Introduction

View of south Molokaʻi, looking eastward from hills above Hale O Lono.

View south from Moloka‘i Shores condominium complex. The island of Lana‘i is in the background.

INTRODUCTION

The South Moloka‘i Reef: Origin, History, and Status

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Moloka‘i is the fifth youngest island in the long chain of volcanoes and volcanic remnants that compose the Hawaiian archipelago (fig. 1). The archipelago extends from the Island of Hawai‘i (the “Big Island”) in the southeast past Midway Island, to Kure Atoll in the northwest, for a total distance of about 2,400 km (1,500 mi). Beyond Kure Atoll, the chain continues as a series of submerged former islands known as the Emperor Seamounts, which extend to the Aleutian Trench off the coast of Alaska. Evolution of the entire Hawai‘i-Emperor volcanic chain represents a time span of nearly 80 million years (Clague and Dalrymple, 1989). The volcanic chain is a result of gradual and persistent movement of the Pacific lithospheric plate (the sea-floor crust and rigid uppermost part of Earth's mantle) over a deep fracture (or hot spot) that extends down to the astenosphere, a less rigid part of the mantle (fig. 2). Plumes of molten lava flowed onto the sea floor, repeatedly creating massive shield volcanoes that exceed 10,000 m (33,000 ft) in relief above the surrounding sea floor. The growth of each volcano is a process that takes half a million years or more to construct most of its mass through sequential volcanic phases—submarine, explosive, and subaerial—of shield growth.

Once formed, each massive island volcano is carried northwestward on the Pacific tectonic plate at rates of 8.6 to 9.2 cm/yr (Clague and Dalrymple, 1989). The postshield processes of alkalic volcanism, subsidence, landslides, rejuvenated volcanism, weathering, sediment deposition, and reef growth have all markedly influenced each volcano’s present-day shape. Subsidence of each island is rapid at first (rates of 2 mm/yr or more; Moore and Campbell, 1987; Moore and Fornari, 1984; Campbell, 1986) in response to the extraordinary weight of large volumes of lava loaded onto the crust. As each island cools and slides northwestward with the sea-floor crust, it continues to subside at decreasing rates, down to the order of 0.02 mm/yr (Detrick and Crough, 1978). The sheer volume of rock that accumulates at each volcano ultimately leads to failure and partial collapse—each island has had spectacular landslides that are amongst the largest on earth (Moore and others, 1989). The large areas of irregular topography on the sea floor around the islands (for example, north of Moloka‘i and northwest of O‘ahu) attest to the magnitude of these events (fig.1).

The normal processes of surface erosion and stream runoff modify volcano slopes early in an island’s history. Those processes, along with development of soils, which occurs relatively quickly in humid volcanic terrain, lead to transport and deposition of sediment in alluvial fans, flood plains, and narrow coastal plains. The final process in island shaping is the establishment of coral reefs in shallow waters that are protected from large waves. Corals colonize exposed rock surfaces very quickly (Grigg and Maragos, 1974; Grigg, 1983), and it is likely that they become established early in the evolutionary history of each island. The development of coral reefs—the massive limestone structures capped by a living ecosystem that border many Hawaiian Islands—takes much longer (Grigg, 1987). Each reef is a thick (meters to tens of meters) packet of reefal limestone that likely accumulated over multiple stages of sea-level shifts (Grossman and others, 2006; Grossman and Fletcher, 2004; Sherman and others, 1999). In most locations in Hawai‘i, modern coral cover is only a thin living veneer on top of older reef structures that formed during an earlier time under different conditions (Grigg, 1983, 1998)

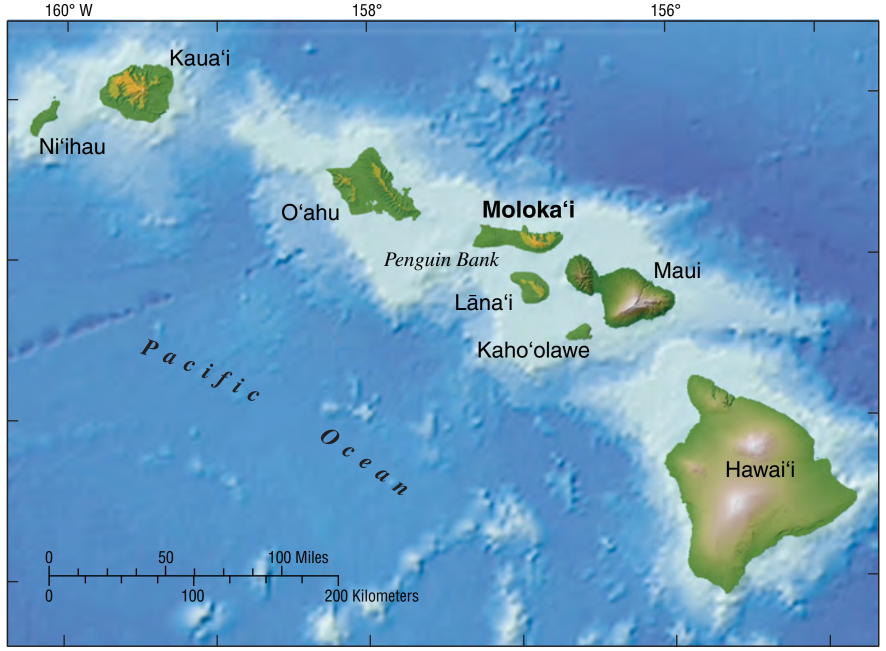

Figure 1. Physiographic map of the eight main Hawaiian Islands, which are the most recent additions to the approximately 2,400-km (1,500-mi) -long Hawaiian chain of islands, atolls, and pinnacles that extends from the Island of Hawai‘i (the “Big Island”) northwest to Kure Atoll. Moloka‘i formed between 2.0 and 1.7 million years ago and is the fifth youngest in the line of more than 107 volcanic edifices in the Hawaiian chain (Clague and Dalrymple, 1989). Only the volcanoes forming Lāna‘i, Maui, Kaho‘olawe, and Hawai‘i are younger.

Moloka‘i—Making of a Unique Island

Despite the similarity in origin and physical processes that it shares with the other Hawaiian Islands, Moloka‘i is unique in many ways. Its marked east-west orientation and its relatively storm- and wave-protected south shore are two important factors that have contributed to development of a spectacular coral reef that is perhaps the most extensive and continuous fringing reef in the Hawaiian chain.

In its original configuration, Moloka‘i was part of a very large island (Maui Nui) that included Lāna‘i, Maui, Kaho‘olawe, and Penguin Bank (fig. 1). As the massive, contiguous island subsided, Moloka‘i, Lāna‘i, and Penguin Bank became an island separate from the others about 300,000 to 400,000 years ago (Juvik and Juvik, 1998). Penguin Bank eventually submerged, and Lāna‘i and Moloka‘i became separated by a small chan-

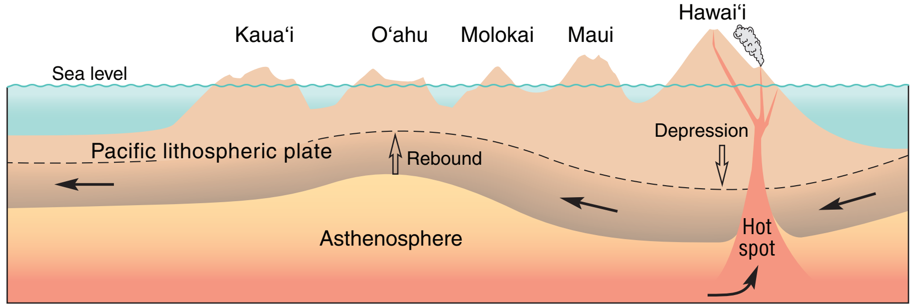

Figure 2. Diagram illustrating the formation of the Hawaiian volcanoes by the eruption of lava rising from a “hot spot”—a thermal plume emanating from deep in the Earth’s mantle. As the Pacific Plate of the lithosphere moves northwestward at rates of about 9.0 cm/yr (3.5 in/yr), a new volcano forms over the hot spot every 100,000 to 500,000 years. Vertical arrows show the depression of the lithosphere under the island of Hawai‘i from the weight of newly formed volcanic edifices and the subsequent rebound of the lithosphere (as shown under O‘ahu) surrounding the depression.

