

Benthic Habitat Maps of the South Moloka‘i Coral Reef

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To document evidence of change in any ecosystem, one must first have a starting point—a “baseline” inventory of resources. Thematic maps providing this baseline inventory are an important tool for assessing changes in coral reef ecosystems, allowing scientists to spatially document changes in coral location, percentage of cover, and relative overall health of the system. In the past decade, scientists and managers have recognized the lack of thematic maps for coral reefs worldwide. In 1998, the White House issued Executive Order 13089 establishing the U.S. Coral Reef Task Force (CRTF). Composed of several Federal agencies, including the U.S. Geological Survey (USGS), the CRTF has the primary duty of mapping and monitoring the coral reefs in the United States and U.S. Trust Territories.

One of the strategic goals of the U.S. Geological Survey is to assist land-use managers by establishing the geologic framework for ecosystem structure and function. Provide here are detailed high-resolution maps and habitat characterization of the reef off the south shore of Moloka‘i, a critical coral reef in Hawai‘i that is of concern to resource managers and the public. The threats to this reef, including excessive sedimentation and pollution, were some of the reasons for selecting this site to develop procedures for producing such maps. The USGS is in a position to provide high-resolution benthic habitat maps of the Moloka‘i reef because it is not under the 1-acre Minimum Mapping Unit (MMU) and 1:6,000 scale restrictions self-imposed on other agencies. These maps can be used as stand-alone static documents or in a geographic information system (GIS) and provide useful information to scientists, managers, and the general public.

Mapping on Moloka‘i

Before 1998, the University of Hawai‘i Marine Options Program undertook the only mapping effort of the south Moloka‘i reef, funded by the U.S. Army Corps of Engineers (Manoa Mapworks, 1984). Qualitative field data were collected over a two-week period using scuba and snorkel, and maps were plotted using 1975 black and white aerial photography at 1:6,000 and 1:24,000 scales as a base layer. These maps provide a useful background to the reef ecosystem; however, the 1975 aerial photographs

were not georectified, and thus no true quantitative measurements of scale and distribution can be made.

In 1999, in response to the mandate set forth by Executive Order 13089, The National Oceanic and Atmospheric Administration (NOAA) National Ocean Service (NOS) implemented a program to provide digital maps of our Nation’s coral reefs for use in a GIS. The south Moloka‘i reef was mapped using orthorectified aerial photography, hyperspectral remotely sensed images, and quantitative field observations (Coyne and others, 2003). The classification scheme used to produce these maps documented 9 out of a possible 23 distinct benthic habitat types on the south Moloka‘i reef and 10 out of a possible 14 morphological reef zones. However, under the restrictions of a 1-acre (64 m by 64 m) MMU and at no finer resolution than a 1:6,000 scale, many smaller details of the reef system were overlooked. Using additional photography and bathymetric data, the USGS has now mapped the south Moloka‘i reef at a much higher resolution.

How the Maps Were Made

The Moloka‘i benthic habitat classification maps in this report were created from visual interpretation of georectified, color aerial photography and SHOALS (Scanning Hydrographic Operational Airborne Lidar Survey) bathymetric data (see Field and others, this vol., chap. 2). In addition to the remotely sensed imagery, we used knowledge from field data collected over a period of four years, from 1999 to 2003. These field data include underwater photographs, video, and visual observations and were collected using towed instruments, scuba and snorkel, and on foot. Mapping was accomplished using a GIS, and a statistical analysis of accuracy was performed. See Cochran-Marquez (2005) for a complete description of background layers, mapping methodology, and statistical accuracy assessment.

The classification scheme used was based on a scheme established by NOAA’s biogeography program in 2002 and subsequently revised in 2004 (NOAA National Centers for Coastal Ocean Science, 2005). Our maps use NOAA’s scheme as a starting point to provide some continuity to the coral-reef scientific community. However, modifications were made to the original scheme in order to better reflect the benthic habitats, geologic substrates, and historical features (such as fishponds) found on Moloka‘i.

More than 4,200 polygons covering more than 120 km² were digitized by interpreting features seen in both the aerial photographs and SHOALS bathymetry, with additional input from underwater video footage, photographs, and field observations. A minimum mapping unit (MMU) of 100 m² was used, but smaller features were mapped if they carried habitat significance (for example, an individual coral colony 2 m in diameter located in an otherwise uncolonized area). The classification scheme uses four basic attributes to describe each polygon on the benthic habitat map: (1) the dominant geomorphic structure or underlying substrate; (2) the major biologic cover found on the substrate; (3) the percent biologic coverage; and (4) the geographic zone indicating the location of the habitat (table 1). Each combination of a geomorphic structure with an overlying biologic cover may be described as a separate habitat. A geographic zone describes the cross-shelf location of a habitat, using terminology common in current coral-reef literature (fig. 1).

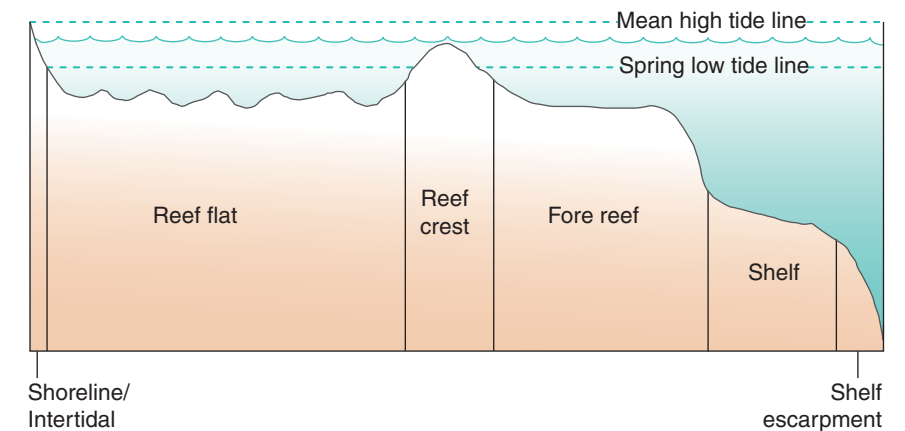


Figure 1. Schematic diagram showing the generalized cross-shelf coral reef zonation of the south Moloka‘i reef. Not shown are the zones land, channel, dredged, or vertical wall (modified from Kendall and others, 2004).

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Table 1. Categories of dominant structure/substrate, major biological cover, percent cover, and geographic zones used in the Moloka'i benthic habitat classification scheme (modified from NOAA National Centers for Coastal Ocean Science, 2005). [Less than 10 percent biological cover is considered to be uncolonized; therefore, <10 percent is not used as a percent biological cover category.]

Geomorphic structure/substrate	Biological cover	Geographic zonation
Hardbottom	Coral	Land
Aggregate reef	Coralline algae	Shoreline/intertidal
Spur-and-groove reef	Emergent vegetation	Reef flat
Aggregated patch reef	Macroalgae	Reef crest
Individual patch reef	Mangrove trees	Fore reef
Pavement	Uncolonized	Shelf
Pavement with sand channels	Unclassified	Shelf escarpment
Scattered coral/rock	(land or artificial)	Channel
Reef rubble	Unknown	Dredged
Softbottom		Vertical wall
Sand	Percent biological cover	
Mud	10% to <50%	
Other	50% to <90%	
Artificial	90% to 100%	
(for example, wharves)		
Artificial/historical		
(for example, fishponds)		
Land		
Unknown		

Table 2. Areas and percentages for each class of dominant structure/substrate on the south Moloka'i reef.

Dominant structure/substrate	Area (m ²)	Area (acres)	Percent
Aggregate reef	5,718,383	1,413.043	4.69
Aggregated patch reef	683,658	168.938	0.56
Artificial	119,770	29.597	0.10
Artificial/historical	116,252	28.730	0.10
Individual patch reef	38,325	9.471	0.03
Land	2,192,241	541.715	1.80
Mud	5,142,276	1,270.678	4.22
Pavement	38,531,126	9,521.240	31.59
Pavement with sand channels	5,029,773	1,242.888	4.12
Rubble	2,428,875	600.188	1.99
Sand	47,047,502	11,625.692	38.57
Scattered coral/rock	1,387,821	342.932	1.14
Spur-and-groove	12,030,578	2,972.823	9.86
Unknown	1,511,423	373.479	1.24
Grand total	121,978,003	30,141.414	100.00%

Table 3. Areas and percentages for each class of major biological cover on the south Moloka'i reef.

Major biological cover	Area (m ²)	Area (acres)	Percent
Coral	34,031,767	8,409.427	27.90
Coralline algae	179,632	44.387	0.15
Emergent vegetation	150,170	37.111	0.12
Macroalgae	16,615,684	4,105.825	13.62
Mangrove trees	2,967,857	733.366	2.43
Unclassified	234,028	57.834	0.19
Uncolonized	66,087,550	16,330.591	54.18
Unknown	1,711,315	422.873	1.40
Grand total	121,978,003	30,141.414	100.00%

The Maps—What They Tell Us

Dominant Structure/Substrate

The south Moloka'i reef is classified into 14 different structures/substrates that compose the reef morphology. The maps on the following pages show the reef in nine different geographic subsets. The dominant structure/substrate and major biological cover maps have been overlaid on aerial photographs for viewing purposes. Nearly 66 km² (54 percent of the total area mapped) consists of combined reef and hard-bottom substrates; soft-bottom sand and mud make up just over 52 km² (43 percent) (table 2).

A major feature of the South Moloka'i reef is the broad, shallow pavement platform of the reef flat, which extends nearly 1.5 km offshore in the Pālā'au and Kamiloloa areas (see Storlazzi and others, this vol., chap. 3). A mud veneer and ancient fishponds lie close to shore on the reef flat, while sand patches and coral-covered pavement dominate the seaward edge of the reef flat.

Seaward of the reef crest, the fore reef alternates between abundant reef and barren, hard pavement. Aggregate reef growth is predominantly in the Wai a Kāne/Pālā'au and Kawela/Kamalō regions. Spur-and-groove formations are more common to the west. The areas off Kaunakakai/Kamiloloa and Pūko'o, however, are barren "dead zones" of hard pavement with little or no active reef development.

The base of the fore reef is around 27-m (90 ft) water depth, where it drops off into a gently sloping sand-covered plain of the shelf zone. Reef development pinches out near the east and west ends of the island, where high wave energy limits growth (see Storlazzi and others, this vol., chap. 11).

Additional structure/substrate descriptions for each geographic subset area may be found on the following pages.

Major Biological Cover

The 14 different structures/substrates are covered with 8 different biological classes. Coral covers 51 percent of the suitable hard substrate

on the Moloka'i reef (more than 34 km² or 28 percent of the overall study area) (table 3).

Major biological cover varies geographically along the inner reef zones (shoreline/intertidal, reef flat, and reef crest). Macroalgae is most abundant on the reef flat in the Kaunakakai (eastern half), Kamiloloa and Pūko'o areas. The majority of the mangroves may be found along the Pālā'au and Kaunakakai shorelines (see D'Iorio, this vol., chap. 16). Wai a Kāne, Pālā'au and Kamalō have large areas of uncolonized sand or barren pavement (fig. 2).

The coral-covered pavement at the seaward edge of the reef flat is dominated by *Porites lobata* colonies. These shallow colonies appear as knobby flat-topped mesas, with live tissue on the sides of the coral mounds. Surface exposure, wave influences, and/or relative sea-level change prevent vertical growth of these coral mounds. These flat-topped coral mounds can be exposed at low tides, making it difficult for live coral tissue to grow. The irregular surface of the knobby mounds sometimes has macroalgae or coralline algae growing on it, and it may contain sediment in the depressions (pukas).

