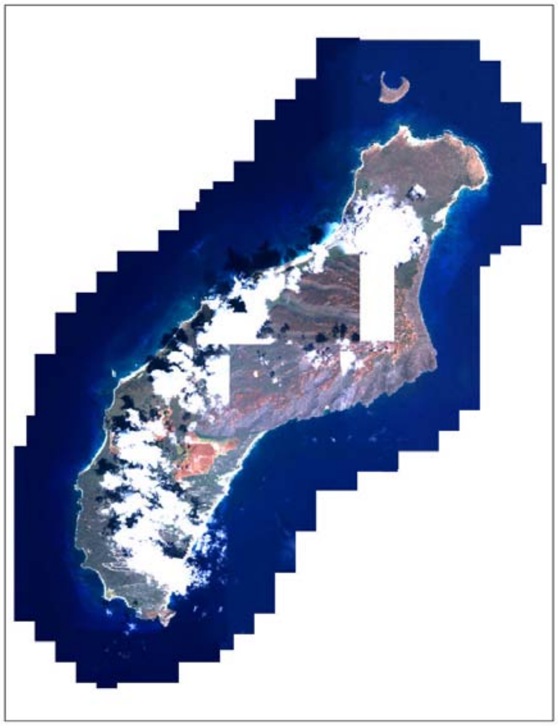
Mapping of Benthic Habitats for
The Main Eight Hawaiian Islands

Task Order I Project Completion Report



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1 INTRODUCTION

Accurate maps of marine habitats are valuable assets for managing resources, including coral reefs, seagrass beds, sandbars and other important habitats for fisheries, tourism and other aspects of the coastal economy. A problem in marine resource management is that the majority of U.S. coral reef resources have not been digitally mapped at a scale or resolution sufficient for assessment, monitoring, and/or research. Because of the lack of geospatial information, a large portion of The National Oceanic and Atmospheric Administration's (NOAA) National Ocean Service (NOS) coral reef research activities has focused on detailed mapping of U.S. coral reef ecosystems. A primary task of NOS has been the coral mapping element of the U.S. Coral Reef Task Force (CRTF) started under the authority of the Clinton Administration Federal Executive Order 13089. One objective of the program was to create benthic habitat maps to support coral reef research and initiate development of products that support management needs and questions. The maps produced by NOS, in collaboration with many Hawaiian Island partners, will provide the fundamental spatial organizing framework to implement and integrate research programs and provide the capability to effectively communicate information and results to coral reef ecosystem managers. Under this purview, BAE Systems (Sensor Solutions Identification and Surveillance) has been contracted for coral reef mapping in the Main Eight Hawaiian Islands (MEHI) using multispectral satellite imagery. Analytical Laboratories of Hawaii LLC (ALH) has been subcontracted to provide mapping and other services to meet the goals of this project. As a result of this project, a series of digital products have been produced that will further NOAA commitment towards completion of the U.S. Coral Reef Task Force's recommendation to develop shallow-water coral reef ecosystem maps for all U.S. waters by 2009.

The primary products of this effort are benthic coral reef habitat maps in geographic information system (GIS) format, produced by delineating habitat boundaries by visual interpretation from multispectral satellite imagery. An important aspect of mapping is making information accessible in a visual database format for rapid analysis. Computerized semi-automated methods have a distinct advantage that allows the user to increase coverage, productivity, and develop active links between the mapped image and the associated database in GIS format. The applications of GIS provide a powerful analytical tool that yields critical information and contributes to the ability to make sensible, long-term natural resource management plans.

In generating the GIS maps, benthic features have been classified using a hierarchical two-tiered coral reef habitat classification scheme, prepared from consultation, meetings and workshops that included the key coral reef biologists, mapping experts and professionals of the MEHI. The classification scheme that was developed by NOAA for all islands of the Caribbean and Pacific was used for this work (Refs.1,2). Subsequent to an intermediate scheme that was developed and used to generate the habitat maps prepared from the NOAA imagery collected during the year 2000, comments and suggestions have been incorporated into a new scheme that includes GIS data organized to separate the geomorphologic substrate structure of the reef system from the biological cover colonizing its surface. For the purpose of this work, habitat is defined by the major and detailed attributes of these two layers. An integral part of this work includes scientifically sound statistical accuracy estimates of the spatial and thematic content of these coral reef habitat maps. These analyses are presented and conclusions are drawn that can be integrated into long-term coral reef mapping objectives.

2 APPROACH

2.1 Imagery

Multispectral IKONOS™ and Quickbird™ satellite imagery, from GeoEye (formerly Space Imaging) and Digital Globe, respectively, was used for creating all maps. The licensing agreement from both companies allowed the customers (BAE Systems and NOAA) a non-transferable, non-exclusive, pre-paid license to use their imagery. Under the licenses, the customers were allowed to:

1. Reformat the Product into different formats or media from those in which it is delivered.
2. Make an unlimited number of hardcopies and softcopies for internal use.
3. Distribute the Product (with copyright markings) on an isolated, non-commercial basis.
4. Modify the imagery Product and make copies for internal use.
5. Distribute works derived from the Product. Derived Works inherited the copyright and license restrictions of the source data.
6. Make the Product available to consultants, agents and subcontractors without the right to transfer, modify, copy or sublicense.

IKONOS imagery was 11-bit precision and included both pan-chromatic and multispectral four-band data. The IKONOS satellite orbits the Earth every 98 minutes at an altitude of approximately 680 kilometers (423 miles). IKONOS is in a sun-synchronous orbit, passing a given longitude at about the same local time (10:30 A.M.) daily and can produce 1-meter imagery of the same geography every 3 days. The satellite sensor elevation angle, the angle from horizon to sensor as seen from the area of interest (AOI), is typically > 60°. Swath size for a single scene is 11 km x 11 km. Information on IKONOS was taken from the Space Imaging website (http://www.spaceimaging.com).

Quickbird imagery had similar characteristics to IKONOS, with 11-bit precision pan-chromatic band and four-band multispectral, but has slightly greater ground resolution and increased blue signal in the panchromatic band. The Quickbird satellite orbits every 93.4 minutes at an altitude of 450 km with a 98 degree, sun-synchronous inclination. Views are revisited with a frequency of 3-7 days depending on latitude at 60-cm resolution and viewing angle can be changed for in-track and cross-track pointing. Swath size for a single scene is 16.5 km x 16.5 km. Information about Quickbird data from the Digital Globe website: http://www.digitalglobe.com/downloads.

Band centers, ground resolution and calibration coefficients for IKONOS and Quickbird are shown in Table 1 and Table 2, respectively. Radiometric calibration was done by multiplying raw imagery in digital units (DN) by the calibration factor and then dividing by the spectral bandwidth. Imagery received from Space Imaging was evaluated for quality before any processing commenced; any raw data containing undesirable environmental features, such as excessive glint, cloud cover, or other factors that obscured bottom features, were rejected.

Table 1. IKONOS satellite data characteristics (post 2/22/01)

Band	λ center (nm)	λ range (nm)	Resolution (m)	Radiometric Cal Factor DN*cm^2*sr/mW
pan	727.1	525.8 - 928.5	1	Not used
blue	480.3	444.7 - 516	4	728
green	550.7	506.4 - 595	4	727
red	664.8	631.9 - 697.7	4	949
NIR	805	757.3 - 852.7	4	843

Table 2. Quickbird satellite data characteristics

Band	λ center (nm)	λ range (nm)	Resolution (m)	Radiometric Cal Factor DN*cm^2*sr/mW
pan	675	450 - 900	0.61	Not used
blue	485	450 - 520	2.44	623
green	560	520 - 600	2.44	695
red	660	630 - 690	2.44	789
NIR	830	760 - 900	2.44	648

2.2 Geometric Accuracy

Accuracy of IKONOS imagery is reported to be 4m CE95, a value measured on-orbit by GeoEye in 2004 and documented in an internal report (Grodecki and Lutes, 2005). Quickbird imagery was reported to have 4.06m CE95 accuracy, orthrorectified using proprietary software and a 30m or 90m Shuttle Radar Topography Mission (SRTM) map or National Elevation Dataset (10m) corrected with ground control points.

An issue with orthorectification in this project, and any other benthic mapping project, was that there was no elevation model for the seafloor like there would be for land. Bottom cover in shallow water with low relief would not have been affected, as the elevation there was assumed to be sea-level. However, reefs with deep trenches or other relief could potentially create some error in geometric positioning, an issue compounded by sea surface refraction changing the apparent position of submerged objects. There is potential to use bathymetric maps to rectify the imagery over reefs but this avenue was not pursued as it was not part of the original project plan and would take additional deal of time to accomplish.

2.3 Image Processing Methods

The mapping approach for this project relied upon traditional hand-digitization techniques, updated by advances in imaging technology. Benthic habitat classification schemes have traditionally relied heavily upon aerial photography as the primary imagery sources for mapping large coastal areas, methods used since the development of powered aircraft. Aerial photos have high resolution and capture detail well but must be collected during good flight conditions, something that does not always occur in coastal regions. Flying multiple times becomes expensive and even then only some of the photos are usable for mapping. New, high-resolution satellite imagers solve one of the major problems with aerial photos by providing multiple orbital passes over an area so that the best images can be selected for mapping. Color image quality with multispectral sensors has also improved, with images collected as calibrated spectral data, an advance that facilitates the use of algorithms to reduce effects of atmospheric haze, aerosols, and even reflectance off the ocean surface.

Advances in global positioning of satellites make mapping with satellite data more accurate and simpler to incorporate into geographic information system (GIS) databases for resource management. The mapping techniques used in this project are similar to "grease pencil" delineation of habitat classes in aerial photos, but now involve a computerized "heads up" digitizing system where information is accessible in a visual GIS database format for rapid analysis. Lines are still drawn around reef features as with the grease pencil but all of the shapes, lines and polygons contain spatial and statistical information about the mapped region. These mapping techniques with four-band satellite image data have been used successfully by Analytical Laboratories of Hawaii LLC in the mapping project for NOAA NOS in the pacific reefs in Palau.

