1.16 Hawaii

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1. Introduction

The state of Hawaii consists of eight main islands: Hawaii, Maui, Kahoolawe, Lanai, Molokai, Oahu, Kauai, Niihau, and 124 small volcanic and carbonate islets offshore of the main islands, and to the northwest (*Fig. 1*). The climate is sub tropical oceanic. Honolulu has a mean monthly temperature of 21.7°C in January, rising to 25.6°C in July, and an average annual rainfall of 802 mm. The Hawaiian archipelago lies in the zone of northeasterly trade winds, which bring high rainfall to the windward mountain slopes while the leeward coasts are in rain shadow. Hawaii's preeminent example of this orographic rain is Kauai's Mount Waialeale, which receives an average 1168 cm of rain a year. In contrast, the dry air descending down Kauai's leeward side creates local semi-arid conditions at Polihale Beach on the west side of the island which receives on average a mere 20 cm of rain a year. In addition to northeasterly waves generated by the trade winds there are ocean swells from all directions, but notably from the north in the winter and the south in the summer months. Tide ranges are small, Honolulu having a mean spring tide range of 0.6-0.8 m.

Geologically the islands are a series of volcanoes. The main Hawaiian Islands are great shield volcanoes built by successive flows of pahoehoe and aa basalt lavas. Some have had prolonged phases of erosion, followed by renewed eruptions.

Hawaiian beaches include creamy white calcareous sand, derived from the tests of micro-organisms, weathered coral, calcareous marine algae, lithic fragments

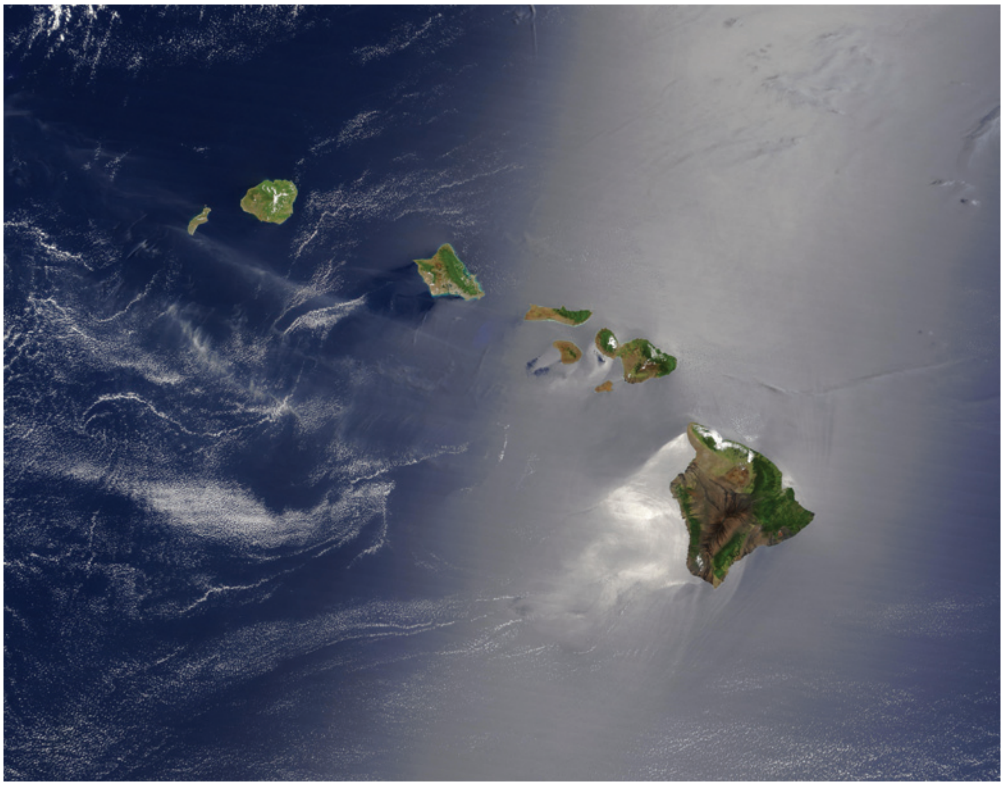


Fig. 1
The Hawaii archipelago consists of eight main islands and numerous smaller volcanic and carbonate islets.