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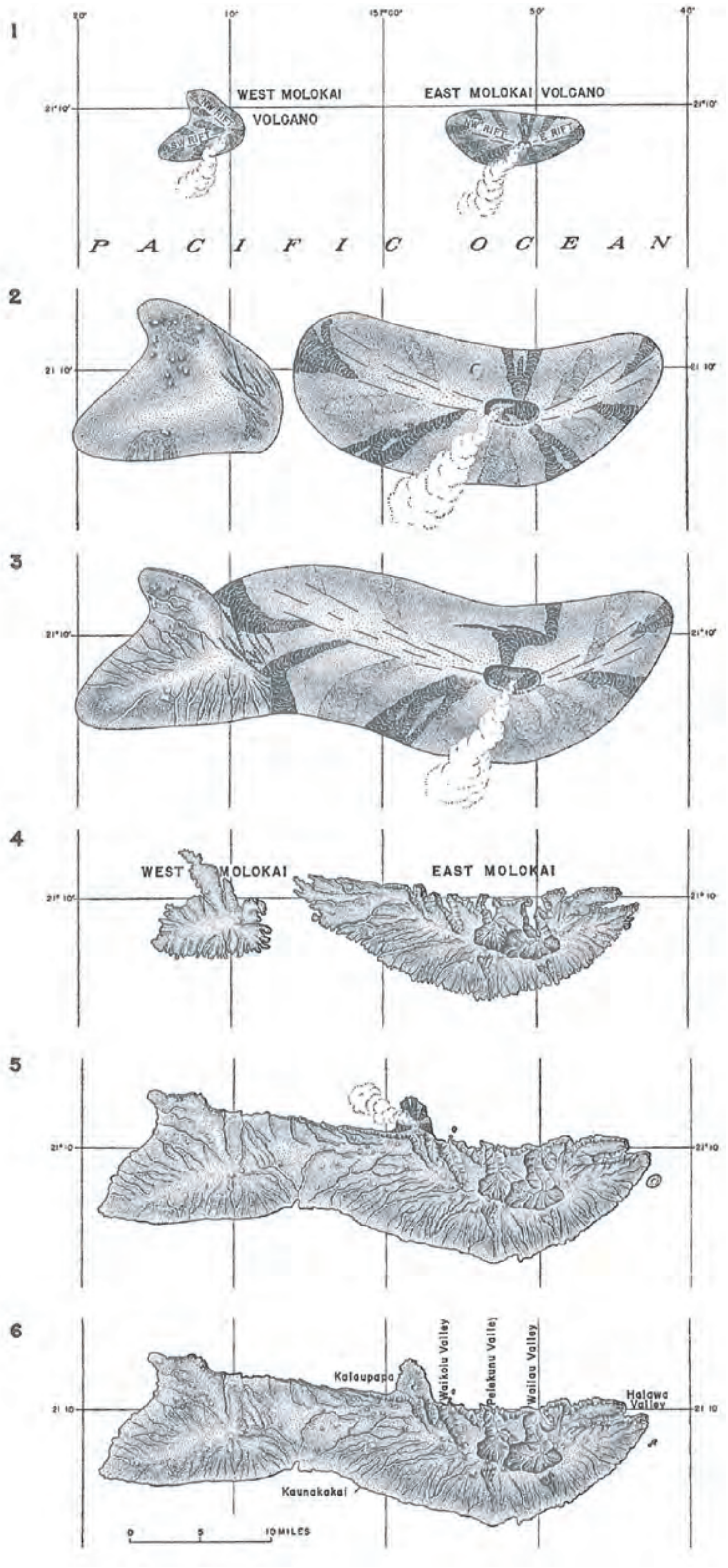


Figure 3. Original drawings from Stearns and Macdonald (1947; reproduced in Stearns, 1966) showing the development of the island of Moloka‘i. Stages 1 through 3 show the two volcanoes forming between 1.9 (west) and 1.75 (east) million years ago and converging to form a single, overlapping volcanic ediface. Stearns and Macdonald thought that the two volcanoes were isolated later by rising sea levels associated with an intergalcial period (stage 4 in the diagram). Long after Moloka‘i was formed, posteruptive volcanism produced the Kalaupapa Peninsula (stage 5). Stage 6 shows the island as it exists today. Stearns and Macdonald's work was published before anyone had inferred that giant landslides formed the pali on the north side of the island (see, for example, Moore and others, 1989), and so that episode is missing from their scenario.

nel about 100,000 to 200,000 years ago (Juvik and Juvik, 1998). The two islands were attached to each other by an isthmus on multiple occasions and as recently as 8,000 years ago, during periods of low sea level associated with global continental glaciations (Grigg and others, 2002).

Moloka‘i was built by two distinct volcanoes, west and east Moloka‘i, that formed about 1.9 and 1.76 million years ago, respectively (Clague and Dalrymple, 1989). The formation of the west Moloka‘i shield volcano (Mauna Loa) at 1.9 Ma (million years ago) was followed by a postshield phase of eruption from 1.8 to 1.75 Ma that capped the caldera (large crater at the summit of the volcano, fig. 3; Stearns, 1966). The east Moloka‘i volcano (Wailau) formed about 1.76 Ma, and it too was capped by post-shield volcanic flows (1.5 to 1.35 Ma) and a rejuvenated phase of eruptions at about 0.57 to 0.35 Ma (fig. 3; Juvik and Juvik, 1998). The geology of Moloka‘i, as originally mapped by Stearns and Macdonald (1947; fig. 4), illustrates the island's evolution by a series of distinct, sequential events: (1) formation of the west Moloka‘i volcano, (2) formation of the east Moloka‘i volcano through two sequences of volcanism, (3) formation of the high sea cliffs (pali) of the north coast by a gigantic landslide, (4) formation of a small shield volcano and caldera forming the Kalaupapa Peninsula, and (5) erosion of the volcano slopes and deposition of alluvium in channels, fan deltas, and coastal plain deposits (Stearns, 1966; Stearns and Macdonald, 1947; Walker, 1990).

The narrow shape of the island and the very high (nearly 1,200 m or 3,900 ft) pali on the northern side of Moloka‘i—among the highest sea cliffs in the world—resulted from a catastrophic landslide following the construction of east Moloka‘i volcano. The landslides that characterize the volcanoes of the Hawaiian chain are some of Earth's largest, and among the Hawaiian slides, the Moloka‘i slide (named the Wailau Slide) is one of the largest (Moore and others, 1994). A large part of the island collapsed, scattering huge volcanic blocks (as much as 6 km, or 4 mi, in diameter) and debris more than 150 km (90 mi) across the sea floor (Moore and others, 1989). Following the landslide, rejuvenated volcanism created the low-relief Kalaupapa Peninsula that abuts the cliffs of north Moloka‘i. The island of Moloka‘i today has a shape reflecting these formative processes (fig. 5).