Of the areas of suitable hardbottom available for coral growth on the Moloka'i fore reef, the highest percentages of coral are found in the Wai a Kāne and Pālā'au areas near the west end of the island and in the Kawela and Kamalō (western half) areas along the center of the island. Studies have shown these areas to have the highest coral coverage in the

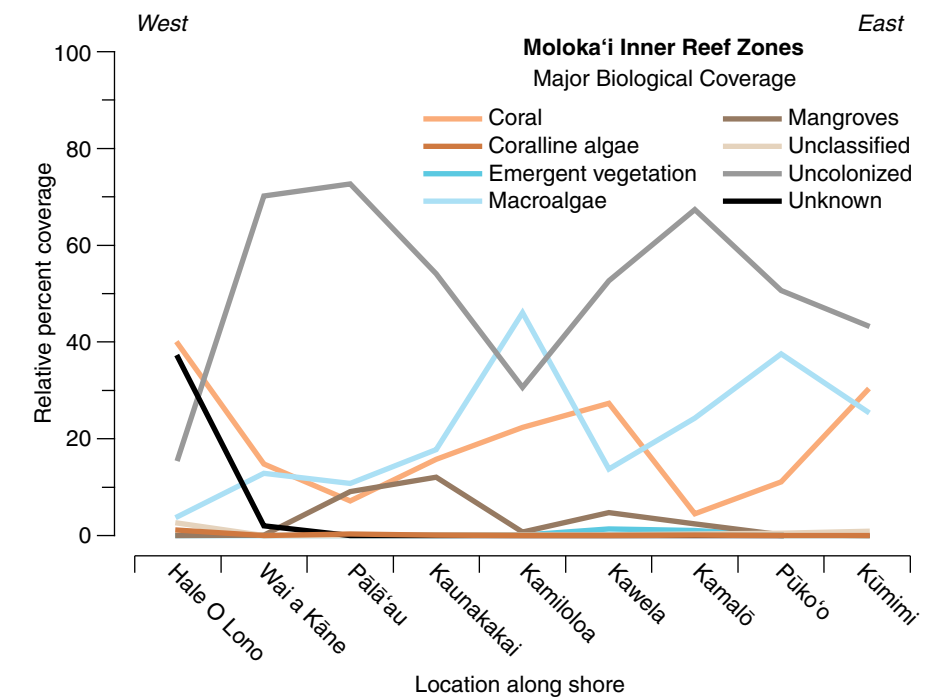


Figure 2. Graph showing the major biological coverage on the inner reef zones (shoreline/intertidal, reef flat, and reef crest) for each geographic area of the south Moloka'i reef. The geographic locations alongshore relate to the map sections shown in the following pages. The percent coverages are relative to each map section.

main Hawaiian Islands (Jokiel and others, 2001). The fore reef in the Kaunakakai (eastern half), Kamiloloa (western half), Kamalō (eastern half), and Pūko‘o areas have large “dead zones” where most hardbottom substrate suitable for coral growth is either barren or covered with macroalgae (for example, *Halimeda* sp.) (fig. 3).

Aggregate reefs and spur-and-groove formations on the fore reef are dominated mostly by *Porites* sp. and *Montipora* sp. Large patches of the macroalgae *Halimeda* sp. may be found in the sand at the base of the fore reef. These calcareous algae are a major contributor to the sand supply on the reef shelf (see Field and others, this vol., chap. 17).

The highest percentages of coral are found at depths between 5 m and 15 m (15–50 ft) across the entire reef (fig. 4). However, abundant coral is also found at depths between 20 m and 25 m (65–85 ft) in some localized areas.

Additional biological cover descriptions of each subset area may be found on the following pages.

Accuracy of Maps

The validity of map classifications is determined with actual on-site checks at random locations and an accuracy assessment. For this project, a total of 816 map points were checked in the field. The overall accuracy of 86.27 percent (with a 95-percent confidence interval of ± 2.36 percent) indicates the number of points on the map which were classified correctly

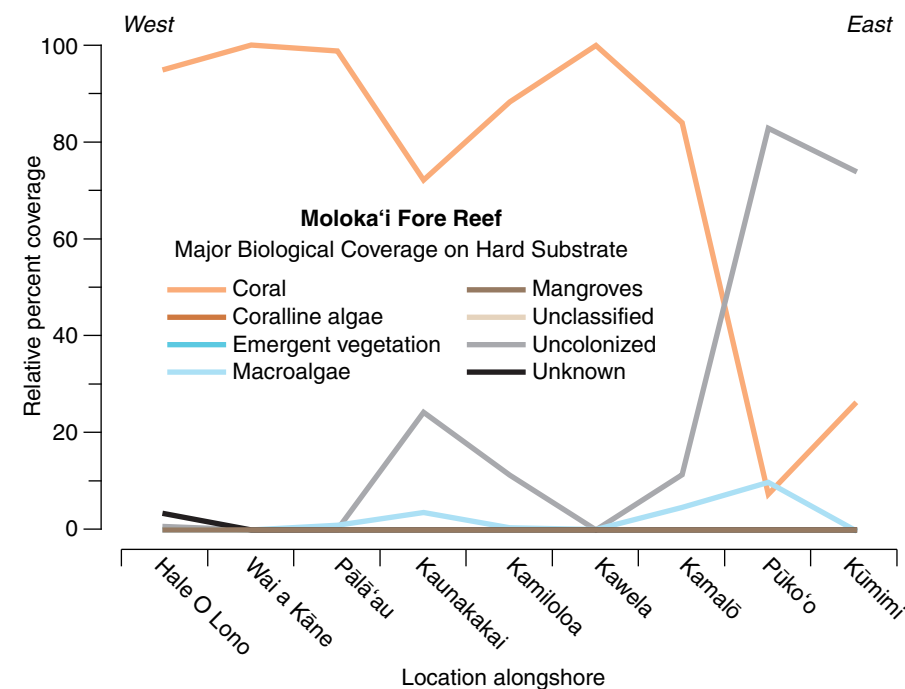


Figure 3. Graph showing the major biological coverage on hardbottom substrates for each geographic area of the south Moloka'i fore reef. The geographic locations alongshore relate to the map sections shown in the following pages. The percent coverages are relative to each map section.

Benthic Habitat Maps of the South Moloka'i Reef

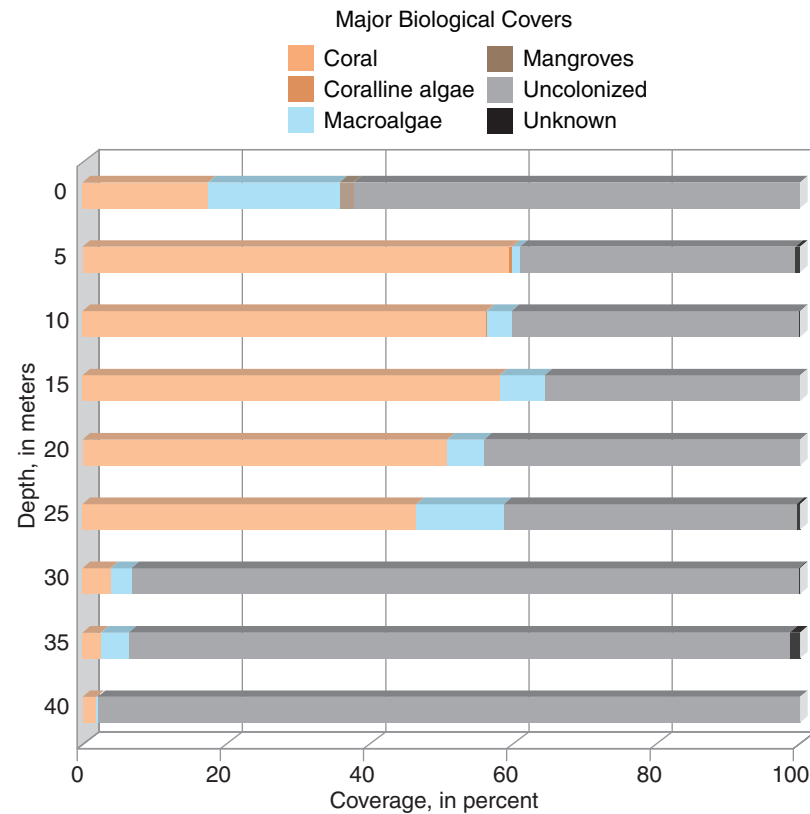


Figure 4. Graph showing the percentages of major biological covers at various depths along the south Moloka'i reef. See text for description.

according to the field check. The greatest amount of error was found in the uncolonized class. In this instance, what was originally mapped as uncolonized sand on the fore reef at depths of approximately 27 m (90 ft) was found many times to be sand with >10 percent macroalgae (*Halimeda* sp.).

After accuracy assessment calculations were performed, any misinterpreted polygons on the Moloka'i reef maps were corrected using the field-check data, thus increasing the accuracy of the final map to greater than 86.27 percent.

Using the Maps

The detailed high-resolution maps provided here document habitat characterization of a critical coral reef in Hawai'i and are for use by managers, scientists, and the general public. These maps can be used by themselves (as shown in this volume), or the digital files may be used in a GIS or with other types of visualization software (fig. 5). Integration of the aerial imagery, SHOALS bathymetry, and field observations made it possible to create detailed thematic map layers reaching depths of 35 m (120 ft), encompassing the base of the Moloka'i fore reef, which is deeper than can be mapped with standard optical remote sensing instruments.

The maps are based on an interpretation of conditions at the time the imagery was collected (1993, 1999, and 2000) and are constrained in positional accuracy by use of a standard GPS receiver (± 3 m). Hence, they are not to be used for navigation and are limited in their use for recognizing small-scale changes in the ecosystem. For example, it would be difficult to discern if bleaching occurs, or if there is a loss of coral colonies due to storm waves or dredging. However, large-scale shifts in the dominant bottom type, such as a change from uncolonized pavement to a predominantly algal-covered or coral-covered environment, could be detected.

