CHAPTER 2

Views of the South Moloka'i Watershed-to-Reef System

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The fringing coral reef along the south coast of the island of Moloka'i is one of the most extensive fringing coral reefs in the Hawaiian chain. For a distance of about 40 km, from Hale O Lono on the west to Kamalō on the east, live coral coverage is estimated to be 60 to 90 percent (see Jokiel and others, this vol., chap. 5), higher than on all but the most protected reefs in Hawai'i. The reef is actively accreting in depths between about 6 and 27 m (20 and 90 ft), creating, as these views presented here show, spurs, grooves, knobs, pits, and pinnacles that are home to thousands of marine organisms. Winter waves from the north restrict active reef accretion beyond the sheltered portion of the coast, but the old reef surface in those areas is still populated by numerous individual coral colonies, invertebrates, and fish. For more information about the distribution of coral see Jokiel and others (this vol., chap. 5), and for more information about the distribution of waves along the reef see Storlazzi and others (this vol., chap. 11).

The images of the south Moloka'i coast in this chapter were created using a combination of aerial photography and high-resolution bathymetric data. The aerial photography was collected in 1993 by the National Oceanic and Atmospheric Administration (NOAA). The aerial photographs were scanned at 800 dots per inch (dpi), yielding an approximate pixel resolution of 1 m, then georectified, color-balanced, and mosaicked by the U.S. Geological Survey to produce a seamless image map covering most of the coastal area on the south coast of Moloka'i. The aerial image maps were then digitally combined with high-resolution bathymetric data to produce the image maps shown in this chapter.

The high-resolution bathymetry was collected in 1999 and 2000 using an airborne laser-imaging system called SHOALS (Scanning Hydrographic Operational Airborne Lidar Survey) operated by a private company for the U.S. Army Corps of Engineers. The SHOALS system employs lidar (light detection and ranging) technology, with laser pulses in two wavelengths, to very accurately determine water depth at points roughly every 4 m along the bottom. For the Moloka'i surveys, lidar data were collected at a 2-m spacing, and more than 12 million depth measurements were collected. The system is mounted in an aircraft, which allows it to quickly cover large areas. The vertical accuracy of the measurements is within 15 cm of the actual water depth. Because it is an optical technology, the maximum depth lidar can measure is dependent on water clarity; a general rule of thumb for the SHOALS system is that it penetrates approximately 2.5 times the depth that a person can discriminate objects visually. During the Moloka'i surveys the approximate maximum depth range recorded by the lidar system was 35 to 45 m (115 to 150 ft).

Each of these two different data sets is extremely useful on its own. The aerial photography provides valuable insight into the types of reef habitat that are found in the shallow areas off the south side of Moloka'i. To the trained eye, different reef environments can be distinguished from one another in the photography, and this information can be used to create maps depicting bottom type and habitat type (see Cochran, this vol., chap. 9). In addition to shallow water environments, the aerial photography also shows areas of land adjacent to the reef. This, in combination with elevation models, can provide important information about the natural and human-caused processes that may affect the reef, such as wave erosion or land clearing.

The usefulness of aerial photography, however, is limited to the shallow water environments that can be seen with the human eye. Even in the relatively clear water found in some areas of the Moloka'i reef, the aerial photography begins to show low contrast in water deeper than about 10 m. At these depths the information provided by the lidar data help to fill in the picture of the reef. The dense network of lidar depth measurements can be used to create a three-dimensional computer image of the reef. This image allows us to gain information about the shape of the reef in areas that would otherwise be too deep to "see" with conventional aerial photography. By overlaying an artificially colored and shaded image on the aerial photography, we can develop a more complete picture of the ridge-to-reef environment, from the land all the way to depths greater than 40 m. This combination of high-resolution bathymetric data and high-quality photographs is a powerful and unprecedented tool for interpreting the geologic processes that contribute to the reef's development.

In the following pages, views of the south Moloka'i reef and the adjacent land are shown using combined aerial photography and lidar. Recent advances in computer-aided mapping technology allow us to display these data sets in both two-dimensional map view and in vertically exaggerated three-dimensional perspective views. Using these two types of images and our observations from field studies, we point out features and patterns on each map sheet that are significant for understanding the processes that have affected, and continue to affect, the evolution of the reef environment. Linkages between the shape of the reef and the processes that shape it are further explored in the following chapter (Storlazzi and others, this vol., chap. 3).

"Blue holes" and channels off Kamalō.

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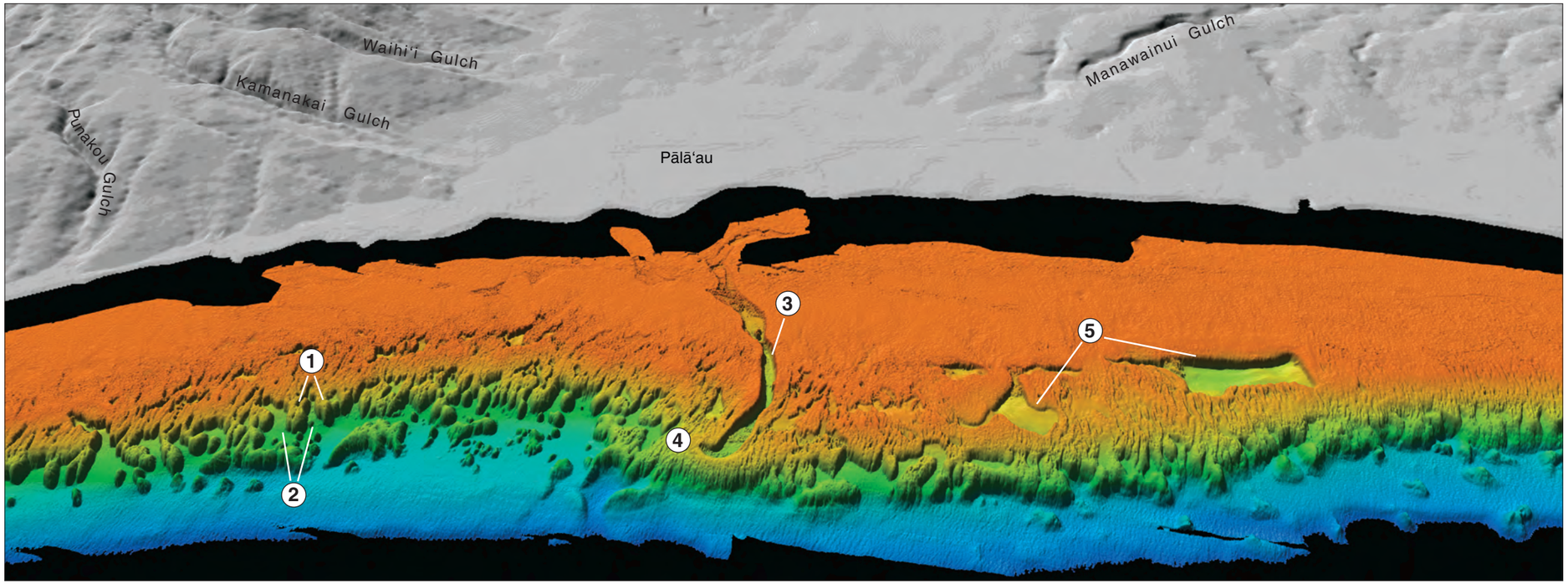
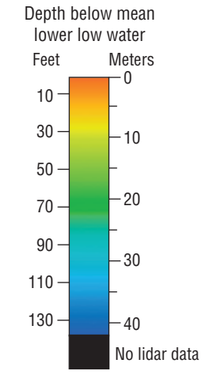
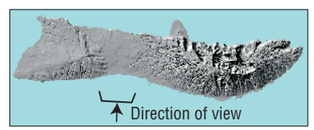
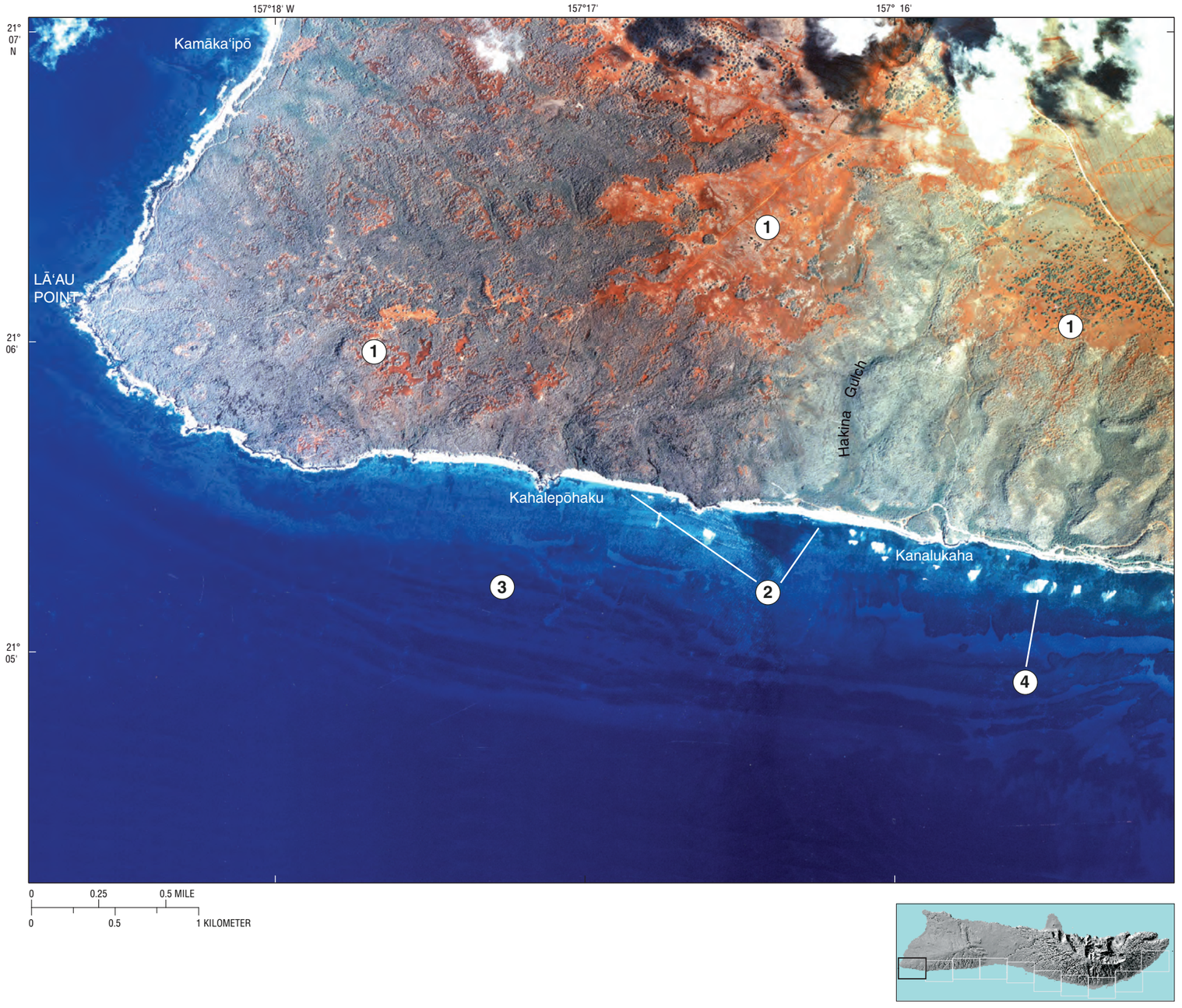






