Geology and Geomorphology of Coral Reefs of the Northwestern Hawaiian Islands

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14.1 Introduction

The Northwestern Hawaiian Islands (NWHI) comprise a portion of the middle of the 6,126 km long Hawaiian-Emperor seamount chain, considered to be the longest mountain chain in the world Grigg (1983) (Figure 14.1). Located in the middle of the North Pacific Ocean, the Hawaiian Islands have been referred to as the most geographically isolated archipelago in the world. The islands are ~ 3,800 km from the nearest continental landmass, the west coast of North America. The nearest other island, Johnston Atoll, is located almost 900 km southwest of the NWHI. A distance of 1,500 km separates the island of Hawai`i at the southern end of the archipelago from the next nearest island, Kingman Reef in the Line Islands. Kure Atoll at the northwestern end of the Hawaiian Islands is the closest point in the archipelago to the northernmost of the Marshall Islands, 2,000 km to the southwest.

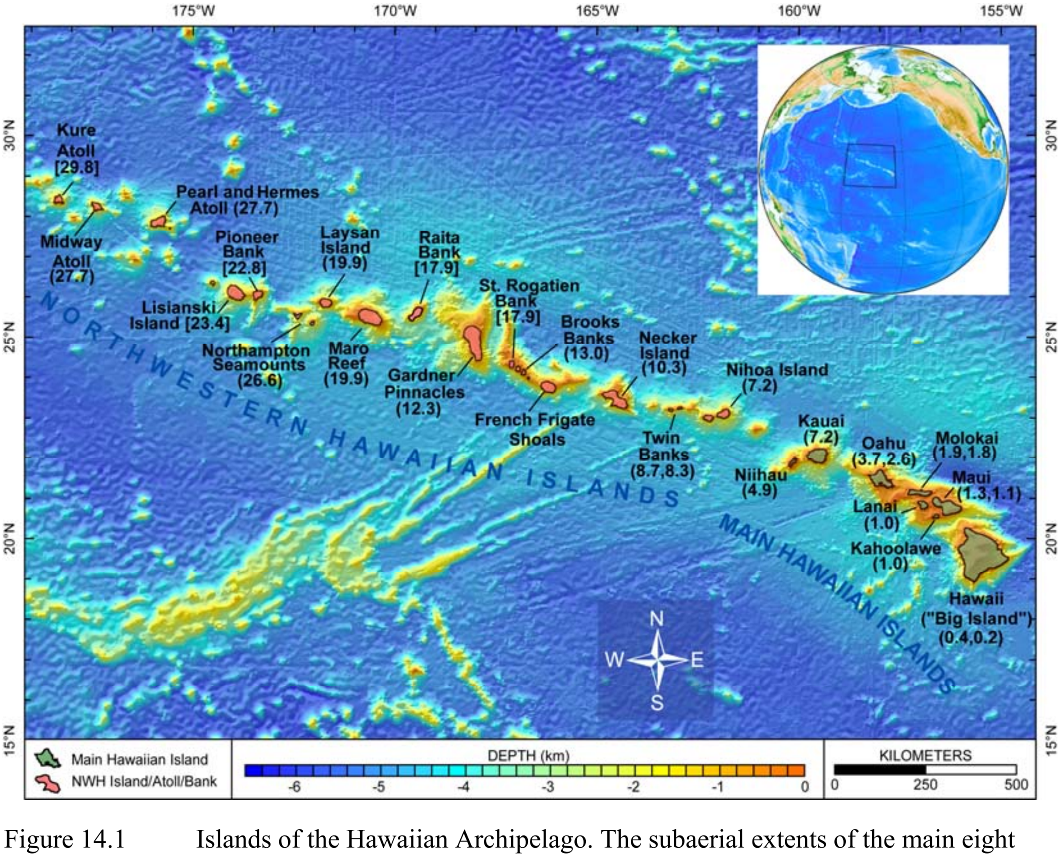

Figure 14.1 Islands of the Hawaiian Archipelago. The subaerial extents of the main eight islands are shown in green. The prominent islands, atolls, and banks in the NWHI, and the shelves around them are shown in pink, overlain on color-coded bathymetry data from Smith and Sandwell (1997). Numbers next to the islands are their ages in millions of years from Clague (1996) that have been measured (in parentheses) or calculated ages (in brackets). The extents of the map are indicated by the box on the globe in the upper right corner.

Because of their physical isolation and low levels of marine biodiversity, Hawaiian reefs feature high levels of endemism. Approximately a quarter of the species present are found nowhere else, and the Hawaiian Archipelago has approximately twice as many endemic coral species as any other area its size in the world (Fenner 2005). This unique area is home to over 7,000 marine species (Hawaii DLNR 2000), the critically endangered Hawaiian monk seal (*Monachus schauinslandi*, Figure 14.2), and provides nesting grounds for 14 million seabirds and 90 percent of Hawaii's threatened green sea turtles (*Chelonia mydas*) (NWHI MNM 2006). Reefs in the NWHI are dominated by top predators such as sharks and jacks, which make up more than half of the overall fish biomass (Figure 14.3). In contrast, top predators in the heavily fished main Hawaiian Islands (MHI) make up approximately 3 percent of the overall fish biomass, which is more typical of coral reefs worldwide (Friedlander and Demartini, 2002, Maragos and Gulko 2002).

Figure 14.2 Endangered Hawaiian Monk Seal (*Monachus schaunslandi*) swims around spur and groove structures at Pearl and Hermes Atoll. Photograph by Molly Timmers.

Figure 14.3 Scientist studies a coral reef at Lisianski Island under the watchful eyes of a shark and an ulua, two of the top predators of the NWHI. Although this is a typical scene in the NWHI, years of fishing pressure make a situation like this quite unusual for most of the world's coral reefs. Photograph by Jean Kenyon.

Although resources in the Northwestern Hawaiian Islands have been exploited by humans since their discovery by ancient Polynesians, their isolation has afforded some protection and helped preserve their coral reef ecosystems. Additionally, most of the atolls and reefs of the NWHI have been afforded some level of environmental protection for almost a century. As a result, the NWHI are the only large-scale coral reef ecosystem on the planet that is mostly intact, a marine wilderness that provides us with insights on what other coral reefs may have been like prior to human exploitation (Fenner 2005).

14.1.1 History and Resource Management

Figure 14 Mokumanamana, also called Necker Island, was a place of spiritual and cultural significance to the native Hawaiian culture a thousand years ago, as it is again today. Photograph by Jean Kenyon.

14.1.1.1 The Political History of the NWHI

The first humans to discover and settle the Hawaiian Islands were Polynesian voyagers, possibly from the Marquesas Islands. Evidence from multiple sites indicates that permanent settlements were established in the MHI by at least 600 A.D., and perhaps several centuries earlier (Kirch 1998). However, it was not until approximately 1000 A.D. that early Hawaiians first arrived in the NWHI. A permanent community was established on Nihoa Island that survived for an estimated 700 years, but disappeared prior to Western European contact, the arrival of Captain Cook, in 1778. Mokumanamana, or Necker Island (Figure 14.4), was never permanently settled, but remains of temporary habitation and numerous cultural sites are found on the island (Cleghorn 1988). Mokumanamana is located approximately 9 km from the present position of the Tropic of Cancer at the northern limit of the sun's path throughout the year. A thousand years ago however, it was directly in line with the rising and setting of the equinoctial sun and a place of spiritual and ceremonial significance to the ancient Hawaiian culture (NWHI MNM 2006).

Multiple lines of evidence strongly suggest that the settlement of the Hawaiian Islands by Polynesian navigators was not limited to the participants of a single voyage. Voyages between the Hawaiian Islands and the Cook, Society, and Marquesas Islands apparently continued for centuries but stopped after about 1200 A.D. (Kirch, 1998). It seems unlikely that a society with such a strong tradition of voyaging thousands of kilometers across the open ocean would not have found other islands and atolls of the NWHI, which lie in a fairly straight line and are a few hundred kilometers apart or less. In particular, the resource-rich French Frigate Shoals is less than 150 km from Necker Island. However, the ancient Hawaiians apparently did not create permanent settlements at any of the other islands, and signs of their visits have not been reported.

Nihoa Island, the southernmost Northwestern Hawaiian Island, was seemingly forgotten prior to its rediscovery in 1788 by Captain Colnett of the British vessel *Prince of Wales* (Rauzon 2001). In 1822, Queen Ka'ahumanu traveled to Nihoa Island and claimed it for the Kamehameha Monarchy, which ruled the Kingdom of Hawaii from 1795 to 1872. One of her successors, King Kamhameha III, claimed Pearl and Hermes Atoll in 1854. In 1857, King Kamehameha IV sent Captain William Paty to explore the NWHI and later that year claimed the recently discovered islands of Laysan and Lisianski. Finally, in 1886, King David Kalakaua claimed Kure Atoll. A group of local businessmen, predominantly of American and European descent and backed by the U.S. military, overthrew the Kingdom of Hawai`i in 1893. In 1898, the entire Hawaiian Archipelago, including the NWHI, was ceded to the United States (NWHI MNM 2006; Rauzon 2001).

14.1.1.2 Midway – The Most Famous Atoll in the NWHI

Thanks to the pivotal World War II battle fought nearby, Midway Atoll is the best known of the Northwestern Hawaiian Islands. Discovered in 1859 by Captain Brooks of the *Gambia*, it was claimed under the U.S. Guano Act of 1856, making Midway the only atoll or island in the NWHI that does not today belong to the State of Hawaii (Rauzon 2001). The U.S. Navy began construction of a channel into the lagoon in 1870 and then abandoned the effort until 1940. In the meantime, The Pacific Commercial Cable Company developed Sand Island at Midway as a station for a cable between Guam and San Francisco that was completed in 1903. Pan American Airways built an airport on the island in 1935, and it became a refueling stop for their Clipper floatplanes on the Manila to San Francisco route. These commercial ventures, especially the cable company, imported over 8,000 tons of topsoil to Sand Island and planted extensively. They transformed the once mostly desolate and unvegetated sand island into the "garden" that it is today, but introduced hundreds of alien species to the NWHI in the process. In 1939, the Navy decided that an air base at Midway was of national strategic importance and commissioned the Midway Naval Air Station on August 1, 1941. A few months later, directly after the attack on Pearl Harbor in Honolulu on December 7th, the station was bombed. The naval battle six months later near Midway was the turning point of World War II in the Pacific theater. In 1957 Midway became a key base in the Distant Early Warning line, a radar screen between Alaska and Hawai`i that was an important component of U.S. strategy in the Cold War. Midway's last military function was as an important refueling station during the Vietnam War, before control of the island was turned over to the U.S. Fish and Wildlife Service in 1996 (Rauzon 2001).

14.1.1.3 Exploitation and Management of Natural Resources

Several research expeditions passed through the Archipelago during the period of rediscovery of the NWHI, contributing to base of knowledge about the area. The naturalist James Dana, on U.S. Exploring Expedition, visited the islands in the late 1840s, followed by the British Challenger Expedition between 1872-1876. The Albatross Expedition of 1902 mostly dredged deep waters around the Archeiplago, and the Tanager Expedition of 1923-4 primarily collected specimens and data (Grigg 2006). These expeditions were primarily driven by scientific inquiry, but most other efforts in the area were focused on resource extraction. The previously near-pristine NWHI were heavily exploited in the 19th and early 20th centuries for seabirds, albatross eggs, monk seals, turtles, guano and other resources resulting in widespread ecological damage and causing populations to plummet (NWHI MNM 2006; Rauzon 2001). The damage was compounded by the introduction of a number of plants, insects, and other animals.

Recognizing the importance of the islands to seabirds, President Theodore Roosevelt put Midway Island under control of the Navy Department in 1903 to prevent poaching by Japanese feather hunters. In 1909, in response to public uproar over the killing of millions of seabirds throughout the NWHI for the feather trade, he established the Hawaiian Island Bird Reservation through Executive Order 1019. This was the first of several steps taken over the following century to protect the living and other resources of the NWHI (Figure 14.5). In 1940, President Franklin Delano Roosevelt changed the name of the Bird Reservation to the Hawaiian Islands National Wildlife Refuge, increasing the level of protection afforded to wildlife and enabling many populations to return to levels similar to those when the islands were first discovered.

Figure 14.5 Although marine life in the NWHI has enjoyed nearly a century of legal protection, a turtle trapped in a derelict fishing net and the remains of a dead bird with its digestive tract full of plastic are grim reminders that anthropogenic threats still exist. Marine debris including nets and other fishing gear, and a wide range of discarded plastic items from across the entire North Pacific Ocean accumulates in the waters of the subtropical front, continuing to entangle marine life and damage benthic habitats across the NWHI. Turtle photograph by Jake Asher; photograph of bird by Jean Kenyon.

Commercial fishing in the NWHI by vessels from the Main Hawaiian Islands resumed after World War II. This practice continued until the Honolulu market declined in the late 1950s. In an effort to relieve pressure on marine resources in the Main Hawaiian Islands, in 1969 the Governor's Task Force on Oceanography recommended developing fisheries in the NWHI. The Governor's Advisory Committee on Science and Technology urged State, Federal, and academic research agencies to conduct collaborative research in the NWHI to further that goal. In response the National Marine Fisheries Service conducted research cruises to the area in 1973 and 1975 and that agency, the Fish and Wildlife Service, and the Hawaii Department of Land and Natural Resources entered in to the Tripartite Cooperative Agreement to survey and assess the living resources of the NWHI (Hawaii DLNR 2000). Aided by tens of millions of dollars of "extended jurisdiction" funding, the Tripartite partners, joined by the University of Hawaii Sea Grant program, conducted a number of studies between 1976 and 1981, eventually resulting in research symposia in 1980 and 1983, and the publicating of 115 papers or abstracts in three volumes of proceedings (Grigg 2006).

In 1983 the U.S. Exclusive Economic Zone (EEZ) was established by President Ronald Reagan. This gave the U.S. jurisdiction over all resources between 4.8 and 322 km (3 and 200 nm) from any of their shorelines and also provided Extended Jurisdiction funds for research within the newly-designated EEZ. Midway Atoll National Wildlife Refuge was established in 1988, followed by the Kure Atoll State Wildlife Sanctuary in 1993. In June 1998 President William J. Clinton issued Executive Order 13089 establishing the U.S. Coral reef Task Force (CRTF), whose mission is to lead, coordinate, and strengthen U.S. government actions to better preserve and protect coral reef ecosystems (CRCP 2007). The creation of the CRTF and passage of the Coral Reef Conservation Act of 2000 has since 2001 made millions of dollars available annually for research and resource management activities in the NWHI, ushering in a new era of discovery. President Clinton also issued Executive Orders 13178 and 13196 in 2000 and 2001, creating the Northwestern Hawaiian Islands Coral Reef Ecosystem Reserve and initiating a process that was expected to redesignate the Reserve as a National Marine Sanctuary. Hawai`i Governor Linda Lingle established a marine refuge in 2005 and signed a law to prohibit all extractive uses in NWHI nearshore waters out to 4.8 km (3 mi) offshore, except at the federally managed Midway Atoll. Finally, on June 15, 2006, President George Bush issued Presidential Proclamation 8031, creating the Northwestern Hawaiian Islands Marine National Monument. This proclamation forms the largest fully protected marine conservation area in the world. The National Oceanic and Atmospheric Administration, U.S. Fish and Wildlife Service, and State of Hawai'i Department of Land and Natural Resources serve as co-trustee management agencies of this 360,000 km^2 tract of islands and surrounding ocean (NWHI MNM 2006). On March 2, 2007 the monument was renamed the Papahanaumokuakea Marine National Monument. The name "Papahanaumokuakea" is composed of four Hawaiian words: Papa, Hanau, Moku, and Akea. Papa can be considered the Hawaiian deity who is the equivalent of Mother Earth, "hanau" means to give birth, "moku" means island, and "akea" means a broad expanse (Nakaso 2007).

14.1.2 Island and Atoll Descriptions

The following section provides information about all of the atolls and islands in the NWHI, and some of the submerged banks, running in order from the northwest to the southeast down the chain. Table 14.1 contains basic information for each of the major islands, atolls, and shallow banks in the NWHI, including the name of an island or other feature, its location, land area and lagoon volume (if any), etc. Additional facts or descriptions of some of them are also included below.

Table 14.1 Characteristics of the islands, atolls, and some submerged banks in the NWHI, listed in order from the northwest down to the southeast. Note that most of the subaerially-exposed islands, sea stacks, and atolls are surrounded by extensive shallow banks. Island ages are from Clague (1996), with values in brackets from K-Ar dated basalt samples, and other ages estimated from geophysical calculations. Lagoon water volumes are from Hoeke et al. (2006).

Island, Atoll, or Bank	*Type of Feature*	*Longitude*	*Latitude*	*Age (Ma)*	*Emergent Land (km^2)*	*Reef Habitat <100 m (km^2)*	*Lagoon Vol. (10^4 m^3)*	*Bank Summit Depth (m)*
Kure Atoll	closed atoll	178° 19.55'	28° 25.28'	29.8	0.86	167	141,000	-
Nero Seamount	bank	177° 57.07'	27° 58.88'	29.1	0.00	17	-	68
Midway Atoll	closed atoll	177° 22.01'	28° 14.28'	[27.7], 28.7	1.42	223	213,000	-
Pearl & Hermes Atoll	closed atoll	175° 51.09'	27° 51.37'	[20.6], 26.8	0.36	1166	2,930,000	-
Lisianski Is. /Neva Shoal	open atoll	173° 58.12'	26° 4.23'	23.4	1.46	979	242,000	-
Pioneer Bank	bank	173° 25.58'	26° 0.71'	22.8	0.00	390	-	26
N. Hampton Seamounts	bank	172° 14.08'	25° 26.84'	[26.6], 21.4	0.00	430	-	5

Laysan Island	carbonate island	171° 44.14'	25° 46.13'	[19.9], 20.7	4.11	57	3,600	-
Maro Reef	open atoll	170° 38.34'	25° 30.2'	19.7	0.00	1508	611,000	-
Raita Bank	bank	169° 30.04'	25° 31.72'	17.9	0.00	650	-	16
Gardner Pinnacles	basalt sea stacks	167° 59.82'	25° 0.04'	[12.3], 15.8	0.02	1904	-	-
St. Rogatien Banks	banks	164° 7.26'	24° 20.0'	14.7	0.00	500	-	22
Brooks Banks	banks	166° 49.31'	24° 7.03'	[13.0], 13.6	0.00	320	-	20
French Frigate Shoals	open atoll*	166° 10.75'	23° 45.99'	12.3	0.23	733	1,910,000	-
Bank 66	bank	165° 49.37'	23° 51.86'	11.9	0.00	0	-	120
Necker Island	basalt island	164° 41.90'	23° 34.64'	[10.3], 10.6	0.21	1538	64.2	-
Twin Banks	bank	163° 3.78'	23° 13.08'	8.7, 8.3	0.00	95	-	53
Nihoa Island	basalt is.	161° 55.25'	23° 3.73'	[7.2], 7.3	0.82	246	-	-

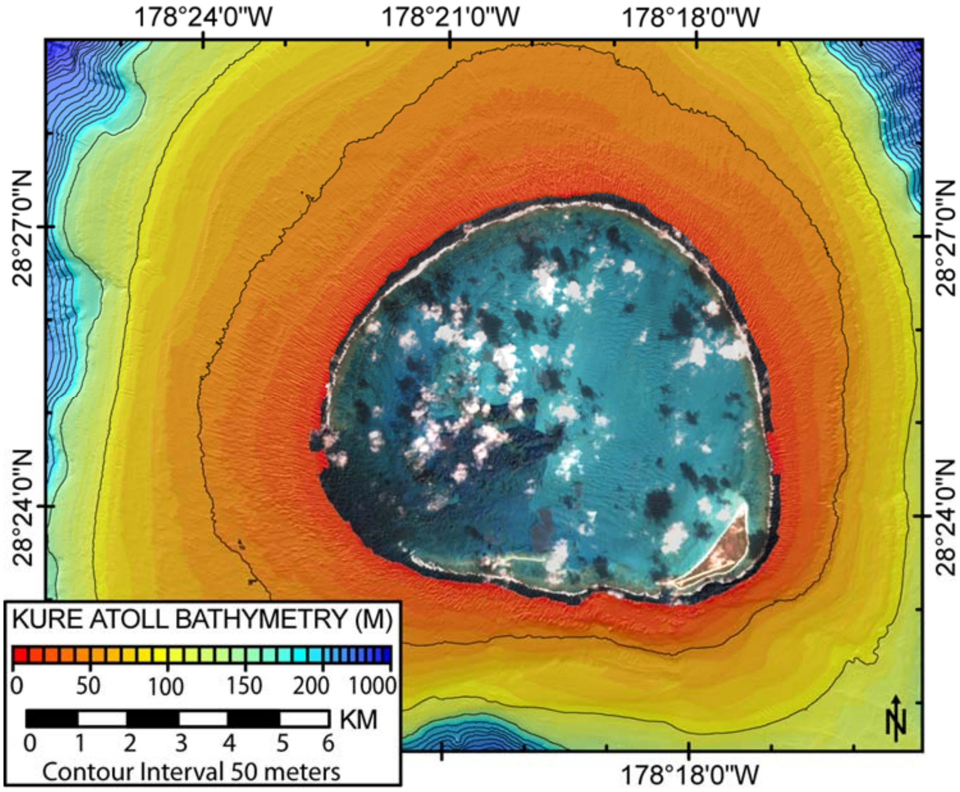

Figure 14.6 Kure Atoll's classic circular rim structure and Green Island in the southeastern corner of the lagoon are visible in this satellite image (© Space Imaging). Distinctive spur and groove morphology outside the atoll rim is evident in recently collected multibeam bathymetry from around many of the islands and atolls of the NWHI (http://www.soest.hawaii.edu/pibhmc/).

