Beck Cove) had the highest sediment loading rates for Kahoolawe and exceeded 5×10^8 kg (561,000 tons) per year (or 125 kg m^{-2} per year) (Chapter 1). Silt and fine sand were also the most prevalent sediments found in the reef areas with Hakioawa and Beck Cove having the highest silt levels. Hakioawa is on the northeastern coast while Beck Cove is at the eastern edge of the coast where there are high cliffs with steep reef areas. Even though the eastern coast is exposed fully to the waves and currents created by the northeastern trade winds, sediment flushing was observed to be low in the areas surveyed. This may be due to the unique topographical features of the area which resulted in the accumulation of silt and other fine particles onto the shallow areas due to eddy effects of the water circulation around peninsulas and embayments where the surveys were conducted. It should be pointed out that the areas surveyed were those sites that could be accessed without danger and difficulties for the survey crew. All the sediment samples were collected from these sheltered sites. The more exposed and hazardous areas on the eastern coast were not surveyed.

South

Watershed topography:

The southern coast of Kahoolawe was seen as high cliffs projecting up from steep reef areas (Figures 1.4, 1.15, Chapter 1). Several large river gulches drain the upper slopes of large watersheds with sparse vegetative cover. These river gulches were seen draining into the ocean over steep sea cliffs.

Bathymetry of Reef Areas:

Similar to the eastern coast, the reef area of the south Kahoolawe was observed to be steeply sloping into deep water with coral communities extending into deep water. There were also some small pockets of sediment deposits scattered around the areas surveyed.

Patterns of Waves and Currents:

The southern coast of Kahoolawe was observed to experience destructive south Pacific storm waves and "wrap-around waves" coming from the eastern swells generated by trade winds. Strong water movement was noted and many areas were not accessible during the surveys.

Silt fraction:

The sedimentation loads for this area averages about 2.0×10^8 kg (220,000 tons) per year (or 47 kg m^{-2} per year) near Kamohio (Chapter 1). Silt and fine sand were in high amounts around the reef areas and the mineralogy of the sediments indicated terrigenous sources. Much like the eastern coast, silt was found to high in the areas surveyed even though waves and currents were strong around the southern coast. Similar to the sites on the eastern coast, the southern coast sites were areas that were shielded from the direct exposure to waves and currents. These areas were in embayments and next to peninsulas or large out-crops of land that served as a buffer against the strong waves and pounding surf. As such, sediments collected in the area were not readily flushed and removed.

West

Watershed Topography:

The western coast of Kahoolawe has gradual land slopes extending towards the reef areas much like the northern coast (Figure 1.15, Chapter 1). A few small river gulches and channels drain the slopes of Kahoolawe and traverse a large tract of vegetated area before draining into the nearshore areas such that sediment loading is low (Chapter 1).

Bathymetry of Reef Areas:

The reef areas slope moderately into deep water and the coral communities are sparse and patchy.

Patterns of Waves and Currents:

This area is exposed to destructive South Pacific swells and storm waves coming in from the open ocean. Water movement is strong and fine particles are probably removed constantly.

Silt Fraction:

Due to the strong water movement in the area and the low input of sediment from land, sedimentation loads were observed to be low (Chapter 1). Fine and coarse sand were the more prevalent sediment types with silt being in low amounts. Mineralogy of the sediments indicated high carbonate and calcite fractions suggesting that the sources were from marine organisms. Flushing and removal of fine silt particles is high due to the strong waves and swells from the south Pacific. It should be pointed out that the southwestern coast of Kahoolawe had more sand beaches and boulder/rubble covered areas compared to the other areas of Kahoolawe. Smuggler's Cove, Black Rock, Twin Sands and Lae Paki had very little silt present and the majority of the sediments collected were larger size carbonate sediments (Figure 3.2, Table 3.1, Table 3.3). These carbonate sediments were mainly from marine organisms.

Effect of local topography and bathymetry

Analysis of the short core samples showed a pattern similar to the bulk station samples with less silt in shallower stations compared to deeper stations. Again, the influence of wave exposure, location and topography are important. Areas with greater water motion and wave exposure tend to have less silt nearshore due to resuspension by water turbulence and winnowing out from the surface layer of the very fine silt sediments. As such, only the heavier and larger fractions remain (Table 3.2). This pattern was evident at Honokoa and Lae Paki with a gradual rise in silt content versus depth and distance from shore. On the other hand, Ahupu, Kaukamoku and Papakaiki represented areas with less turbulence and greater settlement of particles (Figure 3.3). The rapid rise in silt content in shallow areas indicated less silt resuspension due to lower water motion or wave turbulence. Kaukamoku had the lowest water motion and the lowest silt resuspension by wave turbulence among the five sites.

The formation of layers in the deeper zones indicated slight reworking of the surface layers due to waves while the subsurface layers were kept more intact and unaffected. The lack of sediment stratification in the shallower zones indicates a more complete reworking of the sediments compared to the deeper zones (Figure 3.5 shows ripples and resuspension of sediment deposits).

Other factors such as small-scale topographic differences (i.e. bends, projections at the opening of the bay, etc.) and the angle of the slope from the beach to the sea can also influence the amount of silt being deposited. A case in point is Honokoa. The abrupt rise in silt content at the 1 m depth (about 50 m from the beach) was due to the presence of a "dog-leg bend" in this area which may have caused small eddy formations and the accumulation of silt (Figure 3.1). Kaukamoku, on the other hand, was observed to have very silty beach conditions and a prevailing shoreward current as seen by the sediment plume direction.

Sediment and Reef Corals

High sediment loads have been correlated to low coral cover and poor coral diversity by several researchers (Hubbard and Pocock, 1972; Randall and Birkeland, 1978; Cortés and Risk, 1985; Rogers, 1990; Wittenberg and Hunte, 1992). The detrimental effects of sediment on corals, their larvae and other reef organisms have been reviewed by Rogers (1990), Hodgson (1990), Richmond (in press) and Te and Jokiel (in review). While it was evident from these surveys that the coral reefs of Kahoolawe were impacted by sedimentation, a significant positive correlation ($r = 0.471$, $p < 0.01$, $df = 27$; Sokal and Rohlf, 1969) between the percent silt and the percent coral cover of the areas was determined (Figure 3.6). This does not imply that corals around Kahoolawe prefer silty environments or are more resistant to sediment damage as are corals found in the southern Florida reefs (Rice and Hunter, 1993). On the contrary, Hawaiian corals are sensitive to silt loads (Maragos, 1972; Banner, 1974), but other factors such as wave exposure, water motion and localized topography influence the overall coral community tolerance of the sediment stress. Areas with high wave exposure would have low silt content due to winnowing action of the silt/clay fraction by water motion. Low coral cover in these areas may be due to mechanical breakage as caused by the strong waves. This was evident in the southwest and southern coastal areas of Kahoolawe impacted by strong southern swells and storm waves. On the other hand, areas with moderate wave exposure and water motion had deposits with low to moderate silt content due to better flushing and removal of sediments. These areas also had higher coral cover due to protection from mechanical damage caused by storms. The northern and northwestern coasts of Kahoolawe exemplify these conditions.

Sedimentation and Future Changes on the Reefs of Kahoolawe

The sediment deposits on the coral reefs of Kahoolawe are dynamic features that are constantly being replenished by terrestrial runoff as well as by biogenic carbonate material from the reef. These deposits are, in turn, being altered and depleted by resuspension of fine fractions during periods of strong surf and currents. There is a continual movement of materials down-slope that is enhanced by physical disturbance (waves and currents). Biological activity by burrowing organisms and deposit-feeders plays a role in sediment movement and reworking of deposits.

Our observations suggest that sediment deposits on the reefs of Kahoolawe are presently being removed more rapidly than being replenished. This conclusion is consistent with data showing a gradual increase in vegetation cover of the island over the past 20 years (Chapter 1). We noted uncovering of old buried reef structures at many locations previously subject to high sediment loading (Chapter 2, Chapter 4). We found no evidence of corals being buried under newly deposited material. Rapid recruitment of new coral colonies onto newly uncovered reef surfaces was noted at all locations, leading us to conclude that the reefs are presently undergoing recovery as sediment input diminishes.

Grigg (1985) has reported a recovery period of 5 - 10 years for sediment buried Hawaiian reefs after the discharge from the Hamakua plantations was halted. Based on our data (Chapter 2), we also conclude that coral recovery will lag sediment removal from an area by 5 - 10 years. The recovery along the Hamakua coastline followed an abrupt cessation of discharges into the nearshore waters. The recovery process of Kahoolawe will be gradually accelerate as revetation efforts continue to reduce sediment inputs.

This conclusion must be viewed with some reservations as major flood events could again bury the exposed areas within a matter of hours. One could argue that we are only observing the winnowing process that occurs between major sediment deposition events. In any event, revegetation is occurring, and it is likely that sediment deposition will continue to diminish even during storm events. The long term trend will be toward decreased sediment inputs while processes controlling sediment removal will continue at the present rate. The end result will lead to acceleration of the reef recovery process.