Central Moloka‘i Reef

This image is an expanded perspective view of the central portion of the coral reef off south Moloka‘i. Distinctive features include its pervasive rhythmic spur-and-groove formations (1, 2), like those that characterize many other reefs around the world, and the reef channel (3) at Pālā‘au, remnant from a stream valley that was eroded when sea level was lower than present. Note that the channel is surrounded by solid reef at its terminus (4). Also note the large solution pits (5), partially filled with sediment, east of the channel. These pits, also commonly referred to as “blue holes,” result from dissolution of the reef by flowing water, either as surface streams during times of lower sea level or as flow of submarine ground water under present conditions, followed by collapse of the overlying surface. Approximate distance across the bottom of the image is 7.5 km (4.7 mi).

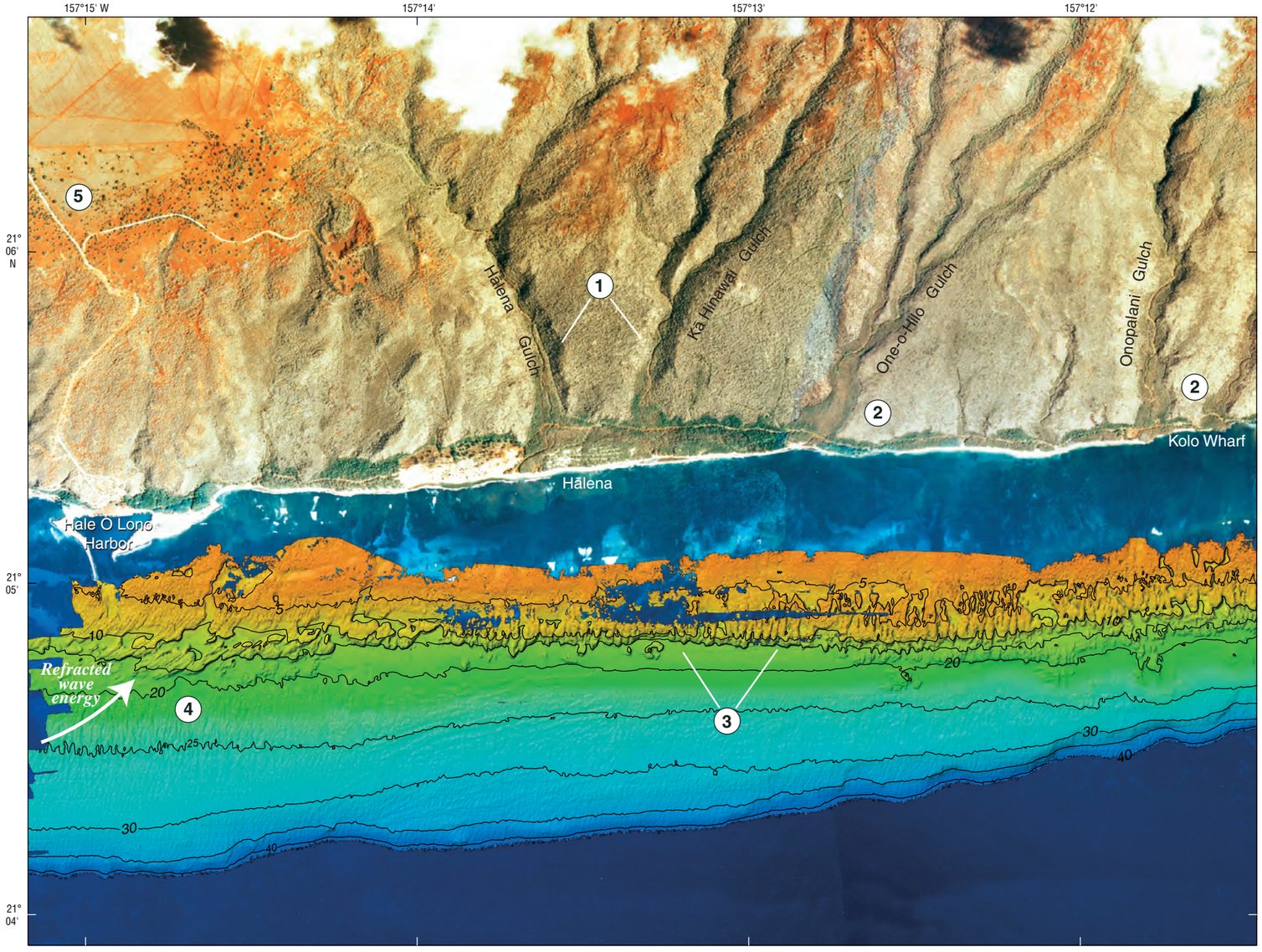


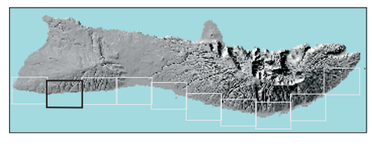
Lā‘au Point

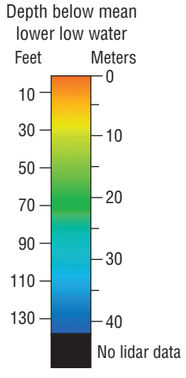
The western end of Moloka‘i is an arid, eroded surface characterized by large exposures of reddish-brown soil densely to sparsely covered by scrub vegetation and grasses (1). The exposures result from low annual rainfall coupled with heavy livestock grazing throughout much of the 20th century. The exposed soil is a source of sediment that is carried to coastal waters during infrequent flood events.

The western beaches (2) of south Moloka‘i are generally wider, more continuous, and composed of coarser sand than the central and eastern beaches. Two factors contribute to this: wave energy and sediment sources. First, the western end of the south Moloka‘i coast receives higher wave energy than farther east, where waves are blocked by the island of Lāna‘i. The southwest coast also receives refracted wave energy from north Pacific swell, and the high wave energy sorts the beach deposits and removes the smaller, lighter particles of fine sand and silt. The second factor has to do with the local availability of beach material. Much of the western shoreline of south Moloka‘i is underlain by older beach sands and beach rock that provide a ready source of material for the modern beach. The adjacent reef also provides a source of coarse material for the beaches.

The modern reef (3) on the westernmost part of south Moloka‘i is not well developed. The inner shelf consists of a dipping surface composed of shore-parallel bands of sand and old reef limestone; individual coral colonies and algae mantle the limestone. This end of the island does not have a well-defined reef crest, allowing waves to break closer to the shore (4) than they do farther east. The barely discernible dark underwater bands in the photograph are exposures of older reef limestone with scattered colonies of coral. Studies of the limestone deposits in this area show that active reef growth ceased about 5,000 years ago (see Engels and Fletcher, this vol., chap. 4). No lidar data was collected in this area, so only aerial photography is shown.