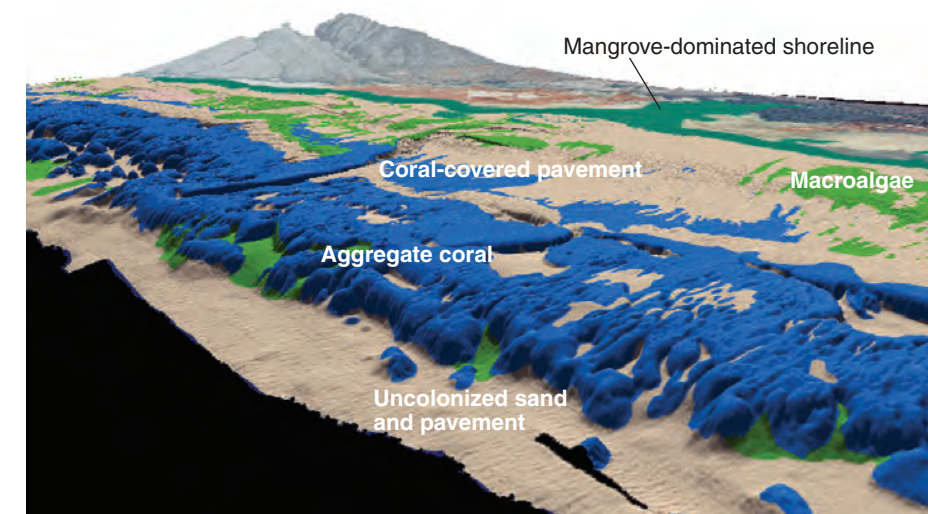
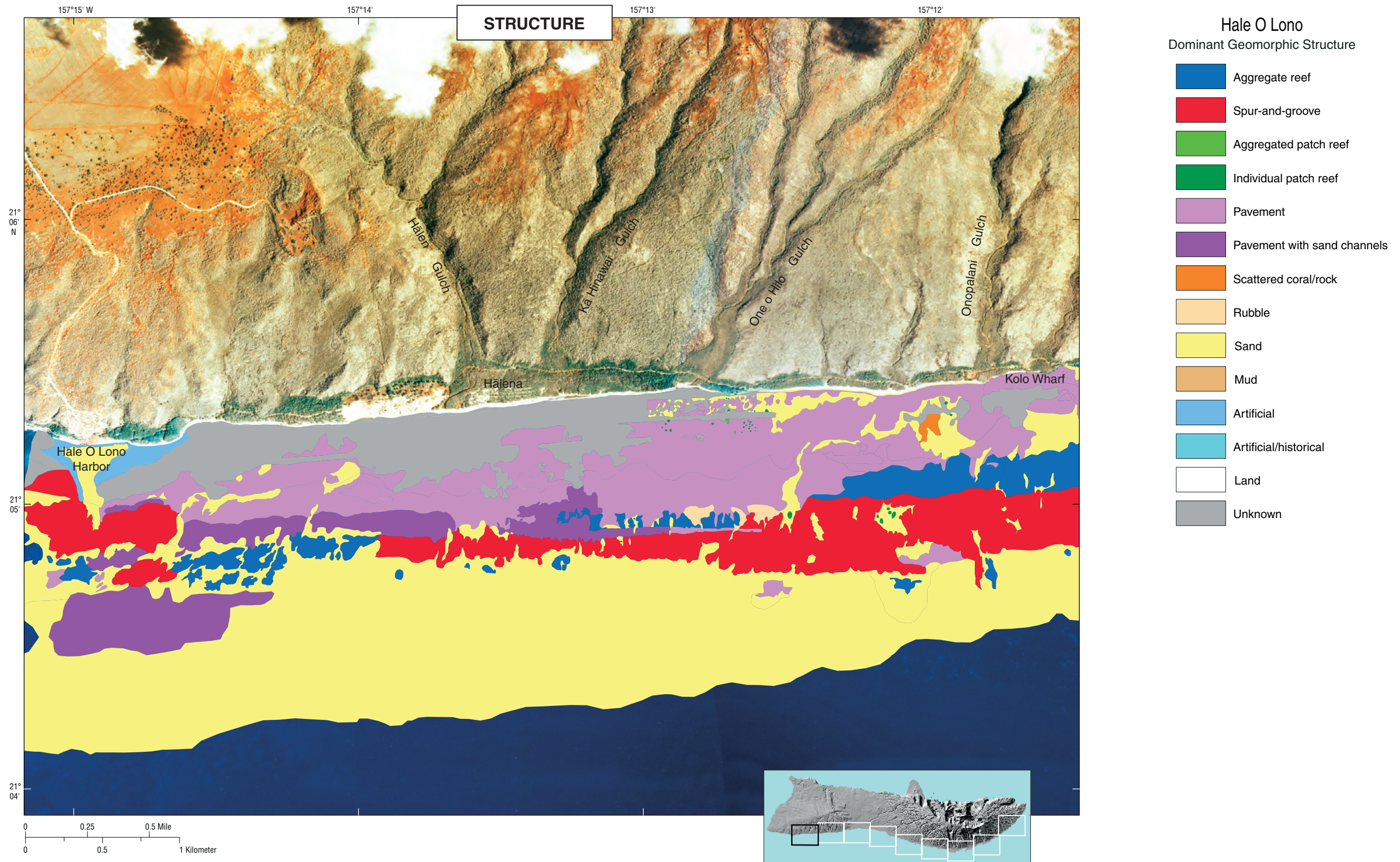
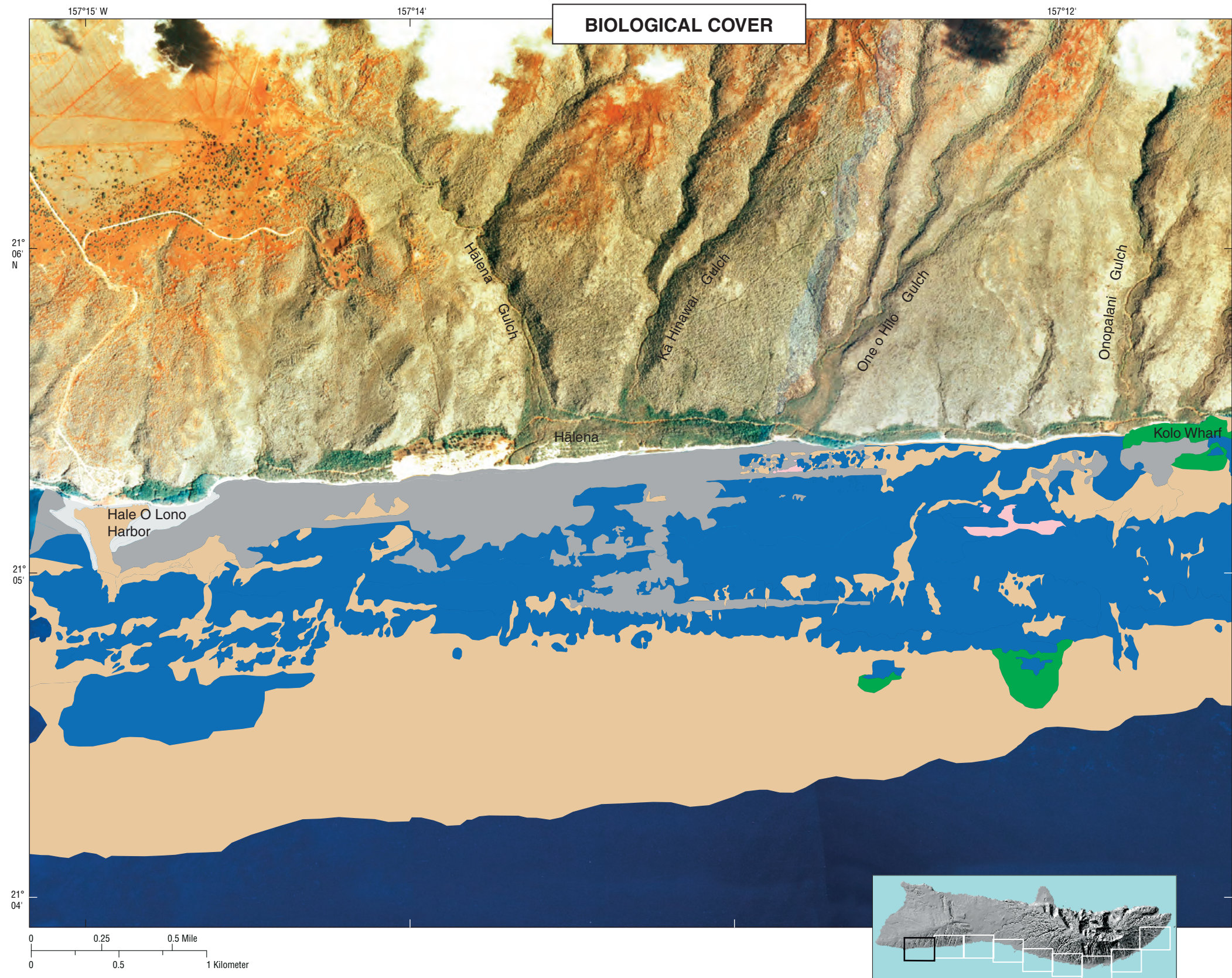
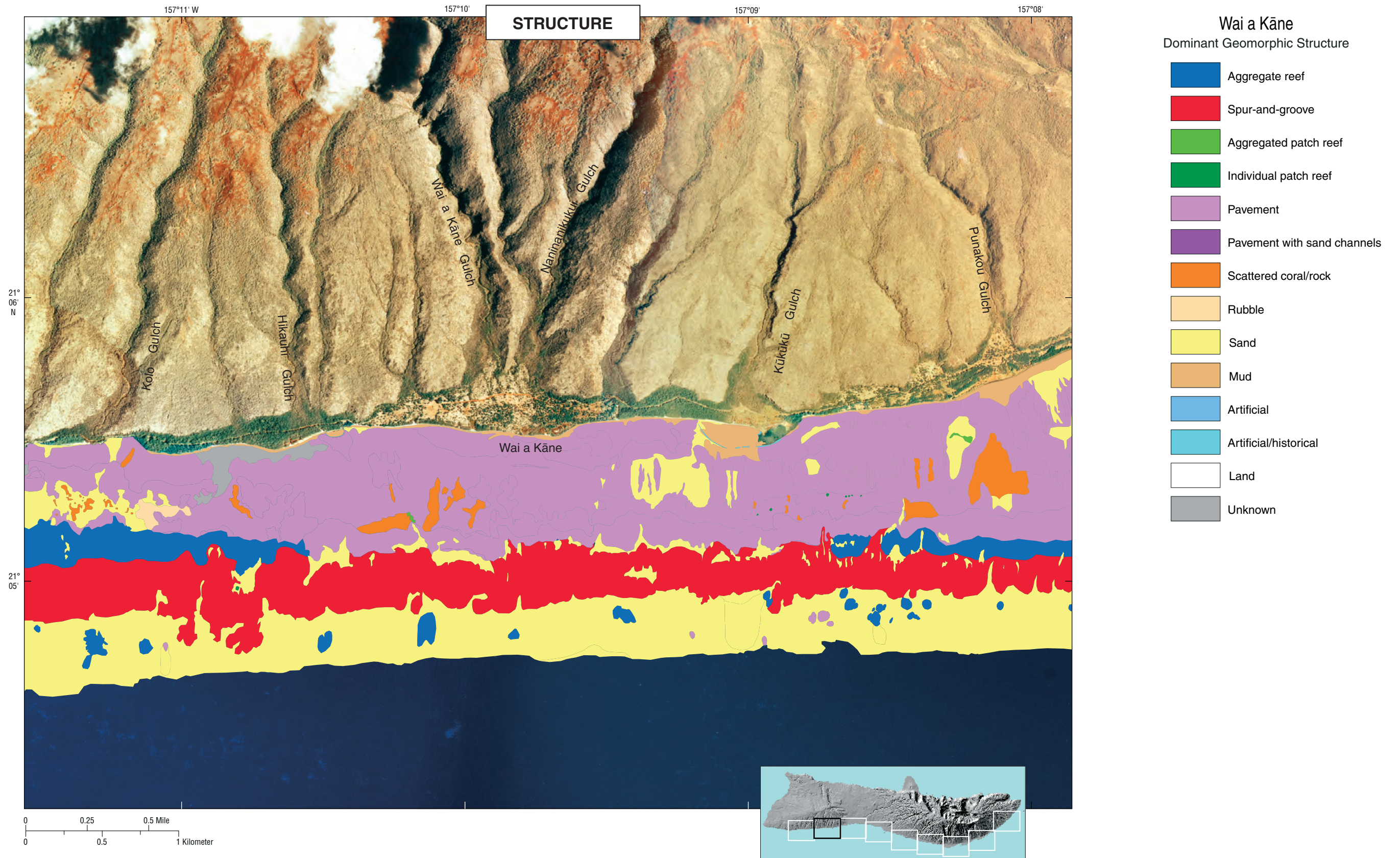


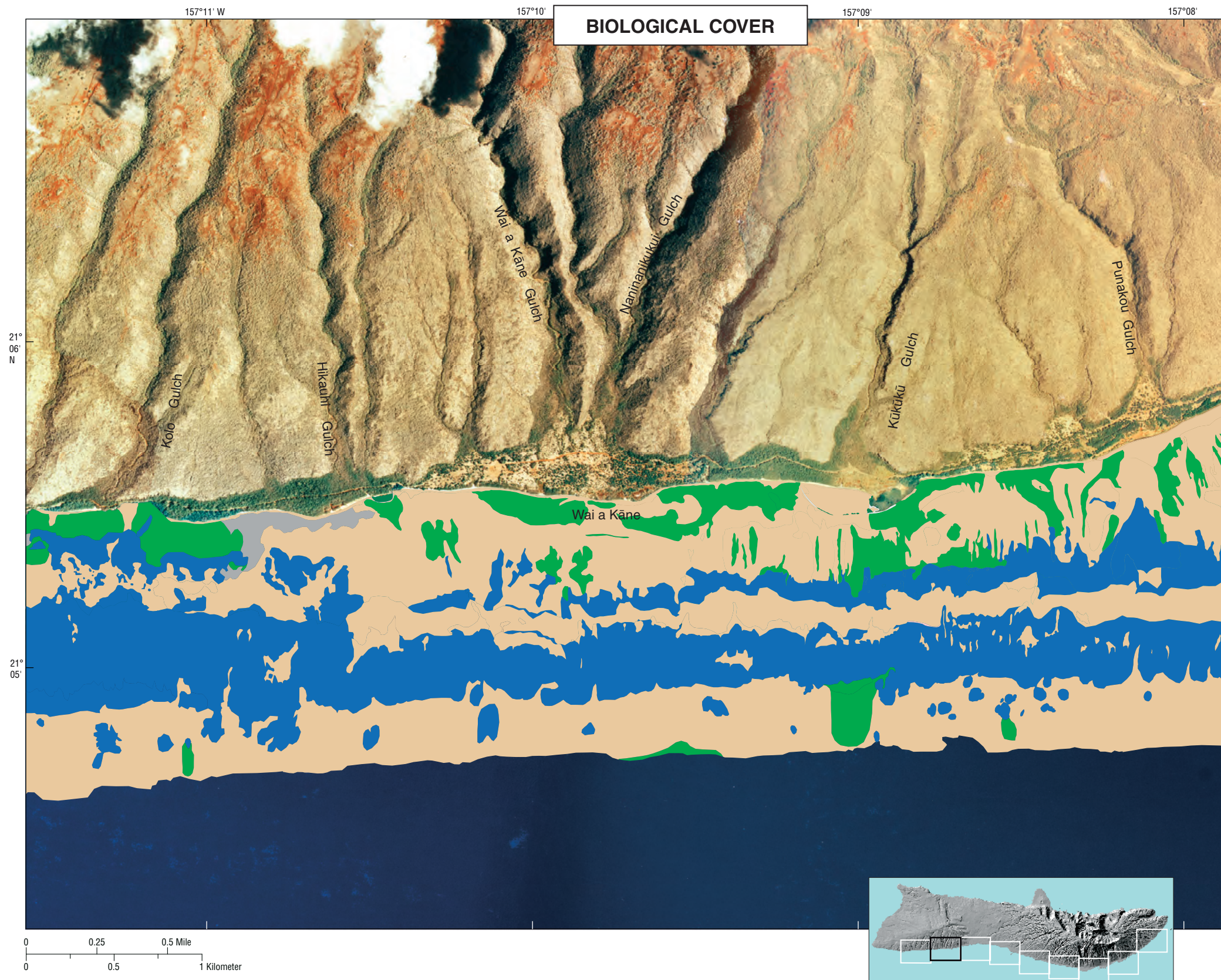
Figure 5. Three-dimensional perspective view, looking northwest, of the Pālā'au region of the south Moloka'i reef showing major biological cover. The natural channel leading from the mangrove-dominated shoreline (blue-green) is visible in the left-center portion of the image. Aggregate coral (blue) dominates the fore reef; the reef flat is a mix of uncolonized sand and pavement (tan), macroalgae (light green), and coral-covered pavement (blue). Approximate distance across the bottom of the image is 4.5 km (2.8 mi).