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Table 3.1. Sediment size fractions from stations around Kaho‘olawe. Station abbreviations as in Table 1.2 (Chapter 1). Sediment fractions are categorized as silt (<63 m); fine sand (>63 m m but <500 m m) and coarse sand (>500 m m). NA--indicates no data

Station	Silt	Fine Sand	Coarse Sand	Description of Sediments
SM10	1.5	23.9	74.6	brown sand with white grains
SM3	0.44	0.96	98.6	brown sand with white grains
BK10	1.4	23	75.6	brown sand with white grains
BK3	NA	NA	NA	
TW10	0.92	15.5	83.6	dark brown sand
TW3	0.62	14.2	85.2	brown sand with white grains
LP10	1.7	26.3	72.1	dark brown sand
LP3	NA	NA	NA	
HN10	2	5.2	92.8	brown sand with white grain
HN3	4.6	48.9	46.4	dark brown sand
OP10	8	12.7	79.3	dark brown sand with black grains
OP3	2	17.1	81	dark brown sand
AH3	1.7	66	32.4	brown sand with white grains
KUC	NA	NA	NA	
KUS	2.6	96.8	0.63	brown sand with white grains
KH10	19	65	15.9	dark brown sand with black grains
KH3	2.5	37.6	59.8	brown sand with white grains
PA10	1.25	33.15	65.6	brown sand with white grains
PA3	4.9	24.5	70.5	brown sand
PI10	2.8	86.6	10.5	dark brown sand with black grains
PI3	3.7	12.7	83.6	dark brown sand with black grains
WA10	11.5	79.9	8.6	brown sand with black silt
WA3	3.8	94.6	1.6	brown sand with dark brown silt
HK10	13	82.3	4.6	dark brown sand with black grains
HK3	NA	NA	NA	
NK10	0.6	1.7	97.7	brown sand
NK3	0.7	4.8	94.5	brown sand
BC10	6	36.2	57.9	brown sand with dark brown silt
BC3	23	61.6	15.2	brown sand with dark brown silt
HL10	0.5	32	67.1	brown sand with white grains
KM10	2.7	40	57.2	dark brown sand
KM3	16.4	82.7	0.93	brown sand with dark brown silt
WK10	1.2	38.7	60.1	brown sand with dark brown silt
WK3	8.5	80.9	10.6	brown sand with dark brown silt

Table 3.2. Size fraction analysis of core samples collected at selected sites around Kaho‘olawe. Size fractions are categorized as silt (<63 m m); fine sand (>63 m m but <500 mm) and coarse sand (>500 mm). Numbers indicate samples were collected from the beach proceeding seaward. Two layers were represented by letters A and B, indicating surface and subsurface layers respectively.

Site Name	Distance from shore (m)	Depth (m)	Silt	Fine Sand	Coarse Sand	Description of sediments
LAE PAKI 2	50	2.7	5.34	76.21	18.45	light brown sand with white grains
LAE PAKI 3	100	7.2	3.43	86.35	10.22	light brown sand with white grains
LAE PAKI 4A	150	8.70	9.41	60.14	30.45	light brown sand with white grains
LAE PAKI 4B	150	8.70	3.60	95.20	1.20	dark brown sand and silt
LAE PAKI 5A	200	10.2	5.92	86.75	7.33	dark brown sand with white grains
LAE PAKI 5B	200	10.2	6.80	90.91	2.29	dark brown sand and clay chunks
HONOKOA 1	0	0	3.32	5.22	91.46	brown sand with black grains and some pebbles
HONOKOA 2	50	0.8	6.30	9.53	84.18	light brown sand with white grains and pebbles
HONOKOA 3A	100	2.4	4.63	7.53	87.84	medium brown sand with pebbles
HONOKOA 3B	100	2.4	11.03	46.22	42.76	dark brown silt and black clay chunks
HONOKOA 4	150	3.7	4.80	11.11	84.09	brown sand with dark brown silt and pebbles
HONOKOA 5	200	8.2	0.58	2.93	96.49	brown sand with dark brown silt and pebbles
HONOKOA 6A	250	8.5	0.77	6.79	92.44	pebbles with brown sand and some large gravel
HONOKOA 6B	250	8.5	13.91	25.73	60.36	dark brown sand and silt
AHUPU 1	0	0	3.27	43.88	52.85	medium brown sand with pebbles
AHUPU 2	50	1.1	4.61	95.06	0.33	dark brown sand with silt
AHUPU 3A	100	3.0	5.53	90.88	3.59	medium brown sand with white grains
AHUPU 3B	100	3.0	9.93	81.35	8.71	dark brown sand with clay chunks
AHUPU 4A	150	4.5	18.59	68.45	12.97	medium brown sand with pebbles and white grains
AHUPU 4B	150	4.5	6.36	88.23	5.41	dark brown sand with clay chunks
KAUKAMOKU 1	0	0	5.42	46.58	47.99	dark brown sand with white grains
KAUKAMOKU 2	50	2.3	2.17	89.87	7.96	dark brown sand with white grains
KAUKAMOKU 3	100	2.9	3.70	87.49	8.81	dark brown sand with white grains
KAUKAMOKU 4A	150	4.4	4.83	92.04	3.14	brown sand with white grains and silt
KAUKAMOKU 4B	150	4.4	11.05	87.78	1.17	dark brown sand and silt
PAPAKAIKI 1	0	0	5.54	34.45	60.01	dark brown with large pebbles and gravel pieces
PAPAKAIKI 2	50	2.3	6.84	89.36	3.80	medium brown sand with white grains
PAPAKAIKI 3A	100	4.4	7.80	91.33	0.87	dark brown sand with white grains
PAPAKAIKI 3B	100	4.4	12.12	85.73	2.16	dark brown sand and clay chunks
PAPAKAIKI 4A	150	6.6	30.80	62.05	7.15	medium brown sand with white grains
PAPAKAIKI 4B	150	6.6	15.36	83.94	0.70	dark brown sand and clay chunks

Table 3.3. Mineralogy of Kaho‘olawe sediments determined by X-ray diffraction. Station abbreviations as in Table 1.2 (Chapter 1). X indicates mineral was present in sample while * indicates trace amounts detected.

Station	fraction	aragonite	calcite	clay	gibbsite	goethite	magnetite	hematite	plagioclase
SM10	silt	X	X	X			X		
	fine sand	X	X						
	coarse sand	X	X						
SM3	silt	X	X	X					
	fine sand	X	X						
	coarse sand	X	X						
TW10	silt	X	X	X	X	X	X		
	fine sand	X	X						
	coarse sand	X	X						
TW3	silt			X	X	X	X		
	fine sand	X	X						
	coarse sand	X	X						
OP10	silt	X	X	X			X	X	X
	fine sand	X	X						
	coarse sand	X	X						
OP3	silt	X	X	X		X	X	X	X
	fine sand	X	X	*			X		X
	coarse sand	X	X						X
KUS	silt	*	*	X	X	X	X	X	*
	fine sand			X	X		X		
	coarse sand	X	X	X	X		X		
WA10	silt	X	X	X			X		
	fine sand	*	*	X			X	X	
	coarse sand	X	X						X
WA3	silt	X	X	X			X	X	
	fine sand	X	X	X			X		
	coarse sand	X	X	*					
HK10	silt	*		X		X	X	*	
	fine sand	*	*	X	X	X	X		
	coarse sand	X	X	X	X	X	X		
BC10	silt	X	X	X	X	X	X		
	fine sand	X	X	X			X		X
	coarse sand	X	X				X		X
BC3	silt	X	X	X	X	X	X		

Station	fraction	aragonite	calcite	clay	gibbsite	goethite	magnetite	hematite	plagioclase
	fine sand	X	X	X					
	coarse sand	X	X						
KM10	silt	*	*	X	X	X	X	*	*
	fine sand	X	X				X		X
	coarse sand	X	X						
KM3	silt			X	X	X	X	X	
	fine sand			X	X	X	X	X	
	coarse sand	*	*	X	X	X	X	X	

Table 3.4. Possible sources of calcite found in Kaho‘olawe sediments based on the mole % Mg content as determined by X-ray diffraction analysis. Station abbreviations as in Table 1.2 (Chapter 1). Abbreviations: foram. = foraminifera; cal. brac. = calcareous brachiopod; crust. = crustacean; cal.algae = calcareous algae.

Station	**Fraction**	**Mole % Mg**	**foram.**	**echinoid**	**asteroid**	**ophiuroid**	**bryozoans**	**cal.brac.**	**annelid**	**bivalve**	**gastropod**	**crust.**	**cal.algae**
SM10	silt	0.81				X	X	X		X			
		14.1	X	X	X				X			X	X
	fine sand	3.25	X			X	X			X		X	
		16.48	X	X	X				X			X	X
	coarse sand	3.33	X			X	X	X		X		X	X
		5.92	X	X		X	X	X				X	
		15.88	X	X	X				X			X	X
SM3	silt	3.46	X			X	X	X		X	X		
		14.98	X	X	X				X			X	X
	fine sand	2.87	X			X	X	X		X		X	
		15.44	X	X	X				X			X	X
	coarse sand	7.31	X	X		X	X	X	X			X	
		14.40	X	X		X	X	X	X			X	
		18.06	X	X	X				X			X	
		23.91											X
TW10	silt	1.45	X			X	X	X		X	X	X	
		5.68	X	X		X	X	X				X	
		12.86	X	X	X	X	X		X			X	X
		16.00	X	X	X				X			X	X
		21.31											X
	fine sand	3.91	X			X	X	X				X	
		17.30	X	X	X				X			X	X
	coarse sand	4.86	X	X		X	X	X				X	
		13.34	X	X	X				X			X	X
		16.03	X	X	X				X			X	X
		18.40	X	X	X				X			X	X
TW3	silt	0											
	fine sand	2.97	X			X	X	X		X		X	
		16.39	X	X	X				X			X	X
	coarse sand	3.49	X			X	X	X		X		X	
		13.70	X	X	X				X			X	X
		17.14	X	X	X				X			X	X
OP10	silt	3.11	X			X	X			X		X	
		11.05	X	X	X	X	X	X	X			X	X
		14.18	X	X	X				X			X	X
		17.17	X	X	X				X			X	X
	fine sand	2.64	X			X	X	X		X		X	
		16.01	X	X	X				X			X	X
OP10	coarse sand	5.36	X	X		X	X	X				X	
		15.94	X	X	X				X			X	X
OP3	silt	3.38	X			X	X	X		X		X	