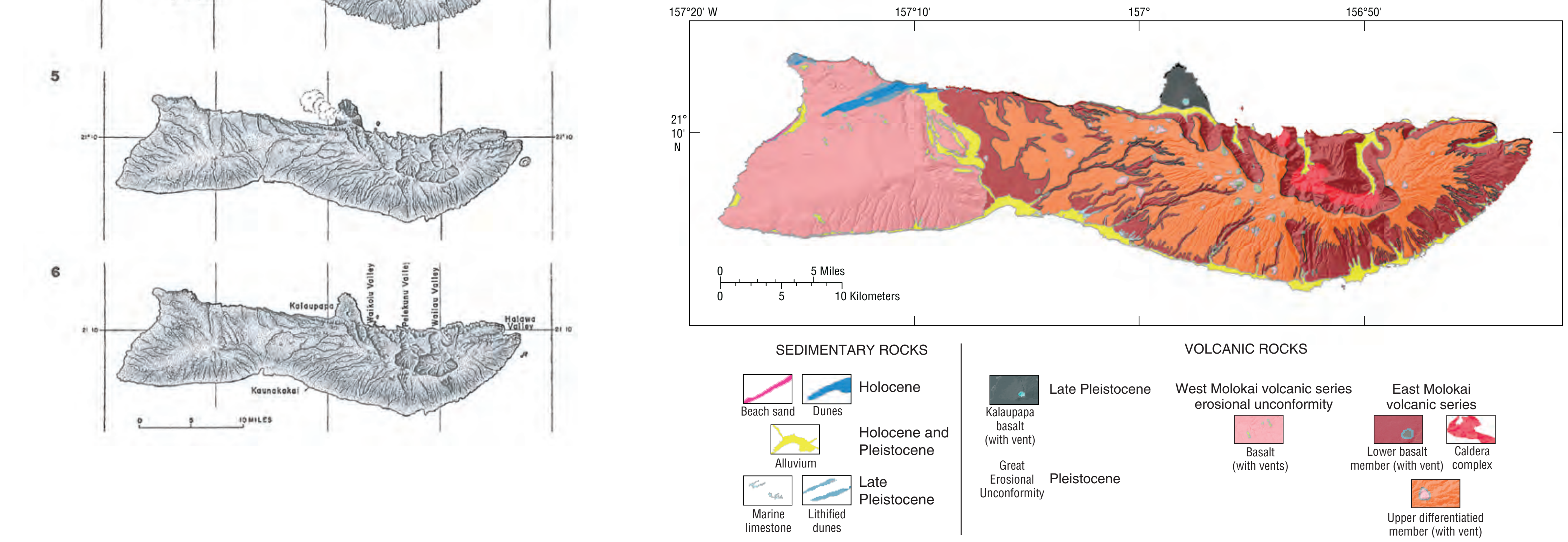
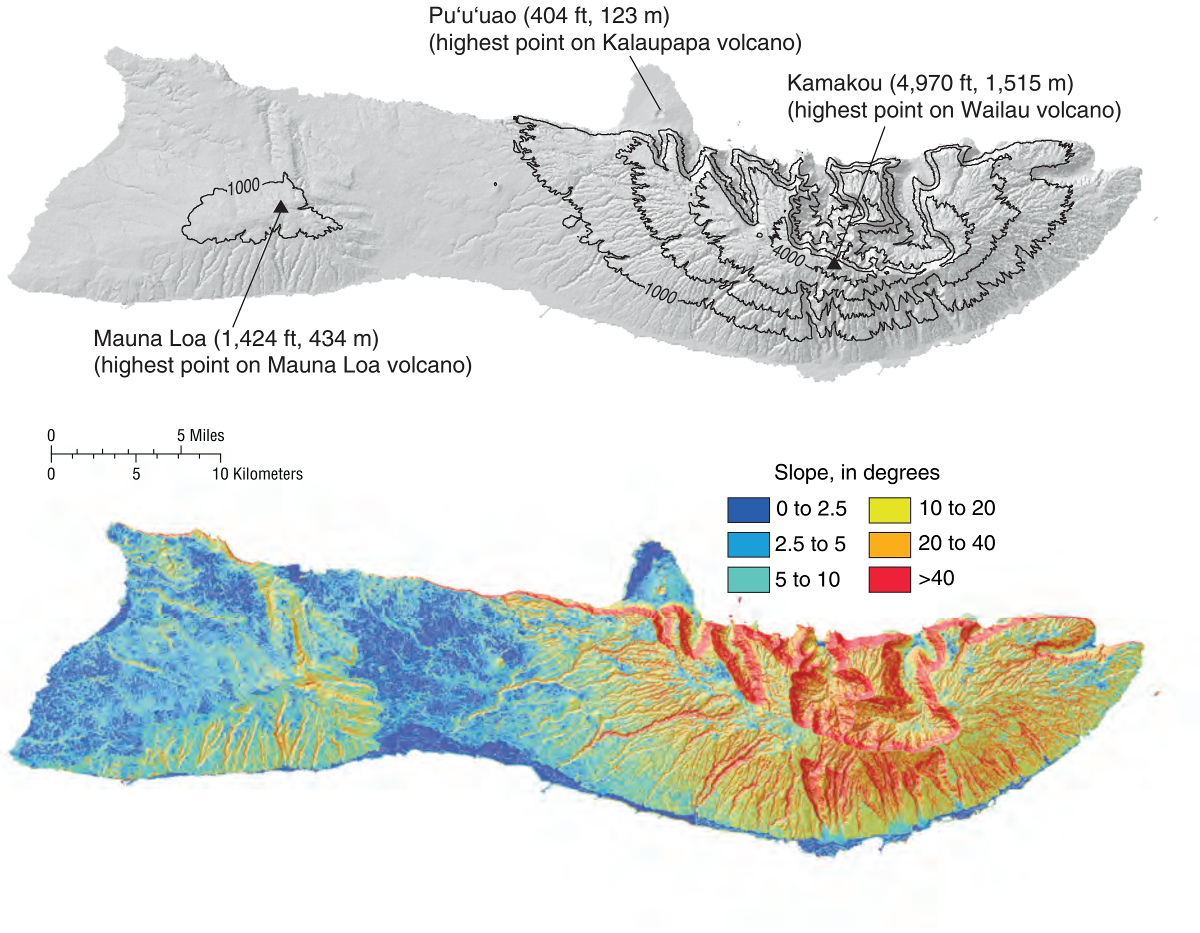


Figure 4. Geologic map of Moloka‘i, from Stearns and Macdonald (1947). Distinguishing features of the geology include the distinction between the west Moloka‘i (Mauna Loa) volcano (pink) and the layered lava flows that constitute the east Moloka‘i (Wailau) volcano (orange and rust brown), the posteruptive volcanism (dark grey) that formed the Kalaupapa Peninsula against the base of the north pali (following the giant landslides that formed those sea cliffs), and the alluvium (light green) that forms a thin band of coastal and deltaic deposits along the south coast.

Figure 5. Maps showing the topography and steepness of slopes on the island of Moloka‘i. The island is dominated by two volcanoes: Mauna Loa on the western side of the island and Wailau on the eastern side. The topographic map (top) shows the dominance—in both area and relief—of the Wailau volcano (east) over the Mauna Loa volcano (west). Mauna Loa has the gently sloping shield shape characteristic of Hawaiian volcanoes. Wailau, in contrast, has areas of steep-sided valleys and some of the highest seacliffs in the world on its northern edge. These seacliffs resulted from a giant landslide, among the largest on Earth, which bisected the Wailau volcano, leaving debris on the sea floor more than 150 km (90 mi) to the north. The Kalaupapa Peninsula is the most recent volcanic addition to the island, having been formed by eruptions subsequent to the giant landslide. The caldera of Kalaupapa (large crater at its summit) is now the site of a brackish lake nearly 240 m (800 ft) deep. On the slope map (bottom), steeply sloping land is shown in red and gently sloping land is shown in blue. The map highlights the relatively low slopes that characterize the west volcano and the Ho‘olehua saddle between the volcanoes. The steepest slopes occur on the pali on the north shore and in the deeply incised gulches on the large east volcano. The maps were derived from a U.S. Geological Survey 10-m digital elevation model (DEM).



Moloka‘i Today: Climate, Land, and the Reef

Seasons, Trade Winds, and Rainfall

Early Hawaiians recognized only two six-month seasons, “kau,” when the weather was warmer and the trade winds blew steadily, and “ho‘oilo,” when the weather was cooler and the trade winds were less consistent (Western Region Climate Center, 2006). Weather analysts today recognize these two seasons with a slight modification: the winter season, ho‘oilo, is seven months (October through April) and the summer season, kau, is only five months (May through September). Rainfall, wind, and storm patterns are quite different for the two seasons. The summer season is warmer, drier, and dominated by northeast trade winds, and widespread rainstorms are rare. In the winter season, temperatures are cooler, trade winds diminish, and low-pressure storm systems bring rain. Each of these two seasons is influential in shaping the land and transporting sediment to the ocean.

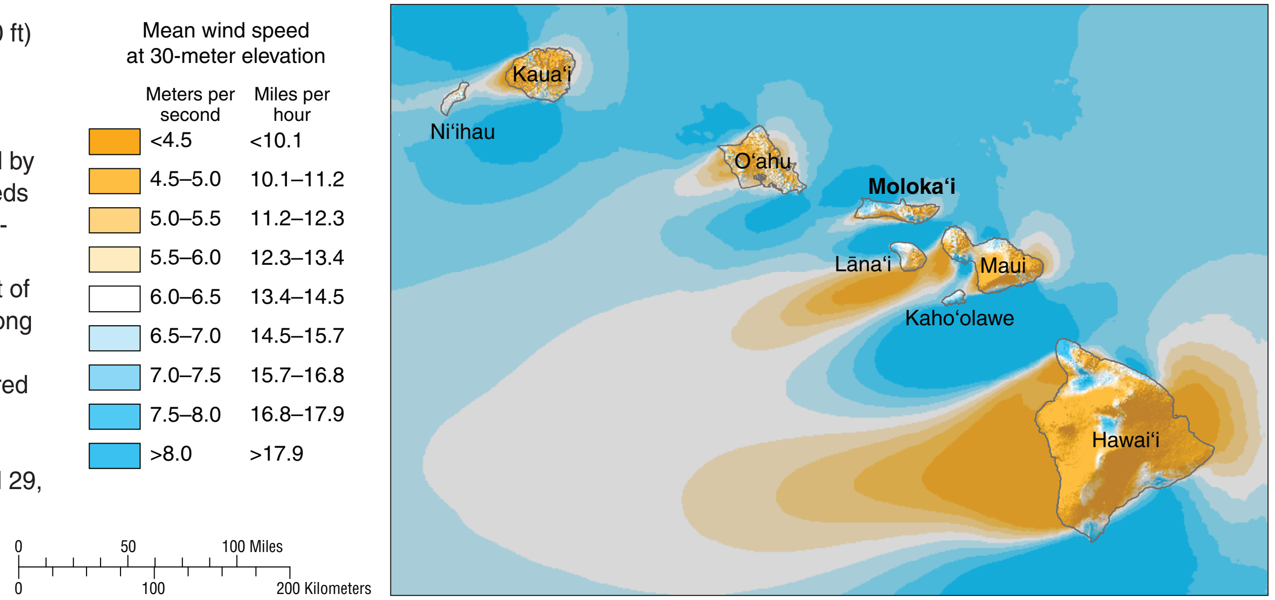
Summer Patterns: Persistent Trade Winds and Low Rainfall

The persistent trade winds that blow in a general east-to-west direction are one of the most prominent circulation patterns in the Earth’s atmosphere. In the tropical Pacific north of the equator, the trade winds blow from the northeast from a region of high pressure known as the Pacific Anticyclone (or Pacific High). The center of this high-pressure system is typically located well north and east of the Hawaiian Islands. The Pacific Anticyclone moves with the seasons, reaching its northernmost position in the summer. This brings the main part of the trade winds across Hawai‘i from May through September, during which time they blow 80–95 percent of the time (Western Region Climate Center, 2006; fig. 6). Trade winds have relatively high moisture content, which yields frequent showers on the windward coasts and at higher elevations but leaves the leeward coasts (south and west) dry. This pattern is clearly depicted by a map of the distribution of annual rainfall on Moloka‘i (fig. 7). Only a relatively small amount of rainfall occurs during the summer months on the leeward coasts, as shown by a 12-year rainfall record from Kaunakakai (fig. 8).