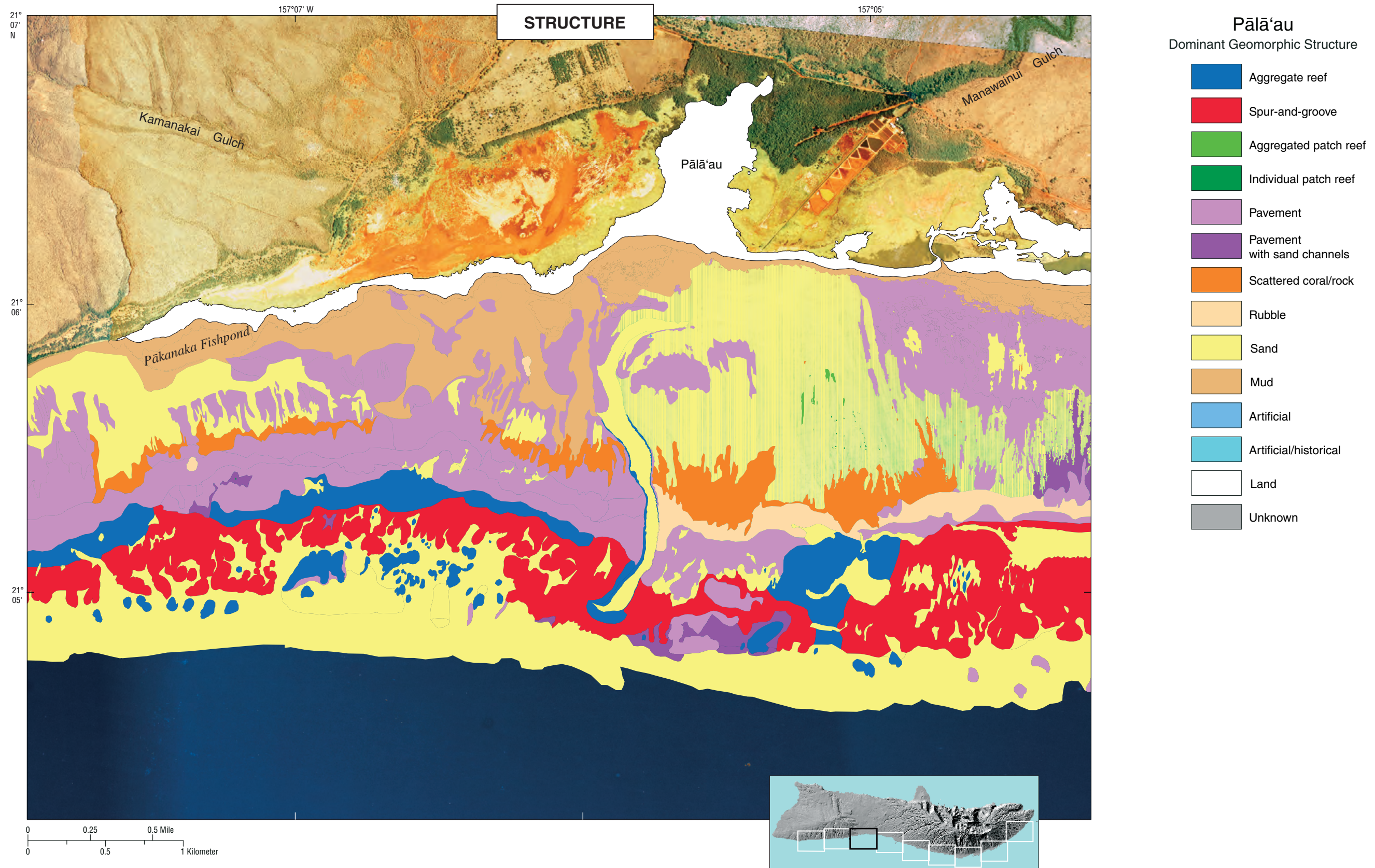


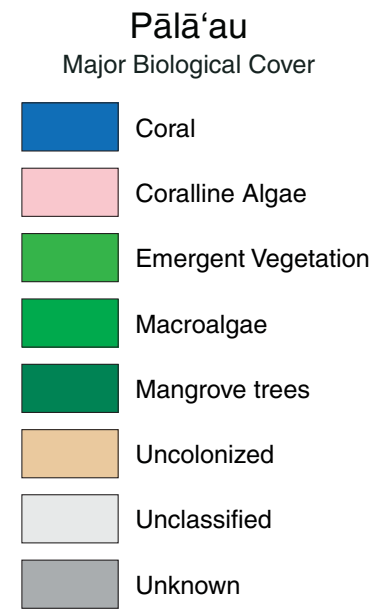
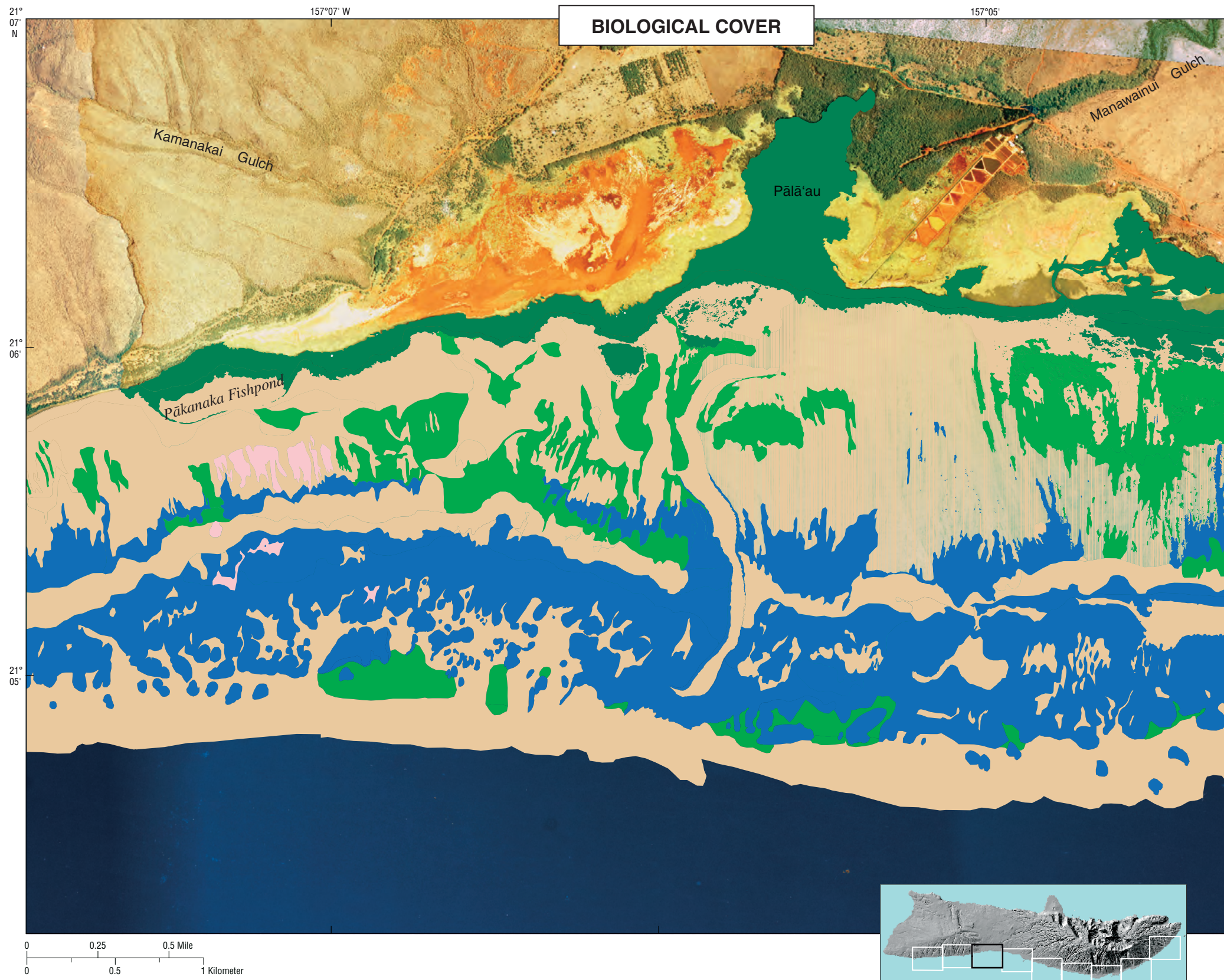
This area marks the western extent of active coral-reef growth along the south shore of Moloka'i. Coral-covered aggregate reef and the spur-and-groove structure of the fore reef trend progressively closer to the shoreline from east to west, before finally pinching out near Hale O Lono. Reef growth further west is limited by high-energy waves from the North Pacific Swell that wrap around the end of the island near Lā'au Point (see Storlazzi and others, this vol., chap. 11). The reef flat here is home to a few scattered individual heads of coral and is steeper than along the central portion of the island. There is no discernable reef crest in this region.





Westward from Wai a Kāne Gulch the reef crest disappears and the coral-covered aggregate reef and spur-and-groove structure begin to trend progressively closer to the shoreline (see previous section). East of Wai a Kāne Gulch, coral-covered ridges are found along the seaward edge of the reef flat, which is relatively deeper here than in the central portion of the island. Several isolated coral-covered mounds are located offshore from the main aggregate fore reef on the deeper portion of the sand-covered shelf.





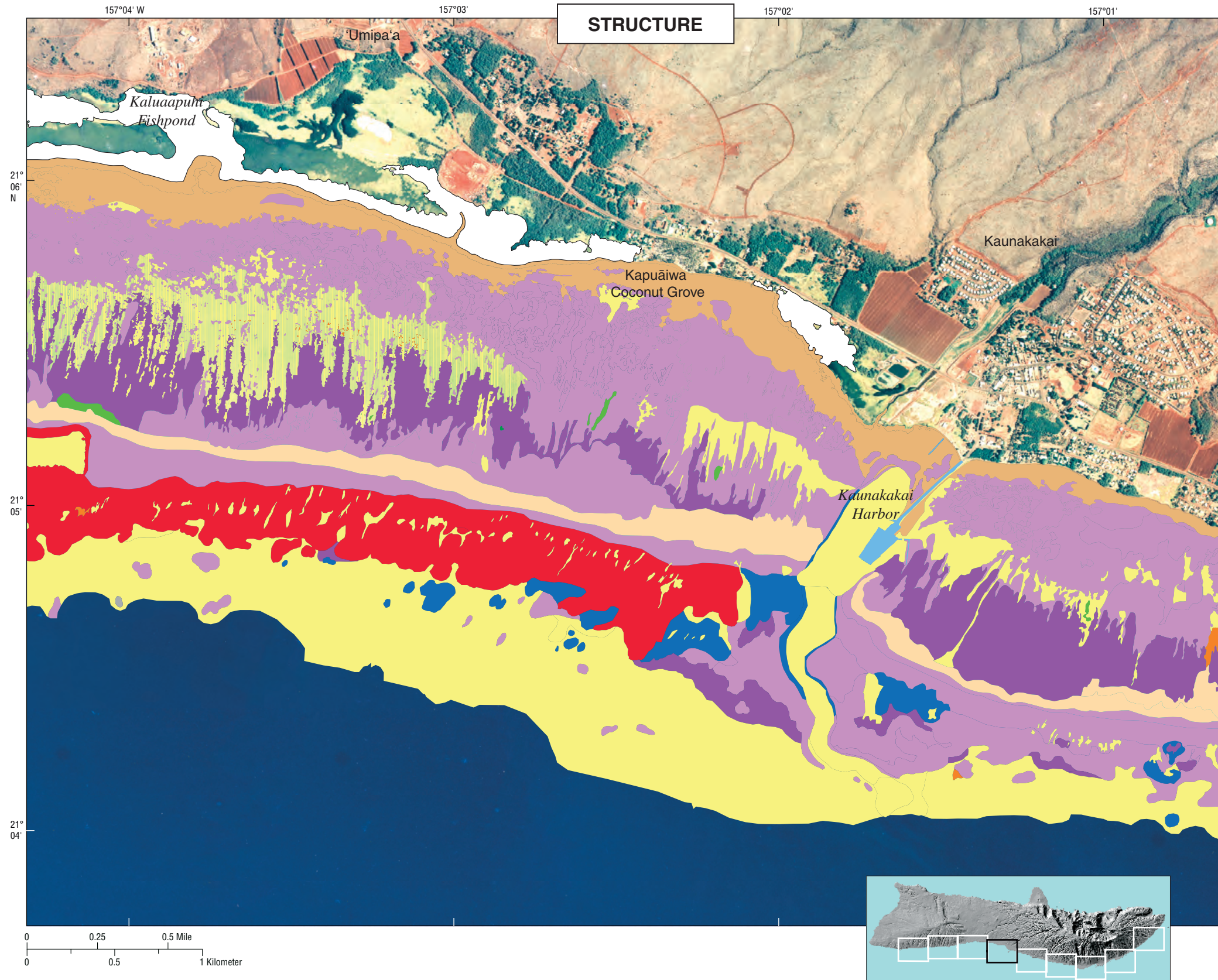
Mangrove trees, planted in an attempt to trap sediment runoff from the island, dominate the shoreline at Pālā'au (see D'Iorio, this vol., chap. 16). However, large amounts of sediment still reach the coast and are deposited on the reef flat. A major offshore feature in this region is a channel that bisects the reef flat, reef crest, and fore reef. The vertical walls of the channel host a number of coral species, except in the turbid, muddy waters close to shore.