(typically of Pleistocene skeletal limestone), mollusc and echinoderm fragments (Harney et al. 2000), and black and green sand derived from volcanic material. Ferromagnesian olivine and other basaltic minerals are relatively unstable in the tropical climate of Hawaii, and are reduced by weathering. Calcareous beaches are dominant on all the older Hawaiian Islands where significant coral reef communities have been able to develop.

The vast majority of Hawaii's reefs are of the *fringing* variety (*Fig. 2*). When an island is young and still volcanically active, lava entering the ocean prevents reef accretion. But moving up the west side of the Big Island where the seafloor is not swept by high swell, the beginnings of fringing reefs attached to the land can be seen and beautiful coral gardens are found. North of the Big Island on the Kihei coast of Maui and extending out from the north Maui shoreline are broad fringing reefs, demonstrating that reef development has a firm foothold on stabilised volcanic coasts. Fringing reefs generally grow in size and become commonplace among the islands north of the Big Island. But among the northwest Hawaiian Islands fringing reefs give way to submerged pinnacles, drowned platforms, and atolls as the volcanic shield structure subsides beneath the waves and the reefs struggle to stay near the surface.

Two organisms serve as principal architects of Hawaiian reefs: scleractinian (stony or hard) corals, and coralline and calcareous algae. There are over fifty species of coral found in the Hawaiian Islands but only a few are common. These grow in a range of forms designed to generally maximize the collection of sunlight and food, and minimize their exposure to stresses made by large waves. *Stout branching, delicate branching, platy, encrusting, doming, mounding*, these and other terms describe the numerous growth forms assumed by corals as they make the most of their environment. The more abundant Hawaiian genera include rice corals (*Montipora* species), lobe and finger corals (*Porites* species), cauliflower or moosehorn corals (*Pocillopora* species), and false brain corals (*Pavona* species).

Coralline algae and calcareous algae are members of a marine plant group on the reef that deposits calcium carbonate in its tissue. When the algae dies, it leaves a fossil skeleton behind that is hard, whitish, and essentially the same chemistry as the coral. A few species of calcareous algae, such as the *Halimeda*, are especially abundant in Hawaii and important reef components. Hard plant debris builds up as piles of sediment in reef environments and are important sources of beach sand, making up over half the grains on many Hawaiian beaches. The coralline algae look like coral and grow in a binding and encrusting form on the reef, competing for space with corals. Most coralline algae are red, but there are some exceptions. A visit to any intertidal rocky coast in Hawaii will reveal the

Fig. 2
Fringing reefs dominate coastal geomorphology and sedimentary processes on shores not influenced by active volcanism (Larsens Beach, Kauai).

encrusting coralline community coloring the rocks a brilliant hue in between the rise and fall of the waves.

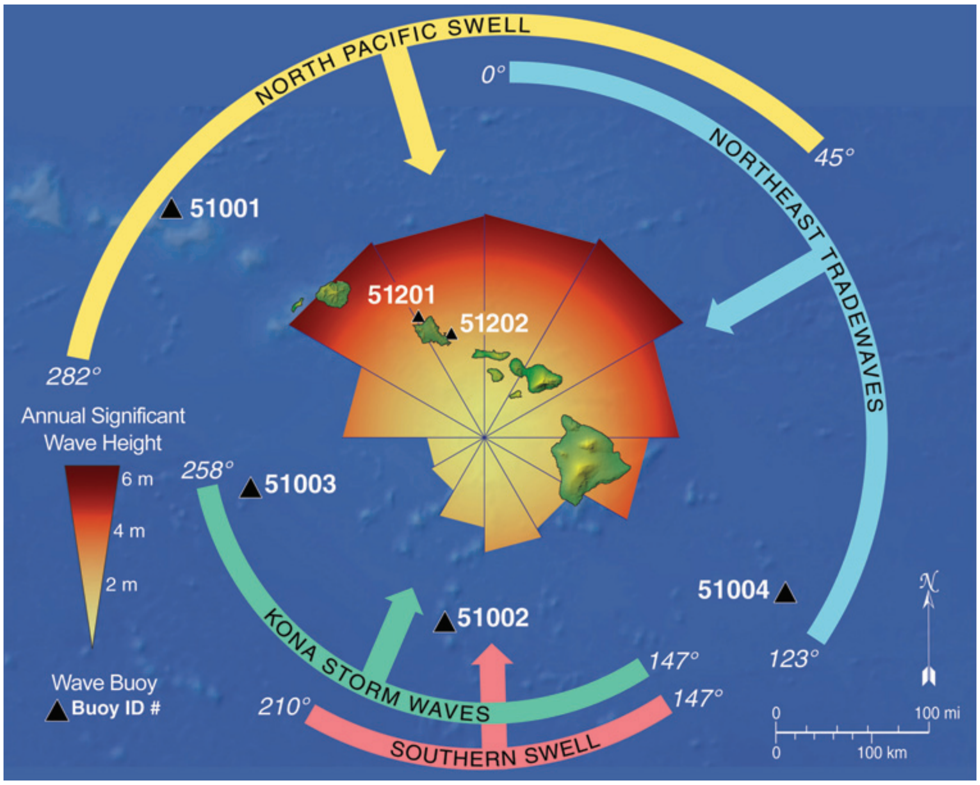
The coastal plains of most Hawaiian Islands hold major calcareous aeolian, littoral, and marine sand deposits formed during and following late Holocene high sea levels and persistent recent aeolian deposition under seasonal winds (Fletcher and Jones 1996; Grossman et al. 1998). Sand is also stored on the reef flat in shore-normal reef channels and shallow Pleistocene karst depressions (Fletcher et al. 2008). Longshore transport dominates sediment movement on the coast in distinct littoral cells.