There is often a strong daily variation in wind direction and speed around the islands because of the increased solar heating of the islands relative to the ocean. By late morning or early afternoon, the sun’s rays typically heat the island and the overlying air mass to the point that the air rises, drawing in more cool air off the sea. This daily intensification of onshore winds during the daytime is often referred to as a “sea breeze.” Conversely, at night, as the island cools relative to the ocean, the overlying air mass cools and sinks, causing offshore flow. Thus, whereas out on the open ocean the winds may blow steadily at 10 km/h (6 mi/h), they might exceed 20 km/h (12 mi/h) off Moloka‘i’s south coast during the day and be less than 3 km/h (2 mi/h) at night.

Tropical storms and hurricanes are infrequent events that generally occur during the summer and early fall. Hurricanes are rare in Hawai‘i (only two have made landfall in the past 24 years), but even if they do not make landfall in Hawai‘i, they may pass close enough to the island chain

Figure 6. Map showing mean wind speed 30 m (100 ft) above the surface for the region of the eight main Hawaiian Islands. Note the large variability in wind speed around the islands, in particular the greater speeds in the channels between the islands, caused by topographic steering. In this region, mean wind speeds over the ocean are highest during the summer trade-wind period. During May through September, winds over the ocean exceed 20 km/h (12 mi/h) 50 percent of the time and are dominantly out of the northeast. Along the south Moloka’i coast, trade winds approach the shoreline from the southeast because they are steered around the east Molokai volcanic cone (1,500 m or 4,970 ft high). Data from AWS Truewind (http://www.awstruewind.com/wind-view.cfm, last accessed April 29, 2008).



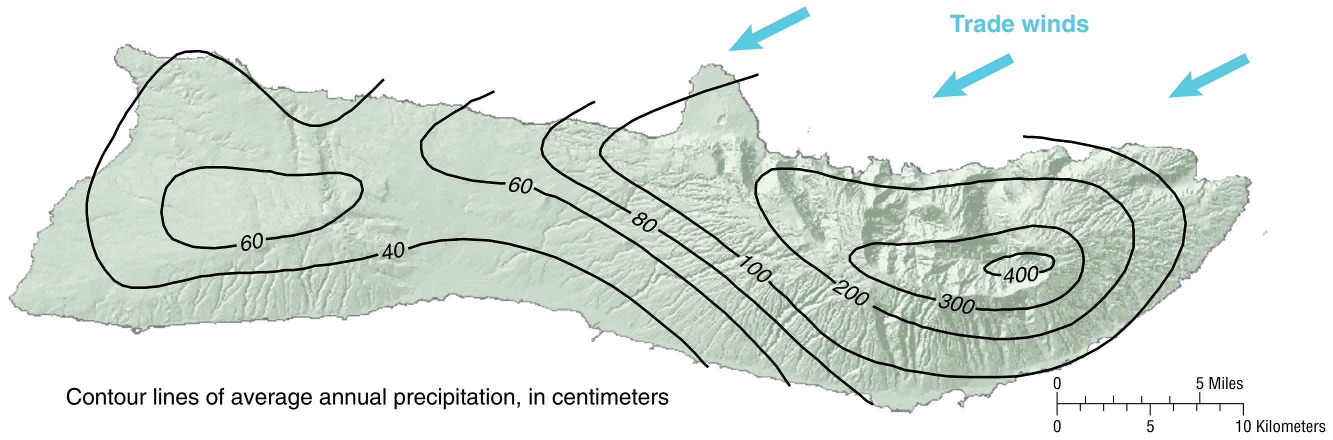


Figure 7. Map showing the distribution of annual rainfall on Molokai. The highest elevations on the eastern half of the island receive more than 400 cm (160 in), and the amounts decrease to the south and west, reaching annual values of less than 40 cm (15 in) along coasts on the western part of the island. Molokai and the other main Hawaiian Islands lie within the trade-wind zone, an area of prevailing easterly surface winds caused by global atmospheric circulation. When these warm, moisture-laden winds meet the island's volcanic mountains, they are forced to rise abruptly and cool. The moisture then condenses to form clouds and precipitates out of the atmosphere in the form of rain. This phenomenon is evident in this map showing the average annual rainfall: most precipitation occurs on the windward, northeastern portion of the island, where high elevations and steep watersheds are found. Much of the southern and western portions of the island receive little rainfall by comparison, because they are blocked from the moisture-bearing wind by the volcanic cone to the east. This accounts for the drier climate found in Kaunakakai and other areas on the south coast. This map was derived from the Hawaii Statewide Planning and Geographic Information System Program (Giambelluca and others, 1986).

to generate heavy rains, high winds, and great waves on the coasts (fig. 9; Fletcher and others, 2002).

Winter Patterns: Decreased Trade Winds and Occasional Storms

From October through April, Hawai‘i is located to the north of the main trade-wind belt. During the winter the trades still blow across the islands, though only 50-80 percent of the time and with wind speeds that exceed 20 km/h (12 mi/h) only about 40 percent of the time. It is during the winter season that light, variable winds are most common, as are occasional very strong winds. The high Hawaiian volcanic mountains have a pronounced topographic effect on the winds, both in winter and in summer, funneling the winds through the channels between the islands and causing the local wind speeds to be much higher than those observed over the open ocean (fig. 6).

Major storms occur most frequently between October and March, bringing heavy rains often accompanied by strong winds. The rainfall record from Kaunakakai (fig. 8) shows the increase in rain in the winter months. Three main classes of disturbances produce major storms. Cold fronts sweep across the islands, bringing locally heavy showers and gusty winds. Low-pressure systems, known locally as Kona storms, bring widespread heavy rains, often accompanied by strong winds from the south or west. Hurricanes strike the islands infrequently but can result in major impacts to coasts and reefs when they arrive.

Drainage Patterns and the Making of an Ahupua‘a

The southern slopes of Moloka‘i are dominated by a series of elongate, shallow-to-deep gulches that are important for the transport of soil from island slopes to the coast; they are also are important to the cultural traditions of native Hawaiians. More than 80 individual gulches reaching to the south coast can be identified on topographic maps of Moloka‘i (fig. 10). The gulches range from tens to hundreds of meters in width and meters to tens of meters in depth; a few are more than 100 m (330 ft) deep. The longest gulches (for example, Kaunakakai, Kawela, Kamalō) emanate from the higher east Moloka‘i volcano. In general, gulches on the south slope of the west Moloka‘i volcano are shorter, narrower, and shallower. The prominence of the gulches on the southern slope of the east Moloka‘i volcano results from three factors that influence stream incision: the greater height of the volcano, its steeper slopes, and the higher rainfall amounts than on the west Moloka‘i volcano.

The early Hawaiians used a complex system of land division and management based on the natural form and boundaries of island watersheds. Islands were subdivided into wedge-shaped parcels, or "moku," extending from the mountain crest to the shoreline. Each moku was subdivided into smaller wedge-shaped parcels, termed "ahupua‘a," which followed the shapes of the watersheds; each had resources that were managed in a way to be self-sustaining (Roberts, 2001). These resources included upland trees, fertile lands for taro production, and coastal areas for salt and fish. Early Hawaiians recognized that effective sustainability of the ahupua‘a required management of the resources and restrictions on the plants and fish that could be harvested, as well as restrictions on the seasons during which they could be harvested. This recognition of the connectivity and interdependence of the different parts of the ahupua‘a—upland ridge, stream valley, coastal area, and reef—is as valid today as it was centuries ago.