The maps and mapping methods described herein were developed using Environmental System Research Institute (ESRI) ArcView™ GIS, Leica Geosystems ERDAS Imagine™, and RSI Inc. ENVI™ software packages. The goal was to map the main eight Hawaiian islands from the coastline to 30m depth, digitizing 3462.5 km^2 of the shore (from a total of 4565.5 km^2 delivered by GeoEye) and creating map products compatible with GIS software. Image data was processed through a number of steps in order to make it easier to digitize bottom features in ArcView. One of the most important steps was atmospheric correction, a step which removed aerosols and water vapor and improved contrast in deep water. A side benefit of the atmospheric correction step was that corrected images could be output in remote sensing reflectance (R_{rs}) (ratio of upwelling radiance to downwelling irradiance), a standard measurement unit for many spectral algorithms. The dataset calibrated in R_{rs} units provides scientific researchers at NOAA with a reliable standardized dataset for future spectrally-based mapping efforts of benthic habitat distribution and health over time.

3 METHODS

3.1 Image Evaluation

Imagery evaluation centered around one main criterion; "Is the bottom visible?" After the satisfaction of the technical and quantifiable parameters were verified, each image was deemed acceptable based mainly on whether bottom features were visible between the shoreline and the 30 meter isobath. The first group of quantified acceptance parameters could be confirmed by the imagery metadata. Those parameters were:

- Elevation angle no less than 68° and no more than 85°
- Horizontal Accuracy: 5 m CE95 (see Section 4.3-4.4)
- Projection/Datum: UTM NAD83

- Units: meters
- Bits per pixel: 11-Bit
- No greater than 20% cloud cover for any given scene
- Acquisition date no later than 2 years from first acquisition date for any given area

Each image was required to meet certain spatial parameters as well:

- Area of Interest (AOI) must be completely filled by imagery
- No significant overlap with previously accepted and mapped imagery

Furthermore, each acceptable image was required to meet certain spectral quality criteria:

- Deep water pixels must approximately match the expected deep water spectra
- Shallow water pixels must approximately match the expected shallow water spectra
- Vegetation pixels must approximately match the expected vegetation spectra
- Glint must not obstruct entire bottom regions - small amount of glint acceptable

After an image had met the more quantifiable criteria, it could then be qualitatively evaluated based bottom visibility. The most frequent obstruction of the bottom was suspended sediment but white caps, white wash, foam, and breaking waves also caused visibility issues.

Images that were not pristine but deemed marginally acceptable were evaluated to estimate the percentage of usable imagery. The area of obstructed bottom (be it from sediment, waves, clouds, etc.) was converted to an ArcView shapefile and subtracted from the total mapping area of that image. If the unusable area was 10% or less of the total, the image was acceptable. Another consideration made regarding the acceptance of marginal imagery was the likelihood of getting better data over the same area at a later time due to the calm nature of winter waves and weather patterns.

3.2 Data Conditioning Methods

3.2.1 Data Processing Overview

The image processing scheme was developed by BAE Systems such that atmospherically corrected, calibrated data could be produced and then used with the ArcGIS Coral Reef Digitizer Extension software developed by NOS (Figure 1). There were slight differences for the processing path of IKONOS and Quickbird Imagery in that IKONOS images were delivered to BAE Systems separated into individual band images and needed to be combined into a single multispectral image before further processing. Quickbird data came as complete multispectral images. All image data were evaluated for general quality before progressing to the next steps in the data analysis stream.

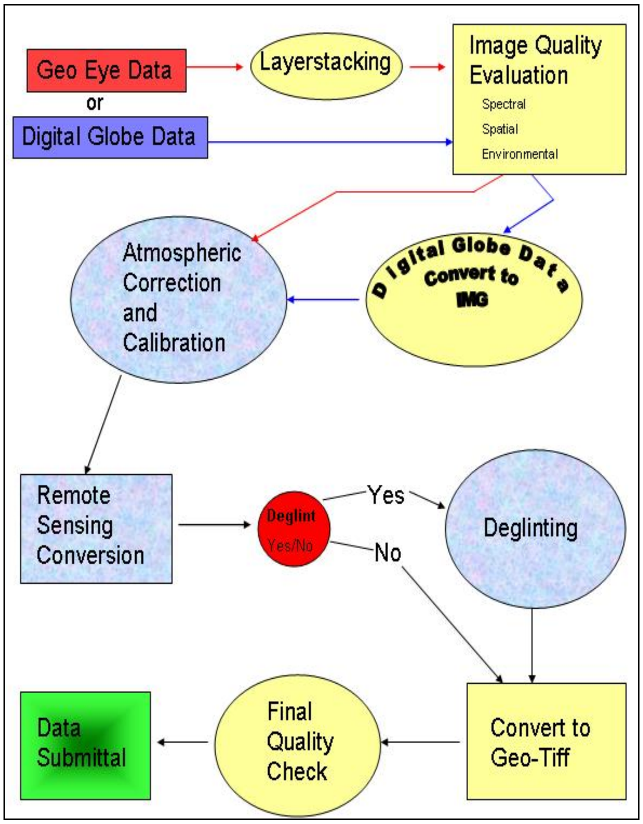

Figure 1. Image processing flowchart for IKONOS and Quickbird data. Only the image processing portion of data flow is shown. Additional steps such as creation of mosaics and metadata are described in the upcoming text.

3.2.2 Atmospheric Correction

Once the imagery was evaluated for overall quality, it was processed for mapping using the program ATCOR2™, an atmospheric correction software plug-in for ERDAS IMAGINE PRO V.8.7 that corrects for aerosols and water vapor and outputs a radiometrically-corrected image in reflectance units. Some key steps for using ATCOR2 are shown below.

1. The Solar Zenith value in ATCOR2 is the angle of the sun off-nadir. GeoEye, however, reported the sun *elevation* (i.e., the angle of the sun from horizon). Thus, we calculated the solar zenith angle:

$$\text{SolarZenith}(\text{deg}) = 90 - \text{SunAngleElevation} \quad (1)$$

   where the sun angle elevation was provided by GeoEye in the metadata files.

2. The tilt angle pertains to the angle of the sensor off-nadir. GeoEye reported the sensor tilt angle as Nominal Collection Elevation in degrees from the horizon. We calculated the angle using:

$$\text{TiltAngle}(\text{deg}) = 90 - \text{NominalCollectionElevation} \quad (2)$$

   where the nominal collection elevation was provided by GeoEye's metadata. Unfortunately, the only tilt angles considered in ATCOR2 for this option were 10, 20, and 30 degrees. The calculated tilt angle was rounded to the closest default angle (e.g., if the tilt angle was 17˚, the closest default angle was rounded to 20˚).

3. The direction (N, S, E, W) to select for this option was determined by the relative azimuth between the nominal collection azimuth of the sensor and the solar azimuth:

$$\text{RelativeAzimuth} = \left|\text{NominalCollectionAzimuth-SolarAzimuth}\right| \quad (3)$$

A relative azimuth of 0˚ = S, 30˚ = E, 120˚ = N, 150˚ = W. All other angles were rounded to the nearest defined angle to determine the direction (e.g., if the relative azimuth was 130˚, the closest defined angle was 120˚ so the direction would be assigned as N).

4. Aerosol type was selected as "midlat_summer_marit"

5. Haze removal was not performed before correction as the function only worked over land and caused problems over water.

6. Output from ATCOR was in percent reflectance, which was then multiplied by a scale factor (normally 10) and saved in integer format. To get remote sensing reflectance (upwelling radiance / downwelling irradiance), the data needed to be divided by (pi*scale factor*100), resulting in units of per-steradian (sr^{-1}). Example spectra are in Figure 2.

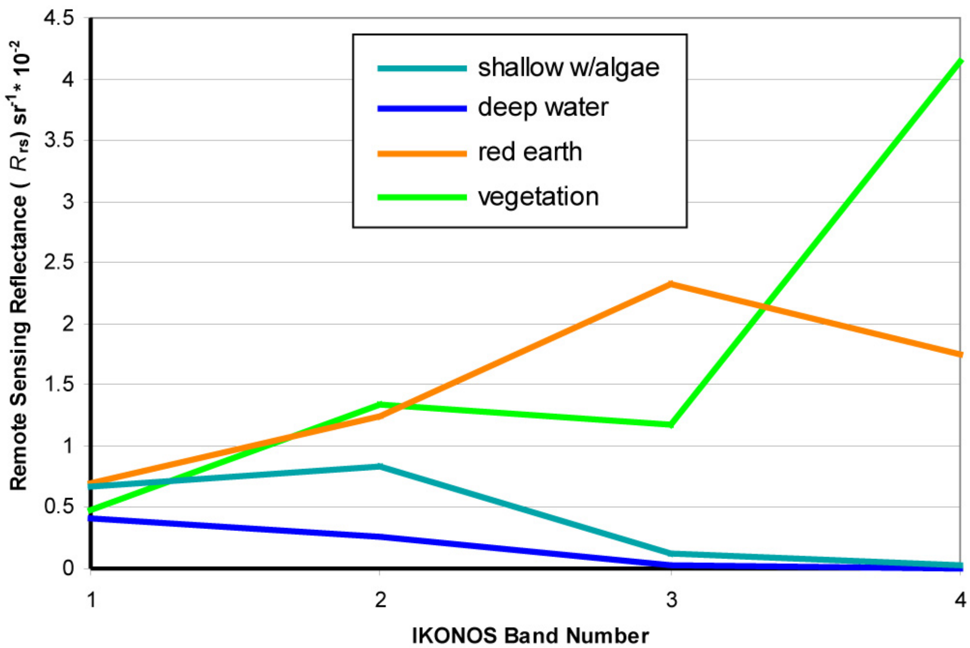

Figure 2. Example remote sensing reflectance spectra of seafloor and ground cover.