The central Pacific location of the Hawaiian Islands exposes them to wind and ocean swells from all directions. Sectors of coastline may have rain, wind and wave shadows, and are either protected from, or vulnerable to, wind or wave impact. The four dominant regimes responsible for large waves in Hawaii are: north Pacific swell, trade wind swell, south swell, and Kona storms. The regions of influence of these regimes, outlined by Moberly & Chamberlain (1964), are shown in (*Fig. 3*); a wave rose depicting annual swell heights and directions has been added to their original graphic (Vitousek and Fletcher, 2008). Inter-annual and decadal cycles including El Niño Southern Oscillation (ENSO) occurring approximately every three to four years, and Pacific Decadal Oscillation (PDO) occurring around 20–30 years, influence the variability of the Hawaiian wave climate. These large-scale oceanic and atmospheric phenomena are thought to control the magnitude and frequency of extreme swell events. For example, times of strong ENSO may result in larger and more frequent swell. Understanding the magnitude and frequency of extreme wave events is important as they may control processes such as coral development, sediment supply, and beach morphology.

In the winter, Hawaii receives large ocean swell from extra-tropical storms that track predominantly eastward from origins in the northwest Pacific. These storms produce waves that travel for thousands of kilometres until reaching the shores of Hawaii. North swell have annually recurring maximum deep-water significant wave heights of 7.7 m with peak periods of 14-18 s. However, the size and number of swell events each year is highly variable – varying by a factor of 2. The annual maximum wave height ranges from about 6.8 m (in 1994, 1997, 2001) to 12.3 m (1988).

Occurring about 75% of the year, the trade winds arrive from the east and northeast with an average speed of 25 km/hr and direction 73°. In winter months, the north Pacific high generating these winds flattens and moves closer to the islands decreasing trade wind persistence. Although the number of windy days in summer months increases, the mean trade-wind speed in summer and winter months remains similar. The trades generate choppy

Fig. 3
Hawaii dominant swell regimes after Moberly & Chamberlain (1964), and wave monitoring buoy locations. From Vitousek & Fletcher (2008).



seas with average wave heights of 2 m ($1\sigma = 0.5$ m) and peak periods of 9 s ($1\sigma = 2.5$ s) from the northeast. Although these represent nominal conditions, trade-wind swell can exceed 5 m in height and have periods of 15–20 s.

Southern swell arriving in Hawaii is typically generated farther away than north Pacific swell. These are usually produced by storms south of the equator near Australia, New Zealand and as far as the Southern Ocean and propagate to Hawaii with little attenuation outside the storm-generated region. South swell occur in summer months (southern hemisphere winter) and reach Hawaii with an annual significant wave height of 2.5–3 m and peak periods of 14–22 s, which are slightly longer than north Pacific swell.