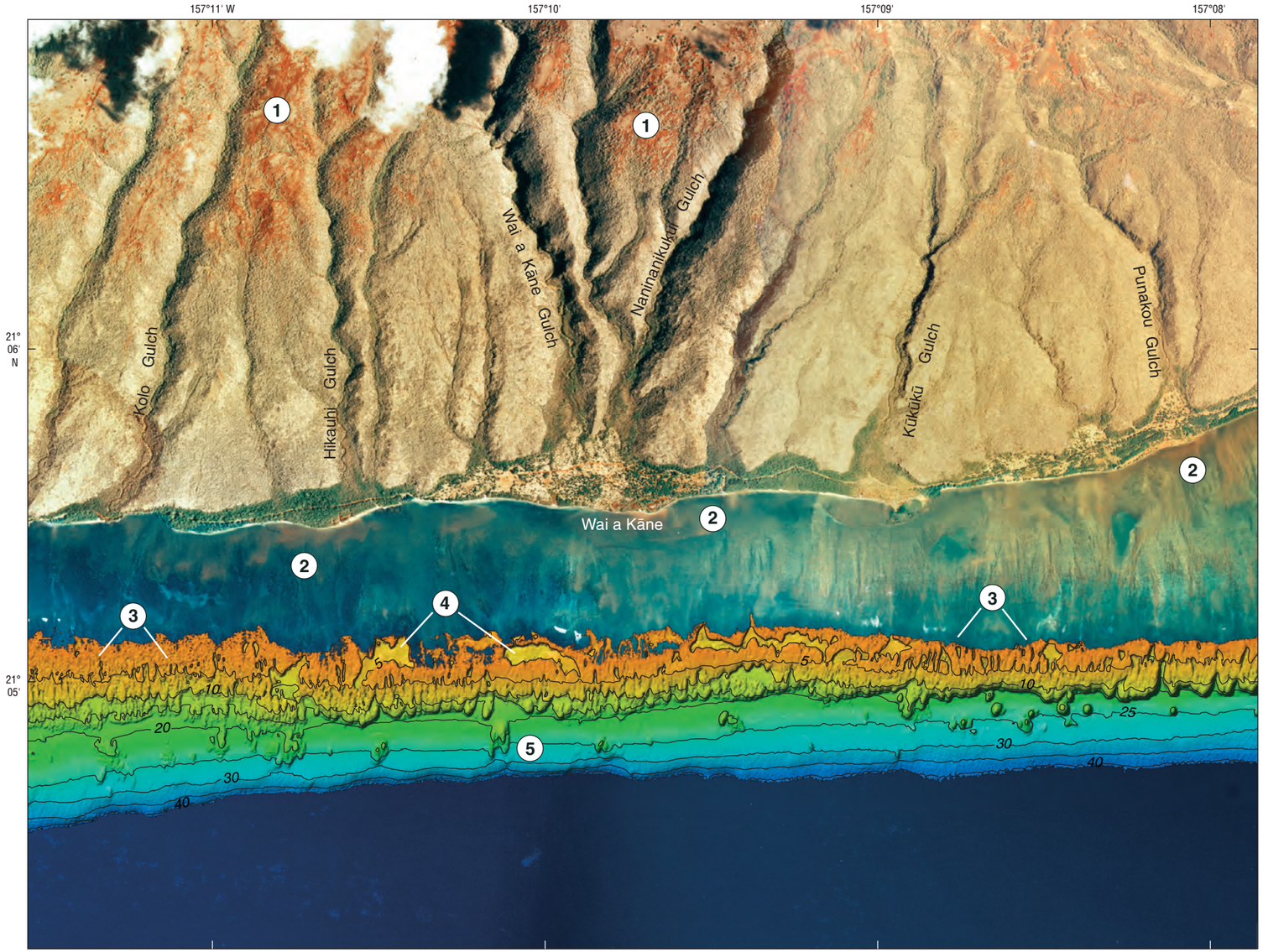


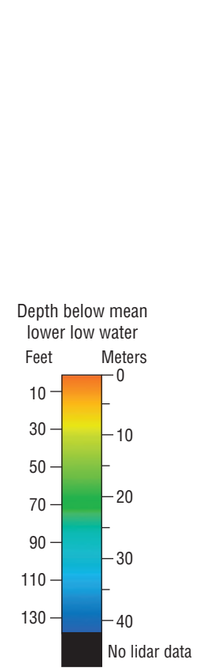




Hale O Lono

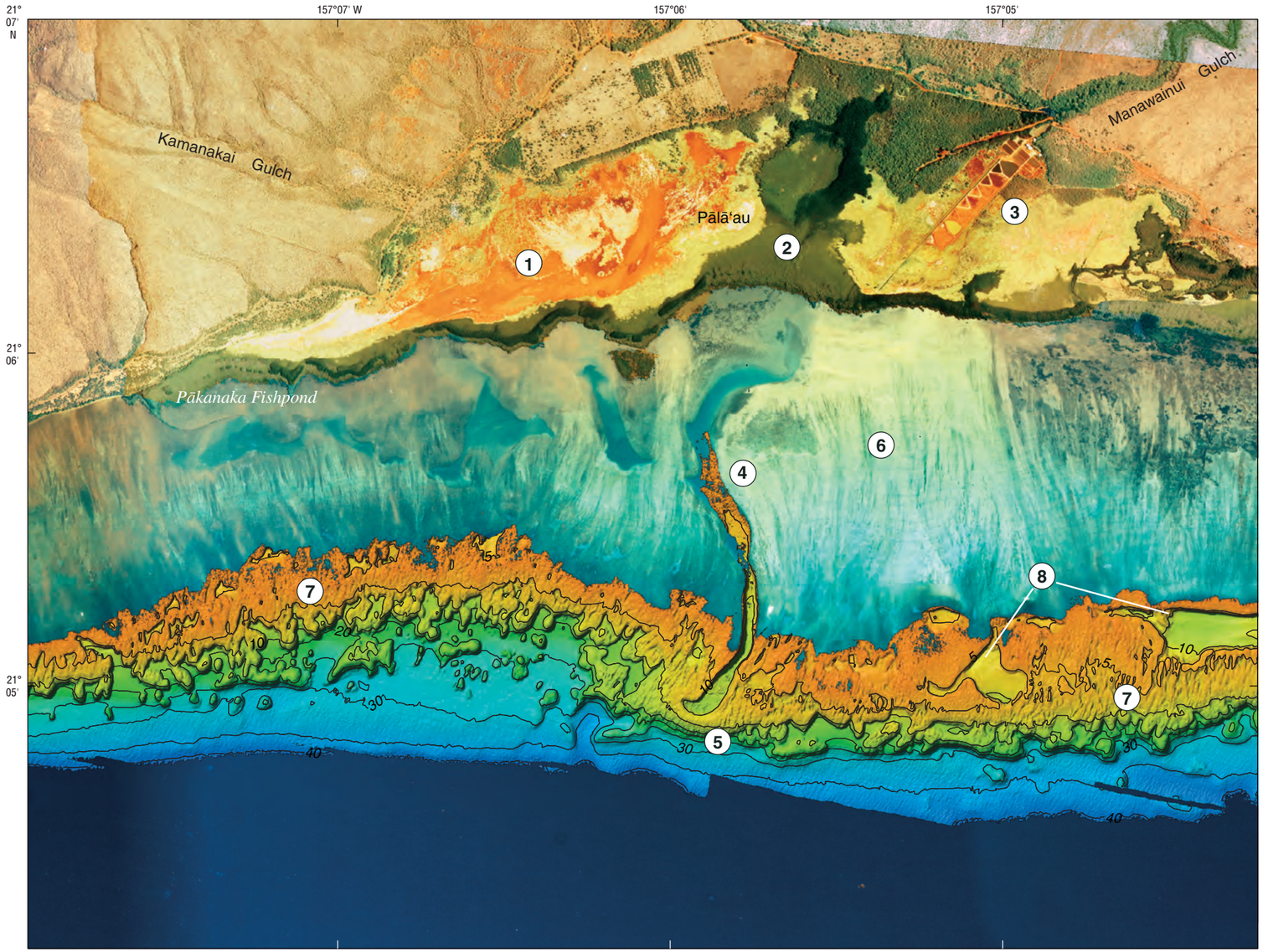
The southern slopes of Moloka‘i are heavily dissected by deep gullies (1), many of which discharge onto the coastal plain, whereas others (2) extend almost completely to the shoreline. Those gullies that meet the shoreline directly are capable of delivering sediment onto the reef during heavy rains and flooding. East of Hale O Lono Harbor, the reef shows the first indication of rhythmic spur-and-groove patterns (3), a common shape of coral reefs that is derived by coral growth along ridges oriented perpendicular to the dominant swell direction. Note that off Hale O Lono, the spur-and-groove morphology curves to the southwest (4), probably because large North Pacific swell wraps around the island and approaches the reef from the southwest, inducing growth along that trend. The road to the town of Mauna Loa can be seen in the upper left of the image (5).