3.2.3 Pan Sharpening

The purpose of pan-sharpening was to spectrally sharpen low spatial resolution image data with high spatial resolution image data. The 4-band color low-resolution (4m) multispectral (MSI) IKONOS imagery was merged with the high-resolution (1m) single-band grayscale panchromatic IKONOS imagery, with nearest neighbor resampling to the high-resolution pixel size. The pan sharpening process was carried out by GeoEye and Digital Globe for their data respectively.

The pansharpened files sometimes did not appear as sharp as the 4m spatial resolution MSI image before processing. This resulted from the slight temporal shift (sometimes up to ½ second) between the MSI image and panchromatic images, an issue known to GeoEye but not fixed during the contract period. The detail (i.e., resolution) of the output file, however, did look much more refined after this pan-sharpening even with the temporal shift.

3.2.4 Glint Removal

Images with moderate amounts of glint were corrected using a BAE Systems automated glint-removal algorithm which utilized the differences in the near-infrared band to distinguish glint from water, land, and the seafloor. The idea behind the technique is that pixels will have a variable fraction of specular reflection caused by the angle of wavelets in relation to the sun. The fraction is proportional to the amount of signal in the near-infrared (NIR) band, which would be negligible in the ocean (Hochberg et al. 2003).

In order to calculate the amount of glint, pixels in the image were segmented based on thresholds of NIR to find those with the highest signal. Land, vegetation and very shallow water often had a high NIR value and were masked out of glint calculations using a band ratio threshold of NIR verses blue. The glint pixels were averaged and the minimum value of the remaining "background" pixels (not glint, land, vegetation, or shallow water) were subtracted to get a glint spectrum. The amount of glint in each pixel was calculated using the NIR band by first subtracting the "background" pixel NIR value, then dividing by the glint NIR value. Glint was removed from all bands by subtracting the glint spectrum in all bands scaled by the ratio of glint in the NIR

The deglinting procedure was carried out with atmospherically corrected MSI and pansharpened data, and only on images that had glint pixels that would hinder the visibility of bottom features. Pansharpening the image after deglinting the four-band multispectral image would reintroduce the glint, so deglinting was always the last step. The final step in deglinting pansharpened data required hand-tuning of the algorithm parameter space since some spectral artifacts were introduced by the pan-sharpening.

3.2.4.1 Deglinting Process

Pixels with the highest 5% of NIR signal were segmented into the "glint subset" to calculate the amount of glint in an image. Land, vegetation and very shallow water often had a high NIR signal and were masked out of glint calculations using band ratio thresholds. Pixels with zeros in all bands, created during image mosaicking, were masked as well.

3.2.4.2 Glint Removal Algorithms

Pixels that fell into the glint subset were averaged to create a single representative surface anomaly spectrum (R_{SA}) that included both glint and reflected light from the background water and seafloor. The background spectrum (R_B) was calculated by segmenting the remaining pixels to remove glint, land, vegetation, lava and very shallow water (< 1m) and taking the minimum spectrum. Subtracting the two produced the final representative glint spectrum (R_G).

$$R_{G_\lambda} = R_{SA_\lambda} - R_{B_\lambda} \tag{4}$$

The amount of glint in each pixel was a function of the signal in the near-infrared Band 4 and was a combination of both glint and the upwelling background spectrum. To find the percentage of glint, the "background" Band 4 value was subtracted from the test pixel Band 4 (R_{TP}), then the result was divided by the glint Band 4 value (Eqn. (5)).

$$G_{\%} = \frac{R_{TP_{Band\,4}} - R_{B_{Band\,4}}}{R_{G_{Band\,4}}} \tag{5}$$

Glint was removed from all bands of the test pixel by subtracting the glint spectrum in all bands ($R_{g\lambda}$), scaled by the ratio of glint in the NIR ($G_{\%}$), from the test pixel spectrum ($R_{TP\lambda}$) (Eq. 6).

$$R'_{TP_\lambda} = R_{TP_\lambda} - \left(R_{G_\lambda}\left(G_{\%}\right)\right) \tag{6}$$

The final product was a deglinted image in unitless irradiance reflectance (E_u/E_d). To calibrate the data into remote sensing reflectance (L_u/E_d), the image was divided by pi (Eq. 7).

$$\frac{L_u}{E_d} \approx \left(\frac{E_u}{E_d} * \pi\right) \tag{7}$$

An example 400x400 pixel subset of a full deglinted image is shown in Figure 3. This data was from the NOAA POC dataset and was extremely glinty, with a poor signal to noise ratio in shallow water. Before glint removal, the bottom features were obscured to the point that a number of small patch reefs and sand channels could not be distinguished. After the glint was removed, the bottom features became pronounced and could be more easily mapped.

Figure 3. An example of deglinted output. Before the deglinting algorithm was run, glint was a major problem when trying to classify bottom features, such as small coral outcroppings in the deeper water outside the reef shelf. Also visible were tracks made by the wake of a passing boat in the bottom left corner. After deglinting, the image is much clearer and easier to use in bottom classification. The boat wake has also been removed.

3.2.5 Mosaicking

One contract deliverable was image mosaics of multiple satellite images. All mosaics were made with atmospherically corrected and deglinted images following the procedures from Sections 3.2.1-3.2.4. Multiple images from each island were "stitched" together to form a seamless map with all surrounding water. In some cases there were gaps on the land, but the water had complete coverage. After the images were stitched together, each of the composite images were balanced so their colors matched one another. This process was completed in ERDAS by histogram-stretching all images and matching color tone to one reference image. The final mosaicking process was also done with ERDAS, utilizing the georeference data from the images to accurately position them in the projection system UTM NAD-83 (Zone 4). An example mosaic is shown in Figure 4. Both multispectral and panchromatic imagery were mosaicked.

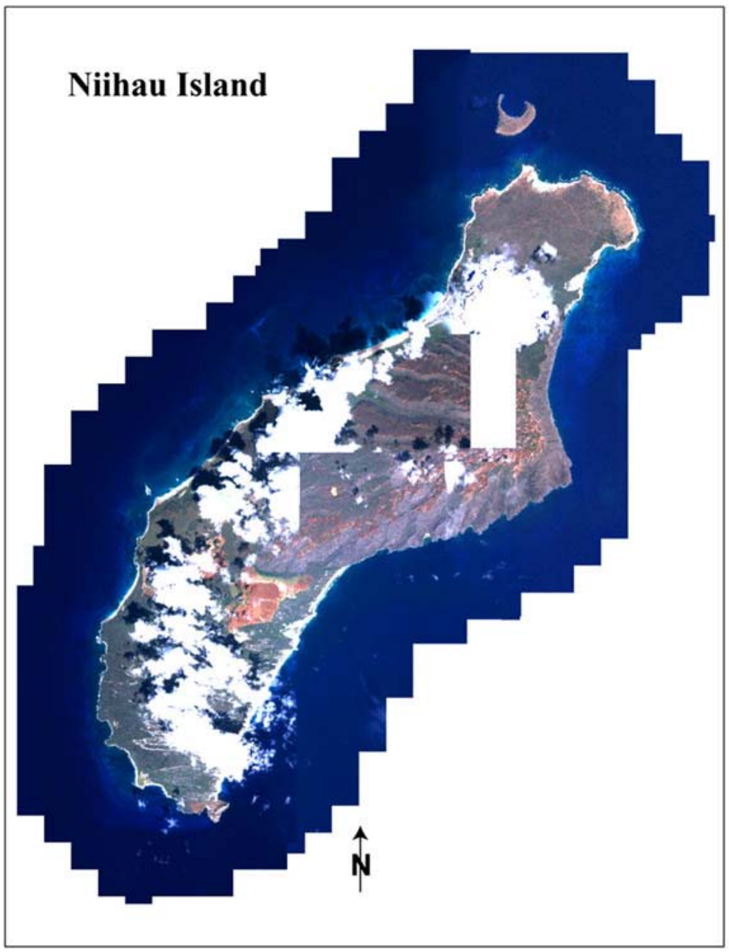

Figure 4. An example mosaic image of Niihau Island, Hawaii.

3.2.6 Metadata

A major pitfall in the geospatial data community is the lack of information to help users determine what data exist, the fitness of existing data for planned applications, the conditions for accessing existing data, and help in data transfer. In 1994, President Clinton signed Executive Order 12906, *Coordinating Geographic Data Acquisition and Access: The National Standard Infrastructure,* which standardizes the documentation of geospatial data collected and produced, while making the documentation accessible to the Clearinghouse network. The Federal Geographic Data Committee (FGDC) has created a standard for the documentation of geospatial data and encourages everyone to use the standard to document their geospatial data.

Metadata was a key component of the NOAA deliverable package and was required for different stages of the data analysis process. The FGDC standard was used to document all geospatial data pertaining to map products. Metadata was created using ArcCatalog (ESRI Inc.), which saves the data as properties and documentation. Properties, such as the shapefile features (bounding coordinates, grid coordinate system) were derived from the file itself. Documentation was completed using templates for atmospherically corrected MSI images and panchromatic images, with descriptive information filled in for each data section.

All images were strictly reviewed before being accepted for final processing. For each imagery bundle delivered, BAE Systems critiqued, on average, over three hundred MSI images. A total of four hundred acceptable MSI and pansharpened images were selected from all bundles to go through the data processing scheme (Figure 1). Associated with each of these raw image files were three metadata files and up to five separate intermediate files that were produced in a particular order during processing. In addition to the image files were ancillary data files, various shape files, templates, maps, spreadsheets, pictures, and other data which needed storage and electronic management. For this reason, a file naming convention was created with an enumerated directory structure to keep track of the processing flow and file associations between MSI, pansharp, metadata, shape files, and maps (Figure 5). Data were categorized by bundle, island, and then image type. Within each image type was a group of directories representing separate stages in the processing scheme.