Kona storms are low-pressure areas (cyclones) of subtropical origin that usually develop northwest of Hawaii in winter and move slowly eastward, accompanied by southerly winds from whose direction the storm derives its name, and by the clouds and rain that have made these storms synonymous with bad weather in Hawaii. Strong Kona storms generate wave heights of 3–4 m and periods of 8–11 s, along with wind and rain, and can cause extensive damage to south and west facing shores. While minor Kona storms occur practically every year in Hawaii, major Kona storms producing strong winds, large wave heights and resulting shoreline change tend to occur every 5–10 years during the 20–30 year negative PDO cycle. Consequently, positive (warm) PDO, and El Niño phases tend to suppress Kona storm activity.

Local relative sea level in Hawaii is not only dependent on global eustatic trends (about 3 mm/yr), but is also affected by subsidence of oceanic lithosphere, which responds elastically to volcanic loading over the hot spot. It is estimated that half of the upward building of Hawaiian volcanoes is reduced by subsidence and that most of the volcanoes have subsided 2–4 km since emerging above sea level (Moore 1987).

The main Hawaiian Islands span about 5 million years in age. They are at differing distances from the hot spot, and thus at different stages of subsidence, and so have different relative sea levels. These relative differences in sea levels are demonstrated by modern tide gauge rates and support the view that subsidence is active over the hot spot (Moore 1987).

Submerged wave cut notches and benches, raised coral reef, subaerial marine terraces, and alluviated river valleys can be found at various elevations and locations around Hawaii, indicating oscillations of land and sea level (Fletcher et al. 2008). A fossiliferous marine limestone (known as the Waimanalo Formation) 3–6 m above sea level on Oahu is a typical example of a past stand of the sea. Holocene sea level has been influenced both by eustatic postglacial meltwater as well as equatorial oceanic siphoning associated with the changing postglacial geoid (Mitrovica and Milne 2002). These led to a high sea level (approximately 2 m) about 3,000 years BP followed by a sea level fall. Tide gauges record a sea level rise since 1900 in Hawaii.

There is widespread but variable coastal erosion in the Hawaiian Islands in response to human interference with sand availability and the inferred influence of eustatic rise. For instance, researchers at the University of Hawaii measured the historical rate of shoreline change on every beach on the island of Kauai. Their data reveal that 72 percent of the beaches on Kauai are eroding and the average rate of erosion is 0.3 m/yr. On 22 percent of the eroding beaches, the rate of erosion is accelerating. In pristine coastal areas calcareous sand stored on the low-lying coastal plain is released to the beach as sea level rises, allowing a wide sandy shore to be maintained even as the beach migrates landward. However, the threat to coastal property has led to extensive armoring of the coastline. Artificial hardening is a form of coastal land protection that occurs at the expense of the beach, preventing waves from accessing the sandy reservoirs impounded behind the seawalls and revetments. Thus, efforts to mitigate coastal erosion have created a serious sand deficiency on armored beaches leading to widespread beach loss, particularly on the most populated and developed islands (Fletcher et al. 2006). The need to address this issue is acknowledged by the state and local communities, and the hope is that a broadly scoped management plan will keep a balance between the natural coastal morphology and human resource demands.

The islands will be considered in sequence from WNW to ESE (which is also their age sequence): Niihau, Kauai, Oahu, Molokai, Lanai, Kahoolawe, Maui and Hawaii (The Big Island).

2. Nihau

Niihau is a small elongated island (29 km × 10 km) that stretches from SW to NE with a 145 km coastline. It lies at the far NW end of the main Hawaiian islands and is the low lying subaerial remains of a shield volcano built about 4.89 million years ago (Clague and Dalrymple 1987).

The horseshoe shaped Lehua Island off the north coast is the product of rejuvenated volcanism and has been sculpted by marine erosion. The steep cliff on the south side of this relatively small island has been notched with caves at the base. The island tapers to low-lying points that border a wide mouthed bay that opens to the north.

The coast of Niihau has a variable morphology. Portions are composed of low volcanic cliffs that have been weathered and shaped by marine erosion, boulder beaches, embayed sandy beach systems backed by 30 m high dunes, erosional sandy coasts where massive slabs of beach rock have been excavated by large swell and stacked on the shore, and small littoral cells with sandy coves.

3. Kauai

Kaui is known for the variety of microclimates that exist throughout the island including temperate regions, dry sand dune complexes and lush river valleys. Volcanic rocks form cliffs and the backshores of beaches, and there are segments of fringing reef cut by paleostream channels, coarse calcareous sandy beaches are separated by rocky points and interspersed with small stretches of boulder coast.