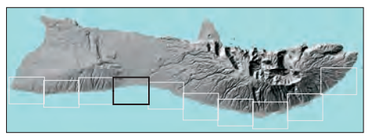


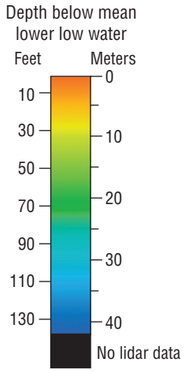


Wai a Kāne Gulch

Red-brown soils (1) are exposed on the hill slopes along the western part of south Moloka'i as a result of low rainfall and heavy cattle grazing (Roberts, 2001). This 1993 photo captured images of plumes of turbid water on the inner reef flat (2). The fore reef here is composed of well-organized, evenly spaced spur-and-groove morphology (3) with some large shallow solution pits (4) and a few spurs in deeper water (5). The deeper spurs, although colonized on their surface, are probably remnants from earlier periods of more active reef growth, as documented by Engels and others (2004).

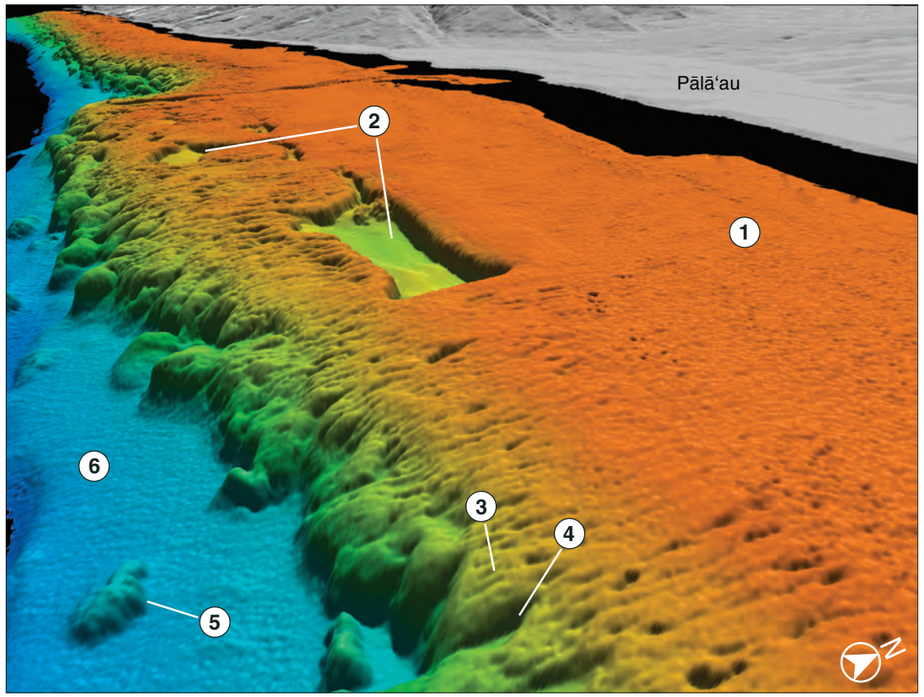




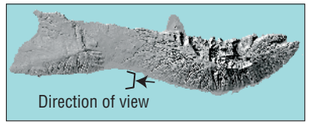


Pālā'au

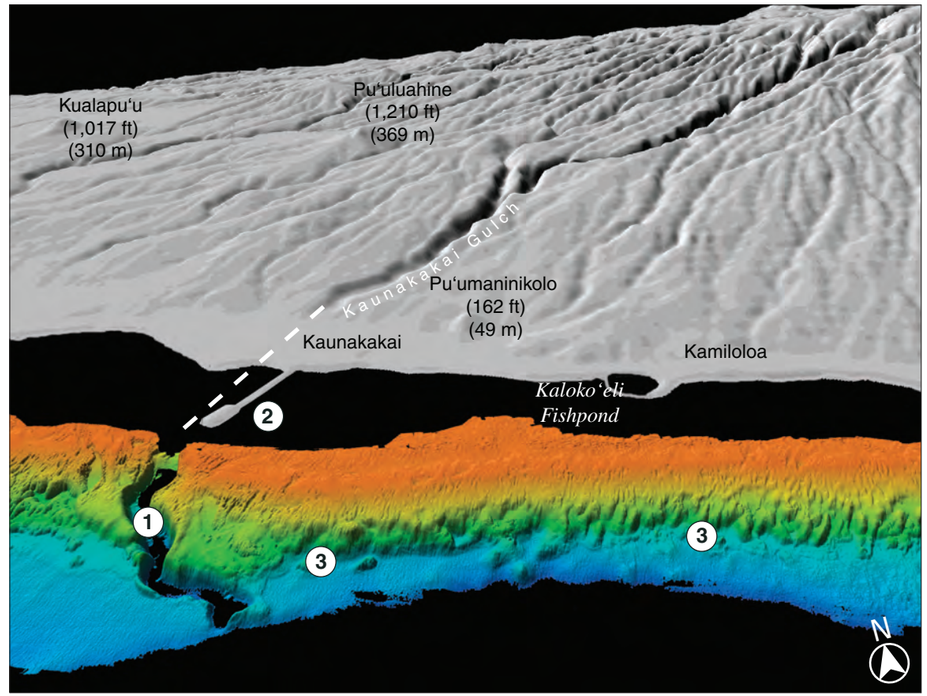
The coastal area at Pālā'au is characterized by an extensive mud and salt flat (1) that formed from heavy flooding and runoff in the early 1900s and an extensive mangrove forest (2) that was established in 1903 to curb the heavy sediment runoff (D'Iorio, 2003). The elongated structure trending northeast-southwest (3) east of the mangroves is a shrimp farm. The reef at Pālā'au is dissected by a meandering channel (4) that resulted from stream erosion during a period of lower sea level (>12,000 years ago). Note that the reef is not breached at the end of the channel (5), possibly from coral growth since that time, or because the water flowed through the porous reef rather than over it. East of the channel the reef flat is a broad, barren surface (6) covered by thin deposits of stained carbonate sand, giving way to an algae-covered rock surface to the east. Near Pālā'au, the reef undergoes a subtle change in orientation, reflecting the overall change in island morphology. The trends of the fore reef on each side of the channel (7) mimic the change in orientation of the shoreline: to the west, the shoreline and reef trend west-southwest; to the east they trend east-southeast. East of the channel, the middle part of the reef is characterized by large pits (8), which likely result from extensive, long-term dissolution by fresh water flowing through the reef, followed by roof collapse.

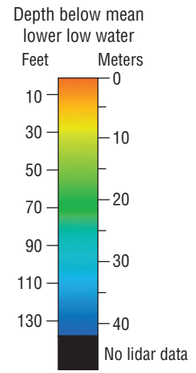


Blue Holes near ‘Umipa‘a

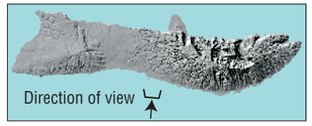


This perspective view of the central Moloka‘i reef near ‘Umipa‘a shows that the inner reef is characterized by a wide reef flat (1) and large, sediment-infilled pits (blue holes) (2). The east-west alignment of the inner walls on the pits (see also image of Pālā‘au area) possibly indicates a regional control related to shoreline history or reef structure. The outer reef has a pronounced spur-and-groove structure (3, 4), which gives way to isolated reef pinnacles (5) and a sediment-covered terrace (6) seaward of the reef. Approximate distance across the bottom of the image is 850 m (0.5 miles).