West of this Pālā'au channel, the reef flat is mostly uncolonized terrigenous mud. Live coral is found along the seaward edge of the reef flat and on the portion of the reef crest near the channel. West of the channel and seaward of the coral-covered fore reef, the sand-covered shelf is dotted with isolated coral-covered mounds.

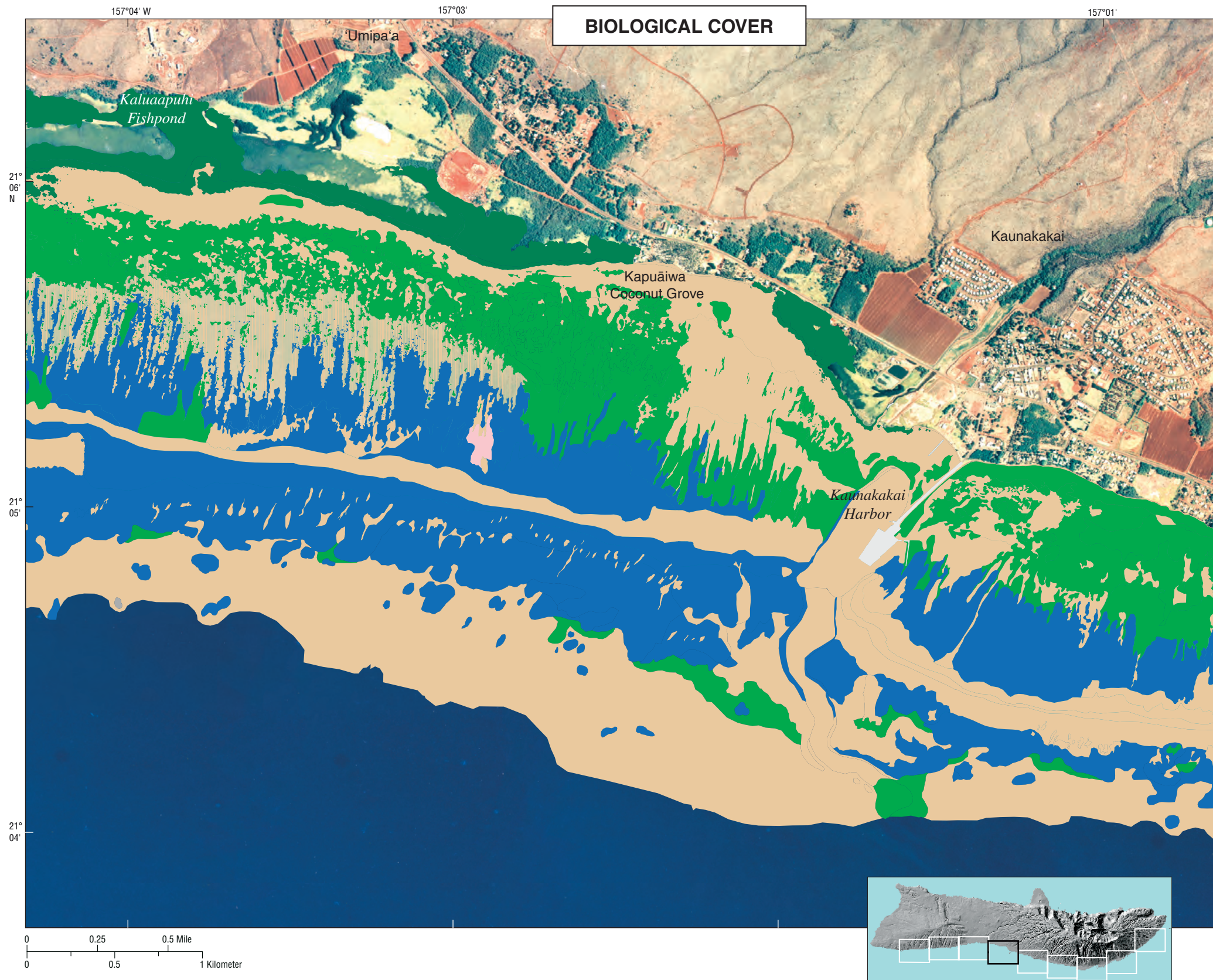
The reef flat is shallower and broader on the east side of the Pālā'au channel. It is dominated by a large area of uncolonized, white carbonate sand. Live coral is found along the seaward edge of the reef flat, and beyond the reef crest on the fore reef.

Two large "blue holes," or pits, are found on the eastern edge of the Pālā'au fore reef. These features were possibly formed by dissolution of the limestone reef by the subsurface percolation of fresh groundwater through the system (see Grossman and others, this vol., chap. 13). The vertical walls of these pits are covered with live coral, and the bottoms are covered with sand.

THE CORAL REEF OF SOUTH MOLOKA'I, HAWAII—I PORTRAIT OF A SEDIMENT-THREATENED FRINGING REEF



- Kaunakakai**
Dominant Geomorphic Structure
- Aggregate reef
 - Spur-and-groove
 - Aggregated patch reef
 - Individual patch reef
 - Pavement
 - Pavement with sand channels
 - Scattered coral/rock
 - Rubble
 - Sand
 - Mud
 - Artificial
 - Artificial/historical
 - Land
 - Unknown



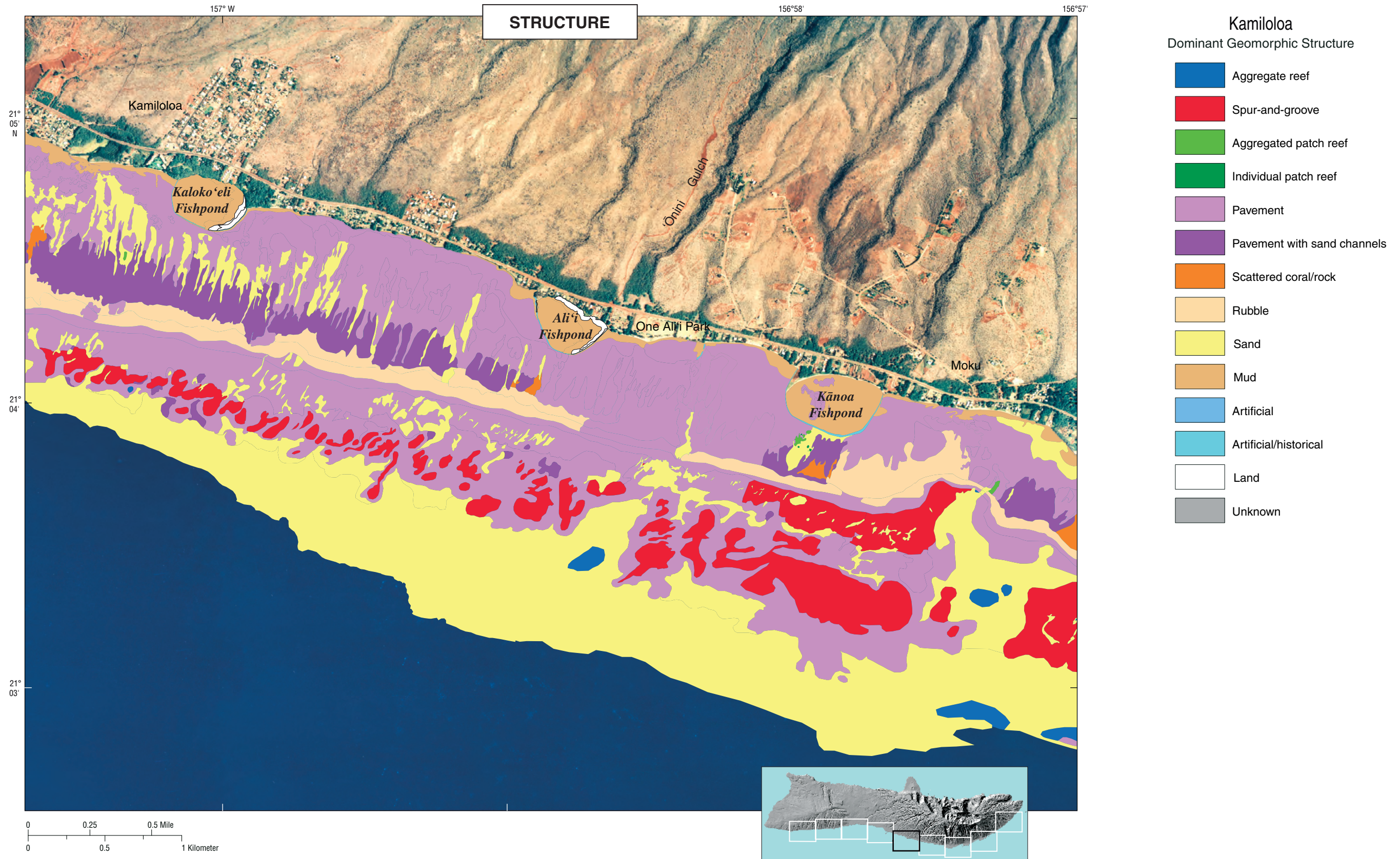
Kaunakakai
Major Biological Cover

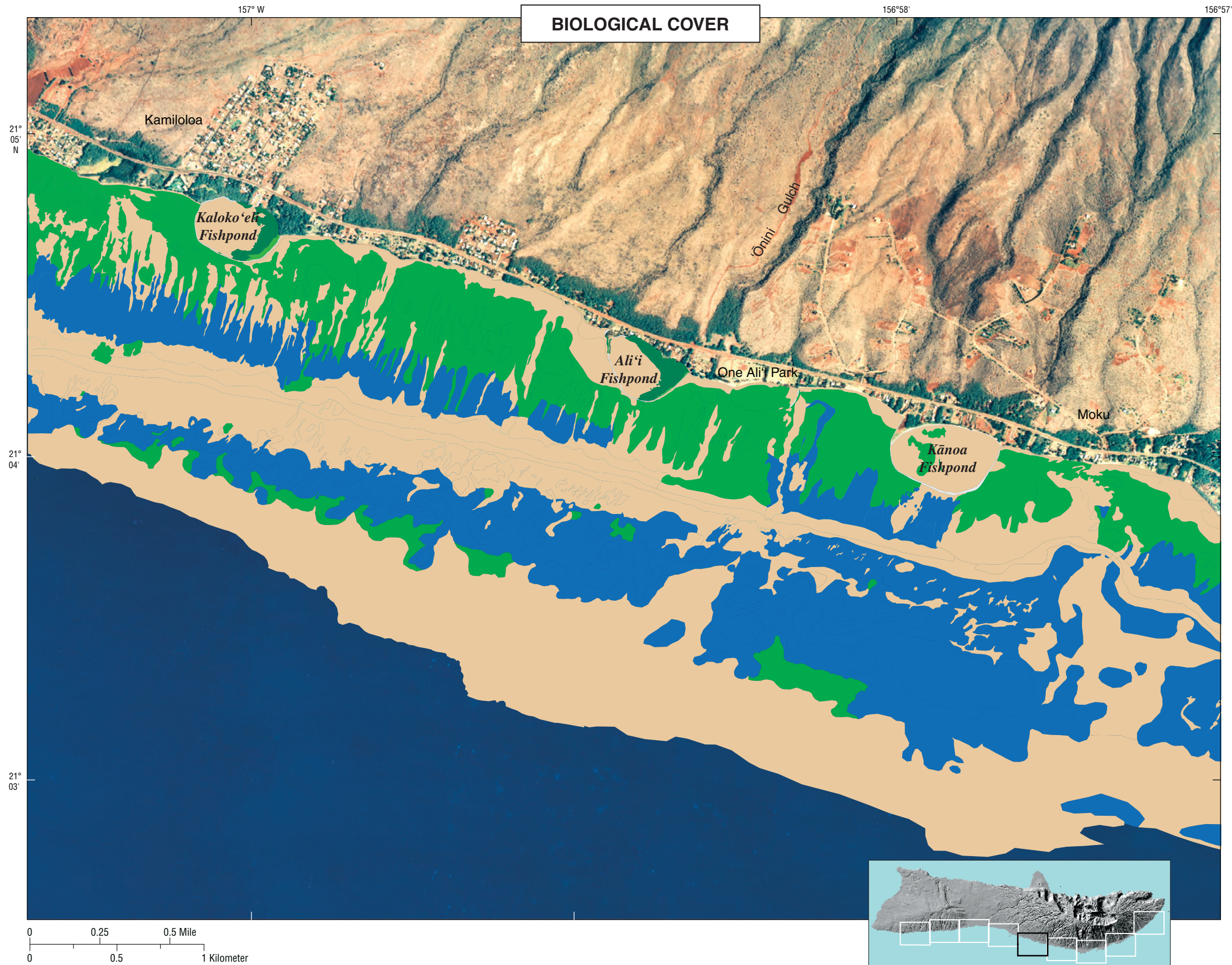
- Coral
- Coralline Algae
- Emergent Vegetation
- Macroalgae
- Mangrove trees
- Uncolonized
- Unclassified
- Unknown

Kaunakakai is the population center of Moloka'i. The impermeable Kaunakakai Wharf extends 0.85 km (0.5 mi) offshore, blocking the east to west transport of water and sediment. The natural offshore extension of Kaunakakai Gulch, which bisects the reef flat, reef crest, and fore reef, has been enhanced by dredging to create a deep harbor next to the wharf.