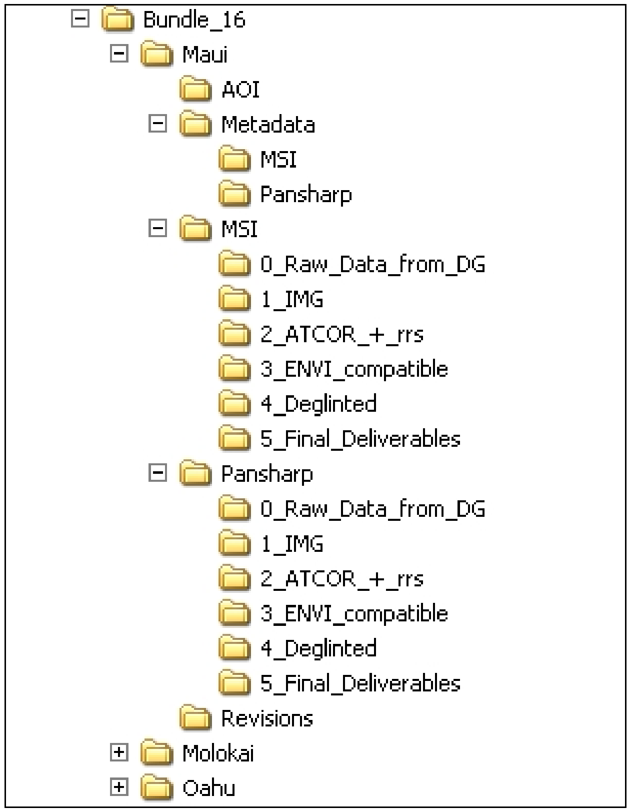

Figure 5. Example of the directory structure employed in order to manage multiple scenes and their ancillary and supporting data files.

The name of each image file was related by the numeric naming scheme used by the image provider (Table 3). Geo Eye used a numeric code where the first six digits represent the product order identification (POID) and the last seven digits refer to the image identification. Digital Globe used an alphanumeric code consisting of the image's acquisition date and time and the image-strip location. The image type, MSI or pansharp, was appended to the numeric or alphanumeric name along with an abbreviated synonym for the stage in the processing sequence that had been completed on that image.

Table 3. The file naming convention used to describe the stage of processing completed on a given image from both image providers. These names were shortened before delivery with a bundle at the clients request.

Image Provider	**File Naming Convention**
Geo Eye	196554_0020001_pan_layerstack_mosaic_atcor_rrs_envi_deglint_tif.tif
Digital Globe	05feb20211614_r1c2_msi_layerstack_atcor_rrs_envi_deglint_tif.tif

3.3 Mapping Approach

High spatial resolution IKONOS and Quickbird imagery proved suitable for visual extraction of the habitat classes and was the best choice for imaging in areas that were too remote to economically acquire the imagery by fixed wing or other platform. Collection constraints were set to control environmental effects such as glare, glint and other interferences that would limit visualization of benthic features. Multiple collects were conducted to ensure that mosaic scenes with contained no more than 20% cloud cover. The mosaic images were used to manually interpret and delineate geomorphologic features, zones and cover type. This task was accomplished by Analytical Laboratories of Hawaii using on screen digitizing in ArcView GIS facilitated by the Coral Reef Digitizer Extension (developed by NOS and published on the NOAA web site http://biogeo.nos.noaa.gov/products/apps/digitizer/).

3.3.1 Development of the Benthic Habitat Classification Scheme for the Pacific

Benthic features depicted in the final map products were classified using a hierarchical, two-level, coral reef habitat classification scheme, consisting of a geomorphologic reef structure, reef habitat zone, and biological cover description. The scheme was prepared through consultation, meetings and workshops that included key coral reef biologists, mapping experts and professionals in the State of Hawaii. The original coral reef habitat classification scheme that was developed by NOAA for the Caribbean was used as a starting point for this work. This classification scheme was influenced by many factors including but not limited to:

- Requests of the management community
- NOS's coral reef mapping experiences
- Existing classification schemes for the Pacific and Hawaiian Islands and other coral reef ecosystems
- Quantitative habitat data for the Hawaiian Islands
- Consideration of various minimum mapping units and technological trends toward preparation of living resource map products using digital techniques from remotely sensed imagery including satellite data.

Eighteen bundles of imagery were originally chosen for classification. The identification and location of these imagery bundles were dictated by the areas where imagery suitable for the mapping process was collected by GeoEye and/or Digital Globe. Acquisition of remotely sensed imagery was challenged by environmental conditions including glint, wind-waves, breaking surf, water clarity and cloud cover, but eventually all data products were delivered as per the contract agreement.

The classification scheme was separated into two levels: the geomorphologic structure of the reef and the biological cover on the substrate. Four major geomorphological structural components were used in the classification scheme. These were subdivided to include benthic habitat geomorphological structure (Table 4). Biological cover of geomorphological structures was divided into nine classes with six density levels (Table 5). Reef habitats were classified into fourteen zones (Table 6). Abbreviations for the habitats are in Table 7.

Table 4. Major geomorphological structures and associated benthic habitat subdivisions.

Unconsolidated Sediments

1. Sand
2. Mud
3. Unclassified
4. Unknown

Coral Reef and Hard Bottom

1. Unknown
2. Aggregate Reef
3. Spur and Groove
4. Individual Patch Reef
5. Aggregated Patch Reef
6. Scattered Coral/Rock
7. Pavement
8. Rock/Boulder
9. Pavement with Sand Channels
10. Rubble
11. Unclassified
12. Unknown

Other Delineations

1. Land
2. Artificial
3. Unclassified
4. Unknown

.1.1.1.1 Unknown

1. Unknown

Table 5. Biological cover classes and density class subdivisions

Biological Cover	Cover Density

1. Coral 2. Seagrass 3. Macroalgae 4. Coraline Algae 5. Turf 6. Emergent Vegetation 7. Uncolonized 8. Unclassified 9. Unknown	1. 10%-<50% 2. 50%-<90% 3. 90%-100%

Table 6. Reef habitat zones

1. Shoreline Intertidal 2. Vertical Wall 3. Reef Flat 4. Back Reef 5. Reef Crest 6. Fore Reef 7. Reef Hole 8. Lagoon 9. Bank/Shelf 10. Bank/Shelf Escarpment 11. Channel 12. Dredged 13. Land 14. Unknown

Table 7. Lookup table for habitat abbreviations from error matrices

Biological Cover	LCoral	Coral 10% - <50%
	MCoral	Coral 50% - <90%
	HCoral	Coral 90% - 100%
	LSeaGr	Seagrass 10%-<50%
	MSeaGr	Seagrass 50%-<90%
	HSeaGr	Seagrass 90%-100%
	LMac	Macroalgae 10% - <50%
	MMac	Macroalgae 50% - <90%
	HMac	Macroalgae 90% - 100%
	LCA	Coralline Algae 10% - <50%
	MCA	Coralline Algae 50% - <90%
	HCA	Coralline Algae 90% - 100%
	LTurf	Turf 10% - <50%
	MTurf	Turf 50% - <90%
	HTurf	Turf 90% - 100%
	Uncol	Uncolonized Hard Bottom
Geomorphologic Structure	AgRf	Aggregate Reef
	AgPtchRf	Aggregated Patch Reef
	IndPtchRf	Individual Patch Reef
	SnG	Spur and Groove
	SCRUS	Scattered Coral and Rock in Unconsolidated Sediment
	Pvnt	Pavement
	Rock/Bldr	Rock/Boulder
	PWSC	Pavement with Sand Channels
	Rub	Rubble

3.3.2 Spatial Data Acquisition

Collection of validation Global Positioning System (GPS) data was needed for accuracy assessment of the habitat maps and for ground validation information used to investigate uncertainties during the manual delineation of zone, structure and biological cover. The accuracy assessment data was generated on a random stratified point basis by selecting specific targets in areas where habitat type was not certain during photointerpretation and needed to be examined in the field or where gradients through habitat type resulted in uncertain habitat boundaries.

3.3.3 Habitat Map Preparation

Traditional methods of stereoplotter digitizing of photo interpreted habitat classes have gradually been replaced by computerized on-screen digitizing methods and GIS databases, which have some distinct advantages, including:

- Elimination of intermediate digitizing steps, reducing error in habitat boundaries.
- Improved productivity with higher quality output.
- Development of an active link between mapped image and the associated database.
- Creation of digital, spatially-explicit products for improving resource management decisions, enhancing biological monitoring strategies and exploring ecological linkages.

The application of GIS provides a powerful analytical tool that yields critical information and contributes to the ability of making sensible long-term natural resource management plans. The maps and mapping methods described in this report were developed using ESRI ArcView GIS software. The coral reef benthic habitat maps were prepared in a five step process (Figure 6).