A key component of the ahupua‘a was the construction of coastal fishponds to raise fish (Faber, 1997). Ancient fishponds are a part of the coastal landscape in Hawai‘i, and particularly so on Moloka‘i's south shore, where they number more than 60, the greatest number for any comparable area in the State. The fishponds, constructed between the 13th and 15th centuries

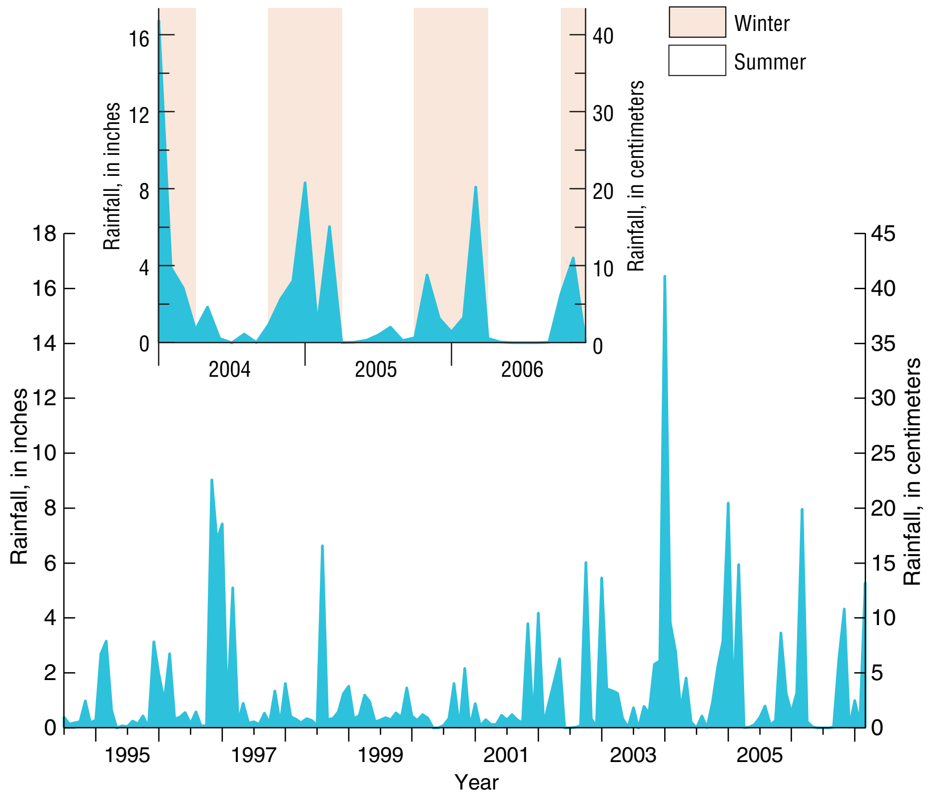


Figure 8. Graph showing monthly rainfall between July 1994 and January 2007 as recorded by a rain gauge at Kaunakakai on Moloka‘i's south coast. Note the distinctly different rainfall patterns between the winters (October through April) and the summers (May through September). Rainfall in the summer is derived from the trade winds and typically is less than 5 cm (2 in) per month. Winter periods, however, derive rain from north Pacific low-pressure systems and commonly yield 15 cm (6 in) or more per month. The inset graph for 2004 through 2006 shows clearly this pattern of most rain occurring in winter periods (brown bars) and little rain occurring in most summer periods.

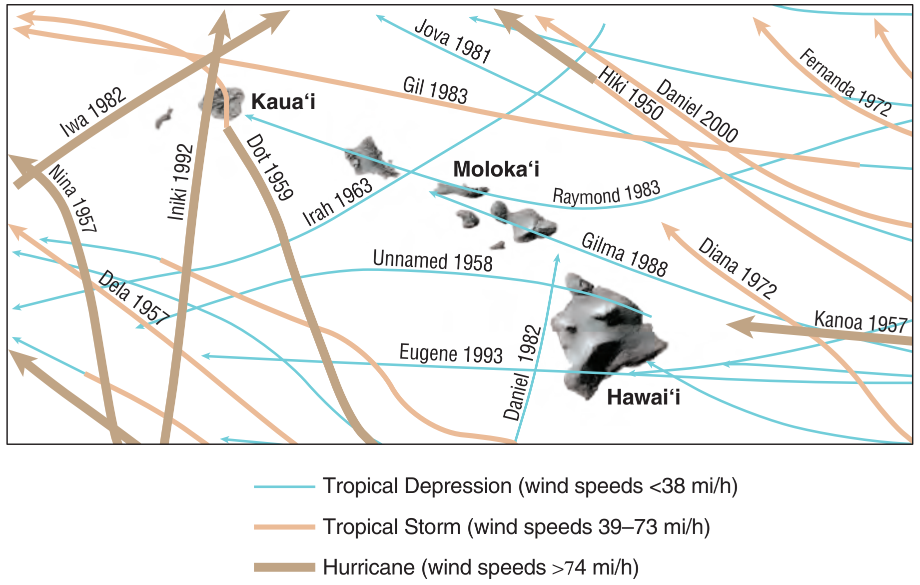


Figure 9. Tracks of major tropical storms that have affected the eight main Hawaiian Islands since 1945. Tropical storms are categorized by their measured wind speed, based on a 1-minute average. A tropical depression has wind speeds that are less than 38 mi/h. A tropical storm has wind speeds from 39 to 73 mi/h. A storm is categorized as a hurricane once the wind speeds reach 74 mi/h. The last major hurricane to strike the islands was Hurricane Iniki in September 1992. Data from the Pacific Disaster Center (http://www.pdc.org/geodata/world/stormtracks.zip, last accessed April 29, 2008).

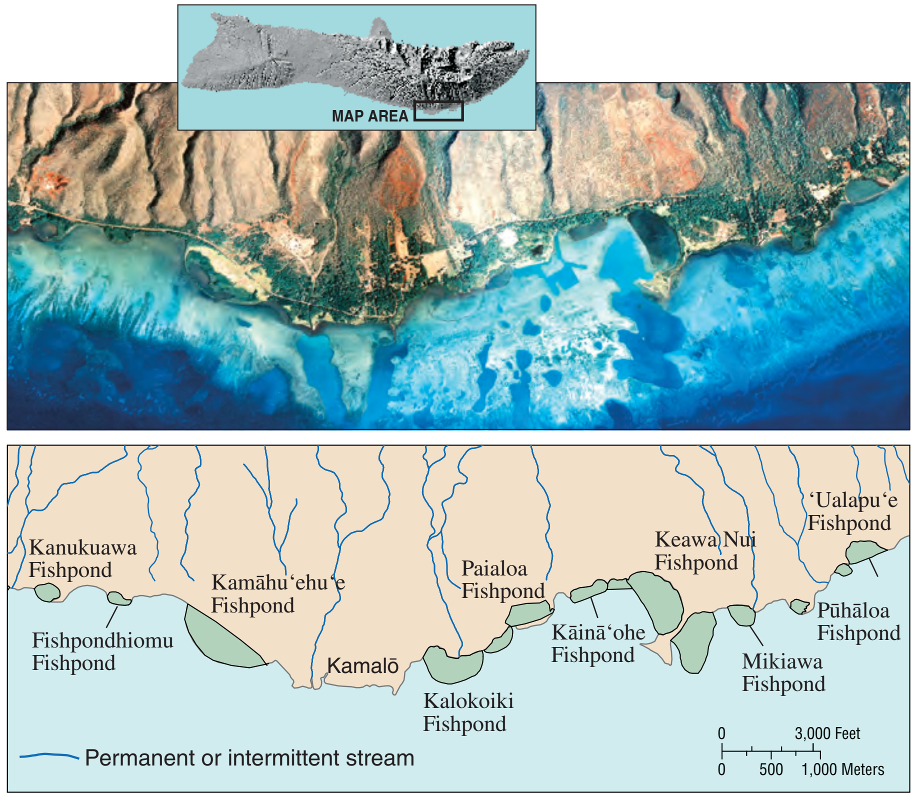


Figure 11. Aerial photograph and interpreted map of part of the south Moloka‘i coast, showing the abundance of fishponds. Most of the fishponds are partly to completely infilled, and others have only submerged remnants present.

(Summers, 1964; fig. 11), played an important role in early Hawaiian life. Today they remain important cultural landmarks, and because of their large number and large size (many are tens and even hundreds of acres) they exert an influence on coastal processes.

Fishpond walls were built with basalt and limestone boulders on the shallow submerged limestone surface of the reef flat in water less than 1 m (3 ft) deep (fig. 12). The walls measured 1 to 6 m (3–20 ft) wide and 0.6 to 2 m (2–6 ft) high, and could be hundreds of meters long. Some of the fishponds (referred to as “loko kuapā”) were entirely enclosed except for a slotted gate (“makaha”) that allowed small fish to enter but restricted them from leaving when they increased in size. Other fishponds (“loko ‘ume iki”) had low walls that were submerged at high tide; walled lanes led into and out of the ponds. Hawaiian pond builders, recognizing the dominant east-to-west wind and current patterns, particularly on the eastern part of Moloka‘i, placed the lanes leading into the ponds on the eastern side and the lanes leading out on the western side.