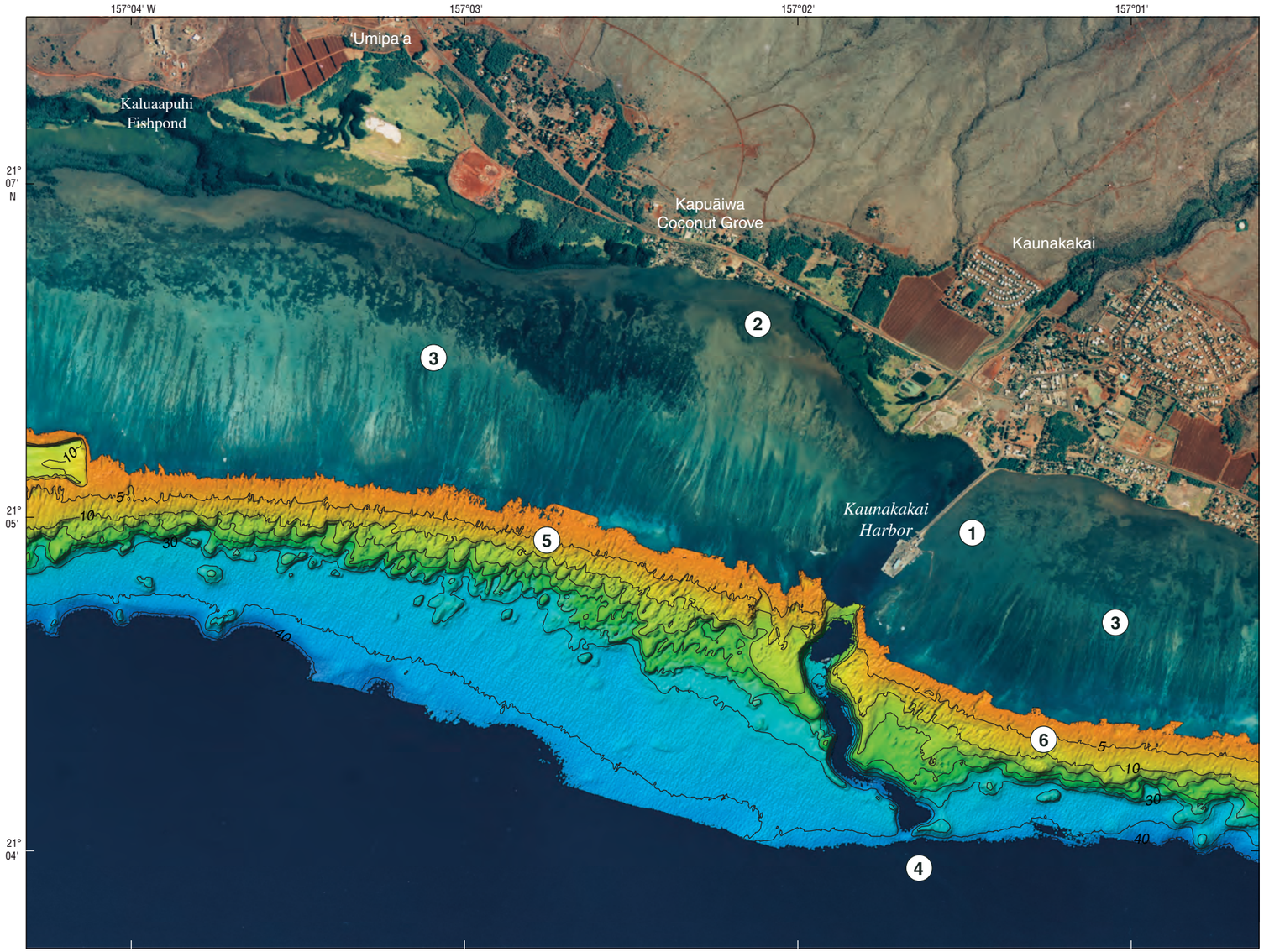


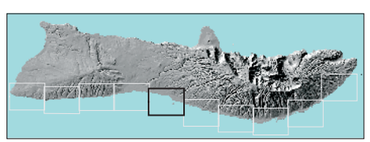


Kaunakakai to Kamiloloa



This perspective view of central Moloka‘i shows the alignment of Kaunakakai Gulch with the reef channel (1) west and offshore of the wharf (2). The channel is interpreted to have formed by stream water flowing out of the gulch when the ocean was at a lower level and the shoreline was farther south (offshore of the present shoreline). The base of the actively growing reef (3) lies at a water depth of about 28 meters (~90 feet). Approximate distance across the bottom of the image is 4.5 km (2.8 miles).





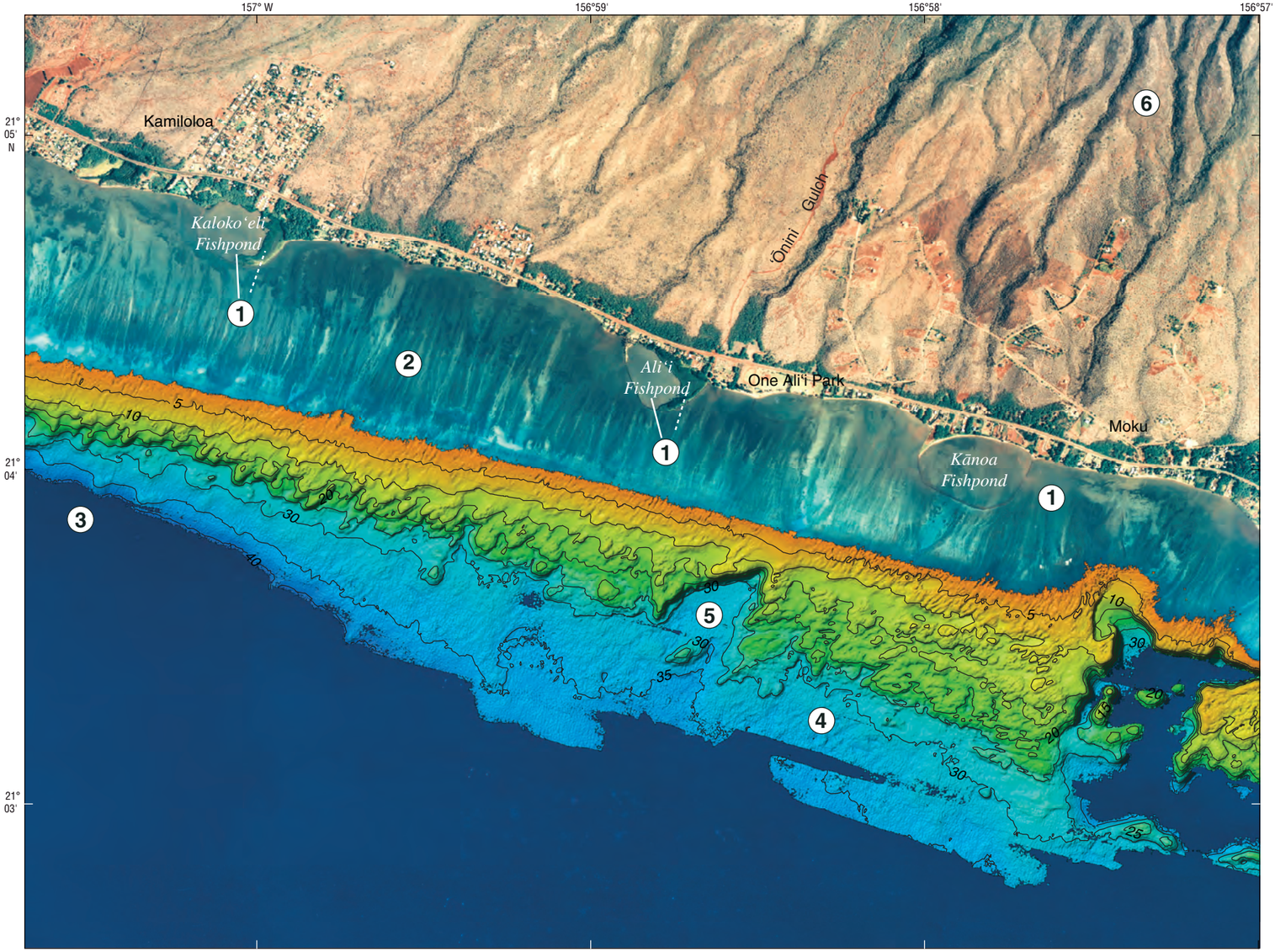
Depth below mean lower low water

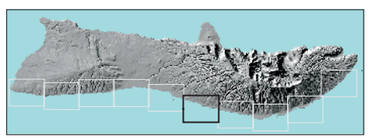
Feet	Meters
10	0
30	10
50	20
70	30
90	40
110	
130	

No lidar data

Kaunakakai

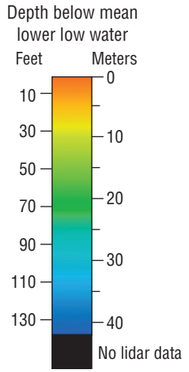
The town of Kaunakakai is the largest town on Moloka'i and sits adjacent to the largest and most important harbor on the island. In 1934 the Kaunakakai Wharf (1) was rebuilt to its present size and configuration. It is nearly 1 km long and solid, and thus it is influential in blocking the westward flow of water and sediment along the reef flat. For more information about sediment movement along the reef, see Ogston and others (this vol., chap. 20). To the west of the wharf (2), the shoreline is eroding at Kapuāiwa Coconut Grove (D'Iorio, 2003), perhaps in response to sediment trapping by the wharf. The reef flat on both sides of the wharf (3) is very broad and mantled by thin layers of muddy sediment and macroalgae. The reef is dissected by the Kaunakakai channel (4), a former stream channel remnant from a period of lower sea level (similar to Pālā'au channel). Note that west of the Kaunakakai channel the fore reef exhibits very well defined rhythmic spur-and-groove morphology (5), but east of the channel the morphology is subdued and flattened (6). This pattern reflects the active, healthy growth of coral west of the harbor and the limited, stunted growth that extends to the east for several kilometers.