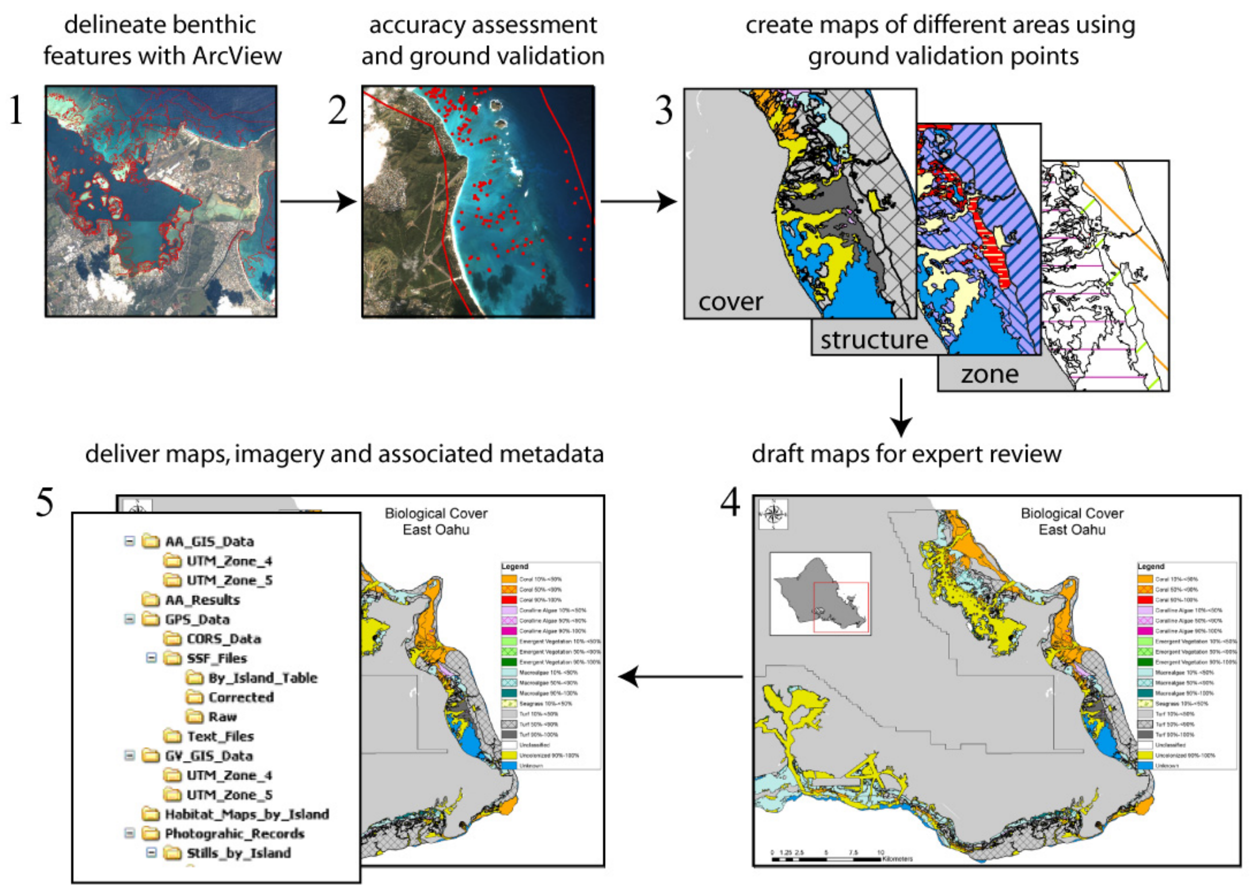

Figure 6. Flowchart summarizing steps for preparation of benthic habitat maps.

The map production steps are as follows:

1. A first draft coral reef habitat map was produced by delineating all features that could be identified by visual inspection of the satellite imagery. This first draft map includes all zones, geomorphologic structure and biological cover types as well as shoreline and unknown areas. It was generated by "on screen" manual image interpretation and delineation in ArcView GIS format using the Coral Reef Digitizer Extension that allows for a custom habitat classification scheme to be developed based on the user's needs. The software allowed for zone classifications to be included and toggled between the legends of the habitats and zones within the GIS system. It also provided the option of setting the area of minimum mapping unit (MMU) and informed the image interpreter when a polygon was being closed that had an area below the selected MMU, providing the option of including or eliminating that polygon. Manual delineation process was conducted with the image scale at 1:6,000 with the MMU set to one acre. All manual delineation was conducted based on the color and texture of the features in the imagery as well as the subcontractor's extensive knowledge of the coral reef systems and field observations.

2. Areas that were difficult to interpret or where the image interpreter needed additional field information were identified and labeled as "ground validation" positions and were explored in the field to enhance map accuracy. A set of field survey positions were created and used for assessment of the map product accuracy. This set of points was generated by stratifying each habitat and structure type and generating randomly distributed field positions. This process step is described in Section 5. These surveys were completed and the maps were edited based on the ground validation information to generate a second draft map product. During this edit, the accuracy assessment data was withheld from the image interpreter.

3. The accuracy of the second draft map was determined based on the field accuracy assessment data. If the accuracy met NOAA standards, the process proceeded to Step 4. If it did not, it was returned to the image interpreter to be further refined. If additional ground validation observations were needed to improve accuracy, they were collected at this time.

4. After demonstrating that the map products met NOAA accuracy standards, the map products were reviewed by local marine biologists, coral reef scientists and marine recourse managers. Comments were integrated into the map products to generate a third draft map.

5. Federal Geospatial Data Committee (FGDC) compliant metadata summaries were prepared for all point and polygon GIS data generated during this tenure. These GIS data and metadata summaries were reviewed by NOAA and prepared for publication.

3.3.4 Field Survey Methodology

The map creation process required extensive field surveys to enhance accuracy of habitat delineations and to measure accuracy of final maps. Two different sets of field data were collected for these different procedures; map accuracy was improved using a set of "ground validation" positions and classification accuracy was measured with a set of "accuracy assessment" positions. The collection methods were the same for both datasets and required the acquisition of a significant amount of GPS data and habitat survey. GPS acquisition methods were used that had spatial accuracy better than 5 m RMS horizontal error. Vertical data were all set to sea level.

3.3.4.1 GPS Data Collection

A Trimble Geo Explorer 3 was used to collect ground validation and accuracy assessment GPS carrier data. Trimble Pathfinder Office Software was used for post processing and differential correction of the raw GPS data to the geographically closest Continually Operating Reference System (CORS). Habitat attribute information was collected on site using the GPS data logger with a custom data dictionary designed to reflect the NOAA classification scheme for benthic habitats of the Pacific (Section 3.3.1). All survey data was collected using the same methods, but descriptions with more detail were logged for points used in accuracy assessment as less detailed information was needed for ground validation. The purpose of the ground validation survey was to investigate areas in the imagery where interpretation of the habitat type was uncertain during the delineation of the first draft map, and often required answers to a few specific questions.

During the field survey, waypoints for sampling were generated using a stratified random sampling regime or were selected to explore specific features in the imagery. Each waypoint that could be safely occupied was navigated to using a suitable sized boat to accommodate the sea conditions. After arrival at the way point, 100 GPS positions were collected at one-second intervals and were averaged to generate a single position. After GIS data collection was complete, the habitat characterization was conducted in a circular area of 7.5 meter radius centered on the way point. Each feature was populated with site-specific data using a custom designed data dictionary and processed using Trimble Pathfinder Software (Table 8).

Table 8. Data collected using Trimble Geo Explorer 3 GPS data logger at each benthic habitat characterization site during field habitat surveys

Site Data	**Habitat Data**
Study Area	Point Habitat Type (1m^2)
UTM Zone	Area 1 Habitat Type (7.5 meter radius)
Site ID	Major Structure and Detailed Structure
GP Date	Hierarchical Biological Cover and Modifier
GPS Time	Estimated Coral Cover
GPS Position	Estimated Macroalgae Cover
GPS Statistics	Estimated Coralline Algae Cover
Depth	Estimated Turf Cover
Image Information	Estimated Emergent Vegetation Cover
	Estimated Uncolonized Bottom

Two benthic habitat assessments were undertaken at each sampling site. The first was a point assessment, conducted by surveying an area of 1 m^2 around the location of a dropped weight.

The second was a general assessment conducted in an area of with 7.5 m radius around the weight. For both habitat assessment methods, workers recorded the geomorphologic structure and estimates of each of the biological cover types in the classification scheme. The depth of the site was recorded using a hand held depth sounder at the surface. Benthic habitat assessments were made using a glass bottom look box, free diving, video drop camera or observing from the surface. All dive surveys were conducted by free-diving down to the bottom or snorkeling at the sea surface. In areas where waves and sea conditions prohibited safe access of the waypoints by boat, the GPS hardware was placed in a watertight box and swum to the survey point. All observations at each position were recorded on the GPS data logger using a custom data dictionary designed to meet the specifications of the coral reef habitat classification scheme. At the end of each field day, data was downloaded from the GPS data logger and differentially corrected to the closest CORS. The Trimble GPS file was then converted to an ArcView GIS shape file and the data was compared with handwritten field notes. All data were processed at the end of each field day.

During the field habitat surveys, mapping personnel made field observations for ground validation and accuracy assessment purposes. Ground validation data were used to elucidate the habitat types where uncertainty existed on the part of the image interpreter during map preparation and to enhance reef habitat and zone interpretation. The field accuracy data collection team independently conducted benthic habitat characterizations and conducted the assessment of the extent to which the image interpretation met the field assessment determinations. These accuracy assessment field data were not made available to the image interpreter during manual delineation of habitat boundaries. During the field survey, geospatial deliverable products were referenced to the North American Datum of 1983 (NAD83) on geoid model 99, affixed to the Pacific Plate. All spatial data was projected in Universal Transverse Mercator (UTM) Zone 4 for the Islands with the exception of the Island of Hawaii where UTM Zone 5 was used. Vertical heights were all reported as sea level.

During all fieldwork, the team placed safety at maximum priority. A safety kit with first aid, spare floatation, emergency flares, drinking water and an emergency position indicating radio beacon (EPIRB) was included on each field mission. All fuel-powered vessels were compliant with US Coast Guard commercial vessel safety regulations.

3.3.4.2 Accuracy Assessment

A data collection methodology was designed and executed to quantify the thematic accuracy of the maps generated at all levels of the classification scheme. The employed statistical analysis methods have been proven robust in similar analysis (Ref. 5,6,7). In this work, a minimum of 25 field habitat observations have been completed per detailed structure as well as detailed biological cover type. The accuracy assessment was prepared from a matrix that compared the attribute assigned to a polygon that was generated from the interpretation of the image with that determination from field observation. Traditionally, the data is organized into columns that represent the field habitat validation data and rows organized into the interpretation of the images. The overall accuracy is typically measured by dividing the total correct determinations by the total number of assessments. This result only incorporates the major diagonal of the table and excludes the omission and commission errors where as the Kappa analysis (Ref. 8) indirectly incorporates the off-diagonal elements as a product of the row and column marginals. Furthermore, the Tau analysis generates a similar statistic as Kappa but compensates for unequal probabilities of groups or for differences in numbers of groups (Ref. 9).