Station	Fraction	Mole % Mg	foram.	echinoid	asteroid	ophiuroid	bryozoans	cal.brac.	annelid	bivalve	gastropod	crust.	cal.algae
		12.03	X	X	X	X	X		X			X	X
		14.90	X	X	X				X			X	X
		18.00	X	X	X				X			X	X
	fine sand	14.90	X	X	X				X			X	X
		16.72	X	X	X				X			X	X
	coarse sand	5.06	X	X		X	X	X				X	
		16.26	X	X	X				X			X	X
		18.99	X	X	X				X			X	X
KUS	silt	0											
	fine sand	0											
	coarse sand	4.54	X			X	X					X	
		14.33	X	X	X				X			X	X
WA10	silt	12.00	X	X	X	X	X		X			X	X
		14.30	X	X	X				X			X	X
		17.42	X	X	X				X			X	X
		21.13											X
	fine sand	0											
	coarse sand	16.00	X	X	X				X			X	X
		18.48	X	X	X				X			X	X
WA3	silt	14.93	X	X	X				X			X	X
		17.46	X	X	X				X			X	X
	fine sand	13.60	X	X	X				X			X	X
		16.64	X	X	X				X			X	X
		19.58							X				X
	coarse sand	16.37	X	X	X				X			X	X
		18.24	X	X	X				X			X	X
		20.94											X
HK10	silt	0											
	fine sand	0											
	coarse sand	15.80	X	X	X				X			X	X
		18.29	X	X	X				X			X	X
		20.93											X
BC10	silt	13.64	X	X	X				X			X	X
		15.86	X	X	X				X			X	X
		18.50	X	X	X				X			X	X
	fine sand	12.49	X	X	X	X		X	X			X	X
		15.21	X	X	X				X			X	X
		19.24							X				X
BC10	coarse sand	4.08	X			X	X	X				X	
		12.34	X	X	X	X	X		X			X	X
		15.36	X	X	X				X			X	X
BC3	silt	10.45	X	X		X	X	X	X			X	X
		13.53	X	X	X				X			X	X
		17.65	X	X	X				X			X	X
	fine sand	14.39	X	X	X				X			X	X
		18.79	X	X	X				X			X	X
	coarse sand	10.37	X	X		X	X	X	X			X	X

Station	Fraction	Mole % Mg	foram.	echinoid	asteroid	ophiuroid	bryozoans	cal.brac.	annelid	bivalve	gastropod	crust.	cal.algae
		15.89	X	X	X				X			X	X
KM10	silt	0											
	fine sand	4.56	X			X	X	X	X			X	
		14.22	X	X	X				X			X	X
	coarse sand	9.02	X	X		X	X	X	X			X	X
		16.22	X	X	X				X			X	X
KM3	silt	0											
	fine sand	0											
	coarse sand	0											

Appendix 3.1: List of organisms and their corresponding moles % Magnesium content. Derived from information in Morse and Mackenzie (1990).

Organisms	mole % Mg content
foraminiferans	1.2 - 19.0
echinoids	4.8 - 19.0
asteroids	10.9 - 19.0
ophiuroids	0.2 - 13.1
bryozoans	0.2 - 13.1
calcareous brachiopods	0.6 - 10.7
annelids	7.1 - 20.2
bivalves	0 - 3.6
gastropods	0 - 2.4
crustaceans	1.2 - 19.0
calcareous algae	8.3 - 35.0

CHAPTER 4: INSHORE FISHERIES AND FISHERY HABITAT, SEA TURTLES, AND MARINE MAMMALS.

John Naughton, National Marine Fisheries Service, NOAA

Abstract

Qualitative observations were made on conditions of reef habitat at sites around Kahoʻolawe. Although the nearshore waters have been off limits to fishing since 1941, it was apparent that the fishery resources have been exploited to varying degrees. Although diversity and abundance of fishes were high, individual fish were relatively small. In addition, the larger, more desirable fish species and sharks were rare, signs of fishing pressure. Ordnance was rarely found, but plastic debris, including fishing gear, was common along the coastline. Sea turtles (*Chelonia mydas*) sighted were immature and free of fibropapillomas. Humpbacks were sighted along the northwest to northeast coastline. A pod of spinner dolphins was sighted along the coastline near Smuggler's Cove.

Inshore Fisheries and Fishery Habitat

Kahoʻolawe nearshore waters have long been known as a rich fishing ground by native Hawaiians. Evidence of this is the fact that 69 known fishing shrines (koʻa) occur around the island (Aluli and McGregor, 1992). A particularly informative account of fishing methods and species caught is detailed in A. D. Kahaulelio's story published in the Hawaiian language newspaper "Ka Nupepa Kuoka" from February 28 to July 4, 1902.

Since 1941 the nearshore waters surrounding Kahoʻolawe have for the most part been off limits to fishing by people other than military personnel stationed on the island. In recent years the U.S. Navy has opened the waters on most weekends to limited fishing with the exception of that involving diving. Consequently, one would expect an abundance of fishery resources to occur in waters surround surrounding Kahoʻolawe, particularly in comparison to the resources found in nearshore waters of the other islands of Maui County.

Methods

One of the objectives of the series of nearshore underwater surveys conducted in 1993 was to document the status of fishery resources and their habitats after 50 years of military use of Kahoʻolawe. At all underwater stations observations were made and recorded on the abundance and size of key "indicator" species known to be of prime value to fishermen in the Hawaiian Islands. Qualitative observations were made on the conditions of coral reef habitat at each station, particularly from siltation and sediment impacts. In addition, evidence of fishing pressure such as nets, line and other gear lost on the bottom was recorded. The majority of these observations were conducted during the March 22-26 survey during which dives were made in various habitats at 17 sites in nearshore waters surrounding the island.

Results

Fishery Resources

While conducting the survey dives in March, it became readily apparent that the fishery resources in nearshore waters of Kahoʻolawe have been exploited to varying degrees. This was particularly true off the northern coastlines of the island. Although diversity and abundance were often high, individual fish were relatively small. In addition, some of the larger, more desirable species were rare, such as the medium and large size carangids (ulua, ‘milu, khala), mullids (km, moana, moana kale, weke a‘a, weke ‘ula) and lutjanids (uku, wahanui), strongly indicating considerable fishing pressure.

On the other hand, fishes such as holocentrids (‘‘, ala‘ihi), scarids (uhu) and lethrinids (m) were relatively abundant and of large size. Fishes in these families are normally taken by spearfishing, which indicates limited fishing pressure by this method of harvesting. Several large schools of *Kuhlia sandvicensis* (holehole) and *Acanthurus guttatus* (maiko) were observed in the surge zone along the northwest coast of the island. These species are usually taken by throw net from shore, again indicating limited fishing pressure by this method.

Indications of fishing pressure were particularly apparent at stations conducted at Hakioawa, south Kanapou, Twin Sands, and O awa palua. Fishing lines were also tangled on the bottom at several places off Maka‘alae and portions of an inshore gill net were found tangled in coral on the south side of Kanapou.

Another indication of fishing pressure was the lack of large, edible limpets (‘opihi) along the northwest and northeast shoreline. Larger ‘opihi were much more abundant along the shoreline on the south side of Kaho‘olawe at Wai Kahalulu and Kamhio. The south coast faces the ‘Alenuihh Channel and is impacted by large seas much of the year, thereby making `opihi gathering difficult and dangerous.

Dominant predatory fish at most of the stations were the introduced lutjanids, *Lutjanus kasmira* (ta‘ape), and *L. fulvus* (to‘au), as well as *Cephalopholis argus* (roi), an introduced serranid. Large schools of juvenile ta`ape were commonly found in finger coral (*Porites compressa*) habitat. Adult as well as juvenile to`au were found in heavily silted habitat and were often one of the only species observed in these degraded areas. This was the case at Ahup, one of the most heavily silt impacted sites surrounding Kaho‘olawe. It appears that when the corals are buried or killed by siltation, the normal reef fish migrate out of the area and to`au occupy the stressed habitat.

An observation well known from other Pacific islands is the abundance of nearshore shark species in areas of little or no fishing pressure. Therefore, the survey team was surprised to find very few sharks during the series of dives. The only sharks sighted were the reef white-tip (*Triaenodon obesus*). Individuals were observed at Kheia and Ahup, closely associated with underwater caves in which this species routinely rests.

At most stations qualitative observations found a high biomass of certain reef fish that are not particularly desirable commercial or recreational species. Large schools of surgeonfish or acanthurids (palani, pualu, maiko, pku‘iku‘i, kala) were common. Schools of *Melichthyes niger* (humuhumu ‘ele‘ele) were particularly abundant, as were *Kyphosus vaiginensis* (nenue) in the surge zone. Schools of these two species could be seen from the air during a helicopter survey on May 14, and appeared to be particularly abundant from Lae o Kukui to Kheia and from Maka‘alae to Lae o Kealaikahiki.

A station conducted at the south side of Hana Kanaia (Smuggler's Cove) found relatively high numbers of desirable recreational and commercial species of fish. These included mu, wahanui, uku, roi, and schools of weke and ta`ape. Large ‘‘ were common in caves and ledges, as were spiny lobsters (*Panulirus marginatus* or ula). Because the U.S. Navy base camp is located at Smuggler's Cove, there is a continual enforcement presence which apparently serves to substantially reduce illegal fishing activities in this area.

Habitat

Nearshore habitat stressed by siltation was found along the east, northeast, and northwest shorelines of Kaho‘olawe. Transition zones were generally Lae o Halona on the southeast side and Maka‘alae on the northwest coast, where sediments changed from terrigenous to predominantly calcareous. The bays along the north and northwest coast have been particularly hard hit by sediment over the years. However, in these areas rich coral reef habitat remains at the tops of the ridges above the range of silt accumulation. In addition, silt appears to be eroding and flushing away from many nearshore sites, exposing hard substrate which is slowly being recolonized by individual coral colonies. Much of this silt removal may have occurred recently during major storm events, such as Hurricane ‘Iniki.

Hurricane ‘Iniki hit the Hawaiian Islands in September 1992. Kaua‘i was directly impacted, however hurricane damage to coral reefs has been observed on the south and west facing coasts of most of the main Hawaiian islands. On the adjacent island of Lna‘i substantial reef damage has been documented on coral reefs from Mnele Bay west to Kaumalapau Harbor immediately following the hurricane. Similarly, on Kaho‘olawe the survey team observed submerged berms of coral rubble from approximately Kamhio on the south coast, around the west end to approximately Ki‘i on the northwest coast. Pieces of live coral were observed in the rubble indicating the berms were formed by a recent storm event. Large rubble berms were observed on the beach between Ki‘i and Maka‘alae which were attributed to Hurricane ‘Iniki. Sand, coral rubble and basalt boulders had also recently been deposited up on the slopes of the Sailor's Hat crater on the southwest tip of Kaho‘olawe. In addition to coral reef damage, numerous areas were observed where silt had recently been scoured away from the base of limestone ridges, thereby exposing hard substrate for coral colonization, as described above.