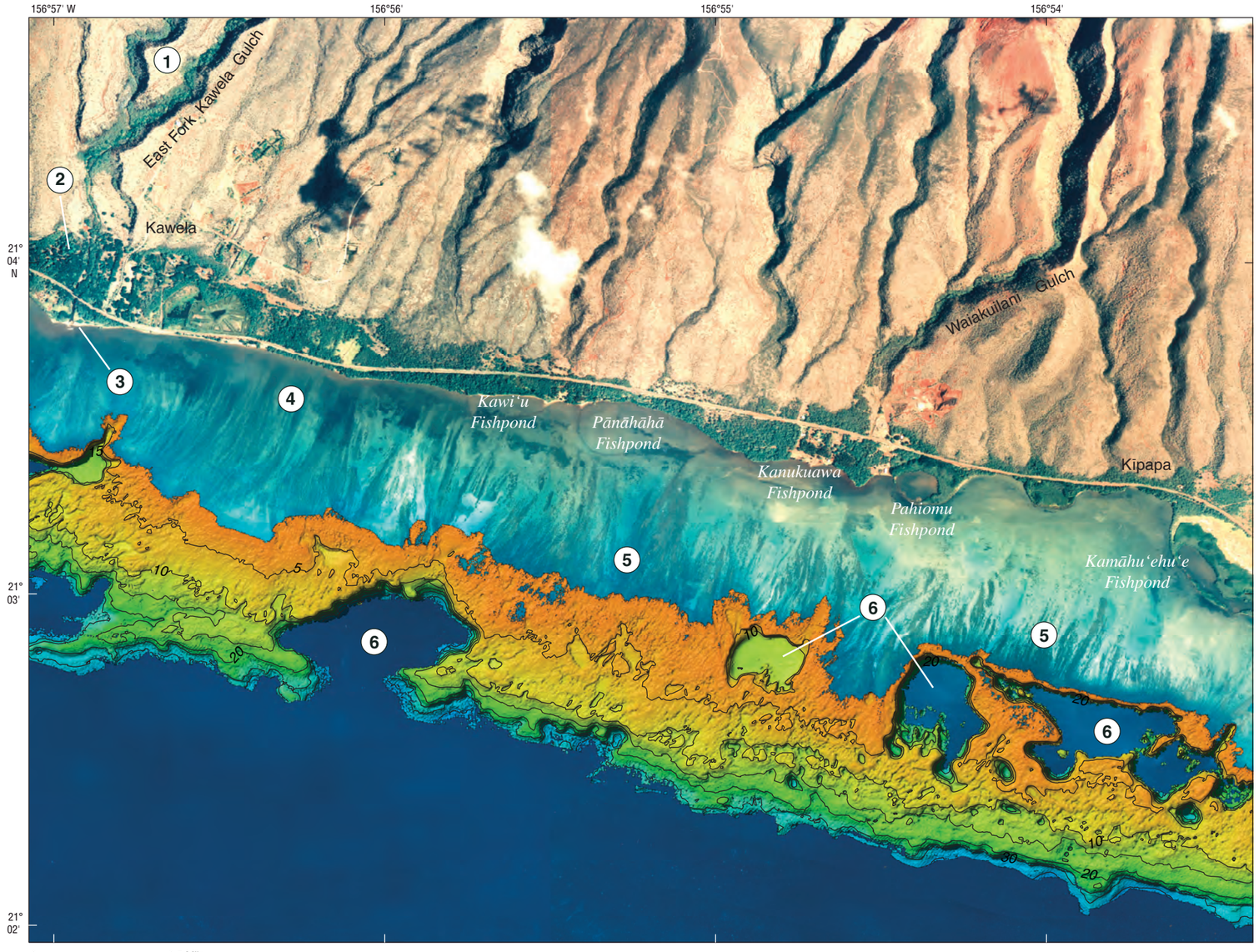




Kamiloloa

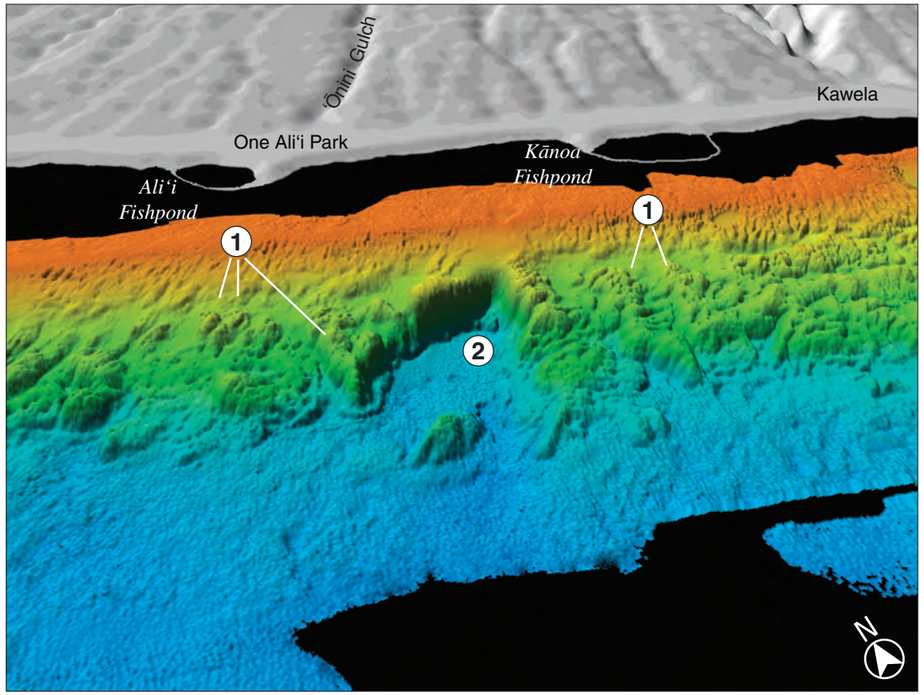
Fish ponds (1) are historical manmade features along the entire south coast of Moloka‘i, and they are particularly prominent along this section of the coast. Note the infilling of the fishponds with sediment (solid lines) and mangrove trees (dashed lines). The reef flat here is broad and nearly flat (2), with a thin covering of muddy sediment and macroalgae. The fore reef shows signs of erosion or non-growth to the west (3), gradually broadens toward the east (4), and becomes segmented by major re-entrants (5). Rainfall and slope gradients are higher on this part of the island than on the western part of south Moloka‘i, contributing to more extensive dissection and erosion on island slopes here (6) compared to farther west.



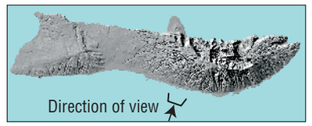


Kawela Gulch

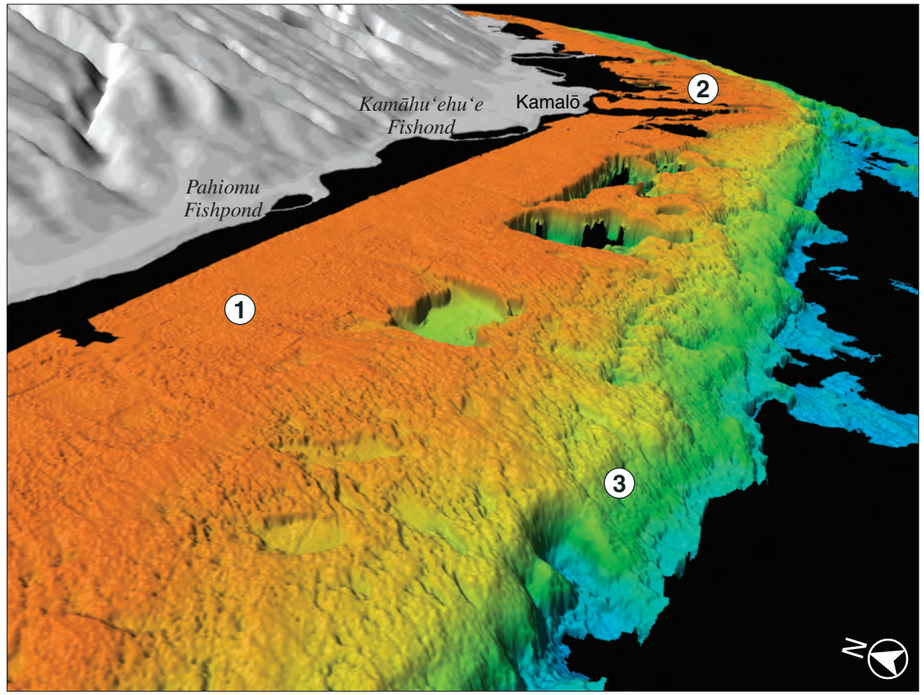
Kawela Gulch (1) is a major pathway of water and sediment to the south coast of Moloka‘i. Deposition of sediment has created a pronounced alluvial fan onshore (2) and a pronounced lobate delta at the coast (3). The inner reef flat here, as farther to the west, is a flat, sediment-covered surface (4) with little coral growth. In contrast, the outer reef flat has appreciable amounts of live coral (Rodgers and others, 2005) growing on low-relief ridges (5) oriented perpendicular to the coast. For more information on the low-relief coral ridges, see Storlazzi and others (this vol., chap. 3). Although several coral species appear within 400 m of the shoreline, coral coverage across the entire reef flat out to 700 m from shore is generally low (<10 percent) with few exceptions (Rodgers and others, 2005). The reef crest and fore reef are characterized by large reentrants, or embayments, and pits (blue holes) (6).