Today, these ancient fishponds influence the coastal environment in several ways. Fishponds are natural accumulation sites for sediment, both that which is discharged directly from stream mouths and silt settling from turbid waters on the Moloka‘i reef flat. Once deposited, the sediment tends to remain in the fishponds (early Hawaiians cleaned the ponds with bamboo rakes) and plants gain a foothold. Mangroves have migrated along the south coast from their originally introduced location at Pālā‘au and taken hold in many fishponds. Once established, mangroves increase the sediment-trapping efficiency of the pond, which then tends to fill more quickly, creating more area for plant growth. A second effect of ponds is the steering of coastal currents by the massive stone walls that extend out onto the reef flat. Two recent studies (Presto and others, 2006; Calhoun and Field, 2008) have shown that coastal flow of water and transport of sediment follow the lobate shape of the ponds; silt is more easily trapped in the spaces between protuberant ponds (see fig. 11). The residents of Moloka‘i have made several valiant efforts to restore selected fishponds to their original condition. Through State funding, the Waialua Fishpond project demonstrated, with very strenuous volunteer labor, the feasibility of restoring two fishponds at Waialua (State of Hawai‘i Department of Lands and Natural Resources, undated).

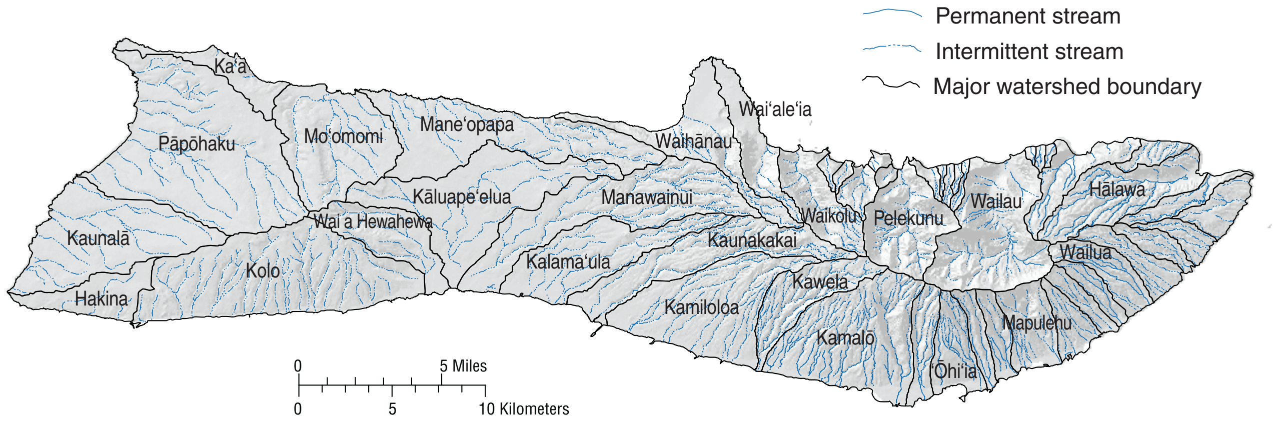


Figure 10. Stream drainages and major watersheds on Moloka‘i. With the exception of the streams that drain the wet northeastern valleys, the majority of streams on Moloka‘i are fed only by surface runoff and therefore flow intermittently—during periods of high precipitation. When heavy rainfall events occur, many of the streams are subject to rapidly increasing flows and flooding. These high flows are a hazard to people and property, and they also deliver high concentrations of sediment to the coral reef. This map was derived from the Hawai‘i Statewide Planning and Geographic Information System Program (Giambelluca and others, 1986).

The Remarkable Coral Reef of South Moloka‘i

The configuration of Moloka‘i and neighboring islands has played a large role in the development of the extensive coral reef bordering the south coast. The island’s elongate east-west orientation perfectly blocks the large north Pacific swell. To the south, Lāna‘i, Maui, and Kaho‘olawe provide an effective shield against destructive storm waves and south Pacific swell. This protection, along with the low gradients of the submerged shelf and the presence of narrow coastal plains and alluvial fans that capture sediment shed from the hillsides, provided an optimum setting for coral growth.

The south Moloka‘i reef is not the result of coral growth in the past century or even the past millennium; nor is it the result of continuous growth. Accumulating evidence on its age and structure indicate that much of the

Bruce Richmond, USGS

Figure 12. Oblique aerial photographs (taken in 1998) of fishponds along the south shore of Molokaʻi. *A*, The large Kānoa (foreground) and Aliʻi fishponds jut out onto the reef flat along the central coast just west of Kawela. Note the accretion of the coast on the updrift side (east, or closest to viewer) of the ponds and erosion on the downdrift side (west, or far side). *B*, Submerged remnants of a fishpond on the reef flat off Wave Crest Condominiums, near Kalaeloa. The size and extent of fishponds on the reef flat, such as shown here, makes them a factor in sediment transport on the south shore and reef flat.

reef originated during earlier periods of reef growth, and it is quite likely that the reef was built during a number of intervals when sea level was at or near its present position (Engels and others, 2004, Barnhardt and others, 2005). In some ways the reef is robust, but in many ways it is not. The material presented in ensuing chapters points out two distinguishing characteristics of the Molokaʻi coral reef—it is remarkable and it is fragile. It is remarkable in its size, continuity, and high degree of coral cover. It is fragile in that it is a thin living coral surface built upon an old eroded coral surface. The entire reef is susceptible to changes induced by coastal development, runoff, fishing, and many other activities.

Forces Acting on the South Molokaʻi Reef

Waves, Tides, and Currents

More than any other single physical process, waves control not only the reef shape and the types of coral that grow on the reef, but even whether or not a reef can form. Waves on the ocean's surface are mechanical energy traveling through water. The water particles in a wave move in a circular motion; these wave orbital motions decrease in size with depth and become more elliptical ("flatter") where the wave orbits interact with the sea floor in shallow water. Every waveform has certain properties used to describe it, as shown schematically in figure 13.

The wave regime off Molokaʻi can be characterized by four end-members, as shown in figure 14—North Pacific swell, Northeast trade-wind waves, Southern swell, and Kona storm waves (Moberly and Chamberlain, 1964). The North Pacific swell is generated by strong winter (October–May) storms as they track from west to east across the North Pacific and has wave heights on the order of 3–8 m (10–26 ft) and wave periods of 10–20 seconds. The Northeast trade-wind waves occur throughout the year but are largest from April through November, when the trade winds blow the strongest. These waves have wave heights on the order of 1–4 m (3–13 ft), but they have very short periods of 5–8 seconds. Southern swell, generated by storms in the Southern and Indian Oceans from April through October, typically has small waves (heights ~1–2 m; ~3–6 ft), but they have very long periods (~14–25 seconds). Kona storm waves occur infrequently when local fronts or extratropical lows pass through the region. Kona storm waves typically have wave heights on the order of 3–4 m (10–13 ft) and wave periods of 8–12 seconds.

Tides are the rhythmic rise and fall of sea level driven by the interaction between gravitational and inertial forces of the Earth, Moon, and Sun. Although the Moon's mass is 27 million times less than that of the Sun, because of its much greater proximity to the Earth (400 times closer), the Moon imparts twice the gravitational force on the Earth and the oceans. The Moon's gravity pulls at the ocean's water, dragging it towards the Moon in a bulge on the side of the Earth closest to the Moon. On the opposite side of the Earth (away from the Moon, where the Moon's gravitational influence is less), the ocean's inertial forces exceed the gravitational forces, causing the water to move away from the Earth and also form a bulge. Over the rest of the Earth's surface, the two forces are relatively balanced. The two bulges in the ocean stay essentially aligned with the Moon as the Earth rotates, and as a coastal area passes under each bulge, it experiences a tidal high when it passes through the bulge and a tidal low when the shore is outside of the bulge.