Overall accuracy of the mapped products was measured using a statistically robust data set composed of random field habitat observations taken at each of eight test areas selected for the MEHI (Table 9). The areas were chosen based on their diverse benthic communities and were representative of other regions around the islands. Sights representative of windward and leeward exposures were used and the accuracy assessment test areas were chosen such that areas that had been used to test the thematic accuracy of products generated previously were not included. The test areas were also of particular importance for managing marine protected areas. Maps of these areas are found in Appendix A.

Table 9. Accuracy assessment test areas surveyed during this work

Island	**Test Area**	**Figure in Appendix A**
Oahu	Kailua, Lanikai and Waimanalo	Figure 9
Oahu	Kahala	Figure 9
Molokai	South Molokai	Figure 10
Lanai	East Lanai	Figure 11
Lanai	Manele Bay	Figure 11
Maui	Oluwalu	Figure 12
Maui	Ahihikina'u	Figure 12
Hawaii	Keahole	Figure 13

3.3.4.3 Ground Validation

The purpose of the ground validation survey was to investigate areas of imagery where uncertainties exist on the image interpreter's behalf during the decision making process of determining benthic habitat type. The GPS data acquisition methods used in this investigation were the same as those used for acquiring habitat data for accuracy assessment but selection of waypoints and summary of data were significantly modified. Waypoints were selected by manually identifying the areas in the imagery where uncertainty existed in interpretation of benthic habitat. These areas were typically gradients through a transition of two or more habitat types or general areas where the habitat type is uncertain. These positions were then converted to GPS waypoints and occupied in the field.

3.3.4.4 Geodetic Control, Accuracy and Verification

Quality control was established by implementation of four analyses: spatial accuracy / precision, GIS quality, data security and tabular data quality. These analyses assured a final product meeting the specification of spatial accuracy of GPS data not exceeding 5 meters at a 95% sigma RMS error from their true geographic location. This plan ensured the reliability and accuracy of the field data collected for benthic habitat accuracy assessment and the final GIS map output.

3.3.4.4.1 Spatial Accuracy and Precision

Data were collected on registered and recently recovered survey markers (

Figure 7) in the area of each survey to determine the spatial accuracy of the GPS positions acquired during this work.

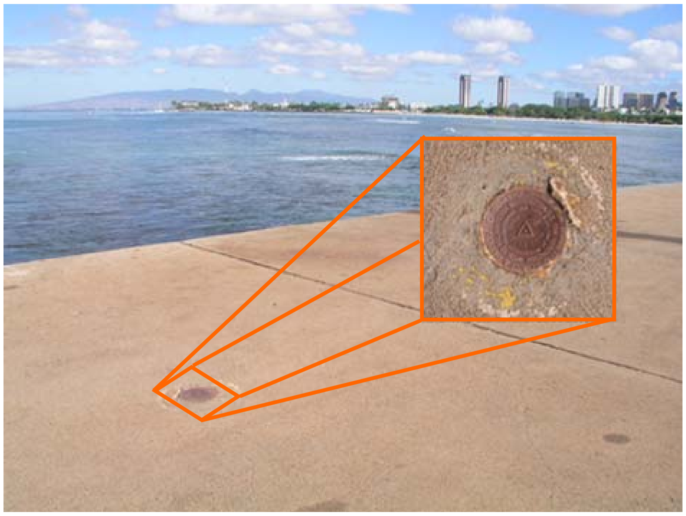

Figure 7. GPS spatial control site; PID TU1256 at Magic Island, Honolulu

The variability in this GPS data quantifies spatial precision without error due to navigation. The field team also navigated to a waypoint in the field at least 20 times and circular error was calculated for that data. This quantifies the spatial error in reoccupying field positions and incorporates error due to navigation. The difference between these two positions gives the error due to station drift in the survey vessel.

3.3.4.4.2 GIS Quality Control

All GIS map products generated during this work were closely examined for error (Table 10). Geometry problems such as multipart, overlapping, sliver and void polygons were identified and corrected using an ArcView GIS Quality Control extension. The extension was also used to topologically clean the GIS data. Polygons that were adjacent and had the same zone and habitat attributes were identified using an ArcView script and all errors were corrected. Attribution of GIS polygons was conducted seamlessly using the NOAA habitat digitizing extension software thus errors were not expected. As an additional step in quality control, a tool within this extension searched the GIS database and identified all polygons where mismatches occurred between the polygon attributes and the habitat classification scheme. GIS data from this work were determined to be free of errors after all tests came up clean.

Table 10. Quality control of GIS data delivered in this work

Topology – All GIS data is built and cleaned
Void polygons – Data are free of void polygons
Adjacent polygons with the same zone or habitat do not exist in the data
Multipart polygons do not exist in the data
Overlapping polygons do not exist in the data
Sliver polygons do not exist in the data
All polygons attributed consistent with the classification scheme
All fields in the GIS data base are populated
All "unknown" zones have unknown habitats

3.3.4.4.3 Data Security

All digital and hard copy records were kept in secure locations and daily backups were made of field data. The field data acquired each day were archived on CD ROM and handwritten records were collected. Chain of custody records were not needed as all data were maintained in secure custody of BAE Systems subcontractors at all times.

3.3.4.4.4 Tabular Data Quality Control

Manual entry of data was minimized to limit the possible introduction of human error. However, in some cases, manual entry of information was unavoidable. These steps were identified and particular attention was given to control these processes. An original handwritten record was made for all data where manual entry was required. This record was securely archived and two independent reviews were conducted of the data subsequent to the transfer of the data to the GIS database.

3.3.4.5 Records and Metadata Summaries

All physical records, with the exception of accuracy assessment field data, were kept in secure archives. Accuracy assessment field data was stored with the field assessment team outside of BAE Systems facilities as this information was not privileged to BAE Systems until map attribute accuracy had been shown to meet NOAA standards. Metadata summaries were prepared in FGDC compliant format for all GIS point and polygon data and were included in with this delivery. Original field notes were included with the delivery of each draft map package for each bundle.

4 RESULTS

This Task Order was organized into eighteen image bundles. Seven accuracy assessment survey areas were selected and populated with GPS surveys based on stratified random sampling methods. Original test area did not meet all contractual requirements for habitat types so the test areas were expanded to include such habitats. This was observed and discussed during the third six-month review of project progress made by NOAA at the BAE Systems offices. COTR requested that the Molokai accuracy assessment area be expanded to include areas of low and medium cover of emergent vegetation. Also, it was recommended that an eighth accuracy assessment area be included as the biological cover class “high macroalgae” was not encountered in the original seven accuracy assessment test areas. The reef flat at Kahala on Oahu was selected for this purpose.

4.1 Acquisition of Accuracy Assessment GPS Data for the MEHI

Six hundred and seventy one (671) waypoints that were stratified within each detailed habitat type were visited and habitat characterizations conducted during this work. Each position was delivered in ArcView GIS format and all contained the full complement of data described in Section 3.3.4.1.

4.2 Accuracy Assessment Data

It was the objective of this work to collect at least 25 field assessments for each of the detailed structure and detailed cover classes that were encountered in the MEHI test areas. The GIS database was queried and the number of positions where each was encountered was tallied (Tables 11 and 12). It should be noted that the number of detailed structure differs from the cover positions occupied, a result of the “Artificial” structure class lacking a cover class. Hence, the structure classes contain more points than the cover class.

Table 11. Summary of major and detailed reef structure classes from accuracy assessment

Major Structure	Count	Detailed Structure	Count
Coral Reef and Hard Bottom	515	Aggregated Patch Reef	32
		Aggregate Reef	93
		Pavement	123
		Rubble	42
		Individual Patch Reef	35
		SCRUS	26
		Spur and Groove	46
		Rock and Boulder	72
		Pavement w/Sand Channels	46
Unconsolidated Sediment	130	Sand	32
		Mud	98
Other	26	Artificial	26
Total	**671**	**Total**	**671**

Table 12. Summary of major and detailed biological cover classes from accuracy assessment

Major Cover	Count	Modifier	Count
Live Coral	227	10%-<50% (Low)	140
		50%-<90% (Medium)	53
		90%-100% (High)	34
Macroalgae	123	10%-<50% (Low)	59
		50%-<90% (Medium)	38
		90%-100% (High)	26
Coralline Algae	59	10%-<50% (Low)	32
		50%-<90% (Medium)	27
Turf	119	10%-<50% (Low)	25
		50%-<90% (Medium)	59
		90%-100% (High)	35
Emergent Vegetation	89	10%-<50% (Low)	28
		50%-<90% (Medium)	30
		90%-100% (High)	31
Uncolonized	28	90%-100% (High)	28
Total	**645**	**Total**	**645**

During this work, four biological cover types were not encountered and were therefore not sampled. These were Low Seagrass, Medium Seagrass, High Seagrass, and High Coralline Algae. A similar tally was generated for primary and detailed biological cover type. Seagrass beds were not encountered during this survey. It is also recognized that high cover of coralline algae occurs only in areas where the minimum mapping unit requirement is not met. As a result, high cover coralline algae polygons were not in these maps and are therefore not tested in the assessment of thematic accuracy.

4.3 Ground Validation Data

In this work, 2,086 ground validation positions were occupied throughout all of the benthic habitats of the MEHI between the depths of 0 and 30 meters. The number of ground validation points per island was related to the size of the island and the amount of reef (Table 13). Most ground validation points were therefore collected on the islands of Hawaii and Oahu, with a large number also collected on Molokai with it high density of coral reefs.