Kure Atoll (Figure 14.6) is the farthest north of all the atolls and islands in the NWHI and presumably the oldest, and has the distinction of being the northernmost atoll in the world. The circular-shaped atoll is about 10 km in diameter and includes two small islets, Sand and Green Islands. The latter was home to a Coast Guard-operated long range navigation (LORAN) station from the early 1960s until 1992, and was supported by the 1,200 m long runway that is still occasionally used today. Claimed by the Hawaiian Kingdom in 1886, Kure was placed under Naval jurisdiction by Executive Order in 1936 and then after World War II was inadvertently returned to the Territory of Hawai`i instead of the U.S. Department of the Interior as were most of the NWHI (Rauzon 2001). The atoll was designated as a state wildlife refuge under the control of the Hawai`i Department of Land and Natural Resources and is also now part of the Papahanaumokuakea Marine National Monument.

Midway Atoll includes three islands: Sand Island, Eastern Island, and the tiny and often changing Spit Islet, encircled by a roughly round atoll rim approximately 10 km in diameter. There is a dredged pass into the lagoon on its southern side that is navigable by ships and another pass on the western side. Sand and Eastern Islands have been extensively modified for commercial ventures and military use, as discussed earlier. Despite the long and often ecologically damaging modifications to the island, Midway has the world's largest nesting colony of Laysan Albatrosses (*Phoebastria immutabilis*), and almost a million birds of a range of species visit the atoll annually (Rauzon 2001). With a century of heavy traffic of humans and cargo, Midway is also home to over 200 invasive species of plants and numerous insects. Black rats had been introduced to Midway and had a significant and negative effect on the flora and fauna there, until they were finally removed in an eradication program in the 1990s. Nineteen species of cetaceans have been found in the waters around the NWHI, with Bottlenose and Spinner Dolphins (*Tursiops truncates* and *Stenella longirostris*, respectively) the most common and often found in Midway's lagoon (Rauzon 2001). With the departure of the military, monk seals have become a common sight on Midway beaches.

Pearl and Hermes Atoll is a roughly oval-shaped atoll approximately 34 km long and half that distance across, with seven small islets, including several with low vegetation. Much of the atoll's lagoon features a well developed and shallow reticulate reef structure nicknamed "the maze," which provides a challenge to small boat navigation (Figure 14.7). The atoll is named for the British whaling vessels *Pearl,* which ran aground there in 1822, and her sister ship *Hermes* that foundered when trying to aid the *Pearl* (Rauzon 2001). In 1928, a population of the black-lipped pearl oyster (*Pinctada margaritifera*) was discovered at Pearl and Hermes Atoll. For the next two years the shells were heavily harvested, mostly to be made into "mother of pearl" buttons, which devastated the oyster population and resulted in a ban on further harvesting (Keenan et al. 2006). A survey in 2003 reported that the current population apparently now has a sustained level of reproduction, but that the species has failed to recover to pre-exploitation levels despite more than 70 years of protection (Keenan et al. 2006). On the brighter side however, the atoll has the highest biomass of reef fish in the NWHI today (Friedlander and DeMartini 2002).

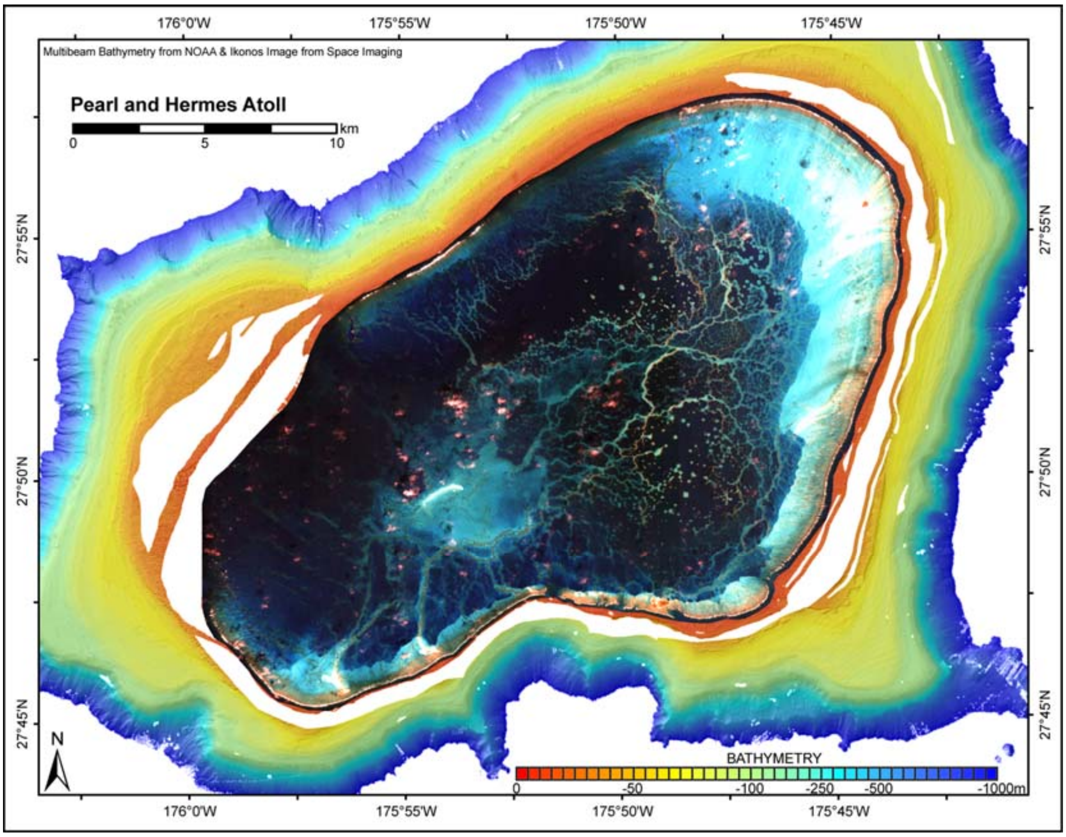

Figure 14.7 Pearl and Hermes Atoll: satellite image of Pearl and Hermes Atoll (© Space Imaging), overlain on high resolution multibeam bathymetry (http://www.soest.hawaii.edu/pibhmc/). The extensive reticulate reef structure evident within the lagoon at Pearl and Hermes is the most well-developed and clearly visible example of this morphology within the NWHI, but it is unclear why this morphology develops.

Lisianski, one of the larger islands in the NWHI, features a 12 m high sand dune on its northern side, an expanse of dry grass, and a few low shrubs. Numerous seabirds are now found on the island, although more than a million birds were harvested from Lisianski for the feather trade, the introduction of mice, and the release of rabbits destroyed the island's ecology for a time (Rauzon 2001). The island is surrounded by an open atoll called Neva Shoals, which lacks a distinct atoll rim. It does, however, contain a network of reticulate and linear reefs which offer protection to the waters within them and are home to what has been described as one of the more scenic "coral gardens" in the entire NWHI (Maragos and Gulko 2002).

Laysan Island is the only low coral island in the NWHI that is not associated with what can be classified as an atoll today, although it may have been during earlier periods. A shallow saline lake covers approximately 0.4 km^2 of the island's interior and serves as a food, water, and rest stop for a wide variety of birds and is a critical habitat for one of the two remaining populations of the endangered Laysan Duck (*Anas laysanensis*) (Maragos and Gulko 2002; Rauzon 2001). Laysan Island is described by many as the "crown jewel" of the NWHI, but suffered from severe exploitation in the late 1800s and early in the 20th century. Hundreds of thousands of tons of guano were mined from the island, and activities of the miners living and working on the island had serious impacts on the island's ecosystem. Many thousands of albatross eggs were harvested from the island, and feather poachers killed hundreds of thousands of birds as well. Rabbits introduced to Laysan Island as potential livestock for a meat canning business rapidly destroyed practically all of the island's vegetation, forever altering its ecology and facilitating widespread erosion (Rauzon 2001). The combined impact of these stresses led to the extirpation of 26 plant species and several bird species. The bird population fell from 10 million in 1903 to about 30,000 by 1923 (Maragos and Gulko 2002; Olson 1996). However, almost a century of wildlife protection and years of effort by the U.S. Fish and Wildlife Service to remove alien species and restore native ones are paying off, and there are many signs that the island is recovering (Maragos and Gulko 2002).

Maro Reef is, similar to Neva Shoals, an open atoll which presently lacks the classical circular atoll rim structure and is composed instead of linear and reticulate reef structure. This type of atoll structure is not reported from any other location in the world. The only emergent land at Maro Reef consists of a few large blocks of reef rock, but at 1,508 km^2, its potential coral reef habitat shallower than 100 m is the second largest in the NWHI. Many of the reef structures at Maro are narrow and unconsolidated in places, and gaps in the reef structure enable wave energy to penetrate into the lagoonal waters, keeping fine sediments suspended in the water column most of the time. Despite the turbidity, Maro Reef is one of the most fertile marine areas in the Hawaiian Archipelago and was formerly one of the areas targeted by a commercial lobster fishery. It has a high diversity of both reef fish and corals, very high coral cover in some areas, and other areas dominated by crustose coralline algae (Maragos and Gulko 2002; Maragos et al. 2004; Rauzon 2001).

Gardner Pinnacles consists of two steep basalt sea stacks, the largest of which is approximately 50 m tall and 180 m long, the last vestiges of basalt above sea level moving to the northwest up the chain (Figure 14.8). Marine habitats shallower than a depth of 20 m are restricted to the immediate vicinity of the stacks themselves, but Gardner Pinnacles has 1,904 km^2 of habitat shallower than 100 m, the most of any island atoll or bank in the NWHI. The shallow shelves around the sea stacks are exposed to wave energy from all directions, so there is fairly low coral cover on them, but markedly more on the southwestern (leeward side) of the stack, and more than at Necker and Nihoa Islands (Maragos et al. 2004). Reef fish diversity is high, presumably due to the large shelf area, and the area formerly provided a significant portion of the commercial lobster catch in the NWHI. Gardner Pinnacles and Necker Island host relatively large concentrations of the Giant Opihi (*Cellana talcosa*), the largest of the Hawaiian limpets, which requires a basalt substrate. Prized as an abalone-like seafood delicacy, the species has been severely overfished in the MHI (Maragos and Gulko 2002).

Figure 14.8 Gardner Pinnacles, the last (most northwesterly) vestige of basalt above sea level in the Hawaiian Archipelago. Photograph by Jean Kenyon.

French Frigate Shoals is the most southerly atoll in the Hawaiian Islands. It is a large open atoll and features a well-developed rim only along the northeastern half, with reticulate reef prevalent inside. The atoll features a basalt sea stack, La Perouse Pinnacle, Tern and East Islands, and eight islets, some of which have mostly eroded away. The continued loss of beach area at French Frigate Shoals has potentially serious consequences for the monk seals and green sea turtles that breed and nest on them and will be discussed in detail later. Tern Island was enlarged by dredging and filling by the U.S. Navy just prior to World War II and features an airstrip that is still in use. The U.S. Coast Guard operated a

LORAN station on the island that was abandoned in 1979, but the USFWS operates a year-round field station there now. Magnificent stands of *Acropora* table corals are found in the lagoon (Figure 14.9) and are more common at French Frigate than at any other location in the archipelago (Maragos et al. 2004). They are believed to have originated from Johnston Atoll, 865 km to the southwest, along with a number of other species, along an occasionally active oceanographic transport corridor from Johnston to French Frigate Shoals. This and another corridor connecting Johnston with islands in the vicinity of Kauai in the MHI are believed to be related to the subtropical countercurrent and the Hawaiian Lee countercurrent (Kobayashi 2006; Maragos et al. 2004).

Figure 14.9 One of many luxuriant stands of *Acropora* table corals found at French Frigate Shoals. Photograph by Jean Kenyon.

Necker Island is a small, steep, and hooked-shaped ridge of basalt with a summit 84 m above sea level, surrounded by the second largest marine habitat shallower than 100 m in the NWHI. The island supports only five species of flowering plants, but 60,000 seabirds of 16 species roost there, and endangered Hawaiian monk seals are known to haul out on the island and forage on the marine terraces there (Rauzon 2001). The broad shelves off Necker have also been commercial fishing grounds for lobster and bottomfish.

Nihoa, a small basalt island of 0.6 sq. km with a summit 275 m above sea level, is the only area in the NWHI known to have been permanently settled by native Hawaiians prior to western contact. The lack of protection from large waves makes it difficult for corals and other species to survive. In shallow waters, the substrate around Nihoa is composed mostly of heavily eroded and wave scoured basalt, with live coral reef limited to depths greater than about 12 m. The surrounding shelf is one of the smaller ones in the NWHI. Heavily exposed to wave energy, stony corals are less abundant and diverse at Nihoa than at atolls and islands in the middle and northern end of the NWHI (Maragos et al. 2004). However, the island does host one of the highest reef fish biomass densities of any island in the NWHI (Friedlander and DeMartini 2002). The area was sufficiently productive to support the ancient Hawaiian community that lived there and, presumably, relied on seafood for protein to supplement their diet of sweet potato. Spared the ravages of guano miners, Nihoa has the most intact coastal ecosystem left in Hawaii. For example, at least 40 of the terrestrial insect, spider, and crustacean species on Nihoa are endemic to the island, and six species of land snails, extinct in the MHI, are still found on Nihoa. The island hosts half a million seabirds of a number of species, including 17 that breed on Nihoa alone (Rauzon 2001). The rats, and many of the invasive insects and plants that have displaced native species on other islands with greater natural resources, have not become established on Nihoa, leaving us with a glimpse of how different the ecology of the NWHI may have been prior to extensive human exploitation. It also highlights the threat of how quickly the remaining ecosystems, marine and terrestrial, can be disrupted in the face of invasive species.

14.1.3 Climate and Oceanography

The NWHI experience high surface gravity wave events which are arguably among the highest of any tropical or subtropical island archipelago. The vigorous Aleutian Low atmospheric pressure system, large scale of the North Pacific Ocean, and the NWHI's central location all combine to create exceptionally high waves, often with long periods, in the region. Extreme wave events (deep water wave heights in excess of 7 m) occur several times in an average year; 4-6 m heights occur on the order of 10 or more times a year (Figure 14.10). Associated wave periods may be as long as 25 seconds, but are more typically 8-18 seconds (Figure 14.11). These episodes are generated from two primary sources, including the aforementioned Aleutian Low, which are mid-latitude cyclones spawned as waves on the polar front (Graham and Diaz 2001; Bromirski et al. 2005). Extreme waves are also occasionally generated from subtropical cyclones known as Kona Lows, which generally form in the vicinity of the NWHI themselves (Caruso and Businger 2006). Ocean waves associated with the Aleutian Low tend to be long period swell from the northwest quadrant. Kona Lows generate extreme waves much less frequently, and these waves tend to be of shorter period and from a more westerly or southwesterly direction. Wave events from both of these mesoscale weather systems are seasonal, with almost all extreme episodes occurring between October and April. These weather systems sometimes bring strong winds (15-30+ m/s (30-60+ knots)) and most of what little rain occurs in the NWHI (Rauzon 2001). In between episodes, easterly trade winds associated with the North Pacific Subtropical High tend to dominate, particularly during the boreal summer. These are the modal conditions, and typically bring waves with 1-3 m wave heights and 7-11 second periods from the east (Figures 14.10 and 14.11). Atmospheric pressure gradients in the NWHI tend to be less than in the MHI during summer, so the resulting trade winds are often somewhat weaker, particularly towards the northern end of the chain. Long period southern-hemisphere swell, which can be significant in the MHI, generally decreases moving north and west. Kure, Midway, and Pearl and Hermes (the northern atolls) experience very little of this swell; it is mostly absent in the wave climatology shown in Figure 14.11 for Midway Atoll.

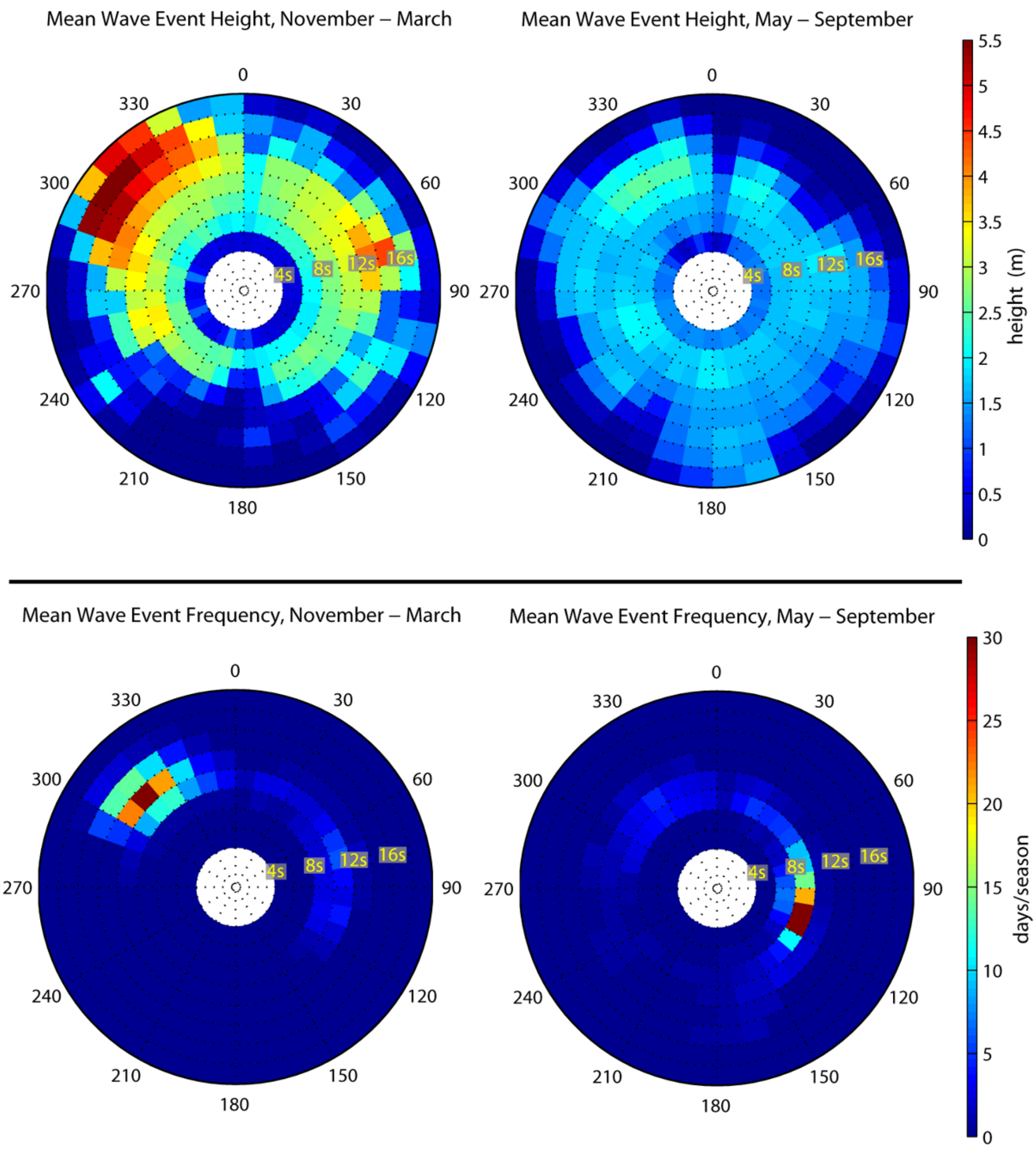

Figure 14.10 Climatological monthly mean, standard deviation, and mean monthly minimum and maximum wave heights derived from NOAA Wave Watch III computations at 6 hour time steps at Midway Atoll from January 1997 through December 2006.