Other impacts to nearshore habitat were from human generated debris. However, despite the years of military bombing and shelling relatively few pieces of ordnance were observed. More fragments of metal were found than unexploded ordnance. Plastic and other debris were common on many beaches, particularly at Beck Cove in Kanapou. A large section of trawl netting, which probably drifted in from the north Pacific, was found tangled in corals on the steep slope of Kamhio.

Sea Turtles

A detailed summary of historical accounts of sea turtles at Kaho‘olawe, as well as recent surveys is given in the Environmental Impact Statement, Kahoolawe Training Area, Hawaiian Archipelago (Environmental Impact Study Corporation, 1979). A former resident of Kaho‘olawe from 1916 to 1941, Mrs. Inez Ashdown, daughter of Angus McPhee, notes that her father's cowboys reported seeing turtles nesting at Smuggler's Cove. In addition, she indicates that this area as known to the Hawaiians as Honukanaenae, which means "chant for turtles". On June 23 and August 23-25, 1978, surveys of sea turtles were made by National Marine Fisheries Service (NMFS) and the Hawaii Institute of Marine Biology. These surveys consisted of aerial reconnaissance, direct observations on land, underwater observations and collection of algae. The June 23 aerial survey covered most of the island's coastline and the three-day survey concentrated on the west end of the island. Results are presented in the EIS (Environmental Impact Study Corporation, 1979).

Sighting of sea turtles for the 1993 surveys are plotted in Figure 4.1. These sightings are from vessel and underwater surveys conducted from March 22 to 26, 1993, and from a helicopter survey on May 14, 1993. The six turtles observed during the March survey were all green turtles (*Chelonia mydas*), by far the most common of the two species of inshore turtles regularly found in Hawaiian waters. It is assumed that the 14 turtles observed during the May 14 aerial survey were also green turtles, although this could not be confirmed.

All green turtles sighted were immature, ranging in size from approximately 40 to 70 cm carapace length. The turtles appeared healthy and free of fibropapillomas (tumors), which are afflicting a growing number of green turtles in Hawaiʻi (Balazs 1986). During the underwater surveys three turtles were hand captured for quick inwater examination for tumors, then immediately released.

It is clear from the surveys that prime underwater sea turtle habitat occurs along the north and northwest coast of Kahoʻolawe. This is consistent with sighting data from the 1979 EIS (Environmental Impact Study Corporation, 1979). The lack of sightings along the south coast is not surprising as the underwater terrain is much more precipitous and lacks the required shallow habitat to support benthic algae growth. None of the sand beaches surveyed by the team found any indication of turtle nesting activities.

As seen in Figure 4.1, a concentration of green turtles occurs from Makaʻalae to Lae Paki, particularly in the area of Lae o Honokoa. It is probable that critical green turtle foraging and resting habitat occurs in this area. However, this was not confirmed during the limited survey period. Further underwater surveys off this coast are recommended.

Marine Mammals

As with sea turtles, the EIS (Environmental Impact Study Corporation, 1979) presents a detailed account of marine mammals found in coastal water of Kahoʻolawe. The EIS describes the occurrence of the humpback whale (*Megaptera novaeangliae*), the spinner dolphin (*Stenella longirostris*) and the Hawaiian monk seal (*Monachus schauinslandi*).

During the 1993 survey humpback whales and spinner dolphins were observed. No monk seals were sighted. However, a survey conducted in September 1992 by the State of Hawaiʻi, Division of Aquatic Resources, sighted a monk seal hauled out on a lava bench in the area of Puʻu Koaʻe.

Humpback Whale

A detailed account of the status of the Hawaiian population of humpback whales can be found in the series Species Profile: The North Pacific Humpback Whale in Hawaiian Waters (Nitta and Naughton, 1989).

The winter range of the Hawaiian humpback whale population is primarily restricted to the area around the main Hawaiian islands from Hawaiʻi to Kaʻula, where they confine themselves to bank areas and coastal waters generally shallower than 100 fathoms. Varying estimates of the Hawaiian population range from 550 to 2,100 whales. Humpbacks can be found in Hawaiian waters from November through May, however, the peak months are January through March - the height of the mating and calving season.

NMFS conducted four humpback whale surveys around Kahoʻolawe from 1976 to 1979 during the peak of the winter season. The humpback whale counts were as follows:

Date	Count
2/26/76	16
2/10/77	23
2/09/78	13
2/08/79	13

The whales were observed predominantly along the north, northwest and northeast coast of the island. The sightings indicate that in February humpback whales consistently utilize the nearshore waters of Kahoʻolawe, with the exception of the precipitous south coast which lacks the requisite broad, shallow shelf. These data are substantiated by aerial surveys and observations by fisherman and other boaters.

The NMFS surveys found that the nearshore waters off Smuggler's Cove, including Kuia Shoal, the northwest coast from Lae o Kealaikahiki to Lae o Kukui and the ʻAllakeiki Channel area between Lae o Kukui and Lae o ka Ule appear to be especially desirable humpback whale habitat bordering Kahoʻolawe. Groups of whales sighted in these areas often include calves, indicating their possible importance as nursery grounds (Environmental Impact Study Corporation, 1979).

During the 1993 March and May survey only one pod of humpback whales was observed around Kahoʻolawe (Figure 4.2). A group of 4 individuals were observed off Lae o Kukui on March 26. Because of the timing of the surveys late in March it is not surprising that few whales were sighted around Kahoʻolawe, as this is toward the end of the winter season. However, many whales remained in the Maui County area. During each morning and afternoon whales were observed while transiting by vessel between Maui and Kahoʻolawe. These whales were generally sighted between Maui and Molokini, and not in Kahoʻolawe coastal waters. In addition, during every dive conducted on the east, north and northwest coast of Kahoʻolawe, humpback whales could be heard vocalizing, but at a considerable distance from the island. These observations indicate that Kahoʻolawe may not be prime humpback whale habitat in the latter portion of the winter season.

Spinner Dolphin

The spinner dolphin is a common marine mammal found in the waters of the Hawaiian Islands. These long-snouted dolphins are found worldwide in tropical and sub-tropical seas. They have been seen off Kahoʻolawe with some regularity, particularly in the vicinity of Smuggler's Cove.

A school of approximately 50 animals was seen on several days during field investigations in November 1979 (Environmental Impact Study Corporation, 1979).

Sightings of spinner dolphins during the March and May 1993 surveys are recorded in Figure 4.2. A school of 20 to 30 individuals was sighted at Smuggler's Cove on several occasions. The name Hono Kanaia translates from the Hawaiian to "dolphin bay", indicating that the area has probably had a resident school of dolphins for many years. Navy personnel interviewed at the Smuggler's Cove base camp stated that the dolphins are regular day time residents in the bay.

Shallenberger (1981) found that certain schools of Hawaiian spinner dolphins can be found with a high degree of regularity in the same area and spend a large part of their time very close to shore in water as shallow as 3 m. Food sources known for spinners consists primarily of mesopelagic fish and squid. Apparently these resident spinner schools rest and socialize in specific coastal areas during the day, then move offshore to feed at night. It is highly probably that the spinner dolphin school seen at Kaho‘olawe is resident to the area and has been for many years.

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CHAPTER 5: ANCHIALINE RESOURCES OF KAHOʻOLAWE, HAWAIʻI.

Richard E. Brock and Julie H. Bailey-Brock, University of Hawaiʻi

Abstract

In 1965 the Sailor's Hat crater was formed along Kahoʻolawe's south coast when the military detonated 500 tons of explosives. The resulting crater is located about 50 m from the shoreline, is approximately 50 m in diameter and penetrates the watertable to a maximum depth of about 5 m. Because the pool at the bottom of this crater shows tidal fluctuation, has a measurable salinity (33.8^{o}/oo) and has no surface connections to the sea, it fits the definition of an anchialine pool. Nutrient analyses of the pool's water show it to be very similar to normal ocean water with the exception of a slight salinity depression (approximately 1o/oo lower than seawater) and an elevation of silica which suggests some intrusion of groundwater into the pool. Dominant species in the pool include an introduced waterboatman (*Trichocorixa reticulata*), the native anchialine shrimp (*Halocarindina rubra*), and the endemic tubeworm (*Vermiliopsis torquata*), as well as several small amphipods, polychaetes, an ostracod and a gastropod. All of the identified macrobiota other than *H. rubra* and the ubiquitous exotic *T. reticulata* are marine in origin. Probable mechanisms for colonization of this 28 year old pool by marine species are by (1) wind, (2) storm waves overtopping the berm separating the pool from the ocean, and/or (3) active migration from the ocean through the subterranean labyrinth of crevices to the pool. Colonization of the pool by *H. rubra* probably occurred through an active migration to this habitat. This species appears to opportunistically colonize marginal habitat that most of its predators are unable to colonize due to physical barriers and/or unsuitable ecological conditions. This life history strategy has probably been an important feature to the success of *H. rubra* in the Hawaiian Islands and may be an important characteristic of hypogeal anchialine species elsewhere.

Introduction

Anchialine pools are land-locked brackish bodies of water that display tidal fluctuations but have no surface connections to the sea. Anchialine pools are restricted to highly porous substrates such as recent lavas or limestone adjacent to the sea. These pools harbor a distinctive assemblage of organisms, some of which are found nowhere else (Holthuis, 1973; Maciolek, 1983).

The anchialine habitat is widely distributed having been reported from the Sinai Peninsula in the Red Sea, from islands in the Indian and Atlantic Oceans as well as from sites in the tropical Pacific including the Hawaiian Islands. Sites with high numbers of anchialine pools are known from Fiji, the Ryukyus and Hawaiʻi. Although Hawaiʻi probably has the greatest number of anchialine pools, many of these have been seriously disturbed by the introduction of exotic species (Brock, 1985; Bailey-Brock and Brock, 1993) such that today the anchialine habitat and usual complement of native species is rare in the Hawaiian Islands.

The water in anchialine pools displays a wide range in physical and chemical conditions due to the interaction of seaward flowing groundwater mixing with intruding seawater (Brock et al., 1987). Because of the varying nature of the habitat, many anchialine species are extremely tolerant and thrive under a variety of physical conditions. Thus Hawaiian anchialine habitats are characterized by a wide range in salinities and all known pools show some depression in salinity due to groundwater percolation.