Table 13. Total number of ground validation (GV) surveys conducted on each Island

Island	GV positions	Island	GV positions	Island	GV positions
Kaula / Niihau	118	Molokai	341	Hawaii	681
Kauai	251	Lanai	104	Maui	290
Oahu	525	Kahoolawe	34	***Total***	***2,344***

4.4 GIS Products, Quality Control Performed and Spatial Accuracy

4.4.1 GPS Data and Field Data Collection

Both point and polygon GIS data were generated in this work. Six hundred and seventy one (671) GPS positions were created using the random stratified method, converted to waypoints and navigated to in the accuracy assessment test areas. Two thousand three hundred forty four (2,344) GPS positions were sampled for the purpose of ground validation. Of these, one hundred thirty-four (134) positions were collected on registered survey benchmarks and an additional twenty positions were collected to determine the reproducibility of occupying a position in the field. These data have been controlled by executing all quality control measures compliant with the proposed methods. CSDGM metadata summaries have been provided for all of these data and 95% sigma RMS error has been calculated for GPS positions as well as on-screen digitizing accuracy (Table 14). These results meet contractual requirements

Table 14. Results of spatial accuracy generated from empirical measurements of GPS field positions and on-screen digitizing

Type of Replicate	**N**	**Contract Standard**	**Circular RMS (M)**
Accuracy generated from replicates on survey benchmark	141	< 5m	1.08
Precision generated from replicates on ground condition	141	<5m	0.96
Accuracy generated from replicates navigating to a waypoint	20	<5m	1.36
Precision generated from replicates navigating to a waypoint	20	<5m	1.11
On-screen digitizing accuracy at 1:6,000 scale	20	<1m	0.94

All GPS raw data has been delivered along with the correction files obtained from the CORS and text files generated during GPS data processing. In addition, all the files needed to recreate the project have been delivered.

4.4.2 GIS Map Products

Seven GIS Polygon Map products have been generated in this work and were delivered as ArcView GIS shape files. The products from the fourteen usable image bundles were merged in the GIS software to generate a single file for each Island of the MEHI. Each product included a projection file and CSDGM metadata summary. The Island files include: Niihau and Kaula, Kauai, Oahu, Molokai, Maui, Lanai, Kahoolawe and Hawaii.

4.4.3 Coral Reef Habitat Map Thematic Accuracy

A comprehensive accuracy assessment has been conducted of the coral reef habitat map product that included all the data collected for the eight test areas of the MEHI. These data were overlaid on the second draft maps generated from visual interpretation of the IKONOS imagery and error matrixes developed to calculate overall accuracy, user and producer accuracy as well as incorrect classifications and Tau coefficient. The detailed cover error matrix is not tabulated due to the large number of classes at the detailed level which made the resulting table is too large to display properly. However, the results of these error calculations are presented in the overall summaries (Tables 15, 16, 17 And 18). Overall, the coral reef habitat maps prepared for the MEHI meet contractual standards of 0.75 and 0.85 Tau for the detailed and major levels of the classification scheme respectively.

Table 15. Coral reef habitat map thematic accuracy of major reef structure classes

		Truth Based on Field Observation				
Polygon Attribute		Coral Reef and Hard Bottom	Unconsolidated Sediment	Other	**Total**	User's Accuracy
	Coral Reef and Hard Bottom	**513**	2	0	**515**	100%
	Unconsolidated Sediment	11	**119**	0	**130**	92%
	Other	0	0	**26**	**26**	100%
	Total	**524**	**121**	**26**	**Diagonal Sum: 658**	
	Producers Accuracy	98%	98%	100%	**Total Observations: 671**	
				Overall Accuracy	**98.1%**	

Table 16. Coral reef habitat map thematic accuracy of detailed reef structure classes

Polygon Attributes	Truth Based on Field Observations													
		AgRf	AgPR	IndPR	SnG	SCRUS	Pvnt	Pvmtw/SC	Rock/Bldr	Rubble	Sand	Mud	Artificial	**Total**	User's Accuracy
	AgRf	**67**	1	1	1		18	2	1	1	1			**93**	72%
	AgPR		**29**			3								**32**	91%
	IndPR			**35**										**35**	100%
	SnG	1			**45**									**46**	98%
	SCRUS		3			**22**	1							**26**	85%
	Pvnt	4	1	1		1	**115**	1						**123**	93%
	PvmtW/SC						2	**44**						**46**	96%
	Rock/Bldr	3					2		**66**		1			**72**	92%
	Rubble						6			**36**				**42**	86%
	Sand					1	4		1		**26**			**32**	81%
	Mud						5					**93**		**98**	95%
	Artificial												**26**	**26**	100%
	Total	**75**	**34**	**37**	**46**	**27**	**153**	**47**	**68**	**37**	**28**	**93**	**26**	**Diag. Sum 604**	
	Producers Accuracy	89%	85%	95%	98%	81%	75%	94%	97%	97%	93%	100%	100%	**Total Obs. 671**	
	Overall Accuracy													**90.0%**	

Table 17. Coral reef habitat map thematic accuracy of major biological cover classes of the MEHI

Polygon Attributes	Truth Based on Field Observations							
		Coralline Algae	Macroalgae	Turf	Emergent Vegetation	Uncolonized	**Total**	User's Accuracy
Coral	**214**	2	3	7		1	**227**	94%
Coral Coralline Algae	1	**58**					**59**	98%
Macroalgae	2	1	**113**	2		5	**123**	92%
Turf	6	6	10	**97**			**119**	82%
Emergent Vegetation					**89**		**89**	100%
Uncolonized	2		2	1		**23**	**28**	82%
Total	**225**	**67**	**128**	**107**	**89**	**29**	**Diag. Sum: 594**	
Producers Accuracy	95%	87%	88%	91%	100%	79%	**Total Obs: 645**	
						Overall Accuracy	**92.1%**	

Table 18. Coral reef habitat map thematic accuracy of detailed biological cover classes of the MEHI

Truth Based on Field Observations

Polygon Attributes	Lcoral	Mcoral	Hcoral	LCCA	MCCA	HCCA	LMacAl	MMacAl	HMacAl	Lturf	Mturf	Hturf	LSeaGr	MSeaGr	HSeaGr	LEmVeg	MEmVeg	HEmVeg	Uncol	**Totals**	User's Accuracy
Lcoral	**124**	4		1	1		2	1		4	3									**140**	89%
Mcoral	4	**46**	2																1	**53**	87%
Hcoral		5	**29**																	**34**	85%
LCCA	1			**26**	5															**32**	81%
MCCA					**25**	2														**27**	93%
HCCA																				**-**	-
LMacAl	1				1		**46**	4		1	1								5	**59**	78%
MMacAl	1						7	**30**												**38**	79%
HMacAl							1	4	**21**											**26**	81%
Lturf	1						1			**23**										**25**	92%
Mturf	5			4	1		2	1		3	**41**	2								**59**	69%
Hturf					1		6				5	**23**								**35**	66%
LSeaGr																				**-**	-
MSeaGr																				**-**	-
HSeaGr																				**-**	-
LEmVeg																**24**	4			**28**	86%
MEmVeg																	**29**	1		**30**	97%
HEmVeg																	2	**29**		**31**	94%
Uncol	2						1	1		1									**23**	**28**	82%
Column Totals	**139**	**55**	**31**	**31**	**34**	**2**	**66**	**41**	**21**	**32**	**50**	**25**	**-**	**-**	**-**	**24**	**35**	**30**	**29**	**Diag. Sum: 539**	
Producer's Accuracy	89%	84%	94%	84%	74%	0%	70%	73%	100%	72%	82%	92%	-	-	-	100%	83%	97%	79%	**Tot. Obs. : 645**	
																			Overall Accuracy	**83.6%**	

Table 19. Summary of thematic accuracy of the MEHI benthic habitat map products

Map Category	**Overall Accuracy**	**Tau**
Major Structure	98.1%	0.971
Detailed Structure	90.0%	0.891
Major Cover	92.1%	0.908
Detailed Cover	83.6%	0.827

4.4.4 Expert Review

The final step in map production was to provide hard copy map products for the expert coral reef researchers and managers in Hawaii for their review and comments (Appendix B). NOAA produced E sheet size hard copies of the entire mapped area for this review. Each map covered five kilometers of coastline. Four meetings were held at the following locations to obtain input from the expert community:

- Honolulu, Oahu July 21, 2006
- Kahului, Maui July 24, 2006
- Hilo, Hawaii July 25, 2006
- Kona, Hawaii July 26, 2006

Of the 7,761 habitat polygons delineated in this work, expert reviewers recommended editing 13. Of the 13 polygons recommended for edit, 11 were edited based on the experts' comments. Two polygons were left unchanged. It was recommended that polygon number 1579 on Oahu be reviewed for the presence of seagrass. It was concluded that as the seagrass that occurs in the MEHI is *Halophyla spp*. and was very small and not visible in the imagery, and therefore was not delineated. The second polygon that was left unchanged, polygon number 361 on Maui, would have delineated a channel in the Kahului Harbor on Maui. Though this channel does exist today, it had not yet been dredged at the time of the acquisition of the imagery that was provided to BAE Systems for mapping. Therefore, the channel was not included in the map.

4.5 Coral Reef Habitat Maps and Thematic Content Summary

A GIS summary has been prepared that presents the areas of each of the major and detailed structure cover classes encountered in the MEHI (Tables 19 and 20). The information is presented in absolute areas (km^2). Of the 1,313 km^2 that have been mapped, 69.7% was coral reef and hard bottom and 29.5% was composed of unconsolidated sediment. Twenty one and eight tenths percent (21.8%) of the total area mapped was colonized by at least 10% live coral cover. Maps of the zones, detailed structure and detailed biological cover for each island are found in Appendix C.