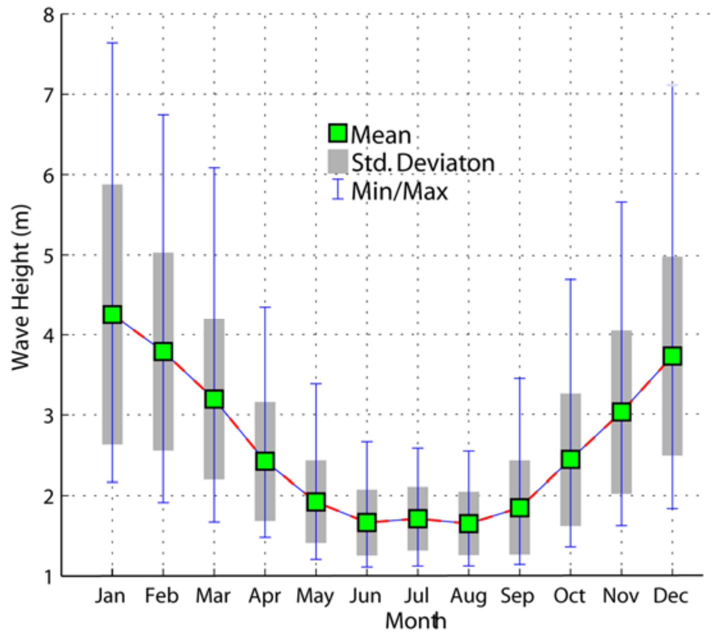

Figure 14.11 Seasonal wave height, direction, and period event climatology derived from NOAA Wave Watch III computations at 6 hour time steps at Midway Atoll from January 1997 to December 2006. Upper panel (a) represents mean seasonal wave event height in given directional and period bin (e.g., between November and March an average wave event with 16-18 second period from 300° has a height of 5.5 m). Lower panel (b) represents mean frequency (likelihood) of occurrence in days per season (e.g., between May and September, 1.5 m wave with 8-10 second periods from 100° occur, on average, 30 or more days in a season).

In addition to the large seasonal change between cyclone frequency (high in winter) and trade wind conditions (predominantly in summer), the mesoscale and synoptic weather features discussed above exhibit great variability in intensity, frequency, mean path, and location over interannual to decadal time scales. At interannual time scales, the Aleutian Low tends to be more intense and track farther to the south (closer to the NWHI) during positive ENSO phase (El Niño) periods (Bromirski et al. 2005). This brings higher winds and larger waves to the NWHI region than are typical in negative ENSO-phase (La Niña) years (Rooney et al. 2004; Wang and Swail 2001). There is also evidence that the mean intensity of the Aleutian Low has increased in the last several decades. Given the currently short span of human observations in the region it is difficult to determine if anthropogenic climate change is a factor, or if it reflects decadal time scale oscillations (Graham and Diaz 2001).

The Pacific Decadal Oscillation (PDO) can be described as an ENSO-like pattern of Pacific climate variability with each phase lasting perhaps 20-30 years.

A key indicator of PDO warm (positive) phases is decreased pressure in the central North Pacific, which is generally reflected by increased number of cyclones on 20-50 year timescales (Bond and Harrison 2000). Hurricanes occasionally strike the Hawaiian Archipelago, usually during summer months, and are significantly more frequent during El Niño periods and warm phases of the PDO. However, even during these periods, hurricane tracks rarely reach as far west and north as the NWHI (Chu 2002). There are some indications that both positive PDO phases and positive ENSO phases tend to weaken the North Pacific Subtropical High atmospheric pressure system and perhaps shift it southward, bringing lighter trades to the NWHI, but there has been little research on the subject (Bond and Harrison 2000; Hoeke et al. 2006).

The location and variability of these mesoscale and synoptic weather patterns are important in defining oceanographic structure and its variability. The ocean, in turn, influences the atmosphere through multiple feedback mechanisms, creating a coupled system. The boundary between the oligotrophic (low in nutrients and high in dissolved oxygen) surface waters of the North Pacific Subtropical Gyre associated with the North Pacific Subtropical High, and the nutrient-rich surface waters of the North Pacific Subpolar Gyre, is often termed the "subtropical front." It is frequently defined as the surface expression (outcropping) of the 17°C isotherm and/or 0.2 mg/m^3 surface chlorophyll concentration (Leonard et al. 2001; Polovina et al. 2001). During the winter, this front is typically located at about 30–35°N latitude and in the summer at about 40–45°N (Polovina et al. 2001). However, subsurface expressions of the front as shallow as 30 m have been recorded as far south as 28°N (Leonard et al. 2001). The location of this front is likely to exert a significant influence on the ecology of the NWHI. Evidence suggests that during southward extensions of the front, waters around the northern atolls at ~28°N are far less oligotrophic than they, or waters further south in the archipelago, typically are. This front migrates significant distances on interannual and decadal time scales, in concert with atmospheric fluctuations; positive ENSO appears to correlate to southern extensions of the front (Leonard et al. 2001). There is evidence that climatic conditions favoring southern extensions of the subtropical front have large decadal time-scale impacts on the ecosystem. Polovina et al. (1994) noted biomass changes on the order of 30-50% associated with decadal climate indices; it appears that this is at least partially due to fluctuations in nutrient enrichment associated with the migration of the subtropical front. Similarly, Antonelis et al. (2003) suggest that the body condition of weaned Hawaiian monk seal pups may be improved during El Niño events due to the enhanced availability of prey species. Besides impacting nutrient availability, the location of this front is associated with the concentration of marine debris (Kubota 1994), which has been shown to most severely impact the northern atolls (Boland et al. 2006; Dameron et al. 2007; Donohue et al. 2000).

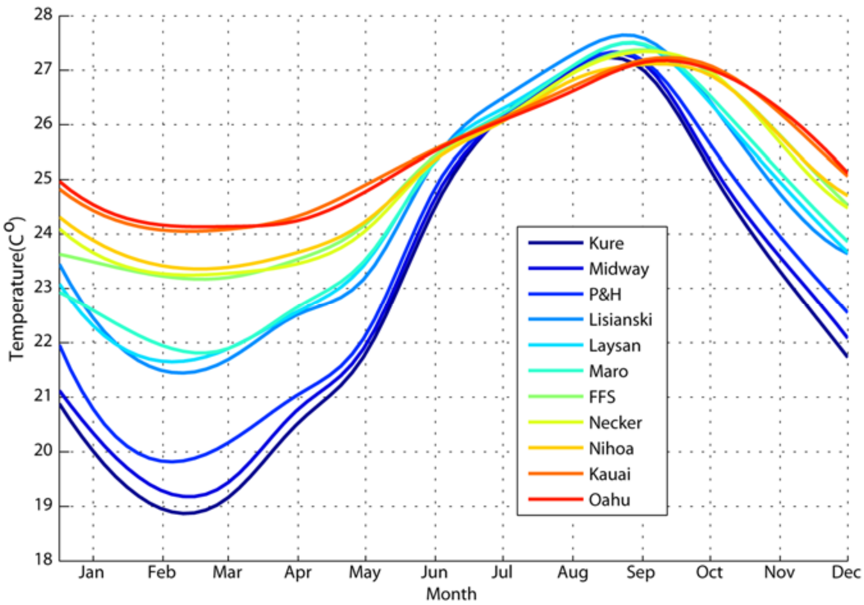

Figure 14.12 Interpolated monthly sea surface temperature climatology for selected Hawaiian Archipelago locations, derived from Pathfinder SST (Vazquez et al. 2002).

During the winter, the NWHI experience much cooler sea surface temperatures (SSTs) relative to the MHI, due to the proximity of the subtropical front and enhanced vertical mixing of surface waters by increased winds and waves. During the summer, however, NWHI surface waters tend to become highly stratified, frequently causing higher SSTs in the northern and central portions of the NWHI than are found in the MHI (Figure 14.12). This is attributed partially to the summertime position of the North Pacific Subtropical High. Large atmospheric pressure gradients south of the high generate strong trade winds and tend to keep SSTs cooler through wind mixing in the MHI. Further north towards the mean center of the high, weaker pressure gradients lead to lighter trade winds which tend to increase stratification and elevate SSTs. Climatological observations indicate that these processes are common.

These processes contributed to mass coral bleaching events which occurred in the NWHI during the summers of 2002 and 2004 (Hoeke et al. 2006). The northern atolls were particularly affected (up to 90% bleached coral in some areas), and severity decreased moving southeast down the chain (Kenyon and Brainard 2006; Kenyon et al. 2006). Figure 14.13 shows that SSTs were anomalously warm during these two events, which were among the highest in an extended record at Midway. French Frigate Shoals and Oahu remained much cooler. Maximum summertime SSTs at Oahu, and the rest of the MHI, are generally cooler than the higher latitude northern atolls of the NWHI. In addition to large-scale oceanographic regimes favoring coral bleaching in the northern NWHI, the large relatively sheltered lagoons and backreef areas of the northern atolls enhance further stratification and elevated localized SSTs. This contributed to the significantly greater coral bleaching at the northern atolls documented in 2002 and 2004 (Hoeke et al. 2006; Kenyon and Brainard 2006).

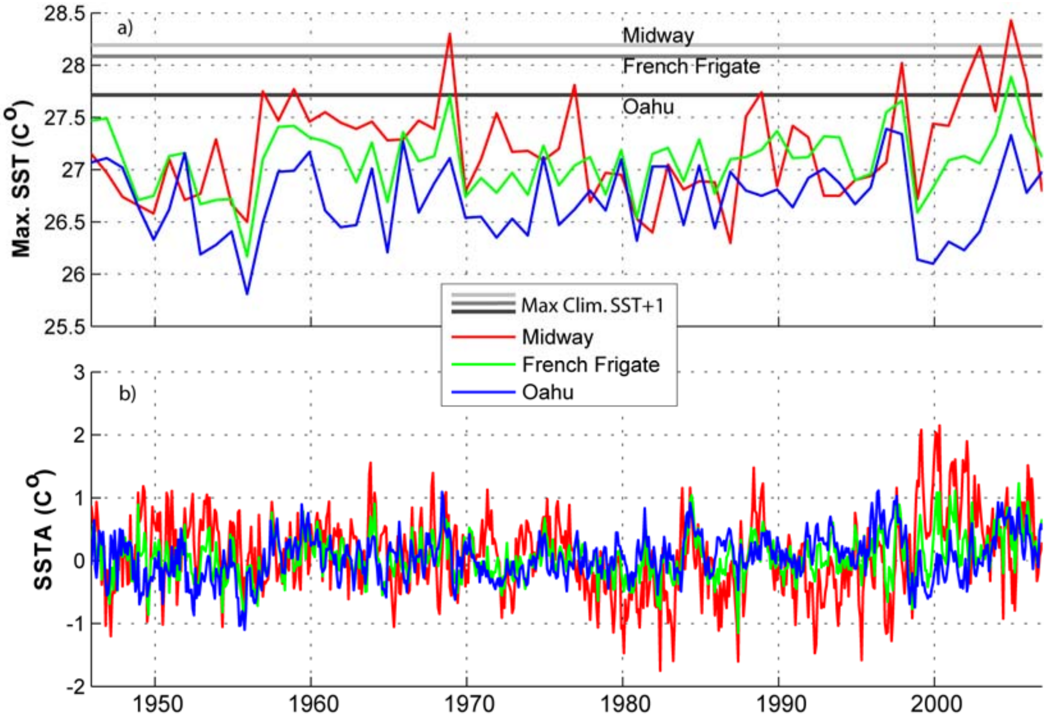

Figure 14.13 Extended-reconstructed sea surface temperature (SST) and sea surface temperature anomaly (SSTA) at Midway, French Frigate Shoals, and Oahu. Upper panel (a) represents maximum monthly SST at each location; grey bar are maximum monthly climatological SST + 1°C, often used as an indication of bleaching conditions (Wellington et al. 2001). Lower panel (b) represents SSTA; greater inter-annual to decadal variability in SSTA at Midway compared to Oahu is evident.

Jokiel and Brown (2004) noted increasing trends in SST over the 1981-2004 period in the Hawaiian Archipelago, particularly at Midway Atoll. This trend is not as apparent in longer time series (Figure 14.13). An extreme SST event at Midway, similar to 2002 and 2004, occurred in 1969 and was followed by several decades of cooler temperatures. These episodes and trends appear to be related to the PDO signal, but large uncertainties exist in the SST records before the advent of satellite SST measurements in 1981. Links between summertime SST in the NWHI, long-term SST trends, the mean position and intensity of the North Pacific Subtropical High, and major climate indices (e.g., PDO and ENSO) have not been well studied.

The information above, drawn from many sources, suggests that the northern atolls of Kure, Midway, and Pearl and Hermes are oceanographically distinct from the rest of the archipelago. The reefs and banks south of Pearl and Hermes in the NWHI generally experience conditions that are increasingly similar to those of Kauai and Oahu the farther to the southeast they are located . The northern atolls however, experience much colder water temperatures, more vigorous waves and winds, and sometimes greatly enhanced nutrient enrichment in the winter. In the summer, they tend to experience lighter winds and higher SSTs relative to the rest of the Hawaiian Archipelago. Two documented manifestations of these differences are the high levels of marine debris recruitment (Boland et al. 2006; Dameron et al. 2007) and the severity of coral bleaching in the northern atolls (Kenyon and Brainard 2006; Kenyon et al. 2006). The reefs and banks in the vicinity of Lisianski and Laysan appear to be a transition area between the oceanographic regimes of the northern atolls and the central-south parts of the chain. The observations discussed above represent broad generalizations: seasonal and interannual variations are large and often deviate from these climatological means. Changes imposed by climate variability and change remain largely unknown and are worthy areas of study.

14.2 Pre-Holocene Reef History

14.2.1 Age and Evolution of Hawaiian Volcanoes

The Hawaiian-Emperor chain is anchored in the central Pacific basin at 19^{o}N, the locus of current volcanism (Figure 14.14). It includes at least 129 massive shield volcanoes that formed over the past 85 Myr, with volcano ages generally decreasing in age towards the southeast (Jackson et al. 1975; Clague 1996). The early Hawaiians were the first to recognize this age trend, which was recorded in their oral tradition of the fire goddess Pele. She was reported to have migrated with her fire southward along the island chain (Westerveldt 1916) causing successively younger eruptions to the south. Early western explorers to Hawai`i also noted the apparent decreasing age of the islands to the south (Dana 1891). The overall age progression of the islands (Figures 14.1 and 14.14) has been confirmed in several studies using radiometric isotopes (Clague and Dalrymple 1987; Garcia et al. 1987), although major gaps remain in our knowledge of the formation time of NWHI volcanoes because suitable samples for radiometric dating are difficult to obtain. It has been found, however, that the frequency of volcano formation has increased over time while the spacing between them has decreased, as shown in Table 14.2. The islands at the younger end of the chain are also significantly higher than those that formed earlier (Clague 1996).

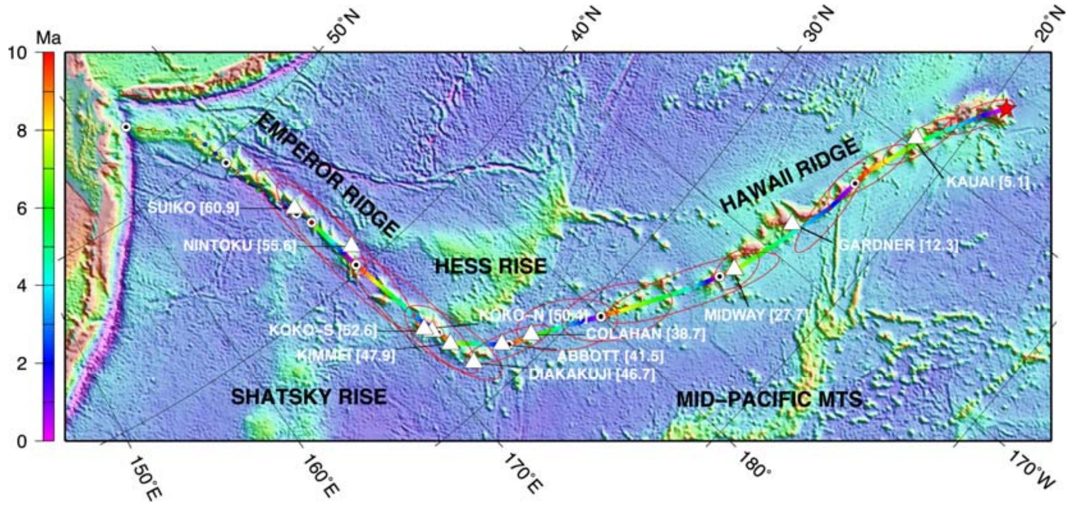

Figure 14.14 Geometry of the Hawaii-Emperor seamount chain. The major bend in the chain has now been dated to 47–50 Ma (Chron 21–22) based on ages (in white) from *Sharp and Clague* (2006) and Clague (1996); Nintoku age taken from *Tarduno et al.* (2003). Predicted hotspot chain track (rainbow line) from the absolute Pacific plate motion model of *Wessel et al.* (2006) shows ages modulo 10; dotted circles indicate start of each 10 Myr section. Hotspot location is located near Kilauea (star). Red ellipses indicate the uncertainty of the reconstruction at selected times (red crosses).

Table 14.2 Frequency and spacing of volcanoes in the Hawaiian-Emperor chain, from Clague (1996). The Hawaiian Ridge includes the NWHI and the seamounts between Kure and the Emperor Chain.

	Number of volcanoes per million years	Spacing between volcanoes (km)
Emperor Chain	1.1	57
Hawaiian Ridge	1.7	45
Main Hawaiian Islands	4.0	30

Various evolutionary sequences have been proposed for the growth of Hawaiian volcanoes starting with Stearns (1946). A current popular scheme divides the growth period into four major stages: preshield, shield, postshield, and rejuvenation (Figure 14.15). The first three stages are responsible for building a massive shield volcano that may reach a maximum thickness of 13 km and a volume of up to 80,000 km^3 (Mauna Loa, the largest volcano on Earth; Lipman 1995). The preshield stage lasts ~250,000 to 300,000 years (Guillou et al. 1997) and is distinct from the shield in producing alkalic magmas (i.e., magmas containing a relatively high percentage of sodium and potassium alkali) (Moore et al. 1982; Garcia et al. 1995). Although observed only at Lō`ihi and possibly Kīlauea volcanoes (Lipman et al. 2003), this stage is thought to be at the core of all Hawaiian volcanoes (Clague and Dalrymple 1987). Loihi Seamount, the youngest volcano in the Hawaiian chain, rises more than 3000 meters above the floor of the Pacific Ocean and is located approximately 40 km south of Kīlauea. Volumetrically, the preshield stage is minor, forming about 1-2 volume percent of a typical overall Hawaiian volcano (Fig. 14.16), although it may create an edifice that is 4-5 km tall (Garcia et al. 2006).

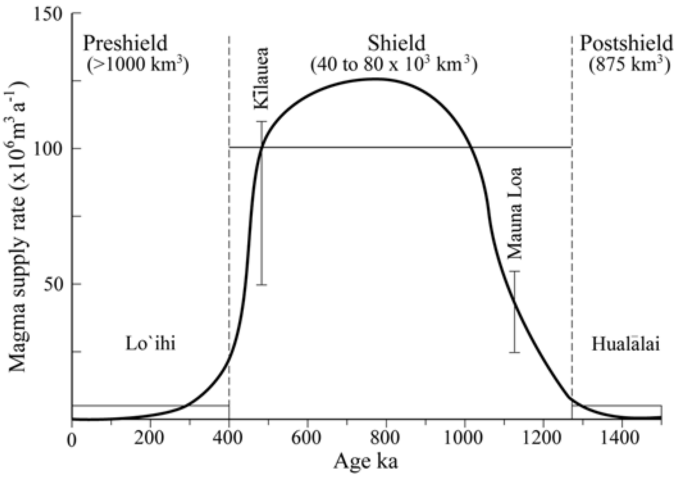

Figure 14.15 Growth history model for a typical Hawaiian shield volcano. This composite model is based on volume estimates for each stage (large boxes). Magma supply estimates (vertical bars) are given for Kīlauea (early shield stage; Pietruszka and Garcia, 1999) and Mauna Loa (late shield stage; Wanless et al., 2006). The preshield stage is represented by Loihi (Garcia et al. 2006) and the postshield by Hualalai (Moore et al., 1987) volcanoes.