The Earth completes a full revolution relative to the Moon every 24 hours and 50 minutes (the diurnal tidal cycle), and thus the two daily high tides occur 12 hours and 25 minutes (the semidiurnal tidal cycle) apart. Different points on the Earth's surface experience different tidal patterns because the Earth's axis of rotation is inclined relative to the position of the Moon. The shape of the ocean basins also plays a role. Most areas have two

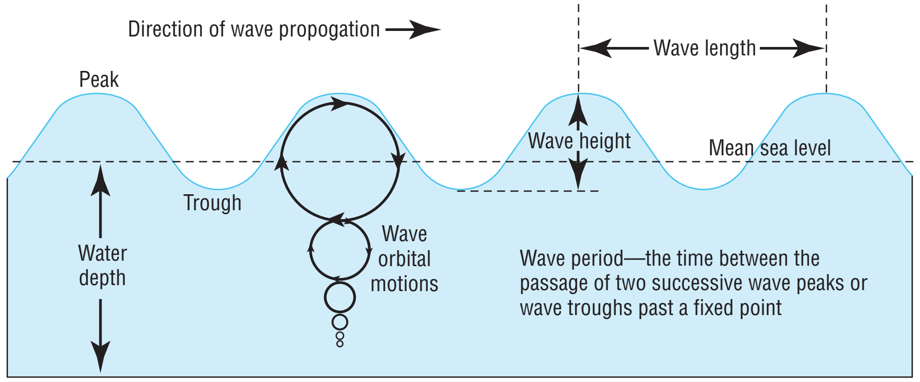


Figure 13. Diagram showing the parameters used to describe ocean surface waves

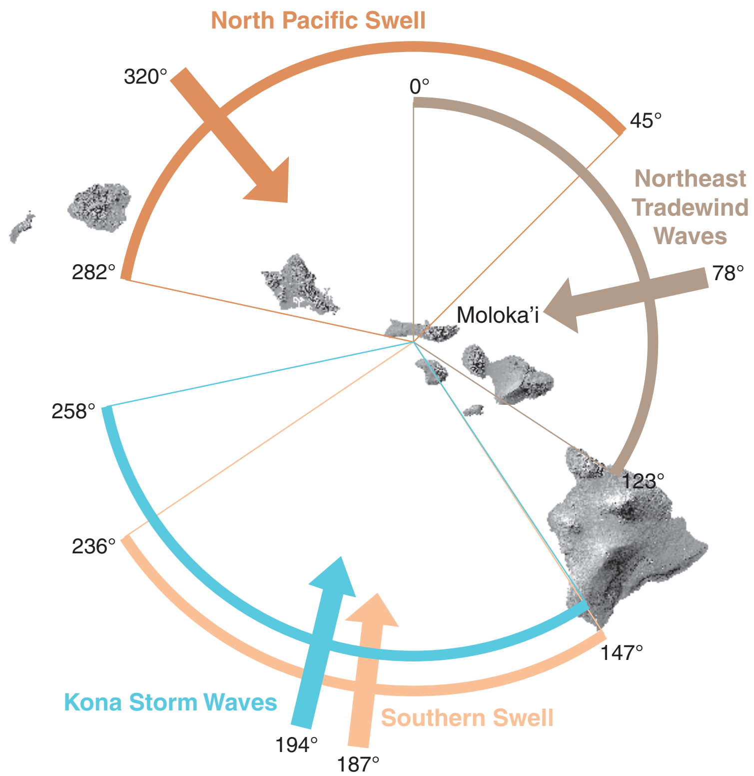
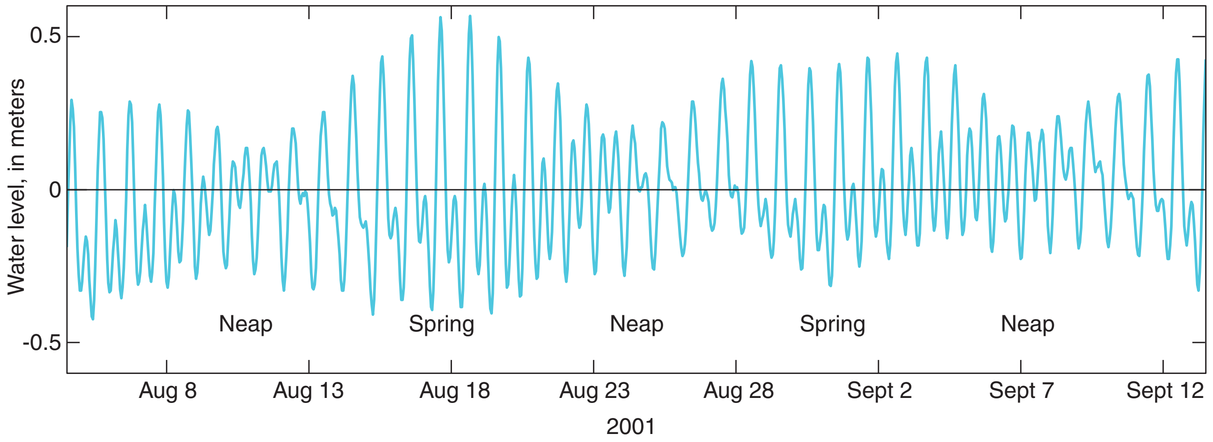


Figure 14. Wave regime for the island of Molokaʻi, modified from Moberly and Chamberlain (1964). The arrows and arcs denote mean directions and range of direction, respectively, for a given wave type. Numbers on arrows are azimuths of the direction waves come from. North Pacific swell occurs throughout the year and generates some of the largest waves in the Hawaiian region, especially during the months from October through May. Northeast trade-wind waves occur throughout the year (50 percent of the time in the winter months, 90 percent of the time in the summer months), but are largest from April through November when the trade winds are strong and consistent. Southern swell, which also occurs throughout the year, generates waves that are typically largest and most frequent from April through October, when they occur up to 50 percent of the time. Kona storm waves, which are neither frequent nor consistent, occur less than 10 percent of the time during the winter months. Note that the region off south-central Molokaʻi, where the coral reef is largest, is shadowed from most of these waves by the surrounding islands and by the island of Molokaʻi itself.

Figure 15. Forty days of tide data collected off Kamiloloa in 2001, displaying south Moloka‘i’s mixed semidiurnal tidal regime. The data set encompasses more than two complete spring-neap tidal cycles, with the peak spring tides on August 18 and September 2 and the minimum neap tides on August 11 and August 25. Moloka‘i’s mean tidal range is 0.43 m (1.4 ft), while the spring and neap tidal ranges are 0.91 m (3.0 ft) and 0.32 m (1.1 ft), respectively. Because the rough topography of south Moloka‘i’s broad fringing reef restricts flow, especially over the shallow reef crest, there is generally a time lag between the tidal elevations on the fore reef and those on the reef flat, with the maximum heights on the reef flat occurring after those on the fore reef (Storlazzi and others, 2004).



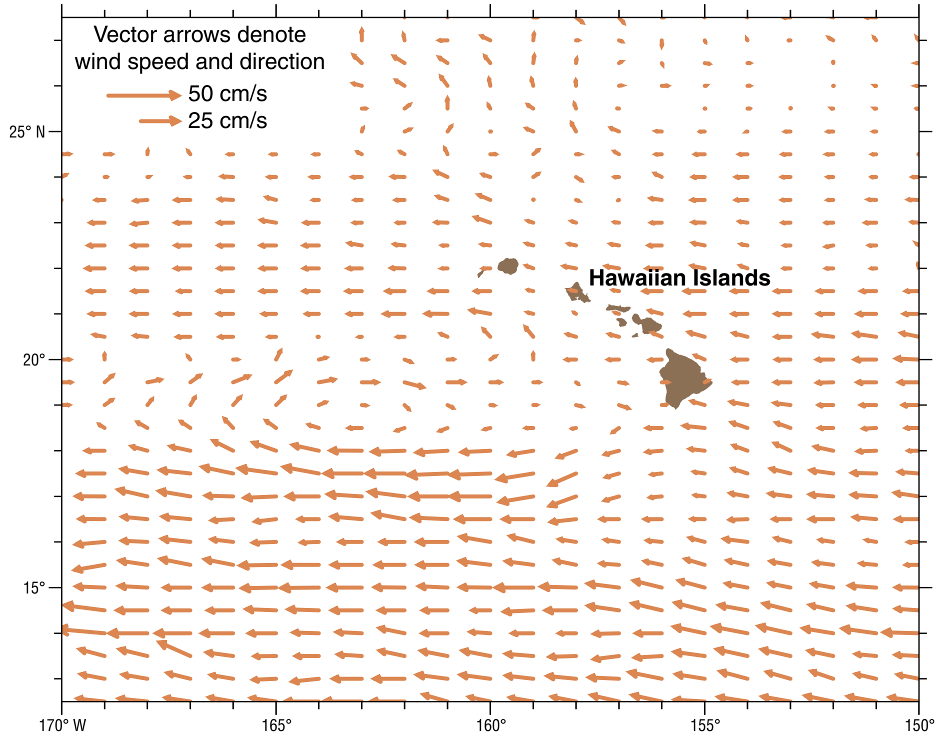


Figure 16. Diagrammatic map of average surface currents in the central Pacific Ocean, based on 40,000 observations of ship drift, 85,000 observations of satellite-tracked drifting buoys, and 8,000 modern current measurements (modified from Flament, 1996). The major current direction is westward through the main Hawaiian Islands, and a large gyre forms in the lee of the Big Island centered near 19° N, 163° W. This large-scale feature is caused by the islands standing in the path of the broad and steady trade winds, causing an ocean-atmosphere interaction that results in an island wake, similar to a river’s flow around a bridge piling (Xie and others, 2001). Circulation in the lee of the islands and close to shore is characterized by vigorous smaller scale eddies or swirls (not visible at the scale of the figure), which cause significant local variability in surface current speed and direction.

high tides and two low tides each day, a pattern that is termed a semidiurnal tide. In Hawai‘i, as in many places, the amplitudes of the two high tides and two low tides experienced each day are unequal, creating what is termed a mixed semidiurnal tide (fig. 15).