Kahoʻolawe has been known as an island poor in freshwater resources. Stearns (1940, page 122) notes:

"On December 7, 1857, P. Nahaolelua, Governor of Maui, and Ioane Richardson made a report to King Lot Kamehameha after inspecting the island (Kahoolawe). The following is quoted from this report: 'There is no freshwater but the old residents stated that during the rainy times freshwater may be found in small pools, but these waters did not last, when the sunny times came they soon dried up.

There are not many places on this island where brackish water may be found. There is only one brackish water which is accessible seen by us, at Ahupu harbor, this brackish water being on the northwest of said island.

And the old residents informed us, that there is another brackish water on the southeast (southwest) side of said island, it is in a bad place under cliff at a place called Waikaalulu (Waikahalulu), Kanapou, the well where Kalaepuni was murdered. These are the only three places known where brackish water may be found on Kahoolawe'".

Stearns (1940) goes on to note that there had been seven dug wells on the island; four of these had been developed in ancient times and were blocked or dry and one of the three wells developed in modern times (at Kaulana) was dry in 1939. The two remaining modern wells had relatively high chloride levels (the Ahupwell = 3,250 ppm and the Hakioawa well = 12,600 ppm). Only two seeps are known and are near Kanapou; these have a combined flow estimated to be less than half a pint per minute and are probably from perched-water bodies (Takasaki, 1991). Thus the available information suggests that Kahoʻolawe has very poor groundwater resources and if the historic records are accurate, naturally occurring anchialine pools were probably never present on the island. Since 1941 Kahoʻolawe has been under military control with limited access to the public. The military has supported its operations on the island by the importation of drinking water and has not relied on natural water sources.

In 1965 the Navy carried out an experiment at Kahoʻolawe to test the impact of high explosives in close proximity to ships. The experiment comprised a series of three explosions each utilizing 500 tons of TNT. These explosives were detonated in February, March and June 1965 on a small peninsula forming the western end of Hana Kanaia. The resulting crater formed by these explosions is approximately 50 m in diameter with a pool at the bottom (at sea level) that is about 5 m in depth (Figure 5.1). This pool has been given the name "Sailor's Hat" after the project's name.

An initial biological inventory was made of the Sailor's Hat pool by The Nature Conservancy of Hawaiʻi (1992). They reported that the salinity of the pool was probably in excess of 12o/oo (but it was not measured) and species observed included the native red shrimp or ʻpaeʻula (*Halocaridina rubra*), amphipods, snails, red polychaete tubeworms as well as an alien aquatic insect (family Corixidae). They attributed high turbidity to high phytoplankton densities. The Nature Conservancy of Hawaiʻi (1992) report is the only biological study that has been carried out of this man-made pool. The present paper reports on the water chemistry and presents preliminary information on the species composition as well as abundance of the common biological resources in the Sailor's Hat pool.

Methods

Water chemistry parameters were measured both in the field and laboratory. Parameters of interest in this study include ammonium, nitrite + nitrate nitrogen (hereafter referred to as nitrate), orthophosphorus, silica, chlorophyll *a*, salinity, temperature and pH. Oxygen concentration was not measured in the field but is suspected to be near saturation at the time of sampling because of the high phytoplankton biomass resulting in low water clarity.

Samples for laboratory analysis were collected in 1 l triple-rinsed, acid cleaned polyethylene bottles by carefully swimming to the center of the pool and filling a bottle at a 10 cm depth (top sample) and a second bottle about 50 cm above the substratum at a depth of 4.5 m (bottom sample). Samples for dissolved nutrient analyses were immediately filtered through glass fiber filters into 125 ml acid-washed and triple-rinsed polyethylene bottles which were placed on ice and subsequently frozen until analysis. Laboratory analyses were carried out by Analytical Services at the University of Hawaiʻi using a Technicon AAII system and procedures given in Strickland and Parsons (1972), Smith et al. (1982), Grasshoff (1983) and Standard Methods (1985).

Chlorophyll *a* samples were collected by filtering known volumes of seawater through glass microfiber filters; filters were stored in light-tight containers and frozen until laboratory analyses were carried out. Laboratory procedures followed Standard Methods (1985) where pigments were extracted and determined fluorometrically. Salinity samples were collected in clean 125 ml polyethylene bottles in the field, filled completely and capped tightly until measurement on an AGE Model 2100 Minisal salinometer in the laboratory. In the field temperature and pH were read on a Hanna Model 9025C pH/temperature meter.

Biological data were collected through a combination of diving with SCUBA in the pool capturing specimens with a small mesh net or by removal of the substratum as well as by making observations from the shoreline. Shoreline observations were used to estimate the relative abundance of the shrimp (*Halocaridina rubra*) as well as to collect representative pieces of substratum. Some organisms were transported alive from the Sailor's Hat pool to the laboratory in 1 l polyethylene bottles for further observation.

Results

The pool was formed by the three explosions in 1965 and is approximately 50 m in diameter and has an apparent depth of 5 m. The crater slope into the pool is steep and covered with talus; along the water's edge are angular basalt rock and boulders up to about 3 m in greatest dimension (Figure 5.1). These shoreline rocks show evidence of tidal fluctuation; this apparent tidal movement (not measured) was estimated to be between 50 - 75 cm. Subtidally, the pool walls are similarly steep, ending abruptly on to a relatively flat mud substratum. It is suspected that the mud is derived from windblown dust as well as *in situ* biological activity. The bottom of the pool is covered by a fine mud that has in places an amorphous cyanophyte and diatom mat over it. Attempts to collect this gelatinous veneer resulted in very little visually apparent material in the collection jars so no identification of the mat flora components was made although a number of diatom species were associated with the hard substratum and tubeworms that were collected. Most of the exposed hard substratum in the pool is located around the perimeter and not out on the pond bottom.

Field work was carried out on 14 May 1993. The results of the two water samples from the middle of the Sailor's Hat pool are given in Table 5.1. The concentration of nitrate nitrogen ($NO_2 + NO_3$) and orthophosphorus (PO_4) are low and are similar to that found in coastal waters. Ammonium (NH_4) is slightly elevated which is probably related to the biological activity (metabolism) in the pool. Silica is elevated over what is usually found in nearshore marine waters; this slight elevation is probably due to the small amount of groundwater that enters the pool. The salinity samples show a slight depression over normal full strength seawater (i.e., 33.8o/oo in the pool versus 34.8o/oo in the ocean). There is evidence of a slight stratification with the lower salinity on the surface. The high salinity of this pool suggests that there is little groundwater intruding into the pool.

The results of the biological inventory are summarized in Table 5.2. Emphasis was placed on the aquatic fauna in this inventory. There are several species that are easily seen and were dominant in the pool at the time of sampling; these species include the red-bodied tubeworm (*Vermiliopsis torquata*), the gastropod (*Bittium zebrum*), the red caridean shrimp or ‘opae‘ula (*Halocaridina rubra*) and the waterboatman (*Trichocorixa reticulata*).

The gastropod *Bittium zebrum* has an Indo-Pacific wide distribution and is one of the dominant microgastropods of coral reefs and tidepools in Hawai‘i (Kay, 1979). The serpulid tubeworm *Vermiliopsis torquata* is common in tidepools and on shallow Hawaiian coral reefs where turbidity is low (Bailey-Brock, 1987). This serpulid is considered to be a Hawaiian endemic (Straughan, 1969) but is not known from other Hawaiian anchialine systems. The `pae`ula (*Halocaridina rubra*) is a native species that is characteristically found in Hawaiian anchialine pools (Holthuis, 1973). On the other hand, the aquatic insect or waterboatmen (*Trichocorixa reticulata*) is a widespread species known from North America and became established early in the Hawaiian Islands (Zimmerman, 1948). The waterboatmen is found in a variety of aquatic habitats from fresh water to saline pools by the sea. Two species of amphipods were in the collection. The most common is *Nuuanu amikai* which is best described as a heavily-built species with reduced eyes. The second species, *Eriopisa laakona*, completely lacks eyes and is characterized by very elongate third uropods. The small ostracod species appears to be in the genus *Jugosocytheris*. This podocopid ostracod appears to be very close to *J. venulosus* which was described as a fossil species.

A number of species were not fully identified either because only a few were collected (such as the polychaete, *Ophryotrocha* sp. - a single specimen), juvenile life stage (the polychaete Family Syllidae, species 2), or because of the difficulty in the taxonomy of the group (e.g., the unidentified white sponge and the small anemone).

Discussion

The Sailor's Hat pool complies with the definition of an anchialine pool (Holthuis, 1973), i.e., is land-locked having no surface connection to the sea, has measurable salinity and shows tidal fluctuation. Most Hawaiian anchialine pools have salinities between 2 to 12o/oo (Maciolek and

Brock, 1974) and there are just a few with salinities above 25o/oo in Hawaiʻi (The Nature Conservancy, 1992). Many of the rarer or more unusual anchialine species are found only in pools with salinities above 12 to 15o/oo (Brock, 1985). Thus despite its creation through human activities, the Sailor's Hat pool represents a rare anchialine habitat in Hawaiʻi.

The nutrient and salinity data show that the water in the pool is primarily marine. The low concentrations of nitrate nitrogen and orthophosphorus are similar to oceanic waters which are typically low in these nutrients (Laws, 1980). Similarly, silica concentrations are low in oceanic waters but like nitrate and orthophosphorus are high in Hawaiian groundwater (Brock et al., 1987). The slight elevation of silica and small salinity depression about 1o/oo) suggests that some small amount of groundwater does enter the Sailor's Hat pool. Chlorophyll *a* is a measure of phytoplankton biomass. The relatively high concentrations of chlorophyll *a* encountered in the Sailor's Hat pool probably serves to strip nutrients (nitrate and orthophosphorus) from any groundwater entering the system. This results in the low nutrient levels measured in the pool.