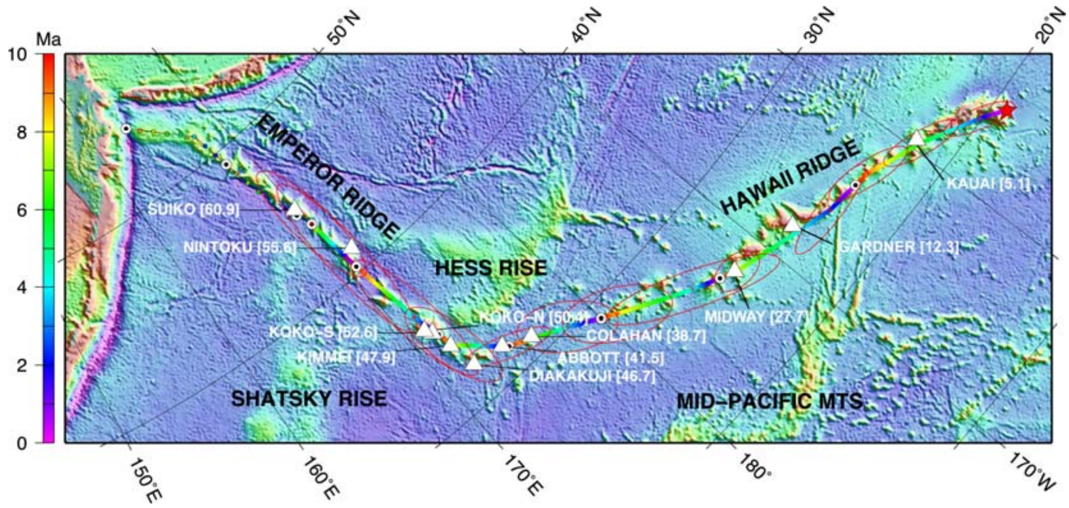

Figure 14.16 Cartoon cross section of a composite Hawaiian volcano at the end of the postshield stage showing rock type proportions. The preshield stage is represented by Lō`ihi alkalic lavas, comprising 1-2 volume % of the shield. The shield stage is based on Mauna Loa and is composed of tholeiites that form the bulk of the volcano (~98%). The postshield stage forms a cap on the shield, comprising up to 1% of the volcano, based on Mauna Kea volcano (Frey et al., 1990). Note the section is two times vertically exaggerated.

As the volcano moves closer to the center of the hotspot and its source experiences higher temperatures and degrees of partially melting, the magma composition switches to tholeiitic (containing less sodium and potassium at similar concentrations of silica compared to alkali basalt) and volcanism becomes more voluminous (Garcia et al. 1995; Guillou et al. 1997). Depending on whether the volcano forms on the flanks of a pre-existing volcano (like most Hawaiian volcanoes, e.g., Necker), or was isolated (e.g., Kure), the volcano emerges above sea level perhaps 50,000-300,000 years after the preshield, forming a subaerial shield volcano. Coral reefs and other aquatic life are destroyed or their growth slowed during this emergence stage as molten rock reacts with seawater in a shallow pressure environment creating fragmental debris (e.g., Moore and Chadwick 1995). However, eruption rates are high during this stage (Figure 14.15) and a stable island is quickly formed as growth rates exceed rates of marine erosion and subsidence (Garcia et al. 2007). Subaerial flows on the new island are a mixture of pahoehoe and a‘a, with a‘a becoming more abundant as the island grows in size (Garcia et al., 2007). After another ~100,000 years, the growing volcano may reach the size of Kīlauea volcano (Quane et al. 2000). Vigorous activity persists for another ~600,000 years creating giant shield volcanoes. Where several shield volcanoes are clustered together (e.g., the French Frigate Shoals area), large islands may form. These islands are subject to giant landslides that may remove large sections of the volcano (e.g., up to 40% for Ko`olau volcano on the island on Oahu; Garcia et al. 2006). Landslides may occur at any stage during the volcano's growth or afterwards, although the largest slides tend to occur during the shield stage.

By the end of the shield-building stage, a Hawaiian volcano is about 1.25 Myr old and has drifted off the center of the hotspot. As it enters the post-shield stage, mantle melting temperatures progressively decrease causing magma compositions to gradually switch back to alkalic (Feigenson et al. 1983; Frey et al. 1990). The volcano is now subsiding at a faster rate (~2.5 mm/year; Moore and Chadwick 1995) than it is growing and the surface area of the volcano shrinks. A record of the volcano's maximum shoreline extent is recorded as an inflection in its slope (Moore and Campbell 1987). The submarine slope of these volcanoes is steeper, generally >15^{o}, than the subaerial slopes, typically 3-7^{o}, with steeper slopes on volcanoes that have undergone postshield volcanism (Mark and Moore 1987). The submerged subaerial lavas form a shelf around the volcano. A rapid decline in eruption rate occurs over the next 250,000 years, which is accompanied by an abrupt shift to more fractionated, more viscous and less dense lava compositions (hawaiites to trachytes; Macdonald et al. 1983), as magmas pond at greater depths (~30 km) before eruption (Frey et al. 1990). These late stage lavas are responsible for the somewhat steeper slopes than on shield volcanoes, although these lavas form only a thin veneer (Figure 14.16). The volcano dies after about 1.5 million years of growth (Figure 14.15), following which it continues to subside and marine erosion shrinks the size of the island.

Many, but not all, of Hawaiian volcanoes experience a period of renewed volcanism 0.6 to 2.0 Myr after the end of post-shield (Tagami et al. 2003). The lavas produced during this 'rejuvenated' stage are generally strongly alkalic and tend to be explosive where they intersect groundwater or coral reefs (Winchell 1947; Walker 1990). Rejuvenated volcanism may last briefly (over several thousand years) producing a few vents and flows. Various models have been proposed to explain the origin of rejuvenated volcanism. One of the two currently favored models suggests that a zone of secondary melting 100 to 300 km northwest of the hotspot forms as the plume of magma is deflected laterally and rises (Ribe and Christensen, 1999). The other model invokes flexural uplift associated with the rapid subsidence in the area of rapid volcano growth (e.g., Bianco et al., 2005), but neither model satisfactorily explains all aspects of rejuvenation volcanism.

It should be noted that not all Hawaiian volcanoes follow this sequence, as some lack post-shield and or rejuvenated stages. Following rejuvenated volcanism, if it occurred, the volcano continues to be eroded by the ocean and to subside under the weight of their massive shields. Eventually, all Hawaiian volcanoes will disappear beneath the waves forming seamounts. The tops of the once high-standing Emperor volcanoes are now more than a kilometer below sea level. Such will be the fate of the NWHI.

14.2.2 Dynamics of the Pacific Plate and Hawaiian Hotspot

14.2.2.1 Horizontal Displacement due to Plate Motion

Tuzo Wilson (1963) hypothesized that the distinctive linear shape of the Hawaiian Island-Emperor Seamounts (Figure 14.14) chain resulted from the Pacific plate moving over a deep, stationary hotspot in the mantle, located beneath the present-day position of the Island of Hawai`i (Figure 14.17). He further suggested that continuing plate movement eventually carries the island beyond the hotspot, cutting it off from the magma source, and volcanism ceases. As one island volcano becomes extinct, another develops over the hotspot, and the cycle is repeated. This process of volcano growth and death, over many millions of years, has left a long trail of volcanic islands and seamounts across the Pacific Ocean floor.

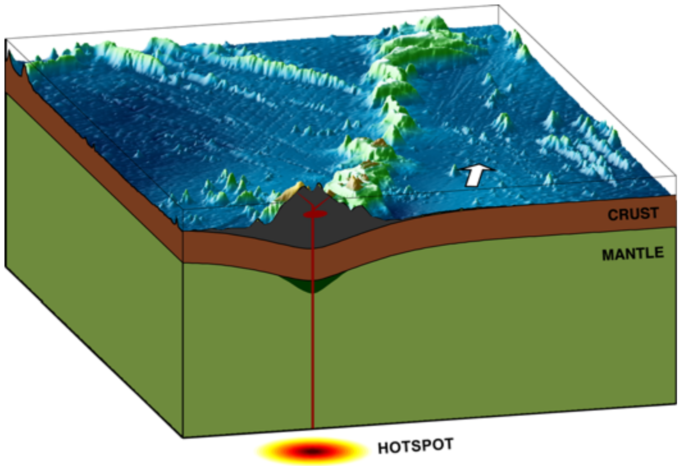

Figure 14.17 Formation of the Hawaii-Emperor seamount chain over the Hawai`i hotspot. Given the thick and strong lithosphere near Hawai`i (~90 Myr old), individual seamounts can grow very tall and breach sea level to form oceanic islands. The large volcanic piles deform the lithosphere, which responds by flexure. The plume beneath the plate feeds the active volcanoes by a network of feeder dikes; some magma may pond beneath the crust as well (Watts and ten Brink 1989). As the plate motion carries the volcanoes away from the hotspot (arrow indicates current direction of motion), they cease to be active and form a linear seamount/island chain.

One of the most characteristic features of the Hawaiian chain is the prominent bend near longitude 172˚E, named the Hawaii-Emperor Bend (HEB). Since the suggestion by Wilson (1963) this feature has been attributed to a ~60˚ change in direction of Pacific plate motion over a fixed hotspot in the mantle beneath Hawai`i (Morgan 1971). A lingering problem, however, was posed by the age of the bend, initially dated to 43 Ma (Dalrymple et al. 1987). Intuitively, such a large change in the motion of the dominant Pacific plate should have left clear and unequivocal evidence of contemporaneous tectonic and magmatic events at the plate boundary; however, careful examination of the record failed to find the expected correlation (Atwater 1989; Norton 1995). Furthermore, rock samples recovered by deep-sea drilling from several Emperor seamounts revealed a frozenin paleomagnetic field that suggested they were formed at a latitude significantly further north (5–10˚) than that of present-day location of Hawai`i (Kono 1980; Tarduno and Cottrell, 1997). Finally, efforts to project the absolute plate motion of Africa, via the global plate circuit, into the Pacific failed to reproduce the characteristic bend at 43 Ma (Cande et al. 1995; Raymond et al. 2000). These concerns gave impetus to alternative models in which the plume responsible for the volcanism was drifting in the mantle "wind" (Steinberger 2000; Steinberger and O'Connell 1998). Such models could simultaneously fit the changing latitude of the hotspot (constrained by paleomagnetics) and the geometry and age-progression of the seamount chain. Some researchers went as far as to conclude that no change in Pacific plate motion was needed at all to generate the HEB. Since the trail reflects the vector sum of plate and plume motion, it could be completely explained by a rapid slowdown in the southward motion of the plume while the plate motion remained unchanged in direction and magnitude (Tarduno et al. 2003).

The reconciliation of absolute plate motion models inferred from the Indian, Atlantic, and the Pacific Oceans requires their propagation via the global plate circuit (Acton and Gordon 1994). Due to incomplete knowledge of the history of all relative plate motion changes between conjugate plate pairs, the projection of the African absolute plate motion into the Pacific is subject to uncertainties that are difficult to quantify. By choosing a slightly different plate circuit for connecting the Pacific to Australia via the Lord Howe Rise, Steinberger et al. (2004) were able to show that the HEB did appear to have a plate motion component and could not simply be due to plume drift. Most recently, an effort to redo the dating of the rock samples taken from around the Hawaii-Emperor Bend region resulted in the startling discovery that the HEB is considerably older than previously thought. Sharp and Clague (2006) reported that the rocks around the bend were formed during the 47–49 Ma interval (Chron 21–22) and, by allowing for 1–2 Myr of construction time, that the bend itself might have formed closer to 50 Ma – fully 7 Myr earlier than the conventional wisdom. These new dates undermine many of the previous conclusions about the lack of correlation between the bend and plate boundary processes since Chron 21–22 is known to have been an exceedingly active tectonic period in the Pacific and elsewhere (Cande and Kent 1995; Rona and Richardson 1978). Sharp and Clague (2006) also argued that the details of the age progression as we approach the bend from the north make it very unlikely that the plume was moving during the formation of the bend, thus strengthening the original explanation (purely a plate motion change over a stationary hotspot) for the origin of the HEB.

Absolute plate motion studies have revealed much of interest in the last decade and new discoveries are happening at a fast pace. Recently, Whittaker and Müller (2006) made a preliminary announcement that they had identified tectonic evidence for a similar bend in plate motion between Australia and Antarctica that appears to be contemporaneous with the Hawaii-Emperor bend. This change is expected to greatly improve the quality of the plate circuit and strengthen the argument for a plate kinematics origin even further. If confirmed, this observation would suggest that the paleomagnetic evidence of more northerly latitudes might have to be explained by true polar wander.

14.2.2.2 Vertical Displacement due to Plate Flexure

As seamounts and islands are constructed, complex interactions between the loads and the responses of the supporting lithosphere and mantle take place. These responses are first and foremost vertical isostatic adjustments and reflect both the rheology and dynamics of the lithosphere-asthenosphere system (Zhong and Watts 2002). To first order, the lithosphere will respond to surface loads as an elastic plate, flexing downward beneath the loads and bulging upward further away. Walcott (1970), who used a broken plate analogy with the break oriented along the ridge, pioneered early modeling of such flexural deformation beneath the Hawaiian Ridge, suggesting an elastic thickness of almost 60 km. Later, Watts and coworkers used Hawai`i as a case study for numerous flexure studies, including a two-ship, multichannel seismic experiment collecting images of crustal structure across the island chain (e.g., ten Brink and Brocher 1987; Watts 1978; Watts et al. 1985; Watts and Cochran 1974; Wessel 1993). These modeling efforts using continuous plates revealed a smaller plate thickness in the 25–35 km range.

The seismic experiment demonstrated beyond any doubt that the lithosphere indeed was flexed downward beneath Hawai`i by several km, confirming directly what had been inferred indirectly from the free-air gravity anomalies across the chain. Furthermore, the detailed study of the seismic images allowed for a better understanding of the evolution of the island chain as evidenced by the stratigraphy of the sediments in the flexural moat (Rees et al. 1993; ten Brink and Watts 1985). Four main lithostratigraphic units were observed within the moat. At the base lies a unit of approximately constant thickness of pelagic sediments, presumably predating the islands. Above it lies a thick wedge of lense-shaped units that are onlapping the flexural arch; these are internally chaotic and thought to represent buried landslide deposits. Next comes a sequence of continuous horizons that offlap the arch and are tilted towards the islands, finally topped by a ponded unit in the deepest part of the moat which contain the most recent sediment deposits. This stratigraphy clearly reflects the competing effects of mass-wasting on a large scale (Moore et al. 1989; Smith and Wessel 2000) and the ongoing flexural subsidence driven by the island construction (Rees et al. 1993; Watts and ten Brink 1989). The bulk of the deformation takes place during the extended shield-building phase after which the lack of additional surface loads causes the flexural subsidence to cease (Moore and Clague 1992).

Once shield-building and rejuvenated volcanism ceases, the islands are passively carried on the back of the Pacific plate away from the center of volcanic activity. Over the last 30 Myr, the plate has on average moved 95 km/Myr over the Hawaiian hotspot (Wessel et al. 2006). However, vertical displacements will continue to moderate the evolution of the islands and seamounts. It has been known since the time of Darwin that volcanic islands are eroded down to sea level and eventually drown altogether (Darwin 1842). The reason for this slow subsidence is the continued cooling of the oceanic lithosphere (e.g., Turcotte and Schubert 1982). Created hot and thin at the mid-ocean spreading center, the lithospheric plate loses heat through the seafloor and the depth-averaged reduction in plate temperature promotes a corresponding increase in density due to thermal contraction. Consequently, the plate must sink deeper to maintain its isostatic balance. Unlike the flexural vertical motions driven by shield-building (Moore 1970) or mass-wasting (Smith and Wessel, 2000), which may reach several mm/yr, the slow thermal subsidence is orders of magnitude smaller, typically in the range or 0.02–0.03 mm/yr for the Northwestern Hawaiian Islands, as predicted by plate-cooling models (DeLaughter et al. 1999; Stein and Stein 1992). It was long assumed that the passing of the plate directly over the hotspot would impart significant heat into the lithosphere, which would "reset" its thermal age and thus explain the rapid shoaling of the seafloor near Hawai`i (Detrick and Crough 1978*)*. However, no heat flow anomaly has yet to be conclusively demonstrated (McNutt 2002), and numerical modeling has shown that the swell uplift is more likely a combined effect of chemical buoyancy and dynamic uplift (Phipps Morgan et al. 1995; Ribe and Christensen 1999). Nevertheless, the subsidence is steady and cumulative and will submerge any island given enough time to act. In equatorial regions, coral growth can generally keep up with this rate of subsidence, but natural variabilities in the climate and the eustatic sea level may combine to overwhelm this ability, as evidenced by drowned reefs along the Hawaiian Ridge (Grigg and Epp 1989).

14.2.3 Sea Level and Reef Development

14.2.3.1 Sea Level

For the purposes of this chapter, the term "coral reefs" refers to areas of biogenic carbonate accretion, some portion of which is composed of scleractinian or stony coral components. Most reef-building scleractinian corals contain and derive a significant portion of their energy budget from zooxanthellae, single-celled algal symbionts residing within coral tissue that utilize photosynthesis to produce carbohydrates and also generate oxygen as a by-product. As a result, scleractinian corals are most commonly found within the top few 10s of meters of the photic zone. Over time scales of decades or longer, the growth and accretion of coral reefs in the NWHI and elsewhere are closely tied to the position of sea level.

Over the entire history of the NWHI they have been impacted by rapid fluctuations in sea level of up to perhaps as much as 150 m, which have been largely driven by glacio-eustatic processes (Cronin, 1999). Sea-level changes resulting from oscillations of the Antarctic ice sheet have occurred since at least the beginning of the Oligocene Epoch ca. 34 million years ago (Barron et al., 1991). More recently, Moran et al. (2006) document a cooling of waters in the Arctic Ocean and the formation of sea ice approximately 45 Ma that is consistent with a global shift in from "greenhouse" to "icehouse" conditions, with the latter characterized by ice sheets periodically growing and receding at both poles.

Sea-level oscillations from the latter half of the Tertiary Period (ca. 1.8-45 Ma) are believed to have been both less frequent and of lower amplitudes than those of the last 800 kyr or so. Based on analyses of cores collected by the Ocean Drilling Program (ODP) off the New Jersey coast on the eastern seaboard of the U.S., sea-level changes of 20-34 m have been reported for the Oligocene (24-34 Ma) (Pekar and Miller 1996). Additional data suggest that fluctuations have occurred over million-year time scales throughout much of the period between 36 and 10 Ma (Miller et al.1996). Although there is considerable debate about the timing and magnitude of ice sheet fluctuations over the last 10 Ma, several lines of evidence suggest that multiple sea-level oscillations of several tens of meters occurred on time scales of 100 ka to 1 Ma (e.g., Cronin et al. 1994; Jansen and Sjøholm, 1991; Naish, 1997; Wilson 1995).

During the late Pliocene and early Pleistocene, approximately 2.7 Ma to 0.8 Ma, the magnitude of oscillations in proxy records of ice volume grew larger than they were during the preceding period. The records show a principal periodicity of ~40 kyr and suggest that fluctuations in sea level were on the order of 40-60 m (Cronin et al. 1994; Lambeck et al. 2002; Naish 1997; Ruddiman et al. 1989). Starting about 800 ka, a strong 100 kyr cycle of oscillations in paleoclimate and ice volumes, and fluctuations in sea level with maximum amplitudes of 120-140 m, were established.

Ice volume changes were first derived more than half a century ago from the ratio of $^{18}O/^{16}O$ recorded in the calcium carbonate shells of foraminifera recovered from deep-sea sediment cores (Emiliani 1955). The total change in the ratio of $^{18}O/^{16}O$ between interglacial and glacial periods is approximately 1.5‰ (Mix 1992). The heavier ratios correspond to periods of high ice volume and reflect the preferential evaporation of the lighter isotope from the oceans and its subsequent deposition in ice sheets, leaving ocean waters with a higher concentration of heavier isotopes. By convention, interglacial periods or stages in the marine isotope record are assigned odd numbers, and even numbered stages represent glacial periods. The period of lighter isotopic ratios characterizing the current interglacial period is referred to as Marine Isotope Stage 1 (MIS 1). The last glacial period is referred to as MIS 2, the interglacial period before that is called MIS 3, and so on, as seen in Figure 14.18.