The north coast beaches receive large winter surf that may create strong currents. Waterfalls cascade down deeply eroded valleys, feeding streams that flow across the beach into the ocean. On the northwest coast one finds the steeply dipping knife-edge ridges and deep erosional V-shaped valleys that have been truncated into spectacular cliffs. The windward and south coasts are characterised by fringing reefs and inter mittent rocky headlands separating distinct littoral cells usually containing calcareous sand beaches. Persistent trade winds and the waves they generate, summer swell from the south, and winter swell from the north all refract around various portions of this coast and influence sedimentary processes. For instance, the Mana Plain on the west shore is a broad accretionary strand plain that originated with falling late Holocene sea level, and converging longshore sediment transport where north swell (refracting from the northwest) and trade wind waves (arriving from the east) deliver sand from two directions at various times of the year.

4. Oahu

Oahu has 180 km of irregular coastline that was greatly influenced by massive landslides that removed about a third of the eastern side of the island and about half the western side. The shape of the island is related to two mountain ranges, the eroded remnants of separate shield volcanoes truncated by the landslides.

The north shore has massive winter surf (waves 15 m high and more), long sandy beaches, rocky points, and patches of beach rock exposed particularly in winter.

The south coast of Oahu has been modified by urban and industrial development (*Fig. 4*). Pearl Harbour formed as the island subsided towards the end of the main shield volcano building phase, drowning the river valleys that drain central Oahu. It contains almost 50 km of coastline backed by extensive wetlands through which highly sedimented waters enter the harbour. Along the shoreline, outcrops of 125,000 year-old skeletal limestone reveal fossil corals (*Fig. 5*) in growth position and other paleoreef features that accreted under the higher seas and warmer temperatures of the last interglacial period.

5. Molokai

The island of Molokai has a 142 km coastline, and was formed by at least three shield volcanoes (MacDonald et al. 1986). Maunaloa (420 m), the West Molokai volcano, is a dry flat-topped shield volcano partly protected from east and NE trade winds by East Molokai (1,514 m), which is wetter and has been cut into deep spectacular valleys and high steep ridges that are lush and vibrantly green. Most of the north coast is cliffed, with prominent ridges and valleys that have been carved by stream erosion. There are sectors of vertical cliff cut in volcanic formations.

6. Lanai

Lanai is a single shield volcano that formed from summit eruptions and along three rift zones between 1.2 and 1.46 million years ago, a classic example of a Hawaiian shield volcano with a gently sloping profile. The small sub-circular island has a 76 km coastline and a dry climate with minimal stream activity. As on Molokai overgrazing of domestic and feral animals in the nineteenth century and widespread deforestation have drastically changed the stability of the soil. The vegetation has never fully recovered and there is considerable wind erosion on the island (Macdonald et al. 1986).

Along the northern coast windy conditions have led to the development of a series of low sand dunes behind beaches that are fronted offshore by a narrow fringing reef. The beaches, known collectively as Shipwreck Beach are composed mostly of calcareous sand punctuated by outcrops of lithified beachrock. Narrow Polihua Beach has a fringing reef.

Fig. 4
The south coast of Oahu is characterised by intense urban development. World famous Waikiki Beach is shown here in a view taken from the summit of Diamond Head, an extinct volcano on the coast southeast of Waikiki.

Fig. 5
The rock shores of O'ahu (photo near Ka'ena Pt.) preserve a record of high sea levels and warmer seas from the last interglacial period (Eemian Interglacial). The yellow line highlights a large coral head that is about 125,000 years old.

7. Kahoolawe

Kahoolawe is the smallest of the main Hawaiian Islands, with just 47 km of coastline around a single shield volcano that formed 1.03 million years ago. It has had a complicated history of human exploitation that has affected its terrain and environment, leaving it dry and barren. In the nineteenth and early twentieth centuries, tens of thousands of sheep and goats were raised on the island. Consequent grazing removed most of the vegetation, leaving the soil exposed to high winds, which eventually removed much of it. The coast has lava headlands separated by sandy beaches supplied with sediment from fringing reefs, with pocket beaches of detrital volcanic sand that lie at the mouths of stream gulches that descend from the centre of the island.