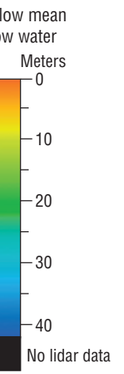


‘Onini Gulch to Kawela Gulch

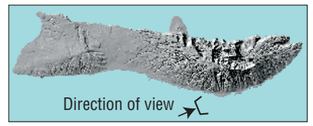


This perspective view of the reef off One Ali‘i Park in east-central Moloka‘i shows the changing shape of the reef. The spur-and-groove structure, dominant farther west (see, for example, the image of Kaunakakai) is not well defined in this area; individual spurs (1) are discontinuous and of various orientations, indicating that coral growth has not been uniform in this area. The large reentrant (2) in the reef may have been the site of stream outflow during a period of lower sea level. Approximate distance across the bottom of the image is 2 km (1.25 miles).

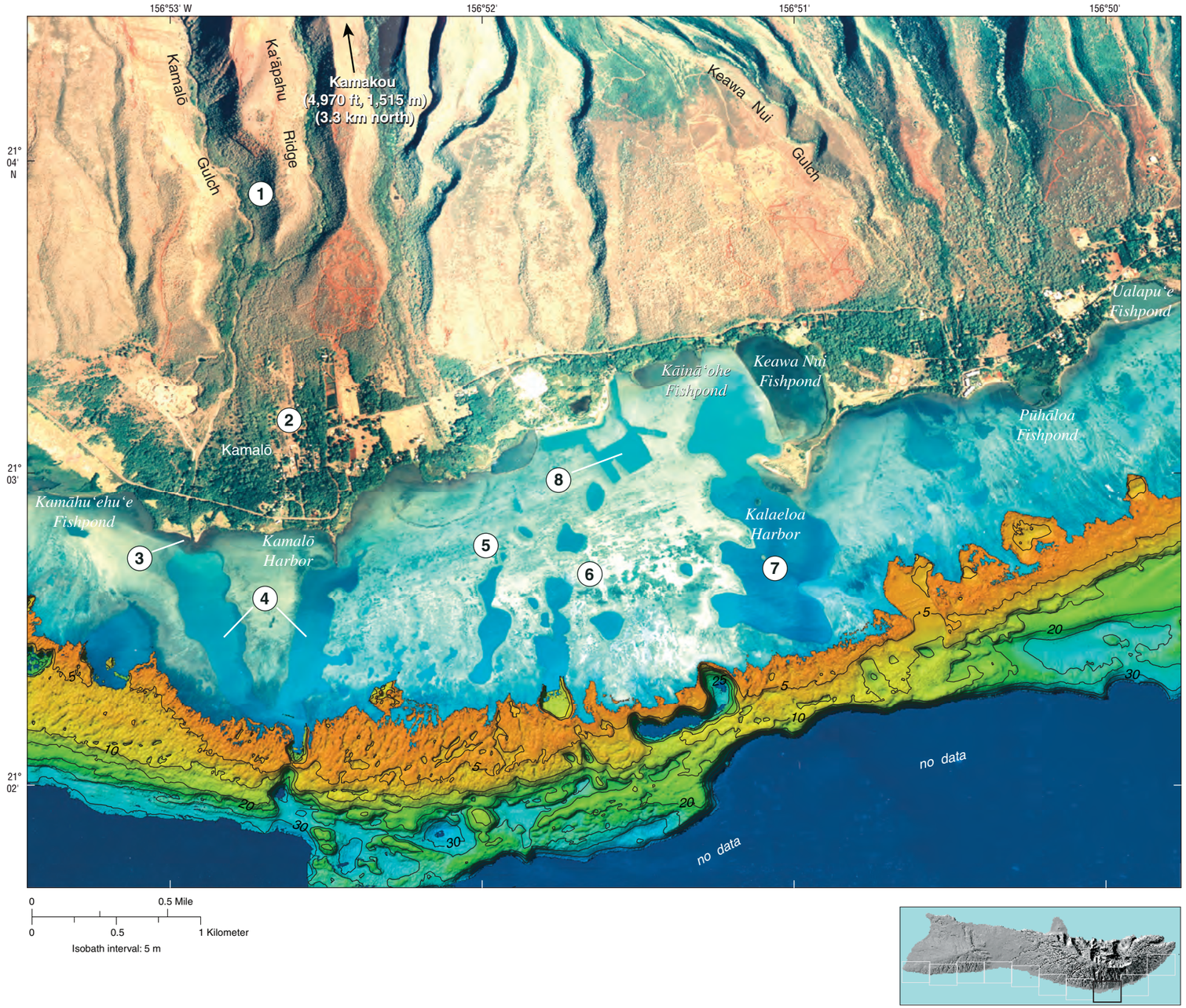




East toward Kamalō

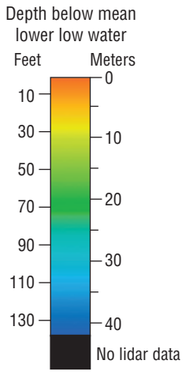


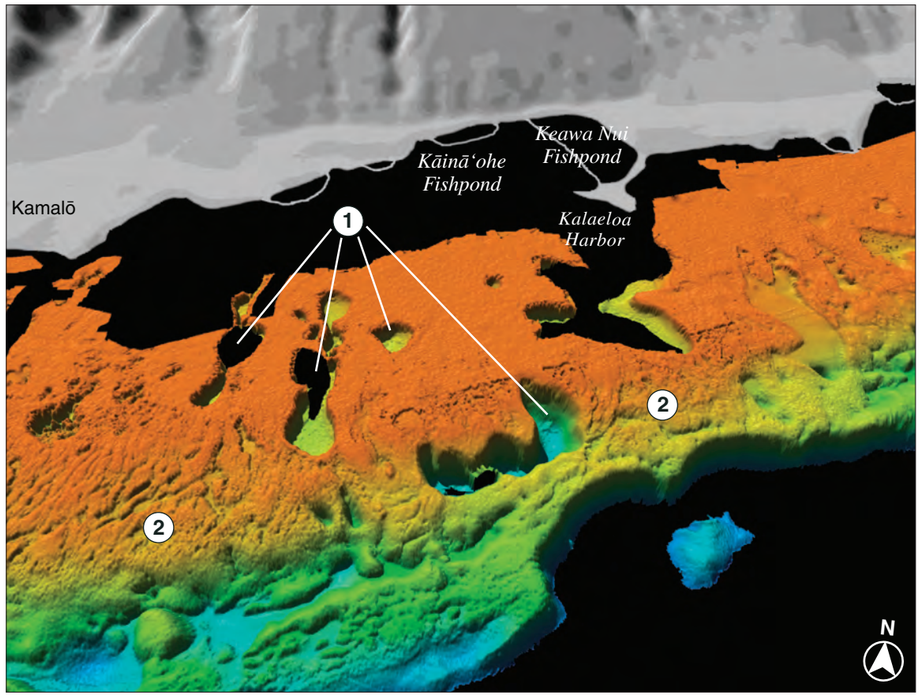
This perspective view shows the change in coastal orientation that occurs at Kamalō. It is this change that leads to higher wave energy east of Kamalō, where the coast is more exposed to winter swell. The near part of the view (1) shows the reef flat that is sheltered from the high wave energy that reaches the reef east of Kamalō. Wave energy plays a major role in the development of the reef. East of Kamalō (2), reef growth is limited. In contrast, the fore reef west of Kamalō (3) is well developed and densely covered with live coral to depths of 28 meters (~90 feet), and small isolated coral colonies may be found deeper. Note the prominent blue holes, which are deeper and more abundant on the eastern end of the reef, perhaps because of the higher levels of precipitation and water flow. Approximate distance across the bottom of the image is 1.3 km (0.8 miles).