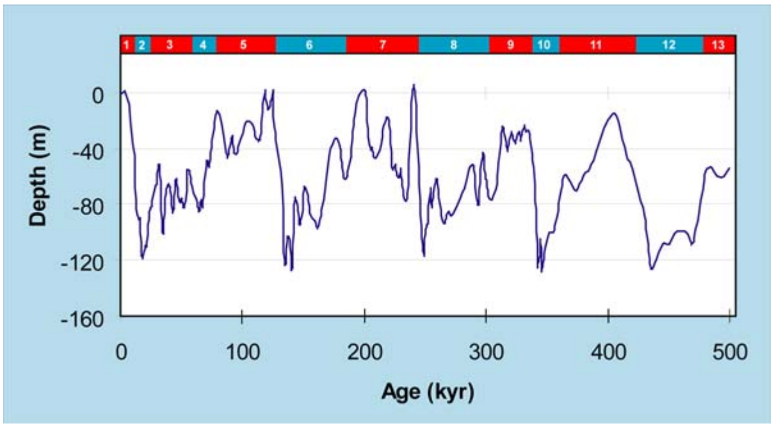

Figure 14.18 Late Quaternary Sea Level. Estimated sea level in the NWHI for the period from 0 to 500 kya, adapted from Webster et al. (2004). Modern sea level is shown at 0 meters, and the position of sea level through time is adjusted for uplift of Oahu and subsidence of the NWHI. Data were also adjusted upward to match the position of MIS 5 deposits in Hawaii. Boundaries of the numbered Marine Isotope stages in the bar at the top of the graph are from Imbrie et al. (1984).

The height of MIS 2, the last glacial period, is often referred to as the Last Glacial Maximum or LGM. During the LGM, from ~30 ka to ~19 ka, the ice-volume-equivalent sea level is inferred to have been -130 to -135 m below present sea level (Lambeck et al. 2002; Yokoyama et al. 2000). Starting at ~19 ka, sudden and strong deglaciation resulted in a massive marine transgression in which sea level rose rapidly. The transgression continued on into the Holocene, reaching present levels ca. 6 ka, and will be discussed in greater detail later.

14.2.3.2 Pre-Holocene Reef Development

Geologists long suspected that the NWHI were still found near sea level due to the upward growth of coral reef, and that the islands themselves were the tops of carbonate caps built on ancient volcanoes that had subsided long ago. Their suspicions were confirmed in the summer of 1965 when two holes were drilled from the surface of Midway Atoll down through an expanse of reef limestone and into basalt (Ladd et al. 1967; Ladd et al. 1970). Their results provide the most comprehensive overview of pre-Holocene reef development in the NWHI currently available.

The first hole drilled at Midway was started on Sand Island inside the lagoon and went through 135 m of carbonate material overlying 17 m of basaltic sedimentary layers before hitting basalt rock. The second hole was drilled just inside the atoll rim on the eastern side of the atoll and penetrated 300 m of reefal limestone and carbonate sediments over 81 m of mostly volcanic clays before entering basalt. Ladd et al. (1967; 1970) analyzed core material and found, based on textural and geochemical information, that the basalts they recovered were erupted above sea level. They also concluded that the volcanic mound was partially truncated by wave action in pre-Miocene time (i.e., prior to 24 Ma), prior to subsiding below sea level. Weathered clays on the subsiding volcanic pedestal were reworked in shallow water and eventually covered by reef deposits. Based on assemblages of mollusks, it was determined that all of the carbonate material was deposited in shallow, warm, reef and lagoonal environments. Coral fragments were found throughout the carbonate sections of the core and even in the volcanic clay layer lying directly above the basalt at the base of the reef hole. These observations led Ladd et al. (1967; 1970) to conclude that corals were at least as important earlier in Midway's history as they are today. Miocene coral fauna was found to be more diversified than later assemblages suggesting a more favorable climate regime during that epoch. Coralline algae were abundant and widespread throughout both cores, suggesting that they have functioned as important contributors to reef building throughout the history of the NWHI.

Reflecting the numerous fluctuations in sea level reported in earlier sections, unconformities in the Midway cores show evidence of at least two periods of emergence during the Miocene and at least one during the Pleistocene (Ladd et al. 1967; Ladd et al. 1970). Furthermore, the lithologies they describe suggest the occurrence of a number of others. Endodontid land snails, which are common on the larger volcanic islands in the Hawaiian Archipelago but are not presently found on the low carbonate islands of the NWHI, were also found in the upper 50 m of both cores, providing further evidence of their temporary emergence.

Given sufficient time and under the appropriate conditions of water temperature and clarity, irradiance, wave energy, and availability of substrate, coral reefs will tend to accumulate off low latitude shorelines. Grigg (1988; 1997) presents evidence that coral reefs have been continuously present in the Hawaii-Emperor chain since the early Oligocene. He argues that closure of the Tethys Seaway, isolation of Antarctica, global cooling, and increased latitudinal temperature gradients collectively strengthened gyral circulation, enabling coral larvae to be transported to Hawaii. Clague (1996) reports that there were no islands with land areas above sea level between 34 and 30 Ma. All species requiring terrestrial habitat for part of their lifecycle were extirpated during this period. Few, if any, scleractinian coral and reef fish species would have been able to recruit to the H-E chain until ca. 30 Ma. Evidence from the Midway cores suggest that conditions were appropriate for coral reef growth ever since the core locations were first inundated during the early Miocene, at least during interglacial periods of relatively high sea level.

Holster and Clark (2000) found that sea surface temperatures (SSTs) in Hawai`i were 3.5 – 6.6°C cooler during the LGM, while Lea et al. (2000) report glacial-interglacial temperature differences as great as 5°C for the tropical Pacific over the last 450 thousand years. SSTs are already so low at Kure that they are on the threshold below which coral reef accretion is precluded (Grigg 1982). It is likely, therefore, that coral reef growth did not occur at Kure during glacial periods, at least during the late Quaternary. As seen in Figure 14.12, winter season SSTs are about 4°C cooler at Kure today than they are at Nihoa Island, Necker Island, and French Frigate Shoals, so it is conceivable that coral reefs may have been able to accrete at the southern end of the NWHI during late Quaternary glacial periods. Also, assuming a constant velocity of the Pacific plate of 7.6 cm/yr since the beginning of the Miocene (Clague 1996), the NWHI would have ranged between approximately 400 and 1800 km southeast of their present locations over the duration of the Miocene. Their more southerly locations during this period enhance the likelihood that at least the southernmost islands were accreting reef material during glacial low stands of sea level.

It is apparent from the Midway cores that environmental conditions were favorable for coral growth in the NWHI, at least during interglacial periods of high sea level. There is little if any other evidence currently available on reef development in the NWHI in the Pliocene and early Quaternary, but it is likely that reef accretion did occur, especially during warmer interglacial periods and on the southern islands and atolls. A number of studies have investigated late Quaternary fossil reefs in the Hawaiian Archipelago, but have usually focused on emerged deposits in the MHI. The relatively few studies that also investigate submerged reef deposits are discussed below and provide a model of Main Hawaiian Islands reef development that can be adapted to the NWHI.

On Oahu, interglacial periods of coral reef accretion were followed by subaerial erosion and diagenesis during the ensuing glacial low sea level stand. Previous reef deposits were, at times, eroded by the next sea level high stand, which also enabled new rounds of coral reef accretion in locations where conditions of sea level, environmental conditions, and accommodation space allowed (Fletcher et al., submitted; Fletcher and Sherman, 1995; Grossman and Fletcher, 2004; Sherman et al., 1999). As a result, late Quaternary reef deposits on Oahu are a complex and interwoven mix of multiple episodes of accretion and erosion.

The primary structural unit of the Oahu insular shelf and an important underlying unit of the coastal plain is a massive limestone shelf, the Waianae Reef (Sterns, 1974) that accreted during MIS-7 and is found there today at depths from -5 m to -20 m. Analysis of cores recovered from the Waianae Reef reveal differences in accretion on different sides of the island, reflecting variations in hydrodynamic forcing that are similar to current conditions. Predominantly coralline algal bindstone and some massive coral facies are observed on the windward (northeasterly) side of the island. Cores from the leeward side contain massive coral facies at a more seaward location and branching coral floatstone, interpreted to be from reef flat and back reef environments, respectively. The suite of sample ages taken from all cores ranges between 206 and 247 ka (Fletcher et al., submitted; Sherman et al., 1999). Fletcher et al. (submitted) contend that other limestone deposits on Oahu are of secondary importance to the Waianae Reef, and that its formation was the result of the first major episode of reef accretion following the volcanic shield-building phase of the island's history. The Waianae Reef was subaerially exposed and heavily eroded and karstified during MIS 6, and in some locations, during later glacial periods as well.

Lying unconformably on the Waianae Reef is interglacial reef accretion from MIS 5e, identified by Sterns (1974) as the Waimanalo Reef. Reef rock from this formation is subaerially exposed in a number of locations around Oahu and other MHI and has been well studied as a result. It is primarily composed of *in situ* coral-algal framestone with some bindstone and grainstone facies present as well. Sample dates from Oahu indicate that the reef was accreting as early as 143 ka and until at least 126 ka. On the leeward side of the island, massive coral framestone of the Waimanalo Reef accreted along the face and base of the seaward wall of the MIS 7 Waianae Reef. A contact between the Waimanalo Reef and underlying MIS 7 Waianae Reef was reported from one core recovered from windward Oahu at -5 m (Fletcher et al. submitted; Sherman et al. 1999). The Waimanalo Reef has been reported from a number of locations under the Oahu coastal plain (Sterns 1974, 1978), but the shallow depth of the contact between the Waianae and Waimanalo Reefs and evidence from long limestone cores recovered from the coastal plain for commercial purposes indicate that the Waimanalo Reef is underlain by the more massive Waianae Reef complex.

As sea level dropped at the end of MIS 5e, framestone accretion from MIS 5a-d occurred on the seaward margin of the MIS 5e reef over the period between ca. 79 – 106 ka and is referred to as the Leahi Reef (Sterns 1974). Continuous accretion of massive coral between MIS 5e and 5d from a core from leeward Oahu suggests that sea level never fell below -25 m relative to modern sea level (Fletcher et al. submitted). The MIS 5a-d period also featured massive deposits of calcareous eolianite, which are found today on the coastal plains of at least the MHI of Maui, Molokai, Oahu, and Kauai. They are interpreted as resulting from large-scale dune deposition occurring during the drops in sea level between MIS 5e and MIS 5a-d, as well as at the end of MIS 5, and from extensive calcareous sediment production during MIS 5a-d (Fletcher et al. submitted; Sterns 1974). The eolianite outcrops on the coastal plains of these islands today have a significant impact on modern sediment dynamics. They also provide substrate for Holocene reef accretion in some locations and form small islets offshore of modern coastlines. Subaerial outcrops of both MIS 5e reef rock and MIS 5a-d eolianite have not been reported in geologic investigations in the northern atolls of the NWHI (e.g., Gross et al. 1969) or in general descriptions of all of the NWHI (Maragos and Gulko 2002; Rauzon 2001). Presumably, this is a result of subsidence of the NWHI since MIS 5.

A broad limestone shelf off Oahu has been observed at depths of -49 to -54 m. Based on its depth, it is hypothesized to have been deposited during MIS 3, ca. 30 – 60 ka (Fletcher et al. submitted), but no samples have been recovered from the structure to confirm this hypothesis. At the end of MIS 3 (ca. 30 ka), sea level dropped 50 m or more as the last glacial period, MIS 2, started. During which time, as discussed earlier, sea surface temperatures may have been warm enough to enable coral reef accretion, at least on the more southerly of the NWHI, although evidence of this has yet to be published.

When trying to compare late Quaternary reef development in the Main and Northwestern Hawaiian Islands, it is important to consider the effects of their different rates of vertical motion. The NWHI are well away from the mantle hotspot and from the effects of lithospheric loading from the islands near it. As a result, the vertical motion of the NWHI follows a trajectory that is generally consistent with that predicted by the Parson-Sclater subsidence curve, at an estimated rate of ca. -0.024 mm/yr at French Frigate Shoals (Grigg 1997), or 0.02 – 0.03 mm/yr for the NWHI in general (DeLaughter et al. 1999; Stein and Stein 1992). Oahu on the other hand, where most of the MHI reef development data are from, is estimated to have uplifted at 0.02 mm/yr from 0-125 kya, and at a rate of 0.06 mm/yr between 125 and 500 kya (Grigg and Jones 1997). Using these rates and depth or elevation data from coral reef deposits on Oahu (Fletcher 1996; Grigg and Jones 1997; Jones 1993), crude estimates of the present depth/elevation of paleo-shorelines can be made. However, in the absence of data on magnitudes of net reef accretion during different interglacial periods, e.g., from cores or possibly from seismic studies, it is difficult to calculate past elevations or depths of the different islands in the NWHI. A general observation that can be made, however, is that relative to Oahu, the stratigraphy of fossil reefs of the NWHI is likely to be less complex and have more of a “layer cake” morphology. Younger deposits will have a greater tendency to overlie older limestone, thanks to the subsidence of the NWHI throughout the Quaternary, and undoubtedly throughout most of the Miocene for the older islands and atolls. Of course, sequences of carbonate reef are also much thicker and older in the NWHI than they are in the MHI. A program of fossil reef coring in the NWHI would help to address the above and other questions regarding patterns of late Quaternary reef accretion and relative sea level change.

14.3 Holocene Reef History

14.3.1 Holocene Sea Level

14.3.1.1 Post-glacial Sea Level Rise and the Holocene Transgression

At the end of MIS 2, about 19 ka, eustatic sea level began to rapidly rise from its inferred position of -130 to -135 m to near modern sea level by about 6 ka, at a mean rate of 10 mm/yr or more. As the sea level curves from Figure 14.19 indicate however, that mean rate is composed of a series of irregularly alternating higher and lower rates. Considerable effort has been made to correlate the accelerations and decelerations of the overall sea level rise to specific events associated with deglaciation. During the first stage of deglaciation, until 14.5 ka, sea level rise was relatively slow at approximately 4 mm/yr. Evidence suggests that it was caused by the decay of the Barents Ice Sheet on the continental shelf of the eastern Arctic Ocean (Elverhoi et al. 1993; Jones and Keigwin 1988; Peltier 1988; Vogt et al 1994).

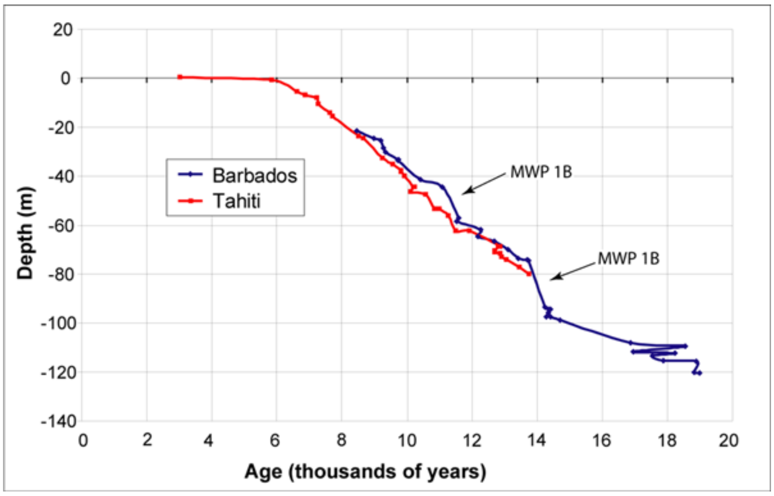

Figure 14.19 Sea level rise during the last deglaciation. A record of relative sea level rise derived from uplifted coral reef deposits on the islands of Barbados and Tahiti (Bard et al. 1990, Bard et al. 1998) that we expect is similar to the sea level rise pattern from the NWHI. Note the two major increases in the rate of sea level rise during Melt Water Pulses 1A and 1B.

Results from ^{14}C dating of *Acropora palmata* corals from Barbados, and a model of their ecology and growth relative to sea level, led Fairbanks (1989) to propose a sudden 24 m jump in sea level. Called Meltwater Pulse 1A (MWP 1A), it is estimated to have started ca. 14.5 ka and lasted less than 1,000 years. The source of MWP 1A has generally been attributed to meltwater released by the decay of the Laurentide Ice Sheet which covered the northern portion of North America (Bond et al. 1992; Keigwin et al. 1991; Teller and Kehew 1994), but has also been attributed to decay of the Antarctic Ice Sheet (Clark et al. 1996).

MWP 1A was followed by a period of reduced sea level rise during a climatic cooling event known as the Younger Dryas (YD), which occurred between approximately 12.5 to 11.5 ka (e.g. Alley et al. 1993; Kennett 1990). There is ongoing debate about the causes, timing, effects on sea-level rise, and other details of this event. Blanchon and Shaw (1995) estimate sea-level rise at 13 mm/yr during the YD, and most researchers agree that there was a several fold decrease in sea level rise rates around this time.

Another meltwater pulse, MWP 1B, raised sea level about 28 m beginning about 11 ka and at rates perhaps as high as 45 mm/yr (Blanchon and Shaw 1995; Chappell and Polach 1991, Fairbanks 1989). Sources of this meltwater are believed to include both the Laurentide and Fennoscandinavian Ice Sheets. Following MWP 1B, sea level rise declined to a rate of ca. 10 mm/yr, reaching or slightly exceeding modern sea levels by 6 ka.

14.3.1.2 Mid-Holocene Highstand

In the equatorial Pacific, Holocene sea level rise continued past 6 ka, reaching levels of 1 to 3 m above modern sea levels between 1.5 and 5 ka (Fletcher and Jones 1996; Grossman and Fletcher 1998; Grossman et al. 1998). Geophysical models suggest that the high stand resulted from an ongoing process of glacial isostatic adjustment (GIA) in areas distant from Late Pleistocene ice cover (Clark et al. 1978). Mitrovica and Peltier (1991) developed the term “equatorial ocean siphoning” to describe a sequence of events consistent with geologic observations of the high stand of sea level. They propose that during a glacial period, the weight of continental ice sheets causes downward deformation of the crust, essentially squeezing the earth at the poles and forcing mantle material to flow towards central equatorial ocean basins. This process results in a gravitational anomaly in these areas and sea levels that are higher than they otherwise would be. Deglaciation resulted in a shifting of mass from the high-latitude continental ice sheets to ocean basins, enabling continents to viscoelastically rebound and material sequestered in the mantle under equatorial ocean basins to flow back to higher latitudes. The timing of the sea level high stand and its decay are attributed to the viscosity and flow dynamics of mantle material.

Sea level notches and beach and reef deposits elevated above the present position of mean sea level and dating from the mid-Holocene are found at a number of locations throughout the equatorial Pacific and the MHI (e.g., Calhoun and Fletcher 1996; Fletcher and Jones 1996; Grossman and Fletcher 1998; Grossman et al. 1998). They have also been documented at Kure and Midway Atolls (Sterns 1941). Gross et al. (1969) dated several samples of reef rock from the emergent atoll rims at Midway and Kure Atolls (Figure 14.20), finding a range of dates between 2.4 and 1.2 ka. They report that the emergent fossil reef must have been deposited at, or slightly below, low tide level and interpret their results and observations as indicating that sea level was 1-2 m above present levels during at least the period from which they have dated samples.

Figure 14.20 A segment of the atoll rim from Midway Atoll. Composed of in situ carbonate reef material, it was obviously deposited during a period of higher than present sea level. Photograph by Jean Kenyon.