West of Kaunakakai Wharf, mangrove trees are found along most of the shoreline. A broad band of terrestrial mud covers the inner reef flat; the middle portion of the reef flat is dominated by algae-covered pavement; coral-covered ridges interspersed with sand are found on the seaward edge of the reef flat. Beyond the reef crest, the fore reef is dominated by healthy coral-covered aggregate reef and spur-and-groove structures, which have high coral coverage offshore of the Kapuāiwa Coconut Grove area. However, the fore reef just west of the channel is barren, possibly owing to dredging activities.

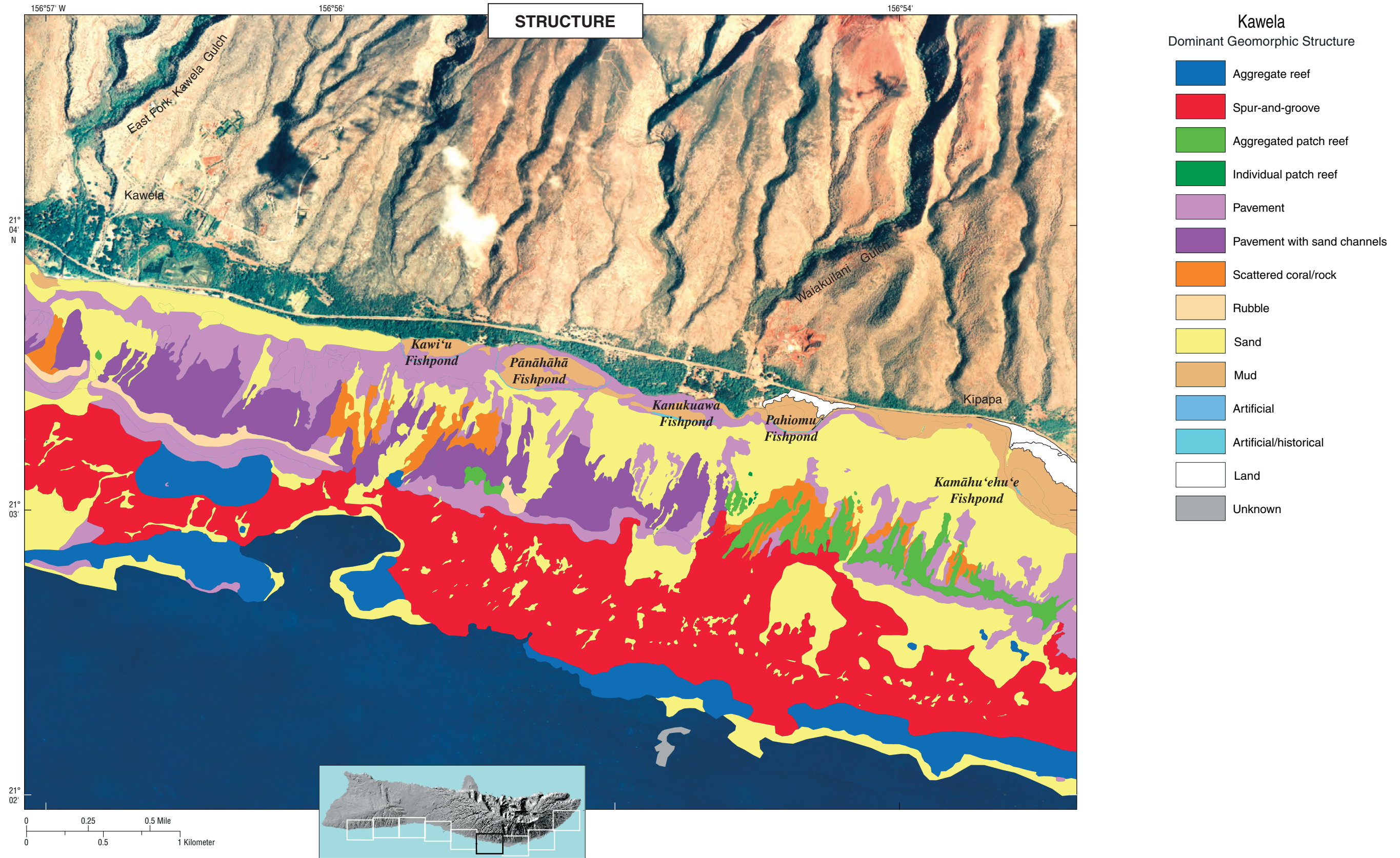
East of Kaunakakai Wharf, the reef flat is dominated by algae and terrestrial mud on hard pavement. A few live corals grow on ridges near the seaward edge of the reef flat. Beyond the reef crest, the fore reef is mostly barren pavement; however, some aggregate reef growth may be found at deeper depths.

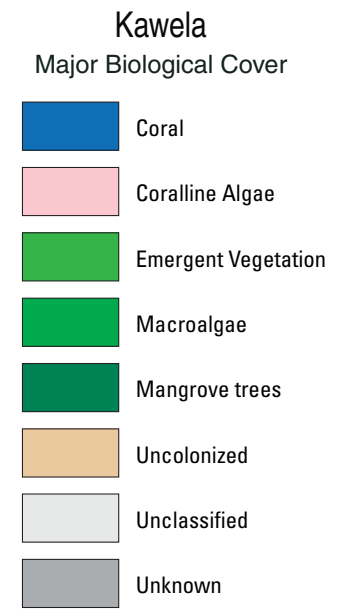
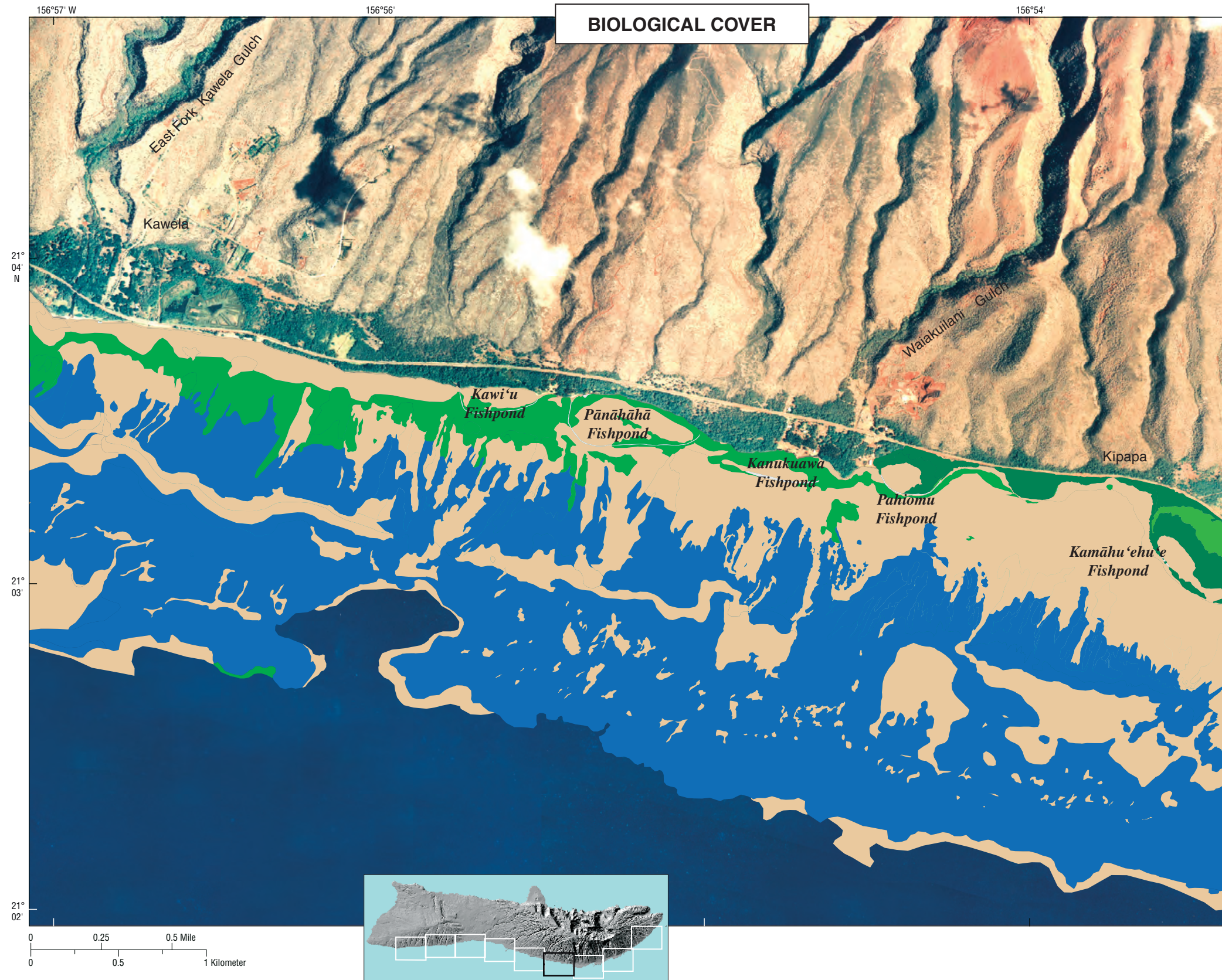




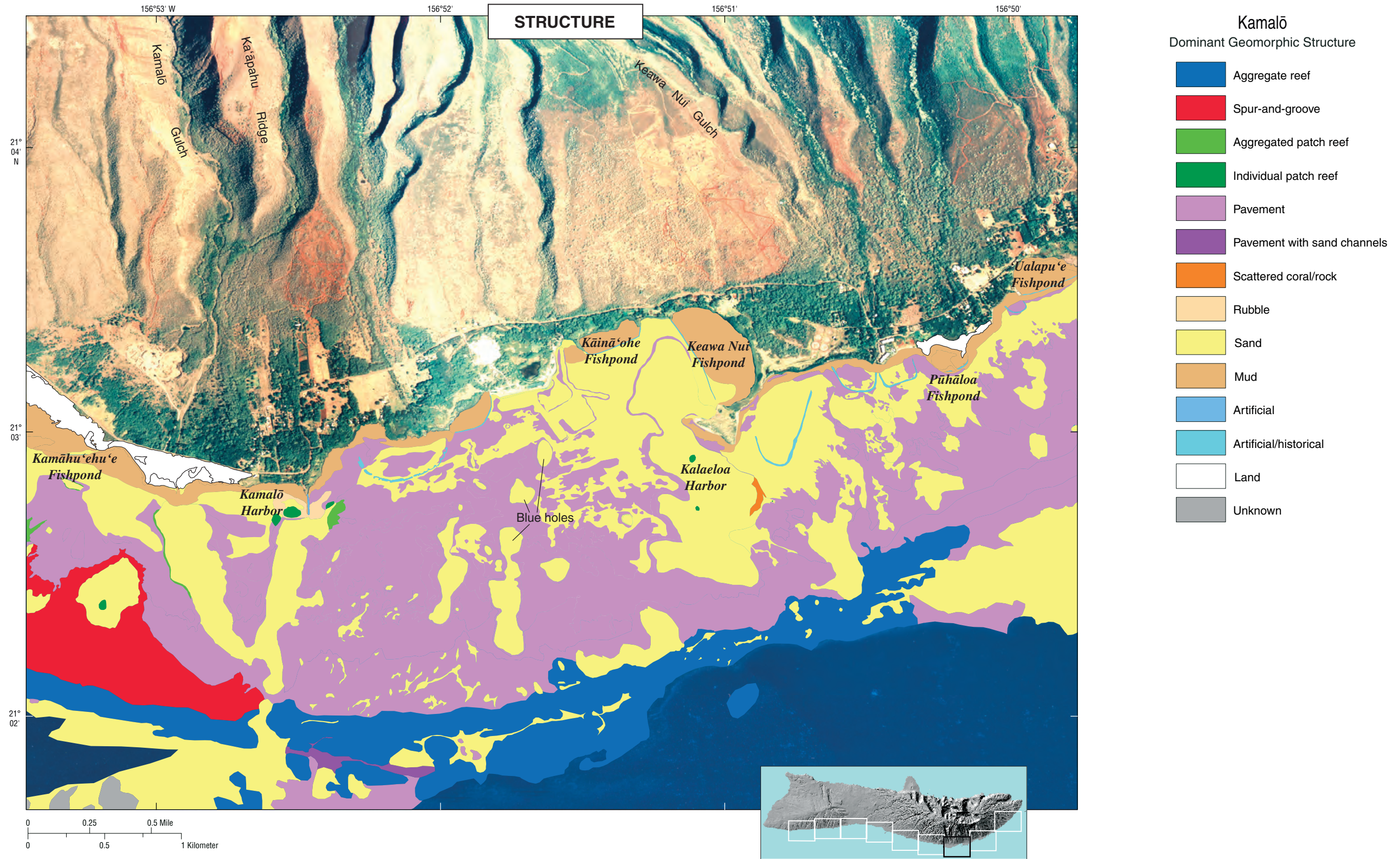
- Kamiloloa**
Major Biological Cover
- Coral
 - Coralline Algae
 - Emergent Vegetation
 - Macroalgae
 - Mangrove trees
 - Uncolonized
 - Unclassified
 - Unknown