The high salinity in the Sailor's Hat pool is not unexpected with the historical accounts of little freshwater present on the island. Chloride concentration was measured in this pool in May 1983 and was reported at 20,300 ppm (36.7o/oo, Yuen & Associates, 1990) which is slightly hypersaline. Hypersaline conditions probably occur during periods of low rainfall and little groundwater input. The brackish water well at Hakioawa which is the last extant well on the island has been sampled on a number of occasions by researchers since 1939. Chloride concentrations in this well have ranged from 18,000 ppm (32.6o/oo) down to 1,200 ppm (2.2o/oo) following 381 mm of rainfall (Takasaki, 1991). In 1939 Stearns (1940) sampled the Ahupwell and found a chloride concentration of 3,250 ppm (5.9o/oo). Since that time, the Ahupu well has gone dry or is otherwise filled in (Yuen & Associates, 1990).

The amphipods identified in this collection of Sailor's Hat are known from Hawaiian coral reefs (Barnard, 1970). The reduced eyes in *Nuuanu amikai* and the absence of eyes in *Eriopisa laakona* suggest that these amphipods may usually reside in a cavernicolous habitats; Barnard (1970) notes that both species are nestlers. The ostracod, *Jugosocytheris* sp. is unusual in that it closely resembles a species known only from the fossil record (*Jugosocytheris venulosus*). Holden (1967) reports that fossils of *J. venulosus* have been collected from the littoral zone in Fiji to depths exceeding 600 m off the Hawaiian Islands.

All of the macrobiota other than ʻpaeʻula (*Halocaridina rubra*) and the ubiquitous exotic waterboatmen (*Trichocorixa reticulata*) are marine in origin. The diversity of species in the Sailor's Hat pool is not great which may be related to the relative isolation of this pool from the ocean, the occasional hypersaline conditions as well as the low level of sampling that has occurred. Probable mechanisms for colonization of the pool by marine species are by (1) wind, (2) waves overtopping the berm separating the pool from the ocean or (3) by active migration from the ocean through subterranean labyrinth of crevices to the pool. Wind dispersal may be important for species that produce small, lightweight spores such as some of the algae. Overtopping of the berm separating the pool from the ocean must occur. We estimate the distance between the pool and ocean to be about 50 m and the height of berm not to exceed 12 m; during our field survey, we did note some beach sand present along the seaward end of the pool which is consistent with deposition by high surf. All of the species other than *Halocaridina* *rubra* may have colonized the pool by being carried in during periods of high surf. High surf has been hypothesized as an important mechanism for colonization of anchialine pools on the West Hawaiʻi coast by marine fish (Brock, 1977).

Halocaridina rubra is the only species encountered in the Sailor's Hat pool to date that is restricted to anchialine habitats. This species has a relatively long lifespan, low reproductive capacity, is euryhaline and omnivorous and is known to live in the coastal brackish watertable on Hawaiʻi, Maui and Oʻahu islands (Bailey-Brock and Brock, 1993). The presence of *H. rubra* in Sailor's Hat suggests that this species is also established in the coastal watertable of Kahoʻolawe. *Halocaridina rubra* will rapidly recruit to newly constructed brackish ponds on the Kona, Hawaiʻi coast (Brock, unpub. data). However, with the introduction of exotic predatory fishes into a pond, *H. rubra* quickly vacates the pool to the watertable below to escape predation but may return within hours if the predators are removed (Brock, unpub. data).

The abundance of *Halocaridina rubra* in the Sailor's Hat pool is low. In most anchialine systems, *H. rubra* is one of the most common species with densities exceeding a thousand individuals per square meter of substratum (Brock, unpub. data). It has been hypothesized that the high densities in pools are the result of the relatively high productivity of the system that provides ample food resources (Brock, 1985). In contrast, food resources in the subterranean watertable beneath anchialine pools must be low and the abundance of shrimp in this setting is probably similarly low (Bailey-Brock and Brock, 1993). Our cursory examination of the Sailor's Hat pool estimated the abundance of *H. rubra* to be about one individual per cubic meter of water. The reason(s) for the low density of *H. rubra* are unknown but may be related to the large numbers of waterboatmen (*Trichocorixa reticulata*) that are present. Waterboatmen are omnivorous, feeding on filamentous algae, diatoms and small animals which are found in the mud and ooze at the bottoms of ponds (Zimmerman, 1948). Waterboatmen may be preying on juvenile *H. rubra* serving to keep their numbers down. Alternatively, there may be other unidentified predators in Sailor's Hat or the ecological conditions in the pool or the surrounding watertable may not favor *H. rubra*.

There are several anchialine shrimp species that are very rare, being known from just a few sites on Maui and Hawaiʻi Island (Holthuis, 1973; Maciolek, 1983). In some cases, species such as *Vetericaris chaceorum* and *Halocaridina palahemo* are known from a single site (Kensley and Williams, 1986). The single common environmental attribute among the known sites having rare species is that all have salinities above 12 to 15o/oo (Brock, 1985). Thus the Sailor's Hat pool with salinity above 30o/oo may be an appropriate habitat for these rare species and if not already present and given sufficient time, may be colonized by them.

The life history and behavior of *Halocaridina rubra* suggests that it is a fugitive species that cannot tolerate the high level of predation that is present in most Hawaiian aquatic systems. Thus *H. rubra* colonizes and is successful in marginal habitats that most predators are either unable to colonize because of physical barriers or the ecological conditions are unsuitable. The Sailor's Hat pool probably represents such a marginal habitat and may be the only site on Kahoʻolawe where this shrimp species has the opportunity to find sufficient food resources to sustain a meaningful population level. Given the ecological characteristics of this pool and barring further human or predator disturbance, it may be colonized and serve as a habitat for other rare Hawaiian anchialine species in the future.

Acknowledgments

The authors wish to thank the military personnel stationed on Kahoʻolawe during our 14 May 1993 visit for their help in making our visit successful. We also wish to thank Drs. F. Cox and P. Jokiel for their support and logistical help in the field and to Dr. W. Cooke for his assistance in identifying the ostracod and amphipods in our collections. The Waikoloa Anchialine Pond Program supported sample processing costs.

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Table 5.1. Summary of the water chemistry parameters from two samples collected in the Sailor's Hat pool on Kaho‘olawe on 14 May 1993.

sample location	nitrite +nitrate N m M	ammonia N m M	ortho P m M	silica m M	chl *a* m g l^{-1}	salinity o/oo	temperature ° C	pH
top	0.10	2.21	0.29	257.24	10.325	33.8727	27.5	8.25
bottom	0.16	1.74	0.26	259.86	9.674	33.8852	27.6	8.26

Table 5.2: Summary of the biological collection made on 14 May 1993 in the Sailor's Hat pool, Kaho'olawe.

Taxon	**Remarks**
Phylum Porifera species?	Silvery-white species encrusting lower surfaces of rocks collected close to shoreline - common.
Phylum Platyhelminthes Order Aceola species?	This flatworm is apparently not in Poulter (1987); found on underside of rock.
Phylum Cnidaria Subclass Zoantharia species?	Small anemone found on rock.
Phylum Entoprocta Family Loxosomatidae *Loxosoma* sp.	Solitary entoproct, some with 2 buds attached near fecal strands of serpulid tubeworms on undersides of rocks.
Phylum Annelida Family Serpulidae *Vermiliopsis torquata*	Abundant tubeworm found on underside of rocks. Worms are brilliant red and quite conspicuous.
Family Dorvilleidae *Ophryotrocha* sp	Singe 11 setiger specimen with brown/black mandibles and serrated margins. Simple and compound setae present but no forked setae.
Family Syllidae syllid species 1	Prostomium with a pair of large lobed palps, antennae and dorsal cirri strongly moniliform. Parapodia short and rounded. Dorsal cirri of alternate setigers are long and short. Ventral cirri digitiform and not articulated. Body cylindrical, anterior region with six red eyes and a long gizzard. Setae are compound, serrated blades with bifid tips that vary in length from short to long within a fascicle and long acicular setae with curved tips occur singly on the parapodia. Color pale with some brown pigment on anterior regions. Living adjacent to tubeworms on rock.
syllid species 2	Single juvenile with 5 setigers. Head with 4 eyes, round anterior margin, a single median antenna and 2 ciliated grooves. dorsal cirri digitiform, setae compound with one acicular seta with a dorsal curved tip. Living adjacent to tubeworms on rock.
Phylum Mollusca Family Cerithiidae *Bittium zebrum*	Abundant on upper surfaces of rocks; common in tidepools and shallow reef areas in Hawai'i.
Phylum Arthropoda Subclass Ostracoda Family Hemicyatheridae *Jugosocytheris* sp.	Species is very similar to J. venulosus which has been described as a fossil.
Order Amphipoda *Nuuanu amikai*	Species has reduced eyes.

Taxon	**Remarks**
Eriopisa laakona	Blind species; probable cavernicolous life history.
Order Decapoda Family Atylidae *Halocaridina rubra*	Confined primarily to edges of pool near rocky substratum; density estimated at 1 shrimp m^{-3} of water. Little pigmentation so shirmp are pale and mean body size from tip of rostrum to posterior margin of the telson is 8-9 mm.
Class Insecta Family Corixidae *Trichocorixa reticulata*	Waterboatmen - abundant in the water column; common in fresh to saline ponds; exotic species.

CHAPTER 6: GENERAL CONCLUSIONS AND RECOMMENDATIONS

Paul L. Jokiel and Evelyn F. Cox, Hawaii Institue of Marine Biology

Conclusion 1. Some reefs around Kaho‘olawe have been previously impacted by high sedimentation. The removal of goats, revegetation, and erosion control on Kaho‘olawe are leading to improvement in these areas. Continued control of sediment input will result in further improvement of these reef habitats.

Recommendation: Continue management of land use, revegetation, and erosion control to decrease sediment input into the nearshore waters. Natural processes will continue the winnowing of sediments present on nearshore reefs, and natural recolonization of exposed substratum will occur, re-establishing communities in equilibrium with the environmental conditions of each site fairly rapidly.

Conclusion 2. There is a wide range of reef habitats and high diversity of corals and fishes in the existing coral reef areas around Kaho‘olawe. In spite of the heavy sediment input, some areas are near pristine and show minimal impacts of human activities. The presence of a high island reef system not impacted by agriculture, industry, and urbanization is a unique scientific resource for monitoring global changes.