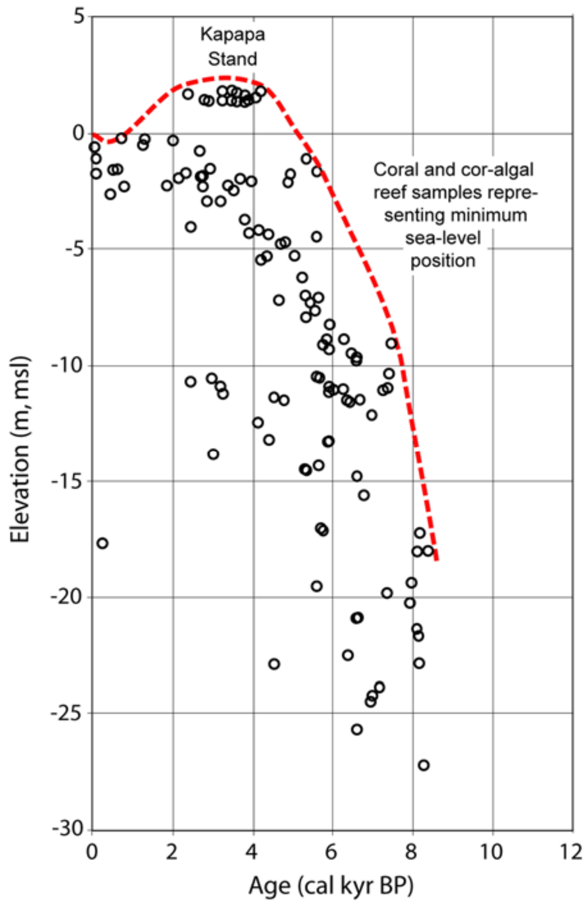

Figure 14.21 Estimated Holocene sea level curve for the northern MHI and NWHI. Each circle represents the age and elevation of an *in situ* coral or other reef deposit (Easton and Olson, 1976; Engels et al. 2004; Gross et al. 1969; Grossman and Fletcher 2004; Rooney et al. 2004). The red dashed line fit to the dated samples shows the minimum position of sea level.

Fossil reef samples recovered from the MHI provide data with which a Holocene sea-level curve can be estimated (Figure 14.21). Results are consistent with the patterns of eustatic and equatorial sea level change discussed above, but more data from the late Pleistocene and early Holocene would be useful. Additional data between the present and about 3 ka would help to better constrain sea level changes following the mid-Holocene high stand. Summing rates of NWHI subsidence and uplift on Oahu reported earlier, the total vertical offset of the NWHI relative to Oahu at 8 ka is estimated to be 0.35 m. Keeping that offset in mind, it is reasonable to use the Oahu sea level curve as a proxy for relative sea level (RSL) in the NWHI over the same period. These sea level data provide constraints on Holocene reef development for the islands and atolls between Oahu and Kure.

14.3.1.3 Modern Sea Level Rise and Loss of Terrestrial Habitat

As with most regions where coral reefs are located, RSL has been rising over recent decades in the NWHI. There are two tide gauges in the NWHI, located at Midway Atoll and French Frigate Shoals which are part of the Permanent Service for Mean Sea Level (PSMSL 2006). Table 14.3 shows rates of change in RSL, with positive values indicating a sea level rise for both islands and for Honolulu in the MHI calculated from monthly sea level observations.

Table 14.3 Rates of relative sea level rise for different periods, at different tide gauge stations in the Hawaiian Islands (PSMSL 2006).

Period	French Frigate Shoals	Midway Atoll	Honolulu
1905- 2003	NA	NA	1.47 mm/yr
1947- 2003	NA	0.58 mm/yr	1.37 mm/yr
1974 - 2001	1.35 mm/yr	2.95 mm/yr	0.65 mm/yr
1992 - 2001	7.42 mm/yr	7.71 mm/yr	-3.97 mm/yr

As expected, the records show a general trend of RSL rise, but with a wide range of rates. It is very unlikely that the changes in rates are a result of variations in subsidence, especially considering the island's ages. The longest Midway record shows a slower rate of RSL rise relative to the same period at Honolulu, but over more recent periods shows increasingly faster rates. These results are consistent with those reported by Caccamise et al. (2005), who find that steric sea level trends (those attributed to thermal expansion of the water column) show falling sea levels to the north of the MHI and rising levels to the southeast between 1945 and 1995. However, between 1993 and 2002 they note an opposite pattern in satellite-derived sea surface heights and attribute the reversal to multi-decadal fluctuations in the spatial structure and magnitude of upper ocean temperature associated with the Pacific Decadal Oscillation.

Whatever the cause, RSL in the NWHI has been rising at moderate rates over the last few decades and several times faster more recently, with potentially dramatic impacts to the ecosystems there. Terrestrial habitats in the Northwestern Hawaiian Islands (NWHI) consist largely of low-lying oceanic sand islands (cays) and atolls, which are home to 4 land bird species, 3 terrestrial snail species, 12 plant species and over 60 species of terrestrial arthropods found nowhere else in the world (Conant et al. 1984). As all of these spend their entire lives on land, the NHWI terrestrial habitat represents their only tether to existence.

The NWHI are also important for large marine vertebrates including sea birds, green sea turtles, and Hawaiian monk seals, all of which feed at sea but require terrestrial habitat with few or no predators to either nest (turtles and seabirds) or raise offspring (seabirds and seals). The endangered Hawaiian monk seal is one of the rarest marine mammals in the world, with a declining population of only approximately 1200-1300 individuals, primarily found in the NWHI (Antonelis et al. 2006). Over 90% of Hawaiian green sea turtles breeding females nest on beaches at French Frigate Shoals (Balazs and Chaloupka 2004). Terrestrial areas in the NWHI are also habitat for some 14 million seabirds of 18 species (Harrison 1990). Nesting of Laysan albatross (*Phoebastria immutabilis*) and black-footed albatross (*Phoebastria nigripes*) occurs almost entirely in the NWHI (Harrison 1990). The sooty, or Tristram's, storm petrel (*Oceanodroma tristrami*) has its most populous remaining breeding sites in the NWHI (Harrison 1990). A significant proportion of the world population of Bonin petrels (*Pterodroma hypoleuca*) also breeds in the NWHI (Fefer et al. 1984, Harrison 1990).

The low-lying land areas of the NWHI are highly vulnerable to sand erosion due to storms and sea-level rise. Sea-level rise reduces cays by passive flooding and active coastal erosion, particularly during periods of seasonal high swell. As a result, the subaerial land area supporting these important littoral and coastal ecologies is at risk. Demonstrating this, cays such as Whaleskate Island, which had been important habitat for green turtles and monk seals at French Frigate Shoals, have been greatly reduced in size during roughly the past 40 years (Figure 14.22) (Antonelis et al. 2006).

Figure 14.22 Whaleskate Island at French Frigate Shoals, NWHI. Once an important nesting island for Hawaiian green sea turtles and a primary pupping site for endangered Hawaiian monk seals, pictured from the air in 1963 (above) and from a small boat in 2002 (below). Photos courtesy of the National Marine Fisheries Service.

Using handheld Global Positioning System receivers and a theodolite, Baker *et al.* (2006) produced the first topographic maps in 3 NWHI locations (Lisianski Island, Pearl and Hermes Reef, and French Frigate Shoals). They then used passive flooding scenarios to estimate the area that would be lost if islands maintained their current topography and the sea were to rise by various amounts. The Intergovernmental Panel on Climate Change (IPCC) evaluation of a number of model scenarios predicted low (9 cm), median (48 cm), and high (88 cm) estimates of sea level rise by 2100 (Church et al. 2001). Thus, passive flooding scenarios were run for each of these levels at mean low water (MLW) and at spring tide.

The uncertainty of predictions increases over time, but the expectation is that sea level will continue to rise beyond 2100 (Church et al. 2001). Moreover, recent evidence suggests that sea level may rise more rapidly than previous models have predicted, due in part to an accelerated rate of ice loss from the Greenland (Ragnat and Kanagaratnam 2006) and West Antarctic (Shepherd and Wingham 2007) ice sheets.

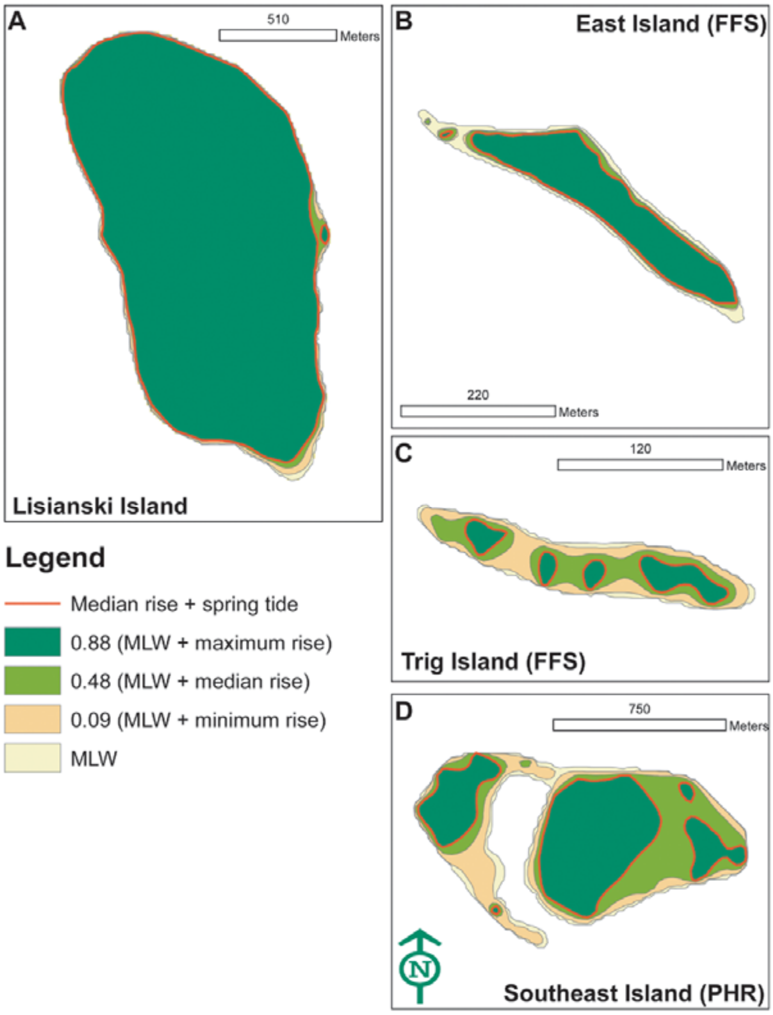

Figure 14.23 Current and projected maps of 4 Northwestern Hawaiian Islands at mean low water (MLW) with minimum (9 cm), median (48 cm) and maximum (88 cm) predicted sea level rise. The median scenario at spring tide is also shown. (A) Lisianski Island; (B) East Island, French Frigate Shoals; (C) Trig Island, French Frigate Shoals; (D) Southeast Island, Pearl and Hermes Reef (Baker et al. 2006).

The projected effects of sea level rise on island surface area varied considerably among the islands examined and depending upon the sea level rise scenario. For example, Lisianski Island is projected to be the least affected of the islands surveyed, losing only 5% of its area even under the maximum rise scenario. In contrast, the islets at French Frigate Shoals and Pearl and Hermes

Reef are projected to lose between 15 and 65% of their area under the median sea level rise scenario, as shown in Figure 14.23.

Loss of terrestrial habitat to sea level rise will likely have considerable impacts on some species and no effect on others. Monk seals require islands for resting, molting, and, most importantly, parturition and nursing. Seals may experience more crowding and competition for suitable landing sites when islands shrink. French Frigate Shoals also hosts nests for ninety percent of Hawaiian green sea turtles, primarily at East Island (Balazs 1976). This may be fortunate since the island is projected to lose a smaller percentage of its area than the others analyzed. A small population of the Laysan finch *Telespiza cantans*, an endangered Hawaiian honeycreeper, occurs on Southeast Island at Pearl and Hermes Reef (the primary population of these birds is on Laysan Island). Considerable habitat would be lost from Southeast Island under the Baker et al. (2006) median scenario (Figure 14.23), which could greatly increase this population's extinction risk (McClung 2005).

Baker et al.'s (2006) projected scenarios treat the islands' current configurations as static, though some, especially the smaller islets, are more likely to be dynamic. Therefore, their projections should be viewed as the currently best available demonstration of the potential effects of sea-level rise. Furthermore, passive flooding scenarios do not take into account ancillary factors that could substantially influence the future of the NWHI. These include erosive recession of the shoreline causing land loss, redistribution of sediments by long-shore drift (resulting in both gains and losses of land area), net permanent loss of sand volume offshore, and onshore sand deposition by overwash during high wave activity. A rise in the groundwater table during sea level rise could also displace seabird burrows. If reef growth does match sea level rise, this could result in increased sand accretion, thereby mitigating losses. For all these reasons, the impact of factors other than simply passive flooding as a result of increased sea level could lead to greater or lesser loss of habitat than presented here.

There are many uncertainties associated with the projected effects of sea level rise in the NWHI. A key issue is whether coral reef accretion will be able to occur at both the appropriate locations and at sufficient rates to enable them to offset future rises in sea level and continue to buffer lagoonal areas. If accretion is sufficient, land areas in the NWHI may continue to enjoy whatever current protection they have from ocean swells. We recommend that measurement of site-specific rates of reef accretion be made a management priority.

14.3.2 Holocene Reef Development

14.3.2.1 Coral Growth Rates, Cover, and Reef Accretion

There are a handful of studies that discuss aspects of Holocene reef development in the NWHI and others from the MHI whose results are relevant to the NWHI. Grigg (1982) reported mean linear growth rates and densities of 10 colonies of *Porites lobata* coral collected from a depth of -10 m on the fore reef of the southwest side of a number of islands and atolls across the Hawaiian Archipelago. He also reported percentages of coral cover from each sampling location and derived an estimate of reef accretion. Using his values of island-specific coral community measures, vertical rates of reef accretion can also be estimated and are shown for four islands in Table 14.4. As the table suggests, Grigg (1982) found that growth rates show a strong latitudinal dependence, with corals in cooler more northerly islands growing more slowly. He also noted that, based on the work of Gross et al. (1969), at least at the more northerly atolls the carbonate contribution from coralline algae is likely to be significantly more than that from corals.

Table 14.4 Latitudinal variations in coral colony growth rates and reef accretion across the Hawaiian Archipelago, from Grigg (1982). Note that coral cover percentages are from high coral cover areas and have been shown by more recent and extensive data collection to not be representative of most areas around these islands.

	Hawaii	Oahu	FFS	Kure
Coral Growth Rate (mm/yr)	13	12	8	3
Density (mg/mm^3)	1.42	1.47	1.4	1.6
Coral Cover (%)	93	61	66	10
Reef Accretion (kg $CaCO^3/m^2/yr$)	15	10	8.9	0.3
Reef Accretion by Corals (mm/yr)	10.6	6.8	6.4	0.2

Leveraging results collected by teams of researchers during visits between 2000 and 2003, Siciliano (2005) reports that the percentage of coral cover at Kure Atoll varies between different geomorphic habitats, with a mean value for the atoll of 20%, as seen in Table 14.5. In contrast and rather surprisingly, another study found no significant difference between benthic communities at most windward fore reef and back reef sites, although they did confirm differences between these areas and lagoonal communities at French Frigate Shoals (Vroom et al. 2005). Siciliano (2005) also collected coral colonies or short cores through coral colonies from all 10 islands in the NWHI to measure annual growth rates. In that study corals in wave-protected back reef and lagoonal environments are found to grow at similar rates of ca. 5-9 mm/yr regardless of latitude. However, in wave-exposed locations results are similar to Grigg's (1982), with rates in the NWHI ranging from ca. 2 – 8 mm/yr and showing a statistically significant decline with increasing latitude.

Table 14.5 Coral cover and predicted net reef accretion at Kure Atoll, from Siciliano (2005). The range of percentages of coral measured at French Frigate Shoals (FFS) and Pearl and Hermes Atoll (P & H) from visits between 2001-2005 are from Kenyon et al. (in press).

Geomorphic Habitat	Kure % Coral Cover	Predicted Net Accretion (mm/yr)	FFS % Coral Cover	P & H % Coral Cover
Fore Reef/Pass	16	1.7	7-9	6-9
Back Reef	27	1.5	10-19	10-15
Lagoonal Patch and Reticulate Reef	27	3.9	8-28	14-20
Mean (weighted) for Kure	20	2.1	-	-

Both of these studies attempted to extrapolate coral growth rates and other data to estimate rates of reef accretion. Grigg's (1982) estimates are for accretion due to corals only. They reflect the linear dependence of coral growth rates on latitude and range from 6.4 mm/yr at French Frigate Shoals to 0.2 mm/yr at Kure, although he suggests that the latter value might be about 0.6 mm/yr when accretion from coralline algae is included. Siciliano's estimate of 1.7 mm/yr for net reef accretion in fore reef environments (Table 14.5) at Kure is a more sophisticated approach which attempts to quantify all sources of carbonate accretion and erosion. Although there is a several fold difference in their rates, it is important to note that both studies conclude that net reef accretion is presently occurring today at Kure Atoll, even in fore reef environments. By extension, their results can be considered to apply to fore reef areas across the entire NWHI, or at least to those on the southwestern sides of islands and atolls.

This conclusion is contrary to results from the MHI. On Oahu, Holocene reef accretion is well documented to have primarily been limited to areas which are sheltered to some degree from high wave energy, particularly from long period North Pacific swell that strikes the Hawaiian Archipelago in the winter (Dollar, 1982; Dollar and Tribble 1993; Grigg 1983, 1998; Sherman et al. 1999; Storlazzi et al. 2002). At locations exposed to wave energy, Holocene accretion is limited to a thin and patchy veneer of living coral and coralline algae resting on an eroding Pleistocene-age fossil reef surface. Even this limited growth is episodically removed by large swell and storms. In more sheltered areas however, such as Hanauma Bay and Kailua Bay, 10-15 m thick sequences of Holocene coral reef have accreted (Easton and Olson 1976; Grossman and Fletcher 2004). We suspect that accretion of corals and coralline algae on most fore reef environments in the NWHI is ephemeral and periodically removed by high wave events. The small size of coral communities (5-20 cm) on NHWI fore reefs supports this hypothesis (Kenyon et al. in press). However, accretion is likely to be occurring at back reef and lagoonal patch and reticulate reef areas. In the absence of data from whole-reef cores Siciliano's (2005) accretion rates for these areas are the best estimates available at this time.

14.3.2.2 Potential Future Impacts of Ocean Acidification on Reef Accretion

Though studies to date have not yet adequately examined the influences of changing seawater carbonate chemistry on past reef accretion processes in the Northwestern Hawaiian Islands, research findings of the past decade have led to mounting concern that rising atmospheric carbon dioxide (CO_2) concentrations will cause changes in the ocean's carbonate chemistry system, and that those changes will affect some of the most fundamental biological and geochemical processes in the sea (Boyd and Doney 2003; Kleypas et al. 2006). Anthropogenic activities have driven atmospheric carbon dioxide (CO_2) concentrations to levels greater than, and increasing at a rate faster than, experienced for at least the last 650,000 years (IPCC 2001; UK Royal Society 2005). Global oceans are the largest natural reservoir for this excess CO_2, absorbing ~1/3 of that emitted each year (Kleypas at al. 2006). According to recent predictions, dissolved CO_2 in the surface ocean is expected to double over its preindustrial value by the middle of this century (UK Royal Society 2005; Kleypas 2006). Oceanic uptake of CO_2 drives the carbonate system to lower pH (acidification) and lower saturation states of the carbonate minerals calcite, aragonite, and high-magnesium calcite. These are the materials used to form supporting skeletal structures in many major groups of marine organisms (Kleypas et al. 2006). Ocean acidification has already reduced surface ocean pH by 0.1 units (equivalent to a 30% increase in the concentration of hydrogen ions) and is expected to reduce surface ocean pH by 0.3 – 0.5 units over the next century (UK Royal Society 2005).

A growing number of laboratory controlled experiments now demonstrate that ocean acidification adversely affects many marine organisms. Organisms that construct their shell material from calcium carbonate (marine calcifiers) are expected to be especially vulnerable. In particular, ocean acidification has been shown to hamper the ability of reef-building corals and reef-cementing crustose coralline algae to calcify, thereby affecting their growth and accretion and making them more vulnerable to erosion (Fabry 1990; Langdon et al. 2000; Langdon et al. 2003). By mid-century, corals may erode faster than they can be rebuilt potentially making them less resilient to other environmental stressors (e.g., coral bleaching and disease) (Langdon, pers. com. 2007). This could compromise the long-term viability of these ecosystems, perhaps impacting the thousands of species inhabiting reef habitats. In addition, ocean acidification may elicit broad physiological responses from non-calcifying organisms through less obvious and unknown pathways.

For the NWHI, which (as described above) have generally low net accretion rates, the predicted decreases in calcification rates (or even reversal to dissolution and increased erosion) in response to ocean acidification could seriously impact the ability of many islands, reefs, and banks to accrete fast enough to keep up with predicted sea level rise. Furthermore, the combined influences of sea level rise and acidification could fundamentally alter the biological and geochemical processes of the NWHI ecosystems. With the potential magnitude and consequences of the predicted changes, we strongly recommend significant new research to observe the spatial and temporal patterns of changing carbonate chemistry, calcification rates, and ecological and geochemical responses in the Northwestern Hawaiian Islands.