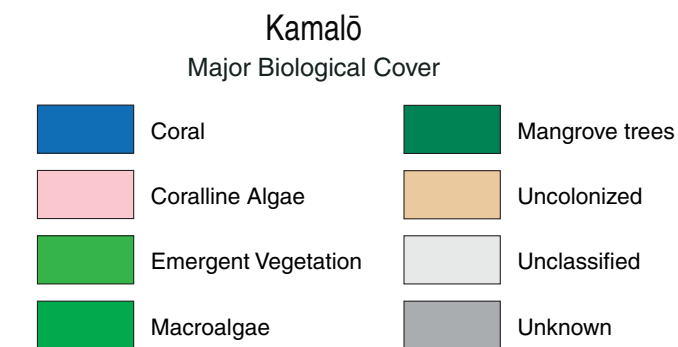
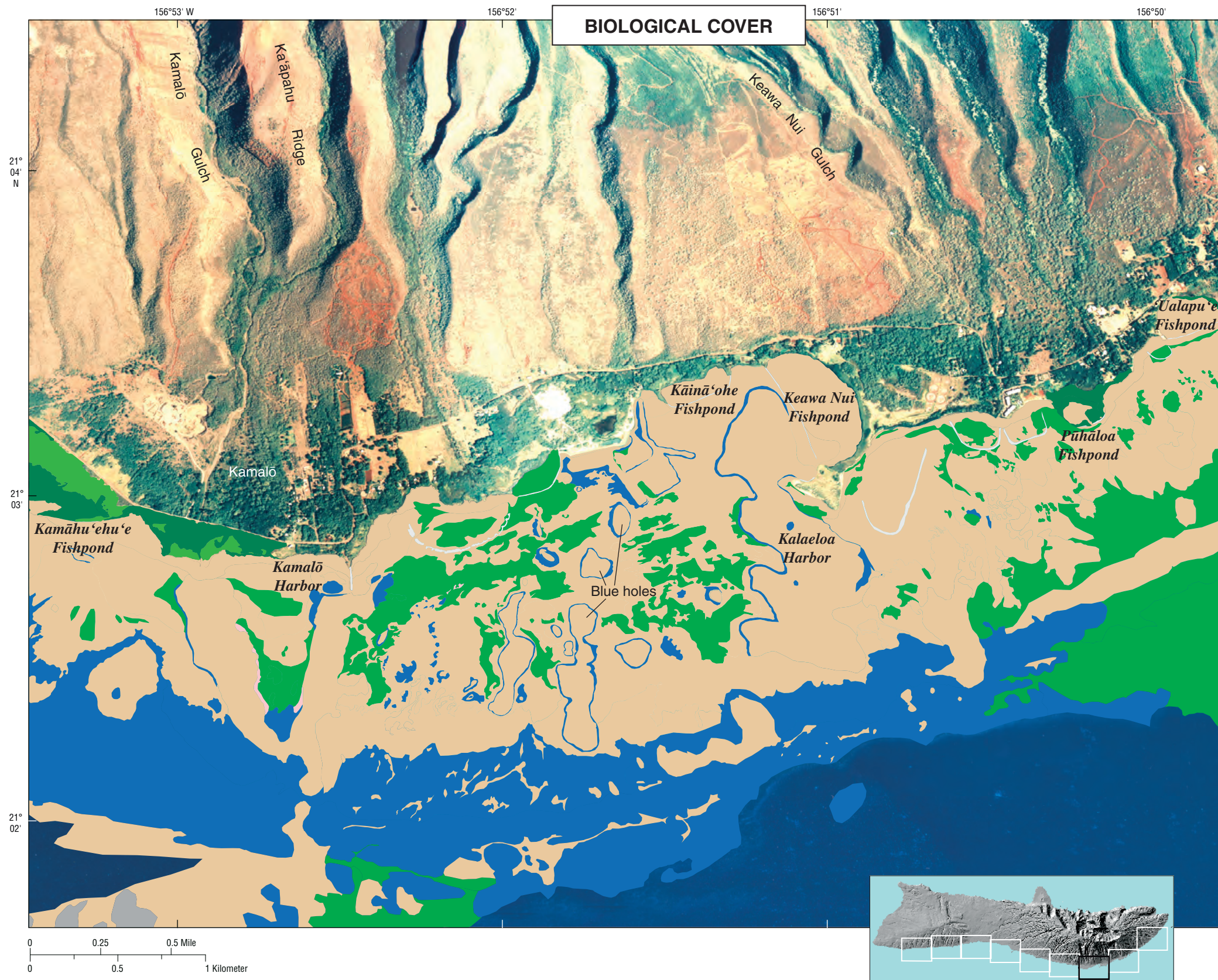
A narrow band of terrestrial mud is found along the shoreline of Kamiloloa, transitioning into the predominately algae-covered platform of the middle reef flat. A few live corals grow on ridges near the seaward edge of the reef flat. The barren fore-reef platform of Kaunakakai (see previous pages) continues eastward through Kamiloloa to One Ali'i (center of this area), with coral-covered spur-and-groove structures found only at greater depths. East of One Ali'i, the shallower areas of the fore reef have increasing coral growth continuing toward the Kawela area (see next pages).





The inner and middle portions of the reef flat at Kawela are a mixture of terrestrial mud, algae-covered platform, and uncolonized sand. Live corals grow on ridges near the seaward edge of the reef flat. The reef crest is discontinuous in this region. The fore reef is dominated by coral covered spur-and-groove structures. The deep embayment southeast of Kawela was possibly created from a major drainage during a period of lower sea-level (see Grossman and others, this vol., chap. 10, for discussion of historical sea-level rise).

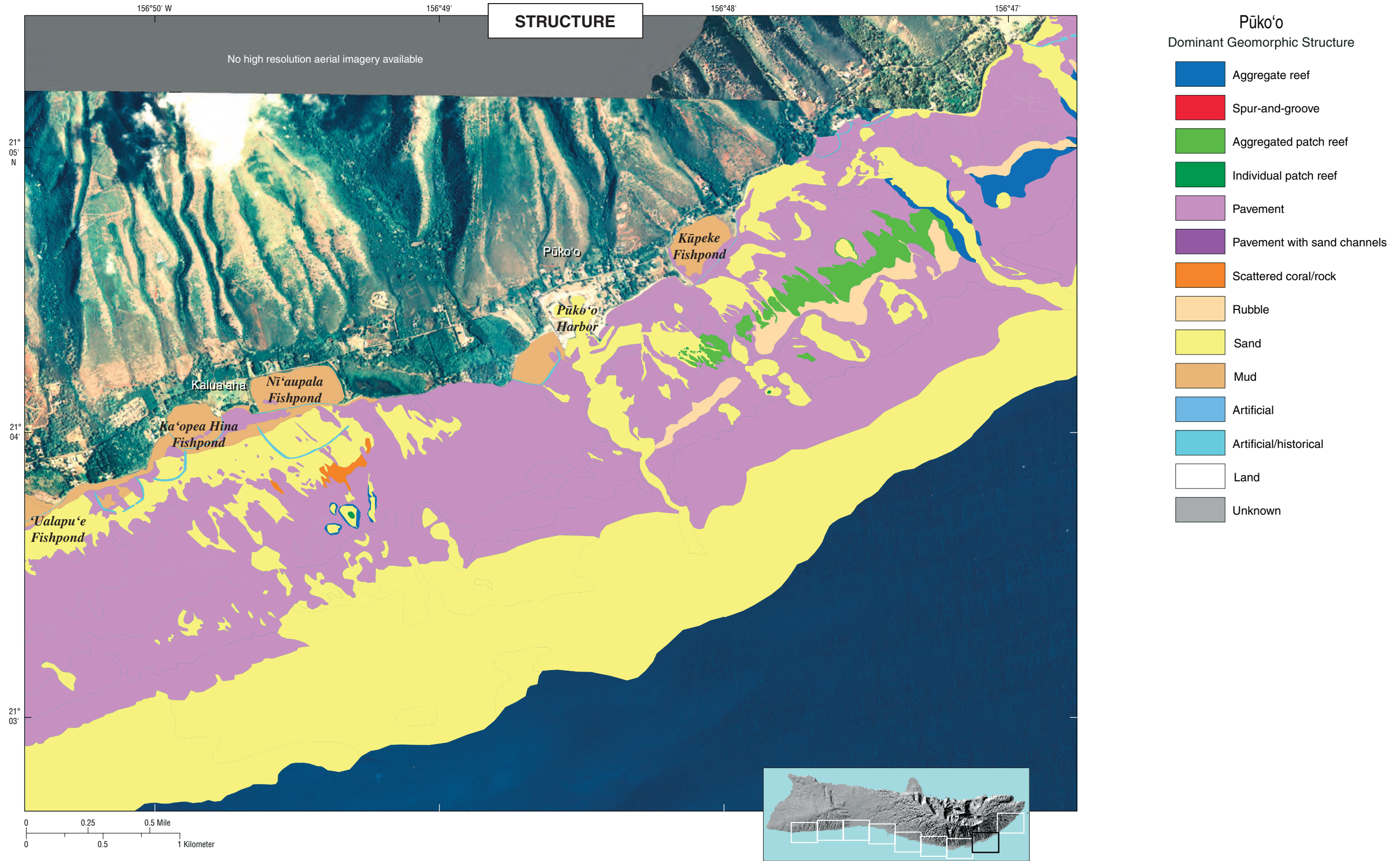


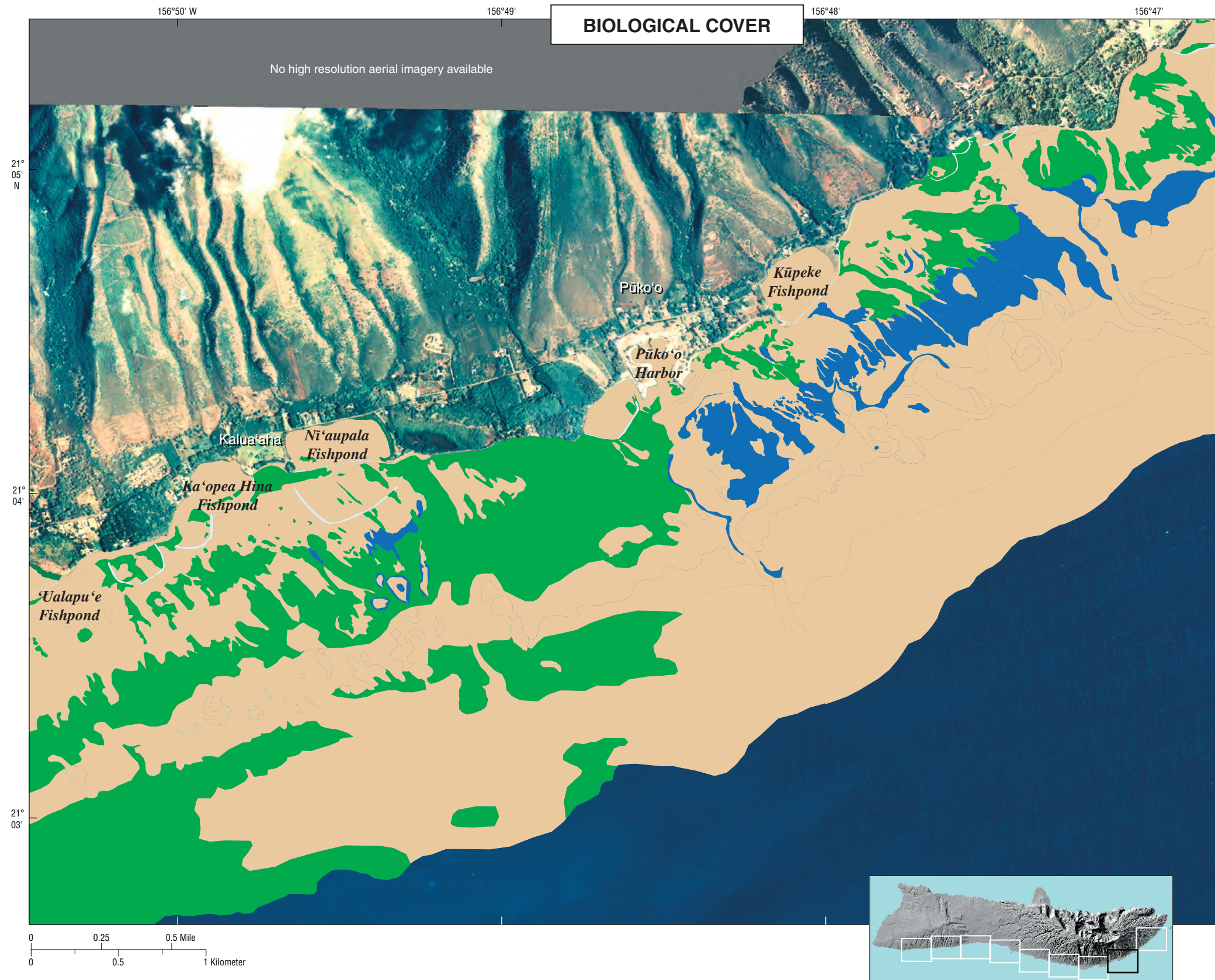


The Kamalō region marks a transition in the shoreline orientation along the south shore of Moloka'i. East of Kamalō, the southeast-facing shoreline and reef flat are more susceptible to constant wave action from the daily trade winds. Siltation from a dredging operation in the 1960s (the rectangular outline of which is still visible) resulted in damage to the reef flat between Kamalō and Kalaeloa and to the downstream Kamalō fore reef (Capt. Joe Reich, oral commun., 2000). Although the fore reef has since regenerated, the reef flat is still mainly uncolonized, bare pavement with some algae-covered areas.