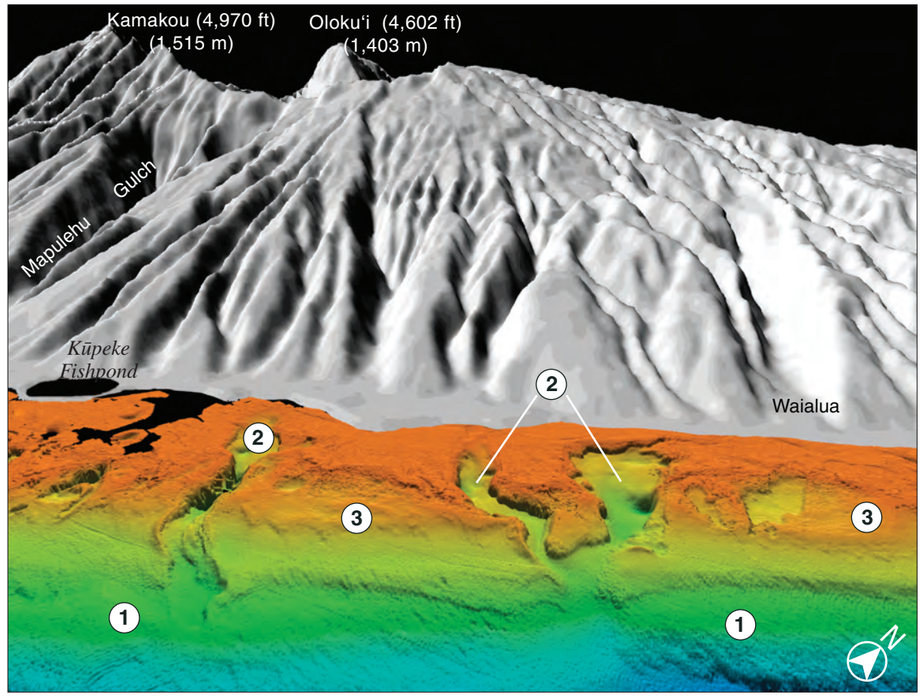


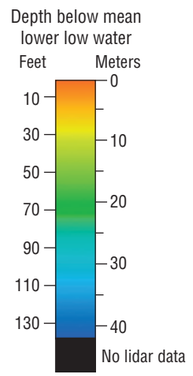
Kamalō

Kamalō is the point where the south Moloka‘i coast changes orientation and consequently becomes more exposed to wave energy eastward; the area also essentially marks the east end of the accreting reef of south Moloka‘i. Whereas the reef to the west of Kamalō appears to be actively accreting, the reef surface to the east consists largely of ancestral reef deposits intermittently colonized by live coral. Kamalō Gulch (1) and its adjacent gulches are the most prominent gulches along the south shore. Running steeply down from the island’s highest peak (Kamakou, 1,515 m or 4,970 ft), the gulches are wide and deeply entrenched. The large amounts of sediment that have been delivered through this system over time have built a large alluvial fan and coastal plain complex (2). The present mouth of Kamalō Gulch (3) discharges runoff directly into deep water through one of two paleochannels (4) incised by stream flow across the reef when sea level was lower than it is today. It is likely that the fine-grained sediment plumes formed during flood discharge from the gulches are driven west along the shoreline by prevailing winds. To the east of the paleochannels lie three pronounced lineations (5, 6, and 7) of deep holes in the reef flat; all three likely mark the location of freshwater flow (surface as well as ground-water discharge) across and through the reef, dissolving older reef limestone in the process. At the landward end of the string of elongated blue holes (6) is an artificially created pit (8) formed by dredging in the 1970s to create a harbor.

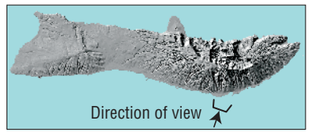






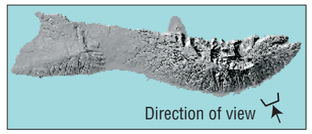


Kalaeloa

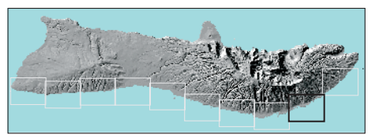


This perspective view of the Kamalō region and farther east shows that the reef is relatively smooth with numerous large blue holes (1). The blue holes are typically 6 to 24 meters (20 to 80 feet) deep and, as already pointed out, likely formed through dissolution of the preexisting reef limestone. The irregular reef surface (2) marks the transition between the actively accreting reef to the west and the sparsely covered limestone surface to the east. Approximate distance across the bottom of the image is 2.7 km (1.7 miles).

Honomuni

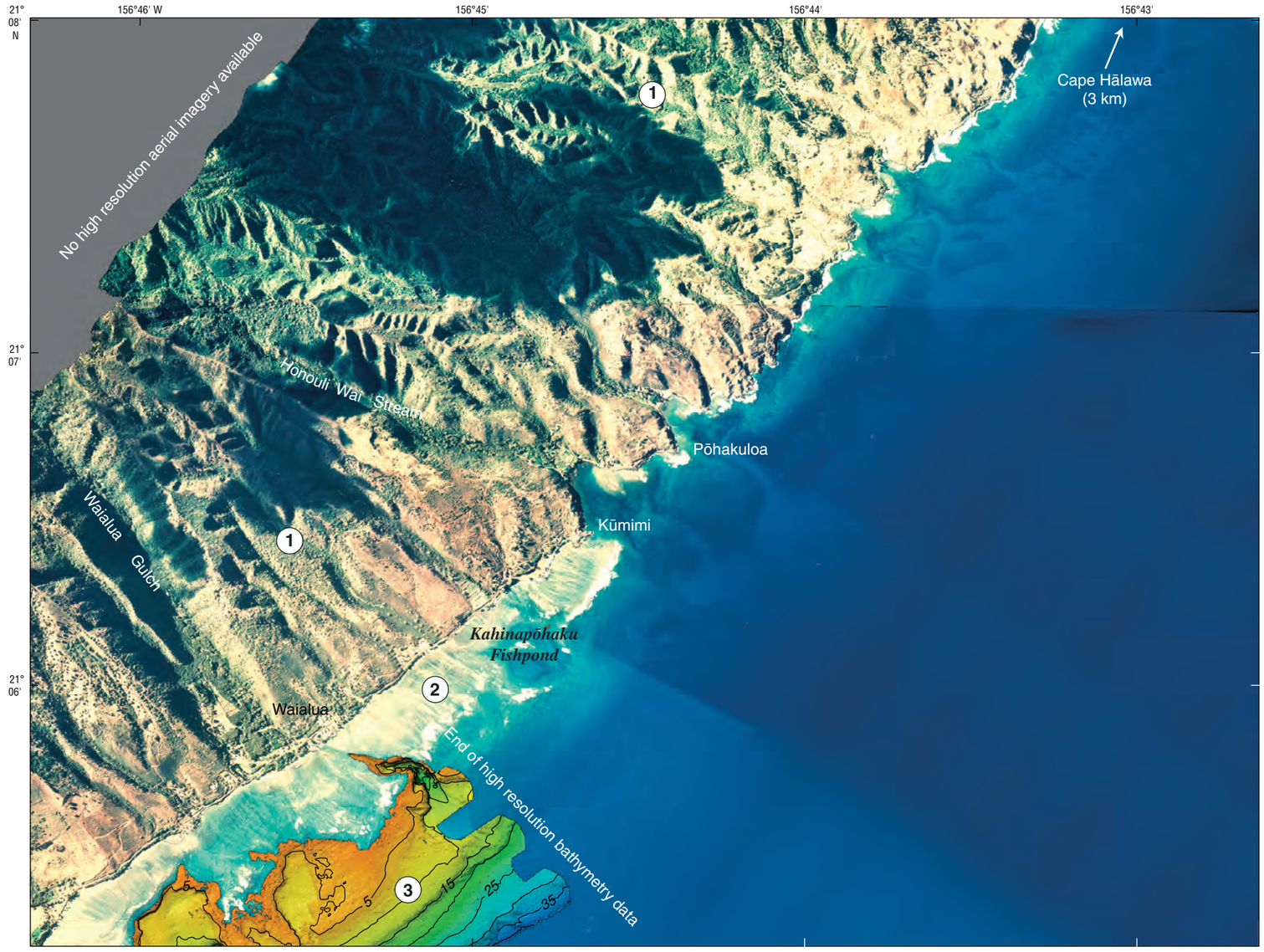


This perspective view shows that the eastern reef of south Moloka‘i is characterized by a smooth surface (1) with numerous channels and blue holes. Many of the large gullies dissecting the steep land surface align with channels incised into the reef (2). There is a complete absence of spur-and-groove formation by coral accretion in this area because of the high wave stresses. Live coral colonies are relatively sparse on the limestone surface (3). Approximate distance across the bottom of the image is 2.8 km (1.7 miles).



Pūkoʻo Harbor

The western shoreline of the Pūkoʻo Harbor image displays good examples of remnant fishponds on the inner reef flat; the stone walls have been knocked down, but the submerged boulders outlining the ponds are still evident in the aerial images (1). Pūkoʻo Harbor itself (2) is the remains of a fishpond that has been altered by dredging and emplacement of fill material. The original rectangular shape of the fishpond was altered in the early 1970s in an attempt to develop a marina. However, after completion of the dredging and accompanying reshaping of the coast in this area, the project was abandoned. The existing fishpond (3) on the reef flat and its upslope gulch are aligned with a channel through the reef (4), another example of freshwater dissolution and erosion of older reef limestone, as is the channel at (5). The fore reef along this part of the island is smooth (6) and lacks the distinctive spur-and-groove pattern that characterizes the reef west of Kamalō (as seen, for example, on the fore reef on the Kaunakakai image).



Kūmimi Point

This map includes the east end of the south Moloka'i fringing reef. The island slope is carved by numerous gullies (1), but there is little net accretion of sediment in the form of deltas or coastal-plain deposits along the shoreline. This reflects both the soil stability provided by lush vegetation as well as high-energy conditions along the shoreline that quickly move any sediment transported to the coast by stream runoff. The reef flat, nearly 2 km wide in the center of the island (see the image of Pālā'au), is barely 0.5 km wide on this image (2) and disappears altogether at Kūmimi (also known as 20-Mile Beach). This section of the coast is subject to repeated high wave energy (Storlazzi and others, 2005), which inhibits growth of the common reef-building coral species. The surface of the fore reef here (3) is colonized by scattered coral colonies, dominantly *Pocillopora meandrina* (rose coral), which is commonly found in high wave settings in Hawai'i. Active reef accretion is not occurring here; the fore reef in this area is simply the remnant of a former reef-building period.

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