14.3.2.3 Patterns of Holocene Reef Development

As discussed above, long-term reef accretion is unlikely at locations in the NWHI exposed to high wave energy from seasonal long period swell. At sites that are sheltered to some degree however, reef growth and accretion is occurring. Detailed studies of reef accretion at several sites on Oahu provide insights into patterns of Holocene coral reef development that are likely to be occurring at sheltered locations in the NWHI. Easton and Olson (1976) analyzed 10 cores across an actively growing fringing reef at the moderately low-energy environment of Hanauma Bay on Oahu's southeastern shore. Grossman and Fletcher (2004) report on their findings based on 32 cores and benthic transects from the moderately high wave energy setting of Kailua Bay on the island's northeastern shore. Both studies found that modern reef growth was initiated 7-8 kya after these areas were inundated during the Holocene transgression. The initial stage of "catch-up" (to sea level, Neumann and Macintyre 1985) accretion was rapid, up to 6 mm/yr, and created a reef composed predominantly of coral framestone. Around 5-6 kya, both studies found that accretion rates stopped altogether or only resulted from rubble accumulation (Kailua Bay), or slowed down and began to include more calcareous algae (Hanauma Bay). A final stage of slow "keep-up" style bindstone accretion is reported at both sites, along with rapid horizontal seaward progradation of the reef at Hanauma Bay. As a whole, Holocene accretion patterns have been controlled by the availability of accommodation space for reef growth, beneath the wave base (Grossman and Fletcher 2004).

The above two studies suggest likely scenarios to describe coral reef accretion in low to moderate wave energy environments in the NWHI. Rates of coral colony growth reported by Siciliano (2005) indicate that the more northerly latitudes would not preclude similar results in lagoonal environments. However, wave-sheltered locations from more northerly atolls in the NWHI which are exposed to cooler non-lagoonal waters are likely to feature slower rates of accretion, lower percentages of coral, and higher percentages of calcareous algae.

Another study from Oahu was conducted at the Punaluu Reef, which is exposed to high wave energy from North Pacific swell (Rooney at al. 2004). Due to its morphology and wave exposure, the Punaluu Reef is more likely than the other two studies to have accretion patterns that are representative of fore reef and reef crest environments in the NWHI. Portions of the Punaluu reef crest are emergent during most of the tidal cycle and were obviously deposited during periods of higher than modern sea level, as was reported above for locations in the NWHI (Gross et al. 1969). These findings indicate that reef crests were active areas of accretion during the mid-Holocene, and suggests that they may be active sites of long-term accretion today.

Results of benthic ecological surveys from Punaluu are consistent with geologic evidence of reef crest accretion. They show that portions of the reef crest below the low tide level have up to 95% live cover of encrusting coral and coralline algae. This is a markedly higher percentage of seafloor inhabited by reef-accreting organisms than was found anywhere else across the reef, and indicates that the reef crest is an area of particularly active growth, and potentially, of accretion. Although quantitative surveys have not been reported for very shallow, high wave energy NWHI reef crests, surveys do report high coverages (37%) of crustose coralline red algae at fore reef areas on the northwestern side of Pearl and Hermes Atoll (Page et al. in review). Growth on the reef crest is possible despite high wave energy from winter swell, apparently because the sloping fore reef breaks the worst of the incident wave energy, and background trade wind swell provides a continuous flow of ocean water from offshore over the reef crest.

Geological and ecological data collectively suggest that shallow reef crest areas, including those in the NWHI, may be able to keep pace with at least moderate levels of relative sea level rise. In the face of predictions of accelerating sea level rise, determining accretion rates in the vicinity of the reef crest has significant management implications for the fate of terrestrial and shallow marine ecosystems in the NWHI.

14.3.2.4 El Niño Influence of Holocene Reef Accretion

As mentioned earlier, wave energy has been shown to be the predominant control of reef accretion in the MHI, both today and throughout the Holocene. Although direct evidence is lacking, patterns of coral growth and wave measurements suggest that this is true for the NWHI as well. However, data from several locations in the MHI show that rapid accretion during early to middle Holocene time occurred in areas where today it is precluded by the wave regime, suggesting an increase in wave energy (Rooney et al. 2004). Analysis indicates that accretion terminated at these locations ca. 5 kya, preceding the best available estimates for the decrease in relative sea-level rise during the mid-Holocene high stand of sea level at ca. 3 kya (Grossman et al. 1998). No permanent accretion is occurring at these sites today, despite the availability of hard substrate at depths between -30 m and the intertidal zone, suggesting that some factor other than relative sea-level rise has altered the ability of these sites to support accretion.

Numbers of both large North Pacific swell events and hurricanes in Hawai`i are statistically greater during El Niño years because of the increased intensity of the Aleutian Low and its more southward locus during these times. The study infers that if those major reef-limiting forces were suppressed, net accretion would occur in some areas in Hawai`i that are now wave-limited. Studies have shown that El Niño/Southern Oscillation (ENSO) was significantly weaker during early-mid-Holocene time, only gaining an intensity similar to today's ENSO signal ca. 5 kya (e.g. Clement et al. 2000; McGlone et al. 1992; Moy et al. 2002; Rodbell et al. 1998). It is hypothesized that this shift in ENSO may at least partially explain patterns of Holocene reef accretion in the Hawaiian Archipelago, and especially in the NWHI, which experience markedly higher wave energies from North Pacific swell than do the MHI.

As discussed earlier, southward extensions of the subtropical front appear to correlate with positive ENSO phases and expose the northernmost atolls to waters that are both cooler than normal and contain higher nutrient concentrations. What impact this ENSO-related phenomena may have on reef accretion at these atolls is unknown, but may be significant and should be investigated.

14.4 Geomorphology of Holocene Reefs

14.4.1 Atolls

14.4.1.1 Atoll Formation

In the NWHI, Laysan Island is the only low coral island in the NWHI that is not associated with an atoll. The term atoll can be defined as a "ring-shaped coral reef that surrounds a lagoon without projecting land area and that is surrounded by open sea" (Parker 1997). The "projecting land area" refers to original volcanic basalt structures, and not to low coral islands, which are common features of atolls. There are approximately 425 atolls in the world, with over 300 in the Indo-Pacific region (Guilcher 1988). Charles Darwin's (1842) famous theory of atoll formation postulates that fringing reef will grow around the periphery of a volcanic island in tropical latitudes. As the reef grows outward and the island subsides, the fringing reef is eventually transformed into a barrier reef.

This progression results in an atoll once “the last and highest” volcanic pinnacle disappears. That progression is clearly visible in the Hawaiian Archipelago moving from the island of Hawaii, at the southeastern end of the chain, to the northwest. The other MHI have fringing reef in many areas, some of which is hundreds of meters or more offshore. Small remnants of volcanic peaks can be seen at Nihoa and Necker Islands, at French Frigate Shoals, and at Gardner Pinnacle. True atolls, as well as low carbonate islands, are found further north in the chain.

Darwin’s theory was generally confirmed in 1951 when the first of several holes drilled through the former Engebi Island (later obliterated by nuclear weapons testing) at Eniwetok Atoll reached volcanic basement rock (Ladd and Schlanger 1960). However, glacio-eustatic sea level fluctuations were an unknown concept in Darwin’s time, although subsequent research has shown their importance on the modern geomorphology of atolls. A general correlation between atoll area and maximum atoll lagoon depth has been recognized for decades (e.g., Emery et al. 1954; Purdy 1974; Purdy and Winterer 2001; Umbgrove 1947). A positive correlation has also been reported for annual rainfall and the maximum depth of atoll lagoons (Purdy 1974; Purdy and Bertram 1993; Purdy and Winterer 2001). Assuming that modern rainfall is a reasonable proxy for precipitation during glacial low stands, the correlations suggest that maximum lagoon depth is primarily a function of preferential subaerial dissolution of the surface of the central portion of an atoll. However, Purdy and Winterer (2001) point out that subsequent interglacial sea levels high enough to flood atoll surfaces but not so high as to drown them would provide accommodation space for new reef growth. Atoll rims, elevated above the sediment-filled basins would preferentially accrete new reef growth. This alternating pattern of atoll rim accretion during high stands and preferential lagoonal erosion during low stands is likely to have been occurring on NWHI atolls throughout the late Quaternary, and to have made a significant contribution to their present morphology.

14.4.1.2 Open versus Classical Atolls in the NWHI

In general, atolls tend to be the best developed on their windward sides (Guilcher 1988), and this is true for those in the NWHI. The degree of variation between windward and leeward morphologies have led to atolls in the NWHI being classified as either classical or open atolls (Maragos and Gulko 2002). Classical atolls feature an emergent or very shallow atoll rim around a deeper lagoon. Although there may be passes or breaks in it, the rim encircles more of the atoll than it does not. Kure, Midway, and Pearl and Hermes Atolls are all considered classical atolls.

The perimeter reef or carbonate rim structure is not present around much or all of an open atoll. Since the atoll rim may not be present at all in an open atoll, the presence of a lagoon is critical to defining whether a carbonate structure is an atoll, island, or reef. The term lagoon can be defined as, "a shallow sound, pond, or lake generally near but separated from or communicating with the open sea" (Parker 1997). The Northwestern Hawaiian Islands of French Frigate Shoals, Lisianski Island/Neva Shoal, and Maro Reef are classified as open atolls and are listed in order of least to most open. Presumably, open atolls are formed in the same manner as classical atolls, but with a definitive atoll rim initially forming only on the windward side, in response to dominant seas and currents from that direction. The positive feedback described above for atoll formation during repeated subaerial exposure followed by submergence during glacial-interglacial cycles would tend to reinforce the original open atoll morphology.

14.4.1.3 Reticulate Reef

Lisianski Island/Neva Shoal and Maro Reef are classified as open atolls because they lack an atoll rim, but still have waters that are in communication with but separated from the open ocean. At these locales reticulate reef, rather than an atoll rim, isolates lagoonal waters. Reticulate reef, so named for its net-like structure, is also found inside the lagoon at Pearl and Hermes Atoll (see Figure 14.7), and smaller extents of reticulate reef are also found at French Frigate Shoals. Reticulate reef in the NWHI appears to often have high coral cover and species diversity (Figure 14.24). This is the case along the sides of the reef structures, and on their tops as well, if the water is deep enough and the reef is protected to some degree from wave energy. At shallower and more exposed locations, encrusting coralline red algae are common (Maragos and Gulko 2002; Page et al. in review).

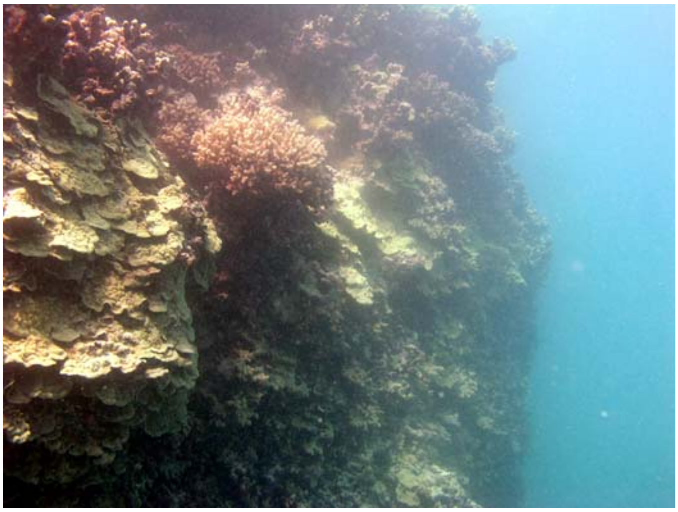

Figure 14.24 High coral cover is evident on the side of this reticulate reef structure at Maro Reef, despite the often relatively turbid water conditions. Photograph by Jean Kenyon.

Reticulate structure is found in many coral reef regions, including for example French Polynesia, Kiribati, and the Great Barrier Reef (e.g., Guilcher 1988; Woodroffe et al., 2004). On the Great Barrier Reef, reticulate reef has been attributed purely to patterns of Holocene reef development on a flat and homogeneous Pleistocene basement (Collins et al. 1996). On the other hand, reticulate reef at Matiaiva Atoll in the Tuamotu Archipelago has been attributed to karstification of fossil reef during a lower stand of sea level, followed by Holocene accretion (Guilcher 1988). The origin of reticulate reef in the NWHI is unknown, although it does appear that the structures are active areas of coral reef accretion, at least in some areas. Modern rates of accretion across reticulate reef networks in the NWHI have yet to be investigated, but this is a research topic of interest from both academic and resource management perspectives.

14.4.2 Spur and Groove Morphology

14.4.2.1 Spur and Groove Formation

One structural pattern, which emerges in many areas across the globe where scleractinian corals are found, is spur and groove reef. Named for the corrugated pattern of alternating coral ridges and troughs that make up the reef's surface, these features are oriented in the direction of wave travel during typical wave conditions. Spur and groove can be seen in aerial and satellite photographs to curve in accordance with the refraction of waves as they approach shore.

Found in fore reef environments which experience moderate to high wave intensity, spur and groove morphology is the result of complementary processes: elevated rates of carbonate accretion on the coral spurs, and accelerated erosion of reef framework in the grooves. The relative importance of these processes to spur and groove formation varies between locations and through time depending on environmental conditions. Regardless of the balance at any given reef, as suggested by Figure 14.25, elevated wave energy accelerates spur and groove formation; both accretion and erosion have been shown to independently accelerate spur and groove formation with increased wave energy (Cloud 1959; Goreau 1959; Kan et al. 1997; Shinn et al. 1981; Sneh and Friedman. 1980; Wood and Oppenheimer 2000).

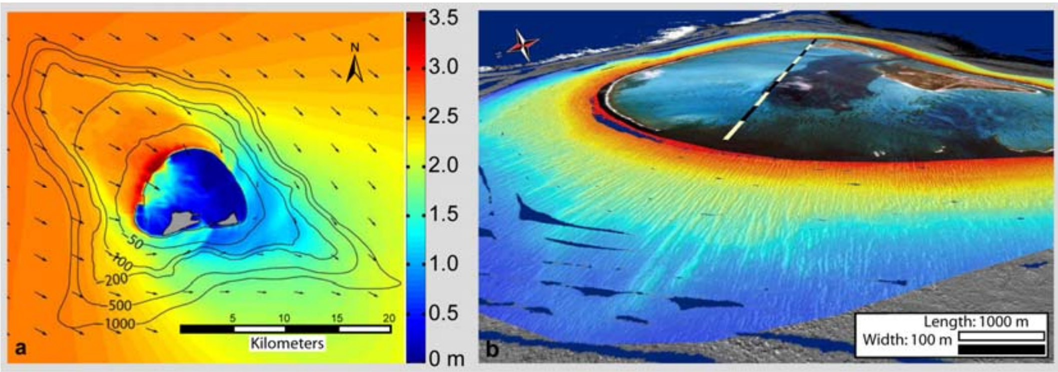

Figure 14.25 (a) A plot of significant wave height generated by a typical northwest storm swell at Midway Atoll, as calculated by the Simulating Waves Nearshore (SWAN, http://vlm089.citg.tudelft.nl/swan/index.htm) model, version 40.51. The northwest swell is the most powerful wave field in the north central Pacific, and consistent with that, model results show high wave energy concentrated on the northwest side of the atoll. Note the wave shadow (in blue) to the southeast of the atoll. (b) A perspective view of Midway from the northwest illustrates preferential spur and groove development in the area most exposed to the northwest swell. Color indicates depth. Spurs extend to a depth of 60 meters (blue). For scale, the 1 km long black and white bars shown in the foreground are overlain across the top of the atoll and indicate a lagoon diameter of approximately 10 km.

The spacing of spurs is controlled by wave power, a function of wave height and period (Munk and Sargent 1948; Roberts et al. 1975; Storlazzi et al. 2003) and may be a harmonic response to the dominant frequency of breaking waves (Shinn et al. 1981). The spur and groove zones found in shallow and more energetically exposed reef tracts tend to have a low amplitude, high frequency morphology. In contrast, spur and groove structures which are more protected by depth and or wave exposure angle develop a high amplitude, low frequency profile (Roberts et al. 1975, Storlazzi et al. 2003). Storlazzi et al. (2003) also found that spur and groove dimensions are relatively stable across depths on high energy reef tracts, but exhibit great variability across depths in more sheltered environments. The tallest, most widely spaced spurs were found in deep, relatively quiescent conditions where only the occasional large swell influences the bottom.

14.4.2.2 Spur and Groove Morphology in the NWHI

Spur and groove geomorphology has been identified at seven locations in the Northwestern Hawaiian Islands, although further mapping may identify more locations. From south to north they are: West Nihoa Bank, French Frigate Shoals, Middle Brooks Bank, Lisianski Island, Pearl and Hermes Atoll, Midway Atoll, and Kure Atoll. Spur and groove features are found on islands and atolls distributed across the NWHI, at a wide range of depths and wave intensity regimes. They can be divided into deep, relict features and shallow, actively developing features. Spur and groove reefs restricted to depths greater than 20-30 meters and unconnected to shallow spur and groove on the fore reef are likely relict features from lower sea level stands. Strong wave action may be forcing sediment scour sufficient to perpetuate pre-existing spur and groove structures, but it is unlikely that their development was initiated at such depths. Deep spur and groove has been observed on West Nihoa and Middle Brooks Banks as well as offshore of some of the atolls, at depth ranges of approximately 40-60 m.

Shallow spur and groove features become better defined and exhibit greater vertical relief to the northwest in the NWHI. French Frigate Shoals has one small area of well-developed spur and groove and a perimeter of moderate-amplitude spur and groove restricted to shallow depths. Lisianski exhibits only small, isolated areas of low amplitude spur and groove limited to shallow depths. The fore reef perimeters at Pearl and Hermes, Midway, and Kure Atolls on the other hand are almost entirely encircled by well-defined spur and groove features which extend down to 60 meters at Midway and Kure (Figure 14.6). Furthermore, the large expanse of high-amplitude spur and groove across the bank tops of Kure and Midway are unmatched anywhere else in the Northwest Hawaiian Islands.

14.4.3 Sea Level Notches and Terraces

14.4.3.1 The Distribution of Sea-Level Notches and Terraces in the NWHI

Morphological features related to former sea-level stands including terraces and notches have long been recognized in the Hawaiian Archipelago on land and beneath the sea. Terraces are characterized by gently sloping shelves created when sea level remained constant long enough for wave action to carve them into the host substrate. In some cases, carbonate-secreting marine organisms may have accreted on top or along the seaward or outer edge of the eroded surface, widening or otherwise modifying its shape. Sea-level notches may be found along the landward or inner edges of terraces, with some of the original host material remaining in place above the eroded notch. The presence of an overhanging visor above a notch indicates a period of relatively constant sea level during which the notch was formed by a combination of biological and mechanical erosion. The still stand was then followed by a rapid rise in sea level that was large enough to flood the overhanging visor to a depth sufficient to remove it from the zone of active erosion, thereby preserving it (Fletcher and Sherman 1995). The identification and cataloging of sea-level notches and terraces are important for developing a record of paleo-sea level in the Hawaiian Islands, which may in turn contribute to our understanding of global climate change.

Attempts have been made to correlate sea-level terraces and notches across the MHI to investigate a wide range of topics including Quaternary sea-level change and tectonic subsidence related to volcanic loading. However, little attention has been paid to similar features in the NWHI because of difficulties associated with accessing the remote banks and atolls. Recent efforts have been made to collect high resolution multibeam bathymetry and backscatter imagery from the atolls and banks in the NWHI (Miller et al. 2004, http://www.soest.hawaii.edu/pibhmc/) and have surveyed approximately 30% of the seafloor between depths of 20 m and 500 m. These data have enabled the following identification of sea-level terraces and associated features.

The low-elevation carbonate islands, atolls, and shallow flat-topped banks in the NWHI all have a major break in slope that ranges between depths of -100 to -200 m at different islands. The break is characterized by a significant change from gently sloping shallow seafloor to the steep and heavily eroded submarine flanks of the islands. The islands, atolls, and flat top banks shallower than -50 m in the NWHI also have terraces at a variety of depths shallower than -100 m eroded into the side of the islands by prolonged periods of relatively stable sea level.

At both Kure and Midway Atolls a series of discontinuous terraces at depths of -30 to -60 m with steep slopes along their outer edges can be traced only part way around the atolls. The terraces are best preserved on the south and east sides where exposure to large northwest swell energy is reduced. On both atolls spur and groove features originate at the fringing reef edge and often correlate further down slope with gullies that cross the shallow terrace ledges.