Recommendation: Implement the Kaho‘olawe Conveyance Commission Recommendation 2.12 that states "The State of Hawai‘i shall recognize the waters surrounding Kaho‘olawe for their pristine nature - and their importance in maintaining numerous marine species populations - and designate these waters with special status under the law."

Conclusion 3. Although the nearshore waters are currently closed to certain types of fishing, our observations indicate that the lack of enforcement has led to considerable fishing pressure on Kaho‘olawe's reefs. Use of the nearshore marine resources, if not regulated, will intensify. There are few places in the main Hawaiian islands that are not heavily fished, and the proximity of Kaho‘olawe to Maui and current levels of fishing indicate that there will be an increase in fishing activities on Kaho‘olawe.

Recommendation: If this area is to become a refugia for marine species in the Hawaiian islands, any management activities must be accompanied with enforcement of regulations.

Conclusion 4. The man-made anchialine pond at Sailor's Hat Crater represents a unique resource in the Hawaiian islands. The ‘pae‘ula is a fugitive species that cannot tolerate the high level of predation in most Hawaiian aquatic systems. Kaho‘olawe represents an important refuge for this species and other biota of these habitats.

Recommendation: Establish a refuge to protect the endemic biota of Sailor's Hat Crater as a unique scientific and educational resource. Prevent introduction of non-anchialine species (e.g. fish) into Sailor's Hat Crater.

Conclusion 5. The nearshore waters of Kaho‘olawe provide habitat for sea turtles, spinner dolphins, monk seals, and humpback whales.

Recommendation: If specific habitats for these animals, particularly with respect to potential nesting and pupping areas for turtles and seals, are designated as refugia for these species, management will be required to protect these areas.

APPENDIX A: CORAL COMMUNITY DATA

Species List for all coral species observed at stations on Kahoʻolawe.

Order Scleractinia
- Family Pocilloporidae
    - *Pocillopora damicornis* Linneaus, 1758
    - *Pocillopora meandrina* Dana, 1846
    - *Pocillopora eydouxi* Edwards and Haime, 1860
    - *Pocillopora ligulata* Dana, 1846
- Family Acroporidae
    - *Montipora verrucosa* sensu Vaughan, 1907
    - *Montipora patula* Verrill, 1864
    - *Montipora dilitata* Studer, 1901
    - *Montipora flabellata* Studer, 1901
    - *Montipora studeri*
- Family Poritidae
    - *Porities compressa* Vaughan, 1907
    - *Porties lobata* Dana, 1846
    - *Porites evermanni* Vaughan, 1907
    - *Porites rus* Forskål, 1775
- Family Siderastreidae
    - *Psammocora nierstraszi* van der Horst, 1921
    - *Psammocora stellata* Verrill, 1864
- Family Agariciidae
    - *Pavona varians* Verrill, 1864
    - *Pavona duerdeni* Vaughan, 1907
    - *Pavona maldivensis* Gardiner, 1905
    - *Gardineroseris planulata* Dana, 1846
- Family Fungiidae
    - *Fungia scutaria* Lamarck, 1801
- Family Faviidae
    - *Leptastrea bottae* (Edwards and Haime, 1849)
    - *Leptastrea purpurea* Dana, 1846
    - *Cyphastrea ocellina* (Dana, 1864)

Order Alcyonacea
- Family Alcyoniidae
    - *Sinularia abrupta* Tixier-Durivault, 1970

APPENDIX B: FISH COMMUNITY DATA FROM KAHOOLAWE

Species list for all fish species observed at stations on Kaho‘olawe.

Class Chondrichthyes
- Family Carcharhinidae
  - *Traenodon obesus* (Rüppell), 1835
- Family Myliobatidae
  - *Aetobatus narinari* (Euphrasen), 1790

Class Osteichthyes
- Family Muraenidae
  - *Gymnothorax flavimarginatus* (Rüppell), 1830
- Family Synodontidae
  - *Synodus* sp.
- Family Belonidae
  - unidentified species
- Family Hemiramphidae
  - unidentified species
- Family Aulostomidae
  - *Aulostomus chinensis* (Linnaeus), 1766
- Family Holocentridae
  - *Sargocentron sp.*
  - *Myripristis amaena* (Castelnau), 1873
- Family Serranidae
  - *Cephalopholis argus* Bloch and Schneider, 1801
- Family Scorpaenidae
  - *Sebastapistes coniorta* Jenkins, 1903
  - *Pterois sphex* Jordan and Evermann, 1903
- Family Kuhliidae
  - *Kuhlia sandvicensis* (Steindachner), 1876
- Family Priacanthidae
  - *Heteropriacanthus cruentatus* (Lacepède), 1801
- Family Apogonidae
  - *Apogon sp.*
- Family Carangidae
  - *Caranx melampygus* Cuvier and Valenciennes, 1833
- Family Cirrhitidae
  - *Cirrhitus pinnulatus* (Bloch and Schneider), 1801
  - *Paracirrhites forsteri* (Bloch and Schneider), 1801
  - *Paracirrhites arcatus* (Cuvier and Valenciennes), 1829
  - *Cirrhitops fasciatus* (Bennett), 1828
  - *Oxycirrhites typus* Bleeker, 1857
- Family Lutjanidae
  - *Aprion virescens*

Lutjanus kasmira (Forsskål), 1775
Lutjanus fulvus (Bloch and Schneider), 1801
Family Lethrinidae
Monotaxis grandoculis (Forsskål), 1775
Family Kyphosidae
Kyphosus sp.
Family Mullidae
Mulloides flavolineatus (Lacepède), 1801
Parupeneus pleurostigma (Bennett), 1830
Parupeneus cyclostomus (Lacepède), 1801
Parupeneus bifasciatus (Lacepède), 1801
Parupeneus multifasciatus (Quoy and Gaimard), 1825
Parupeneus porphyreus (Jenkins), 1903
Family Chaetodontidae
Chaetodon auriga Forsskål, 1775
Chaetodon quadrimaculatus Gray, 1833
Chaetodon lunula (Lacepède), 1802
Chaetodon miliaris Quoy and Gaimard, 1824
Chaetodon fremblii Bennett, 1829
Chaetodon kleinii Bloch, 1790
Chaetodon ornatissimus Cuvier and Valenciennes, 1831
Chaetodon trifasciatus Mungo Park, 1797
Chaetodon unimaculatus Bloch, 1787
Chaetodon multicinctus Garrett, 1863
Chaetodon reticulatus Cuvier and Valenciennes, 1831
Heniochus diphreutes Jordan, 1903
Forcipiger flavissimus Jordan and McGregor, 1898
Forcipiger longirostris Broussonet, 1782
Hemitaurichthys thompsoni Fowler, 1923
Family Pomacanthidae
Holacanthus arcuatus Gray, 1831
Centropyge potteri (Jordan and Metz), 1912
Family Pomacentridae
Abudefduf sordidus (Forsskål), 1775
Abudefduf abdominalis (Quoy and Gaimard), 1825
Plectroglyphidodon imparipennis (Vaillant and Sauvage), 1875
Plectroglyphidodon johnstonianus Fowler and Ball, 1924
Stegastes fasciolatus (Ogilby), 1889
Dascyllus albisella Gill, 1862
Chromis hanui Randall and Swerdloff, 1973
Chromis agilis Smith, 1950
Chromis ovalis (Steindachner), 1900
Chromis verater Jordan and Metz, 1912
Chromis vanderbilti (Fowler), 1941

Family Labridae
Cheilinus unifasciatus Streets, 1877
Labroides phthirophagus Randall, 1958
Pseudochilinus octotaenia Jenkins, 1900
Pseudochilinus tetrataenia Schultz, 1960
Bodianus bilunulatus (Lacepède), 1801
Coris venusta Vaillant and Sauvage, 1875
Coris flavovittata (Bennett), 1829
Coris gaimard (Quoy and Gaimard), 1824
Anampses cuvier Quoy and Gaimard, 1824
Thalassoma duperrey (Quoy and Gaimard), 1824
Thalassoma ballieui (Vailland and Sauvage), 1875
Thalassoma trilobatum (Lacepède), 1801
Thalassoma purpureum (Forsskål), 1775
Halichoeres ornatissimus (Garrett), 1863
Macropharyngodon geoffroy (Quoy and Gaimard), 1824
Gomphosus varius Lacepède, 1801
Stethojulis balteata (Quoy and Gaimard), 1824
Family Scaridae
Scarus sordidus Forsskål, 1775
Scarus perspicillatus Steindachner, 1879
Scarus psittacus Forsskål, 1775
Scarus rubroviolaceus Bleeker, 1849
Scarus dubius Bennett, 1828
Family Zanclidae
Zanclus cornutus (Linnaeus), 1758
Family Acanthuridae
Acanthurus guttatus Bloch and Schneider, 1801
Acanthurus triostegus (Linnaeus), 1758
Acanthurus leucopareius (Jenkins), 1903
Acanthurus olivaceus Bloch and Schneider, 1801
Acanthurus dussumieri Cuvier and Valenciennes, 1835
Acanthurus blochii Cuvier and Valenciennes, 1835
Acanthurus achilles Shaw, 1803
Acanthurus nigrofuscus (Forsskål), 1775
Acanthurus nigroris Cuvier and Valenciennes, 1835
Ctenochaetus strigosus (Bennett), 1828
Ctenochaetus hawaiiensis Randall, 1955
Zebrasoma flavenscens (Bennett), 1828
Zebrasoma veliferum (Bloch), 1797
Naso lituratus (Bloch and Schneider), 1801
Naso unicornis (Forsskål), 1775
Naso hexacanthus (Bleeker), 1855
Naso brevirostris (Cuvier and Valenciennes), 1835

Family Scombridae
Acanthocybium solandri (Cuvier, 1831
Family Blenniidae
Exallias brevis (Kner), 1868
Cirripectes vanderbilti (Fowler), 1938
Plagiotremus goslinei (Strasburg), 1956
Family Monacanthidae
Cantherhines sandwichiensis (Quoy and Gaimard), 1824
Cantherhines dumerilii (Hollard), 1854
Pervagor spilosoma (Lay and Bennett), 1839
Family Balistidae
Rhinecanthus rectangulus (Bloch and Schneider), 1801
Rhinecanthus aculeatus (Linnaeus), 1758
Sufflamen bursa (Bloch and Schneider), 1801
Melichthys vidua (Solander), 1844
Melichthys niger (Bloch), 1786
Family Ostraciidae
Ostracion meleagris Shaw and Nodder, 1796
Family Tetraodontidae
Canthigaster amboinensis (Bleeker), 1865
Canthigaster jactator (Jenkins), 1901
Arothron meleagris (Bloch and Schneider), 1801

APPENDIX C: RESPONSES FROM DIVE OPERATORS ON MAUI

(Note, because it is illegal to SCUBA dive in waters off Kahoʻolawe, no names will be used, except where the names are printed in public documents.)