8. Maui

The island of Maui is composed of two large volcanoes separated by a low-lying isthmus. The West Maui Volcano (formed 1.6 million years ago) at an elevation of 1,764 m lies to the west of the massive Haleakala volcano (formed 0.8 million years ago) with a summit that reaches 3,055 m. Maui has 193 km of coastline that fringes the two main shield volcanoes and the isthmus. Again the north coast has large ocean waves, and cliffed headlands of volcanic rock alternate with sandy beaches.

9. Hawaii

The island of Hawaii lies over or just north of the Hawaiian hot spot and is composed of five volcanoes and one active seamount: Kohala, Hualalai, Mauna Loa, Kilauea, Mauna Kea and Loihi (located offshore). Of these, only Mauna Loa, Kilauea and Loihi are considered active, while Haulalai is dormant with its most recent eruption ending around 1800–1801.

The island has 428 km of coastline and is so large relative to the other Hawaiian islands that it is known locally and abroad as the Big Island.

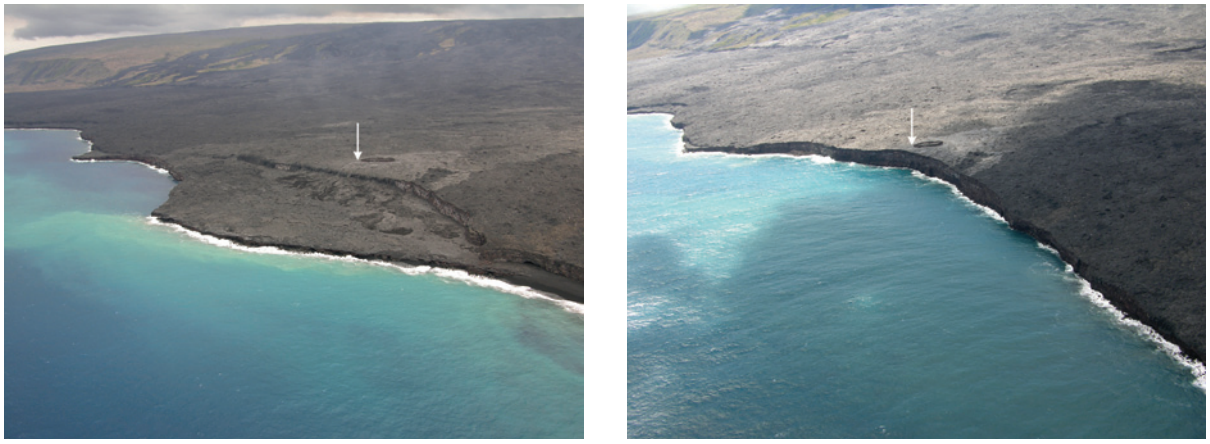
Well-developed black and green sand beaches signify the reworking by waves and currents of recent lavas. These beaches are relatively limited along the rough volcanic coastline, and white calcareous sands are restricted because of poor coral reef development due to recent volcanic activity. There is lush vegetation in the NE, where the annual rainfall is 1,500–4,000 mm.

The west coast of the Big Island has narrow white sand beaches and lush coral growth at several locations. Locals and visitors alike find that the shoreline has numerous spectacular examples of Hawaiian coastal environments.

Kilauea is a large active volcano on the SE flanks of Mauna Loa. On 12 May 2002 the Mothers Day Flow commenced on the south flank of Kilauea and travelled as molten lava through pre-existing lava tubes down to the coast, where it formed a broad lava lobe. When the lava flows into the sea the molten rock (which may exceed 1100°C) creates steam plumes When pāhoehoe lava enters the ocean for extended periods of time, new land is created in the form of a fan-shaped platform known as a lava bench. Lava pouring into the ocean from either surface flows or lava tubes cools rapidly, usually shattering in the cold water into sand- to block-size fragments. These accumulate along the shore to form a loose foundation that can support overlying lava flows which build a bench above sea level. However, the bench is deceptive; while it looks like solid land, it will in fact eventually collapse into the sea (*Fig. 6*) sweeping unwary visitors to their death. National Park Service personnel usually rope these

Fig. 6

A lava bench at East Lae'apuki on the south shore of the Big Island (left) collapsed during the night of 13 August, 2007 (right). (photo by T. Orr)



dangerous areas off to protect the public. Nonetheless, foolhardy hikers are seen on these dangerous features, and have been lost when they visited the wrong place at the wrong time.

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