At Pearl and Hermes Atoll, a terrace at ca. -90 m encircles almost the entire atoll, but lacks a prominent seaward ledge which makes the feature hard to distinguish. A series of terraces at -30 to -70 m on the west side of the bank become narrower and eventually disappear on the northwest side of Pearl and Hermes where the atoll flank is locally very steep.

Multibeam data are currently available only from the southwestern side of Maro Reef, but indistinct terraces are present just above the major slope break at ca. -100 m and at -45 to -55 m. A prominent 10-15 m high ledge on its seaward side and steep slope with a notch cut at its base helps to distinguish a terrace at -28 to -32 m. Linear gullies and channels cross the terrace edge and the terrace top exhibit varied seafloor morphologies, including expansive sand fields and channels dotted with pinnacles and hard bottom areas with rough topography.

On the southwestern bank at French Frigate Shoals, two terraces exist above the major slope break. The deeper terrace at ca. -50 m is discontinuous and does not have a pronounced ledge, whereas the more prominent terrace at -25 to -35 m terminates seaward at a 5-15 m high ledge. Gullies cross the ledge and isolated blocks of material and notches are present at the base of the scarp on its landward side. The morphology of the shallow terrace suggests that coral reef has accreted on top of it. The seaward edges of the prominent shallow terraces at Maro Reef and French Frigate Shoals are distinguished in the backscatter data by a distinct change in acoustic intensity. Intensity ranges from high on the outer edge of the terrace and on the steeper slopes above and below it to low along the inner margin of the terrace. Backscatter results suggest that the shallow terrace serves as a sink for sediment that is washed out of the atoll.

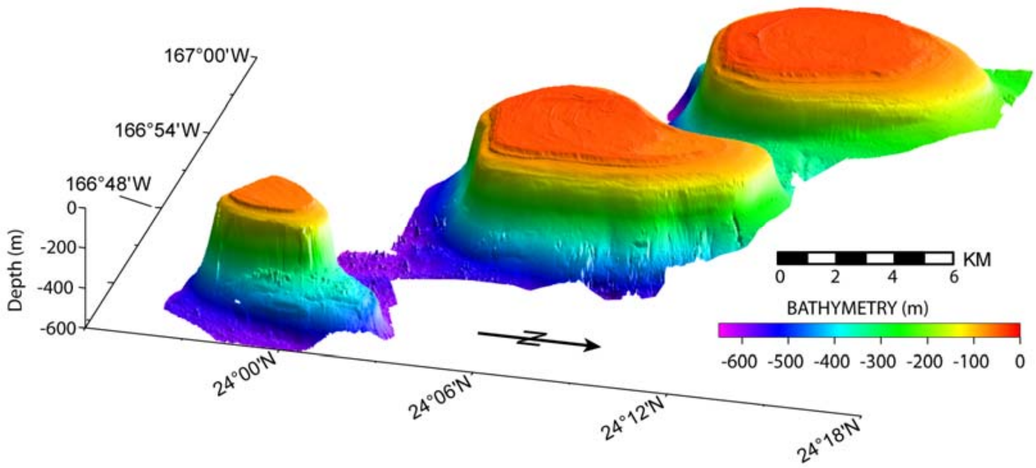

Figure 14.26 Perspective view of Brooks Banks as seen in Multibeam bathymetry (http://www.soest.hawaii.edu/pibhmc/pibhmc_nwhi_utm3n_Brooks.htm) looking from the northeast. The flat-topped and terraced nature of submarine banks in the NWHI is exemplified by East, Middle, and West Brooks Banks. The major break in slope on each is below 100 m. A prominent terrace at a depth of 58-65 m on East Brooks can be correlated with similar features on Middle and West Brooks banks. A terrace at 35-40 m is present only on Middle and West Brooks banks. We hypothesize that arcuate and linear ridges present on top of the shallow terrace are drowned reef or beach rock deposits. Blocky material interpreted as probable mass wasting and landslide debris is present at 350 m on the northeast flank of East Brooks.

Flat submarine banks in the NWHI were planed off by erosion when their tops were subaerial or just below sea level. The Brooks Banks are four neighboring flat-topped banks northwest of French Frigate Shoals that include, from southeast to northwest, Southeast Brooks, East Brooks (EB), Middle Brooks (MB), and West Brooks (WB) Banks (Figure 14.26). The major break in slope on all three is at -100 to -120 m except on the southwestern side of EB where a portion of the bank edge is missing. We interpret this as a probable landslide head wall because comparable smaller features occur on the northwest flank of EB, and blocky material lies down slope at -350 m. Equivalent features in the MHI were similarly interpreted by Mark and Moore (1987). EB is the smallest of the three banks, with a prominent terrace at -58 to -65 m, marked by a 10-15 m high steep slope on its seaward margin. Both MB and WB are shallower and larger than EB. Outer terrace edges are well defined on both banks at -60 to -65 m and -35 to -40 m. The tops of all three banks gradually deepen to the north, possibly reflecting more erosion due to the impact of north and northwest swell energy, or karst processes during periods of subaerial exposure. The origin of curious linear and arcuate ridges on the tops of MB and WB is uncertain, but we hypothesize that they may be reef or beachrock deposits.

In summary, on the more northerly NWHI such as Kure and Midway Atolls sea-level terraces and notches are difficult to distinguish but generally group in the -30 to -60 m depth range. On the more southerly banks and atolls, wave-cut terraces and notches are more easily distinguished and group into depth ranges similar to those identified in the MHI. One group of features lies in the -45 to -65 m range and may correlate with the Penguin Bank shoreline complex (pbsc), while another group at -25 to -45 m appear in a similar depth range to the Kaneohe shoreline complex (ksc) (Colbourn et al. 1974; Fletcher and Sherman 1995). Fletcher and Sherman (1995) suggest that the pbsc and ksc may have been formed during MIS 3 (ca. 50-64 ka) and MIS 5 (ca. 79-110 ka), respectively.

As with similar features in the MHI, sea-level terraces and notches in the NWHI are discontinuous and difficult to recognize and correlate between different islands. The problems with identifying a single feature on all sides of all islands are probably due to a combination of erosion, burial, and because terraces may have never formed in certain locations (Colbourn et al. 1974). Additionally, a single terrace may have been occupied by sea level on more than one occasion, and our understanding of paleosealevel is rudimentary, making it difficult to correlate the formation of any given terrace or notch to a specific period of time. The large distances between the islands and banks of the NWHI and the drastic differences in island and bank size further complicate the situation. However, sea-level features in the NWHI group into general depth ranges that, especially in the younger NWHI, may correlate with features at similar depths in the MHI. Further analyses and additional data are needed to better understand the history of sea-level terraces and notches across the Hawaiian Archipelago.

14.4.3.2 Drowned Sea-Level Notches and the Endangered Hawaiian Monk Seal

Monk seals were first documented using shallow submerged caves in the early 1980s when divers encountered them during surveys of the shallow reefs of the Northwestern Hawaiian Islands region as part of the multi-agency NWHI tripartite investigation. The seals were observed wedged into tidal and sub-tidal cracks and sea caves of the basalt islands of Gardner Pinnacles, La Perouse Pinnacle, and the islands of Necker, Nihoa, Kaula, and Lehua. Similar sheltering by seals has been seen in shallow reef caves just offshore from the sand islets of the atolls. Seals were thought to use these caves as a refuge from predators and to avoid social competition with other seals for the limited beach area on the few sand islets of the atoll.

Figure 14.27 Monk seal and French Frigate Shoals outfitted with a CRITTERCAM. Photograph by Birgit Buhleier.

Between 1995 and 2001, computer controlled video cameras (National Geographic Television's CRITTERCAMs (Figure 14.27)) were attached to monk seals at French Frigate Shoals to identify key foraging habitats. A total of 42 cameras were deployed on adult males and 9 juveniles (male and female) collecting 69 hours of underwater surveillance. Twenty-eight of the seals were seen to take up stationary positions on the bottom. Half would make a series of prolonged broadcast vocalizations, and the rest appeared to be sleeping. Vocalizations were limited to the adults (only males were instrumented) and occurred on open bottom. The resting seals used overhangs and ledges of the bottom as dens. The resting episodes were as long as 15 hrs during which the seals were motionless except for periodic subdued trips to surface to take a breath.

Documentation of this underwater resting redefines surface-based perspectives of the monk seal foraging. Early foraging estimates used the seals time away from the beach as a measure of foraging effort when in fact considerable time spent away from the beach is spent resting in underwater caves. More interesting is the fact that underwater caves are clearly a resource the seals exploit and are an important component in the seal's submarine landscape. The underwater caves include reef caves and sea level notches (Figure 14.28). Reef caves are generally ledges and voids formed as part of the configured structure of the reef matrix. Monk seals were seen resting in these structures at depths as shallow as the intertidal and as deep as 20 m. Sea level notches are submerged ledges and sea caves that occur considerably deeper and have been carved out of the base carbonate by ocean waves and bioerosion during previous low stands of prehistoric sea level.

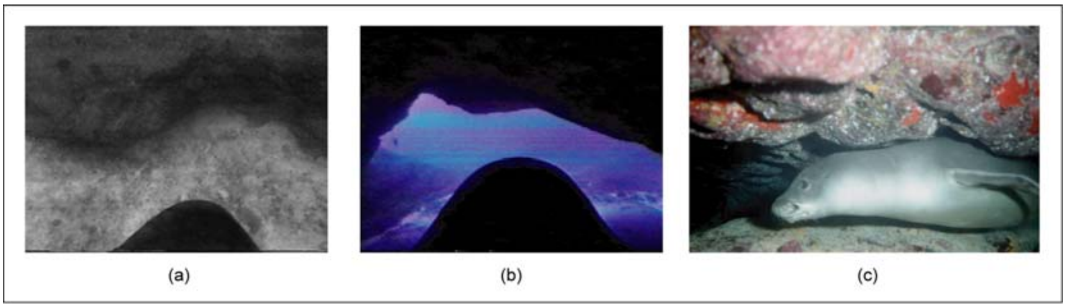

Figure 14.28 Video grabs from monk seal CritterCams, courtesy of the National Geographic Mission Program. Monk seal resting habitat on Brooks Banks. (a) Overhead view of a sea level notch or overhang imaged by CritterCam. (b) CritterCam view of the entrance of a cavern used as a resting spot by Monk seals. (c) Monk seal at rest in a cave.

Monk seals are generally solitary animals and space is limited on the sand islets of the atoll. Use of the underwater caves provides a means to rest at sea without drifting off site. It also affords concealment from predators and other seals. Most of the resting was seen inside of the atoll close to the seals haulout beaches, but some were at the neighboring banks including the sea level notch of SE Brooks and the summit reef caves of Middle Brooks. In general, the banks of the NWHI are low relief tracts of seafloor (Parrish and Boland 2004, Kelley et al. 2006). Thus, areas with caves represent a limited resource that seals are likely to identify and revisit to rest and extend their foraging range to more remote grounds. Future studies should assess the degree to which such undersea features influence the foraging behavior and at sea movements of the endangered Hawaiian monk seal.

14.4.4 Drowned Islands and Banks

14.4.4.1 Darwin Point

Kure Atoll has the farthest north emergent land in the Hawaii-Emperor Chain, with all of the 63 seamounts and guyots further north than Kure (Clague 1996) now permanently below the depth at which coral reef can accrete. Rotondo (1980) determined that over at least the past 20 Ma the latitude at which guyots north of Kure drowned, or subsided below the depth at which coral reefs can accrete, ranged no further north than between 27-31° N. Building on Rotondo's results, Grigg (1982) coined the term Darwin Point to refer to a threshold for atoll formation and stated that a Darwin Point exists at the northern end of the Hawaiian Archipelago at 29° N latitude, where Kure Atoll is located. Grigg (1982) states that the reef at Kure has kept pace with sea level, but that the mean growth rate for corals there (0.2 mm/yr) represents 22% to 60% of the carbonate necessary to keep pace with sea level rise. Grigg (1982) further suggested that the additional 40-78% of the required carbonate is produced by other calcareous organisms such as coralline algae, molluscs, bryozoa, etc.

Results from studies in the MHI mentioned earlier suggest that the fore reef at Kure and other islands and atolls of the NWHI are generally not accreting. However, rapid growth rates of corals from inside the reef crest (Siciliano 2005), and the presence of mid-Holocene age emergent fossil reef (Gross et al. 1969) suggest that accretion in these areas may be able to keep up with moderate rates of sea level rise. A program of reef coring at Kure would help to elucidate Holocene patterns of reef accretion and evaluate the atoll's potential to adapt to rates of accelerated sea level rise projected for the future by some studies (Ragnat and Kanagaratnam 2006).

14.4.4.2 Drowned Banks

In addition to the islands and atolls in the NWHI that have emergent land, a number of drowned banks are also found there at a range of depths. It has been suggested that the reason that some islands manage to keep up with sea level rise while others do not may be related to erosion by high wave energy. Grigg (1982) points out that there is a negative correlation between the surface area of bank tops and drowning of banks. Exploring that idea further, Grigg and Epp (1989) identified a total of 37 islands, atolls, and banks in the NWHI with summits shallower than -200 m. They calculated the summit area of these banks as the area enclosed within the -180 m (100 fathom) contour and their summit depth as the shallowest flat surface area exceeding 1.0 km^2. Plotting results for all 37 islands and banks, they found that the logarithm of bank summit area is inversely related to depth. Noting that the flat tops of the banks suggests that they were all truncated by wave action, Grigg and Epp (1989) hypothesize that smaller banks are truncated faster and to deeper depths than larger banks. Once eroded to deeper depths, banks are more likely to be found below the critical depth of -30 to -40 m. Below these depths, it is unlikely that they will be able to accrete significant volumes of coral reef and maintain the bank's position near the surface under even very moderate rates of relative sea level rise.

We note from Grigg and Epp's (1989) data that there are no bank tops between depths of ca. -70 m and -110 m. A cluster of bank summits are found at depths of ca. -50 to -70 m, and additional bank tops are found below -110 m and above -50 m. We hypothesize that the banks in the shallower cluster (-50 to -70 m) were above the -30 to -40 m critical depth of drowning for coral reefs (Grigg and Epp 1989) during MIS 3 and so were able to actively accrete coral reef. This hypothesized accretion may have enabled the banks to both increase their summit area and decrease their depths during the 30 kyr duration of MIS 3. Banks below the gap (i.e., currently deeper than 110 m) were likely below the critical depth during MIS 3 and unable to accrete coral reef. Vertical reef accretion at a modest 1.3 mm/yr is sufficient to generate a 40 m depth difference between the tops of bank summits above and below the -70 to -110 m gap. This scenario is reasonably consistent with estimated depths of sea level during MIS 3 of approximately -50 to -80 m below present sea level (Lea et al. 2002). This issue could be addressed by sampling and dating carbonate from the cluster of bank tops in the -50 to -70 m depth range, and from those below -110 m.

14.5 Future Research

The paucity of work on geologic aspects of reef development in the NWHI is not surprising considering the logistical difficulties associated with work in this remote area. However, as a result, a number of significant questions remain to be answered regarding late Quaternary reef accretion and relative sea level change in the NWHI. With unprecedented rates of climate change predicted to fundamentally alter many of the biogeochemical processes both globally and in the NWHI, the urgency of addressing these questions and improving our understanding of these processes is greater than it has ever been. Although the NWHI are well protected from direct human impacts, they remain highly vulnerable to the significant climate change-related threats of coral bleaching and disease, ocean acidification and decreased calcification and accretion rates, sea level rise, and others. It is important to begin improving our understanding of past and present biogeochemical processes in the NWHI as soon as possible. Through improved knowledge and understanding of these processes, past, present, and future, our ability to identify and assess options to increase resilience and long-term adaptability and sustainability of these ecosystems will be enhanced. A few of the most important research needs have been pointed out in the preceding pages and are reviewed below.

The collection and processing of high-resolution multibeam bathymetry for shallow to moderate (-20 to -500 m) depths in the NWHI is only about 30% completed, but should clearly be continued. Most of the seafloor shallower than -20 m is characterized by occasional soundings. Depths have been estimated using satellite imagery, but those data have numerous gaps due to cloud cover and are found to be unreliable below about -12 m. The development of complete and seamless digital terrain and bathymetry models for all the NWHI to a depth of at least -500 m would be a significant asset for unraveling patterns of reef development and for a host of other research and management needs. There is an active program of multibeam mapping in the NWHI (http://www.soest.hawaii.edu/pibhmc/pibhmc_nwhi.htm). A complementary effort to map emergent land and shallow water areas using bathymetric Light Detection and Ranging (LIDAR) is recommended.

Results of the Oahu relative sea level curve are reasonably consistent with the eustatic and equatorial sea level curves discussed above and are used as a proxy for relative sea level in the NWHI. However, the limited temporal extents of the Oahu curve and lack of data from the NWHI make it difficult to interpret patterns of coral reef and coral island development in the NWHI and to predict future morphologies. The development of a sea level curve for the NWHI would provide an important tool for these efforts, as well as a representative dataset for the central North Pacific gyre, which would be of interest to paleoclimatologists and others. A program of fossil reef coring such as has been conducted on Oahu and other MHI in recent years (http://www.soest.hawaii.edu/coasts/research/index.html) would be very helpful for developing a sea level curve.

Further mapping and analysis of sea level terraces and notches, and constraining their ages of formation through core analysis, would also contribute to our understanding of past sea levels in the NWHI. Mapping of these features would also be a critical step towards better understanding their influence on the foraging patterns of the endangered Hawaiian monk seal.

In the face of predictions of accelerating sea level rise and ocean acidification, determining "whole reef" accretion rates in different geomorphic zones at a range of islands and atolls across the NWHI would be useful. In particular, accretion rates from reef crest areas have significant implications for the fate and management of terrestrial and lagoonal habitats in the NWHI which, in turn, are important to the many marine species with links to these habitats. Reef crests may prove to be "keystone areas" for the protection of environments inside atoll rims from some of the effects of sea level rise. Concurrent with examining whole reef accretion rates, it is necessary to understand the spatial and temporal structure of seawater carbon chemistry cycles and their impact on calcification and accretion processes. If accretion is sufficient to keep pace with future rates of relative sea level rise, terrestrial and lagoonal environments in the NWHI may continue to enjoy whatever current protection they have from ocean swells. Determining long-term rates of reef crest accretion through core analysis, and monitoring of reef crest benthic communities, are required to effectively address this important issue and should be a management priority.

Rates of terrestrial habitat loss and the factors that cause it are critical for several endangered or threatened species in the NWHI. A study of historical shoreline change using existing survey charts and aerial photographs may be able to provide a longer-term perspective of the evolution of islands and islets of the NWHI than currently exists. Such a perspective may be of particular importance to shoreline dynamics, given the multi-decadal nature of climatic fluctuations such as the Pacific Decadal Oscillation (PDO), which have been shown to influence shoreline processes in the MHI (Rooney and Fletcher 2005). Also, an understanding of the patterns and causes of long-term change are critical to the design of effective measures to mitigate terrestrial habitat loss.

Continuous time series of surface and subsurface temperatures, salinity, and wave energy from existing instrument networks in the NWHI (http://www.pifsc.noaa.gov/cred/oceanography.php) are of only a few years duration. It is hard to interpret the geological significance of measurements, such as temperature spikes associated with recent bleaching events (Hoeke et al. 2006; Kenyon and Brainard 2006), without a longer-term context in which to evaluate them. Records of SST and salinity covering periods of decades to as much as a century or longer can be developed using stable isotope analyses of cores extracted from large living coral colonies. These data would be of use to both local resource managers as well as to the climate change research community.

It was noted earlier that there are no bank tops between depths of ca. -110 m and -70 m in the NWHI, but that a cluster of banks do exist at depths of ca. -70 to -50 m. We hypothesize that the banks in that cluster were above the -30 to -40 m critical depth of drowning for coral reefs (Grigg and Epp 1989) and so were able to actively accrete coral reef during MIS 3. This issue could be addressed by sampling and dating carbonate from this cluster of bank tops in the -50 to -70 m depth range and from bank tops below -110 m.

The studies suggested above are but a small sample of some of the more obvious and pressing of a wide range of other geologically related research topics waiting to be addressed in the NWHI. This chain of islands, banks, and atolls is unique in terms of the high latitude of its northwesterly atolls, the wide geographic range it covers, the high percentages of endemic species that inhabit it, and the high degree of protection from anthropogenic disturbance it has received over the last century. We anticipate that work in these extraordinary islands over the next few decades will make significant contributions to our understanding and management of coral reefs around the world.

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