A unique feature of the reef flat in this area is a series of "blue holes." The alignment of the blue holes suggests that they may be old stream channels, formed during a time of lower sea level, that were subsequently segmented by new coral growth after sea level attained its present position. An alternative hypothesis is that they were formed by dissolution of the limestone reef by the subsurface percolation of fresh ground water through the system (see Grossman and others, this vol., chap. 13). The vertical walls of the blue holes are covered with live coral, and the bottoms are covered with carbonate sand.

There is no reef crest in this region, possibly because of the higher wave activity experienced on this part of the island. The algae-covered pavement of the deep fore reef directly off Kamalō is a remnant of damage from the dredging operations. The shallower portions of the fore reef have regenerated and show substantial aggregated coral; however, this coral growth ends abruptly just east of Kalaeloa, where the fore reef transitions into an algae-covered pavement.

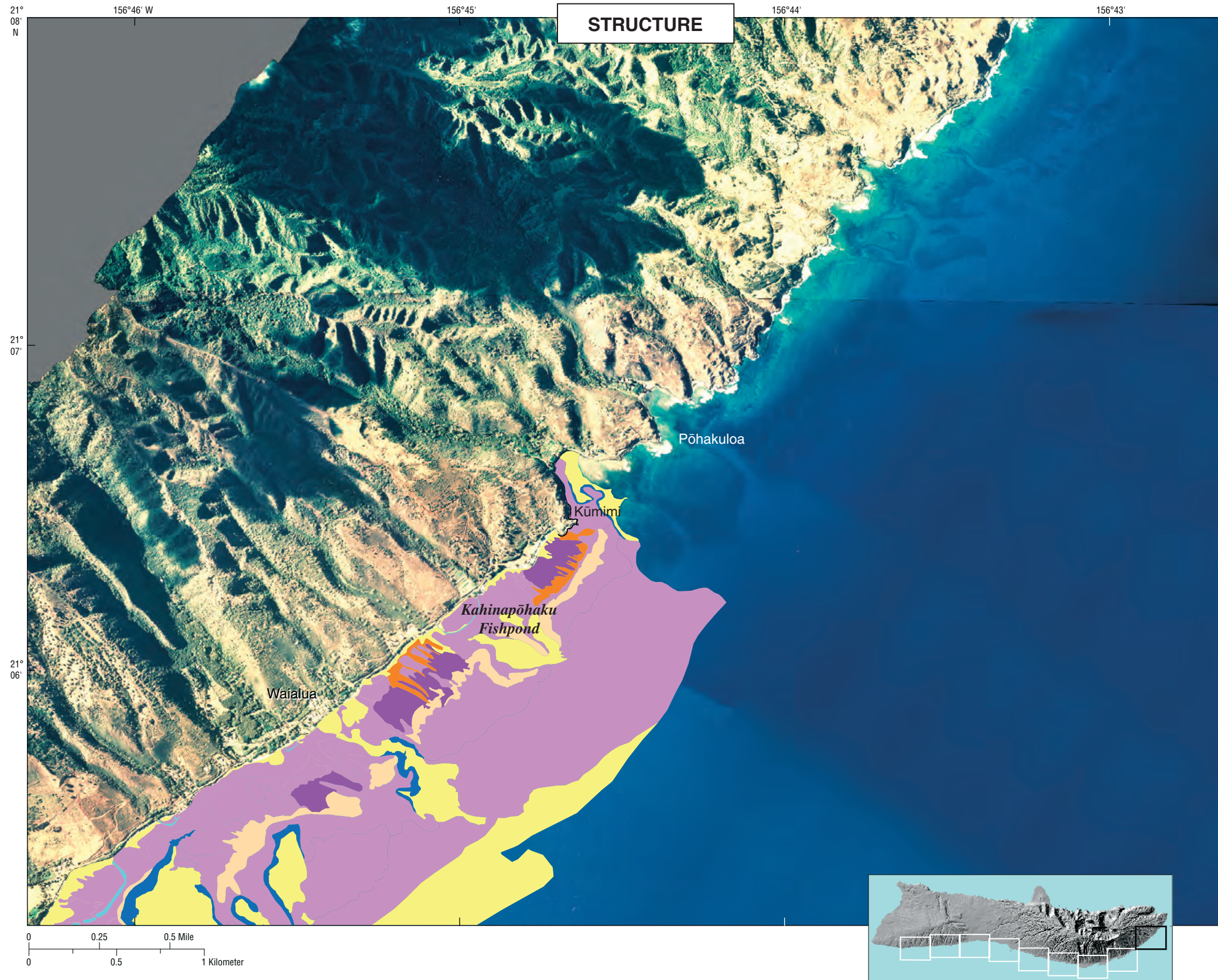




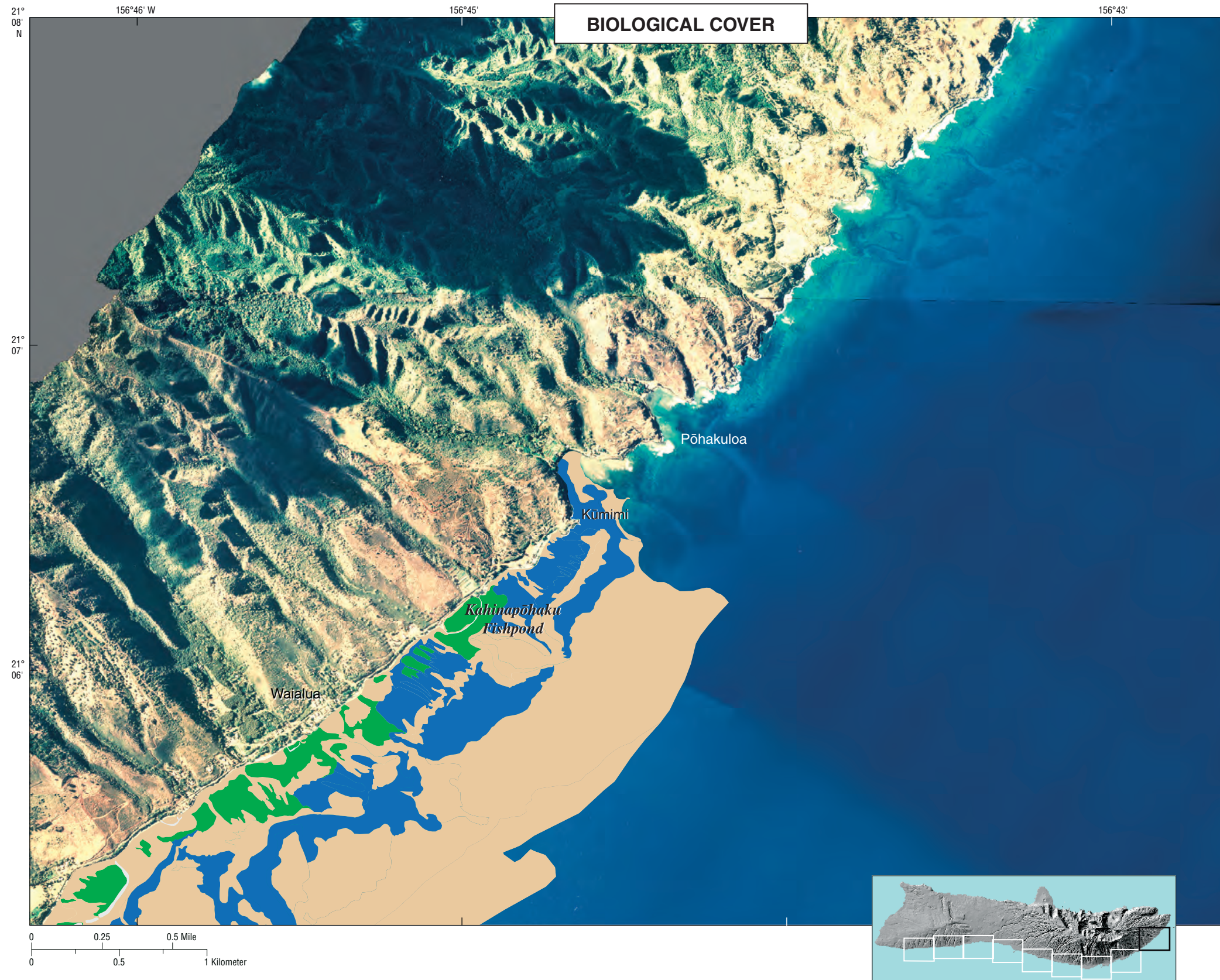
The reef flat west of Pūko'o Harbor is a mixture of algae-covered and sand-covered pavement with rare bits of live coral on scattered rocks. Ridges of aggregated patch reef are found along the seaward edge of the reef flat east of the harbor; however, the actual fore reef is only an algae-covered pavement. Several deep channels that correspond to onshore drainages bisect the reef flat, reef crest, and fore reef, and live coral is found on the vertical walls of the channels.

The reef crest is nonexistent west of Pūko'o Harbor, possibly owing to higher wave activity; however, it is present east of the Harbor. East of Pūko'o Harbor, the reef crest and fore reef begin to trend closer to the shoreline as they approach the eastern extent of aggregate coral growth along the southeast shore of the island.

THE CORAL REEF OF SOUTH MOLOKA'I, HAWAII—I PORTRAIT OF A SEDIMENT-THREATENED FRINGING REEF



- Kūmimi**
Dominant Geomorphic Structure
- Aggregate reef
 - Spur-and-groove
 - Aggregated patch reef
 - Individual patch reef
 - Pavement
 - Pavement with sand channels
 - Scattered coral/rock
 - Rubble
 - Sand
 - Mud
 - Artificial
 - Artificial/historical
 - Land
 - Unknown



- Kūmimi**
Major Biological Cover
- Coral
 - Coralline Algae
 - Emergent Vegetation
 - Macroalgae
 - Mangrove trees
 - Uncolonized
 - Unclassified
 - Unknown

Also known locally as “Rock Point” or “20 Mile Beach,” Kūmimi Point marks the eastern extent of the fringing coral reef off the south shore of Moloka‘i. Although scattered areas of live coral are found northeast of here, aggregate reef growth is limited by high-energy waves from the North Pacific swell that wrap around the end of the island near Halawa (see Storlazzi and others, this vol., chap. 11).

West of Waialua, the reef flat consists of sand and algae-covered pavement with little or no live coral. However, the reef flat from Waialua to Kūmimi consists of many live coral heads and ridges. The reef crest is found fairly near to the shore in this region and provides protection from offshore waves to snorkelers enjoying the reef flat environment. The fore reef consists solely of a barren, sloping pavement.

Suggested citation:

Cochran, Susan A., 2008, Benthic habitat maps of the south Moloka'i coral reef, *Chapter 9 of* Field, M.E., Cochran, S.A., Logan, J.B., and Storlazzi C.D., eds., *The coral reef of south Moloka'i, Hawai'i; portrait of a sediment-threatened fringing reef*: U.S. Geological Survey Scientific Investigations Report 2007-5101, p. 77-97 [http://pubs.usgs.gov/sir/2007/5101/sir2007-5101_chapter09.pdf].