Of 12 dive operators contacted on Maui, 6 indicated that they have visited and/or take dive groups to Kaho`olawe. Two dive operators, Ed Robinson's Diving Adventures and Mike Severns Diving, advertise Kahoʻolawe destinations in their brochures. Ed Robinson gives detailed information on dive sites at Kahoʻolawe - the following excerpt is from ***The Ultimate Dive: Favorite Dive Sites Handbook***, prepared by Ed Robinson's Diving Adventures.

Ulua Ridge

When the trade winds die and the Navy opens Kahoolawe, we head for this spot. You'll find a combination of healthy coral reef and a lava ridge that drops to over 300 ft. A school of large white ulua (jack) is often seen cavorting around the 60 ft. pinnacle and down the drop-off. Black coral, eagle rays, and sharks can be part of this dive, too. The current is often strong on this 60- to 110-ft. dive, so we save this site for "adventure" days when we can share it with experienced divers.

Kahoolawe Grotto

Larger than the Cathedrals of Lanai, this is a cave dive suitable for all levels of experience. It is situated at the base of a sheer cliff and cuts deep into the side of the island. At a depth of only 40 ft., the cavern runs horizontally for several hundred feet. There are no rooms or side tunnels, and divers are always in view of the gaping entrance. From inside, the silhouette of divers and lava formations is backlit by dancing bands of silver sunlight. Bring a wide-angle lens on this dive. Sharks, lobster, and shells are the expected finds in this area.

1001 Species

Roger thinks this dive is the closest he has seen in Hawaii to the reefs of Palau - and that's saying a lot! Healthy coral reef rolls quickly to beyond diving depths and is adorned by multiple schools of butterfly and other tropical fish. We usually do this as a drift dive at 20 to 80 ft. since current is often present. It's appropriate for all levels of divers.

Shoal Reef (or Boulder Reef)

On the far side of Kahoolawe Island lies a large shoal. Around large boulders and lava ridges divers find a mixed bag of animals and invertebrates at about 40 ft., some rarely seen around Maui. It's a long trip but worth the time it takes to get to this distant and untamed area.

Scarecrow Point

A mile around Kahoolawe, back toward Maui from Shoal Reef, lies on of the least dived and most interesting areas. On this 10- to 70-ft. dive you can expect to see pufferfish by the dozens, lobster by the bushel, and schools of squirrel fish that block the way through caves. It's one of the best exploratory areas we have, but access depends on the weather.

Most operators who take groups to Kahoʻolawe indicated that the weather was the critical factor. Only on calm days do they attempt to make the trip, as it is a longer distance to go than to sites on Maui or Molokini, and many of the reefs are not considered exceptional for diving. The general opinion was that the areas around Kanapou, as described above at Ulua Ridge, Kahoʻolawe Grotto, and 1001 Species, are the best for commercial tours - the waters are clear, scenery is interesting, lots of fish and other species can be seen, and the safety of the dive can be determined while traveling to Molokini by the presence or absence of breakers along the cliff faces. One operator also voiced the opinion that the reefs on the northern coast have been heavily sedimented and therefore are not attractive areas to visiting divers.

A letter to the editor of *Sources*, September/October 1993, by Leslie Farel, Owner of Dive Maui, voiced opinions commonly heard from dive operators concerning the designation of the area as a preserve. The text of the letter is quoted below:

"In response to the recent articles in *Sources* on marine sanctuaries, all is not what it often appears superficially."

"Here in Hawaii, no one wants a marine sanctuary, save a few government individuals who neither asked our vote nor listened to our arguments in public meetings. In a recent meeting, over 300 residents argued against the sanctuary and signed petitions refuting it. We were asked a few years ago whether we wanted such a designation and said then that we didn't, but we got it regardless. Fishermen are concerned that, like in many sanctuary areas, fishing rights and catches will be limited. ... Hawaiians make their living from sea and land. Restrictions go against their culture as well as their economy. Charter boat operators were concerned that restrictions would prohibit channel crossings and reef touring. Maui law has already prohibited certain watercraft during whale season (winter) and some tour operators are out of business during those months. The dive industry is concerned that since high speed boats cross the channels between islands during whale season that diving will be restricted to coastline reefs subject to high swells, fresh water run-off and low visibility during those months, if allowed at all. Furthermore, Molokini Preserve, contained within this whale preserve, is our most popular location. Officials will not tell us what plans are for this islet. Another island, Kahoolawe, a former naval target range, now in trust for potential Hawaiian cultural education, is another preserve within this larger preserve. Molokini falls not only within the whale sanctuary, but within the potential boundaries of the suggested Kahoolawe Preserve. One question asked over and over is, since the whales are only here during the winter months, why is this unpopular preserve designated all year. In addition, the whales are already protected under the federal endangered species act. NOAA seems to feel we need this preserve to protect what is already federally protected. Many have questioned what the real intent of the feds are in designating this preserve and what boundaries and restrictions will be established without the consent and permission of the users. No one has answered these questions, leaving Hawaiians wondering, imagining the worst. One speaker in a recent meeting told of ... his forced evacuation from land that had been in his family for hundreds of years. Hawaiians have seen the invasion of their islands by missionaries, by workers imported by large agricultural corporations and by, most recently, mainland tourists. The little they have left they can call their own their protect feverishly....

What will happen to access to dive locations and use permission is yet to be seen. While Hawaii has no private beaches, officials have already attempted restricting access by commercial operations to beach sites. Oahu charges instructors a user's fee to bring tax-paying customers to dive. While the state permit system has not been affected on Maui, instructors have been told to vacate beaches by police. If we cannot use the beaches and they intend to restrict boating activity, how will people go diving? This is a potentially serious situation that needs attention by anyone who has enjoyed diving in Hawaii and wants to continue doing so."

Leslie Farnel, NAUI #6092

Owner, Dive Maui

APPENDIX D: ANNOTATED BIBLIOGRAPHY

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Includes fish species list with relative abundances from six sites (Papakaiki, Kahulani, Ticum east and West and Black Rock, and Twin Sands) surveyed by a Marine Option Program team of student divers 15-16 May 1976.

Aluli, N.E. and D.P. McGregor. 1992. Mai ke kai mai ke ola, From the ocean comes life: Hawaiian customs, uses, and practices on Kaho‘olawe relating to the surrounding ocean. Hawaiian Journal of History 26:231-254.

Descriptions of some of the 69 coastal fishing shrines discovered on Kaho‘olawe and traditions of marine resource use. Gives translations of some of the place names on Kaho‘olawe: Hanakanai`a is dolphin harbor, Honukanaenae means tired turtle and is said to be a turtle nesting spot. Ko`ele Bay refers to a variety of `opihi. Kuheia means squid point and is flanked by two points, Laehilukea, white hilu (fish) point, and Laehilu'ula, red hilu point. Laepuhi means eel point. Nalaekohola, names for the two points of Ahupu, refers to humpback whales.

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Ashdown, I.M. 1979. Recollections of Kahoolawe. Topgallant Publishing Co., Honolulu, Hawaii. 71 pp.

Ashdown provides information on the ranch run by her father, Angus MacPhee, between 1917 and 1945. Includes photographs of Kuheia, location of the ranch headquarters.

Ballena Systems Corporation, K.F. Casey, B.A. Baertlein, and B.L. Donaldson. 1992. Unexploded Ordnance on Kaho‘olawe: Historical Review, Technology assessment, and Clearance Planning. Kaho‘olawe Island Conveyance Commission Consultant Report No. 3. 165 pp.

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Clark, R.J.K. 1980. The beaches of Maui County. University Press of Hawaii, Honolulu, Hawaii. pp. 125-138.

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"In general, reefs are poorly developed due to the steep insular shelves and periodic stress from heavy siltation during storms. The best reefs are found off the west end at Kuia Shoal; elsewhere they are patch and often only thin veneers on underlying basalt foundations."

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Maps showing place names, area of hardpan, areas of ordnance hazard, environmental zones, and historical sites.

Judd, C.S. 1917. Kahoolawe. Hawaiian Almanac and Annual 1917:117-125.

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Final report of the KICC. Includes a history of the island, status of place names, terrestrial zones of native vegetation, maps of the hardpan and revegetation efforts, ordnance estimates, committee's recommendations.

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National Oceanic and Atmospheric Administration. 1991. Kaho‘olawe Island National Marine Sanctuary Feasibility Study. Prepared for Sanctuaries and Reserves Division, NOAA. 45 pp.

"The marine environment adjacent to Kahoolawe is comprised of steep insular shelves with limited reef development. Coral habitat types are generally limited to species that have adapted to, and can survive in silt-laden environments such as Porites, Pocillopora, and Montipora".

Biological resources and cultural/historical uses of marine resources merit further investigation for sanctuary status. Limited reef development, particularly of corals that can survive in silt-laden environments. Fish diversity high. Other marine wildlife, pilot whales, false killer whales, Pacific bottlenose dolphins, spinner dolphins, monk seals, and green sea turtles use the nearshore waters. Includes summary of prior surveys of marine resources.

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Reports on the terrestrial plant survey of Kaho‘olawe, commissioned by the KICC. Includes a discussion of Sailor's Hat, indicating surface salinity of 12 pp, and presence of `opae`ula shrimp (*Halocaridina rubra*), amphipods, snails, and red polychaete tube worms as well as well developed phytoplankton bloom making the waters turbid.

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