When the Sun and the Moon are aligned relative to the Earth, the combined gravitational forces of the Moon and Sun cause a very strong tide called a “spring” tide; spring tides happen approximately every 14 days at the times of new and full Moons. When the Moon and Sun are at a right angle with the Earth (first and last quarter lunar phases), their gravitational forces act separately from one another, causing a relatively weak “neap” tide approximately every 14 days. Both spring and neap tides are highlighted in figure 15. The tidal range, which is defined as the maximum water height at high tide minus the minimum height at low tide, is greatest during spring tides and least during neap tides. Although the full tidal range in Hawai‘i is relatively small compared to other coastal areas on Earth, tides are important to the reef in terms of transporting nutrients and larvae and flushing sediment and other pollutants.

The currents in the northwest Pacific Ocean form a large basin-scale clockwise circulation, called a gyre, centered at about 28° N latitude. At the latitude of Hawai‘i, the flow is roughly from east to west and increases in intensity southward (fig. 16). At the ocean’s surface, however, these large-scale ocean currents are strongly influenced by surface winds. This causes complicated circulation patterns, especially in the vicinity of the Hawaiian Islands, where topographic steering of the surface winds occurs. Circulation in the sheltered lees of islands is characterized by vigorous and changing eddies or swirls, causing significant temporal variability in surface current speed and direction (Flament, 1996).

Infrequent Events: Tsunamis

A tsunami is a very long period wave generated by a large, rapid displacement of water in the ocean. The name derives from the Japanese term for “great wave in harbor.” Landslides, earthquake faulting, submarine volcanic eruptions, and even meteorites have caused tsunamis throughout Earth’s history. Over the course of human history, earthquakes have been the most common tsunami-generating source (estimated 95 percent), followed by violent volcanic eruptions, such as those of the Indonesian volcanoes Tambora in 1815 and Krakatau in 1883 (Soloviev, 1982).

Tsunamis are often hundreds of kilometers in length (the wavelength), but in deep water they may be only a few centimeters to a meter or so in height. Tsunamis travel at several hundred kilometers per hour in the deep ocean basins and thus can propagate across the entire Pacific Ocean in less than a day’s time (fig. 17), potentially devastating coastal areas very far from where they originated. Hawai‘i, located in the center of the seismically active Pacific Basin, is susceptible to tsunamis generated from around the basin’s rim. In the 20th century alone, deadly earthquake-generated tsunamis struck the Hawaiian Islands in 1946, 1952, 1957 (fig. 18), 1960, and 1975. Overall, 26 tsunamis have been recorded in the Hawaiian Islands since 1812, or one every 7 years on average, although many of them have been inconsequential (Lander and Lockridge, 1989).

Because of their long wavelengths, tsunamis act like shallow-water waves even in the deep ocean basins. Although their heights in deep water are very small, they become much taller when they enter into shallow water because increasing drag on the sea floor slows them down. However, when tsunamis strike islands with narrow, steep shelves, they tend to have

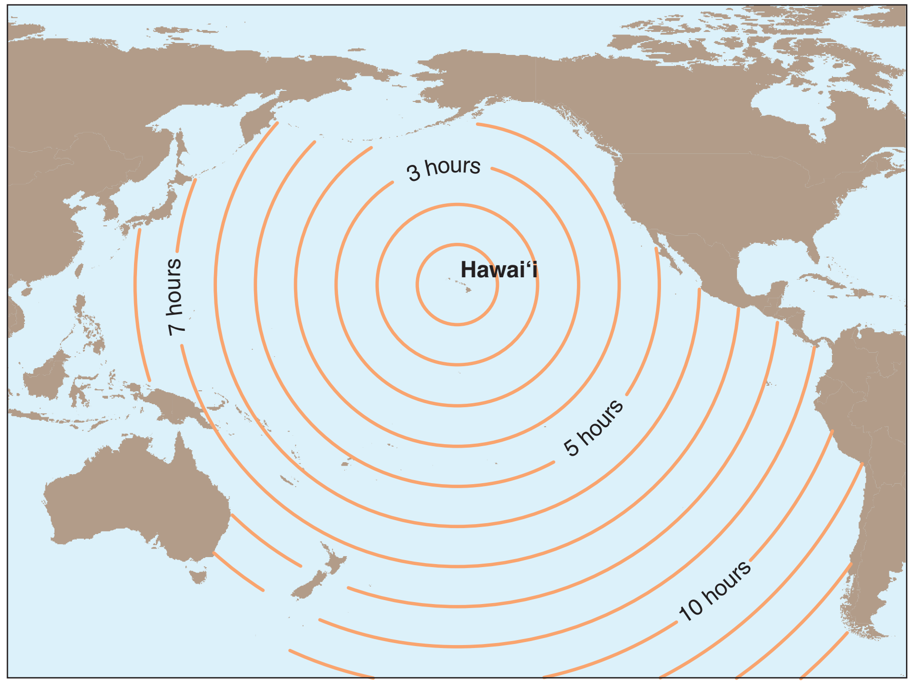


Figure 17. Map displaying approximate travel times required for tsunami waves generated anywhere on the rim of the Pacific basin to reach Hawai‘i (U.S. Geological Survey, 1997). The travel times are estimated assuming a tsunami speed of 1,000 km/h (600 mi/h). Therefore, the contours on the map are spaced at 1,000 km, or one hour of travel time.

larger run-up heights than when they strike coastal areas with broad, gently sloping shelves where more of the tsunami’s energy can be dissipated. Like shallow-water waves, tsunamis are also susceptible to energy loss by refraction around and dispersion between islands. Although the Hawaiian Islands are, in general, susceptible to high tsunami run-up because of their lack of broad shelves, the south shore of Moloka‘i is protected by the surrounding islands of O‘ahu, Lāna‘i, Kaho‘olawe, and Maui and has been affected less by large tsunamis than other Hawaiian locations. During the 1946 tsunami, for example, wave run-up heights on the north, east, and west sides of Moloka‘i averaged 10 m (35 ft), while those along the south shore averaged only 2 m (7 ft). Fletcher and others (2002) rank the tsunami hazard along the south Moloka‘i fringing reef moderately high at both the eastern (Kamalō to Kūmimi) and western (Hale O Lono to Pālā‘au) ends of the island and moderately low along the central portion (Pālā‘au to Kamalō) of the reef, where it is sheltered by Lāna‘i and Kaho‘olawe.

No studies have actively investigated the impact of any of these tsunamis on coral reefs in Hawai‘i. Observations from the December 26, 2004, Indonesian tsunami suggest that most of the damage to reefs throughout the Indian Ocean occurred in embayments, where the force of the tsunami waves was concentrated. Much of that damage was caused by debris dragged over the reefs by receding waters, rather than by the waves themselves (Fernando and others, 2005).

Figure 18. This series of three historical photographs (*A-C,* in chronological sequence) shows the arrival of a tsunami at Laie Pt. on the island of O‘ahu in March 1957. This tsunami was generated by a magnitude 8.6 earthquake located about 3,700 km (2,300 mi) away in the Aleutian Islands of Alaska.

Henry Helbush

Results from Recent Research on the Moloka‘i Reef

The foregoing summary of the processes that shape the Hawaiian Islands is a prelude to the main focus of this volume—the coral reef off south Moloka‘i. The chapters of this publication present our current scientific understanding of the reef itself, including its overall character and the processes that influence its long-term health. Chapters 1 through 9 summarize the origin of the reef and the character and distribution of its inhabitants, particularly corals, fish, and algae. Following those discussions, chapters 10 through 14 document key natural processes—waves, currents, runoff, and ground water—and how they affect the reef. Finally, chapters 15 through 21 address the topics of sediment runoff and toxic pollutants—why and how they are delivered to the reef, and the behavior and ultimate fate of island-derived material on the reef.

Moloka‘i is but one volcanic island in the tropics among very many worldwide. Its fringing coral reef is likewise only one among very many. It is therefore likely that many other reefs are influenced by a similar suite of physical processes and that many of those reefs also face threats from island runoff, similar to those reported here for Moloka‘i. With an eye towards those other reefs, as well as to Moloka‘i, the closing discussion following the chapters reviews the issues facing the Moloka‘i reef and the pathways that might be undertaken to ensure the long-term survival of one of the most spectacular reefs in the Hawaiian chain.

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