Table 20. Coral reef habitat thematic content summary of the major and detailed structure classes of the MEHI

Coral Reef Structure Type	Major and Detailed Habitat Area (Km^2)							
	Niihau and Kaula	Kauai	Oahu	Molokai	Maui	Lanai	Kahoolawe	Hawaii
Pavement	0.140	127.891	187.895	70.923	32.529	9.136	5.608	1.598
Spur and Groove	0.000	1.103	19.999	6.865	4.201	4.203	0.000	4.086
Individual Patch Reef	0.000	0.000	1.775	0.011	0.127	0.000	0.000	0.000
Aggregated Patch Reef	0.000	0.001	0.646	0.567	0.462	0.028	0.000	0.000
Aggregated Reef	0.000	7.824	10.716	12.081	18.360	5.808	0.000	11.398
Rock/Boulder	98.564	8.115	17.905	15.997	46.169	7.143	0.000	87.157
Pavement with Sand Channels	0.000	21.302	43.440	7.834	0.595	0.000	0.000	0.466
Rubble	0.000	0.495	2.081	0.232	0.110	0.019	0.000	0.157
Scattered Coral/Rock	0.000	0.465	1.292	2.095	0.148	0.023	0.000	0.105
Total Coral Reef and Hard Bottom	**98.704**	**167.196**	**285.749**	**116.603**	**102.702**	**26.360**	**13.246**	**104.969**
Sand	14.438	55.746	64.028	51.019	98.996	14.053	6.333	20.069
Mud	0.000	1.643	49.428	6.195	0.657	0.108		5.067
Total Unconsolidated Sediment	**14.438**	**57.390**	**113.456**	**57.215**	**99.623**	**14.161**	**6.403**	**25.163**
Artificial	0.000	0.365	4.689	2.232	0.200	0.076		0.270
Total Other	**0.000**	**0.365**	**4.689**	**2.232**	**0.200**	**0.076**	**0.000**	**0.270**
Total Coral Reef Area	**113.142**	**224.951**	**403.893**	**176.049**	**202.525**	**40.597**	**21.219**	**130.403**

Table 21. Coral reef habitat thematic content summary of the major and detailed biological cover classes of the MEHI

Biological Cover Type	Major and Detailed Habitat Class Area							
	Niihau, and Kaula	Kauai	Oahu	Molokai	Maui	Lanai	Kahoolawe	Hawaii
Coral (Major Cover)	**5.050**	**67.064**	**56.727**	**32.407**	**55.918**	**15.020**	**10.371**	**74.705**
10%-<50% (Detailed Cover)	5.050	67.064	52.451	11.191	46.303	9.740	7.263	59.914
50%-<90% (Detailed Cover)	0.000	0.000	4.264	10.788	9.615	4.350	3.108	11.917
90%-100% (Detailed Cover)	0.000	0.000	0.011	10.428	0.000	0.930	0.000	2.905
Macroalgae (Major Cover)	**0.180**	**49.748**	**98.751**	**57.955**	**71.785**	**12.000**	**0.000**	**2.025**
10%-<50% (Detailed Cover)	0.180	49.131	87.771	53.854	51.953	7.900	0.000	1.878
50%-<90% (Detailed Cover)	0.000	0.617	10.164	4.084	8.751	4.100	0.000	0.139
90%-100% (Detailed Cover)	0.000	0.000	0.816	0.017	11.081	0.000	0.000	0.008
Coralline Alg. (Major Cover)	**0.640**	**0.887**	**4.793**	**0.074**	**0.713**	**0.080**	**0.000**	**1.505**
10%-<50% (Detailed Cover)	0.640	0.434	3.964	0.074	0.683	0.080	0.000	1.147
50%-<90% (Detailed Cover)	0.000	0.452	0.809	0.000	0.030	0.000	0.000	0.358
Seagrass (Major Cover)	0.000	0.000	0.020	0.000	0.000	0.000	0.000	0.000
10%-<50% (Detailed Cover)	0.000	0.000	0.020	0.000	0.000	0.000	0.000	0.000
Turf (Major Cover)	**92.770**	**50.314**	**132.795**	**47.820**	**31.364**	**5.210**	**4.444**	**26.022**
10%-<50% (Detailed Cover)	3.860	5.320	19.670	2.945	1.772	0.990	0.391	4.438
50%-<90% (Detailed Cover)	17.820	44.826	110.287	43.123	28.450	4.170	4.053	18.158
90%-100% (Detailed Cover)	71.090	0.168	2.837	1.752	1.142	0.050	0.000	4.164
Emergent Veg. (Major Cover)	**0.000**	**0.284**	**1.779**	**4.462**	**0.000**	**0.000**	**0.000**	**0.000**
10%-<50% (Detailed Cover)	0.000	0.000	0.074	0.279	0.000	0.000	0.000	0.000
50%-<90% (Detailed Cover)	0.000	0.000	0.003	0.079	0.000	0.000	0.000	0.000
90%-100% (Detailed Cover)	0.000	0.284	1.703	4.104	0.000	0.000	0.000	0.000
Uncolonized (Major Cover)	**14.520**	**56.288**	**104.329**	**30.469**	**42.047**	**8.470**	**6.403**	**25.106**
Total Cover by Island	**113.160**	**224.585**	**399.174**	**173.188**	**201.827**	**40.780**	**21.218**	**130.132**

5 DISCUSSION

Six points were not used in the accuracy assessment analysis. These points were numbers 276, 277, 278, 283 and 304 which fell in unknown polygons in the Kailua test area and number 146 which fell outside of the north eastern corner of the Kailua test area. The GIS data base therefore has 671 points, but 645 were used in the AA error matrix. This difference in points used to generate the structure and cover error matrices was caused by the detailed structure class of "Artificial" lacking a cover class.

5.1 List of Products Delivered

The project was designed such that the BAE Systems would deliver draft imagery, GIS field data and draft map products (Table 21 and 22) for 18 bundles. These products were to include all of the GPS products necessary to recreate the project and CSDGM compliant metadata.

Prior to the project completion work (Phase III) it was apparent that the exceptionally fragmented nature of the imagery lead to equally fragmented map products which would be essentially useless to NOAA. To make the map information more cohesive the draft map deliverables were merged into single island deliverable products. This streamlined the NOAA effort of plotting these maps during preparation for the expert review and made them much more useful to the coral reef manager and researcher community for whom they were intended. As all of the original fragmented files, field and GPS data needed to reconstruct the project have been delivered as agreed, BAE Systems has prepared final products to streamline the completion of this project for all interests including the Normalized Difference Vegetation Index (NDVI) added in Contract Amendment #005 as of September 2006 (Table 23). The file structure of all of the delivered data, including ground truth photos and video, GPS coordinates and notes are shown in Figure 8.

Table 22. Contract line items that have been delivered during this tenure. AA = accuracy assessment. GV = ground validation

Completion of Contract Line Items 0002A, 0002B & 0002C		
By Bundle	**Description**	**Level of Completion**
1	Bundle No. 1 Field Data (AA and GV)	Complete
2	Bundle No. 1 Draft Maps	Complete
3	Bundle No. 2 Field Data (AA and GV)	Complete
4	Bundle No. 2 Draft Maps	Complete
5	Bundle No. 3 Field Data (AA and GV)	Complete
6	Bundle No. 3 Draft Maps	Complete
7	Bundle No. 4 Field Data (AA and GV)	Complete
8	Bundle No. 4 Draft Maps	Complete
9	Bundle No. 5 Field Data (AA and GV)	Complete
10	Bundle No. 5 Draft Maps	Complete
11	Bundle No. 6 Field Data (AA and GV)	Complete
12	Bundle No. 6 Draft Maps	Complete
13	Bundle No. 7 Field Data (AA and GV)	Complete
14	Bundle No. 7 Draft Maps	Complete
15	Bundle No. 8 Field Data (AA and GV)	Complete
16	Bundle No. 8 Draft Maps	Complete
17	Bundle No. 9 Field Data (AA and GV)	Complete
18	Bundle No. 9 Draft Maps	Complete
19	Bundle No. 10 Field Data (AA and GV)	Complete
20	Bundle No. 10 Draft Maps	Complete

Table 23. Contract line items that have been delivered during this tenure – continued

Completion of Contract Line Items 0003A, 0003B & 0003C		
By Bundle	**Description**	**Level of Completion**
21	Bundle No. 11 Field Data (AA and GV)	Complete
22	Bundle No. 11 Draft Maps	Complete
23	Bundle No. 12 Field Data (AA and GV)	Complete
24	Bundle No. 12 Draft Maps	Complete
25	Bundle No. 13 Field Data (AA and GV)	Complete
26	Bundle No. 13 Draft Maps	Complete
27	Bundle No. 14 Field Data (AA and GV)	Complete
28	Bundle No. 14 Draft Maps	Complete
29	Bundle No. 15 Field Data (AA and GV)	Complete
30	Bundle No. 15 Draft Maps	Complete
31	Bundle No. 16 Field Data (AA and GV)	Complete
32	Bundle No. 16 Draft Maps	Complete
33	Bundle No. 17 Field Data (AA and GV)	Complete
34	Bundle No. 17 Draft Maps	Complete
35	Bundle No. 18 Field Data (AA and GV)	Complete
36	Bundle No. 18 Draft Maps	Complete

The final delivery includes all components requested in the scope of work for this contract. The digital data included with this package are listed in Figure 5. Original field notes for all CLINs were delivered with the CLIN shipments throughout the project.

Table 24. List of deliverable products in this work. FGDC compliant and valid projection files have been delivered with each GIS item including accuracy assessments and ground validation.

Completion of Contract Line Items for Final Deliveries		
CLIN	**Final Deliverables**	**Status**
0004B	Final Imagery Packet by Island	Complete
0004C	Final GIS Packet by Island	Complete
0004D	Final Map Packet by Island	Complete
0004G	Project Completion Report	Complete
0005A	NDVI Packet	Complete

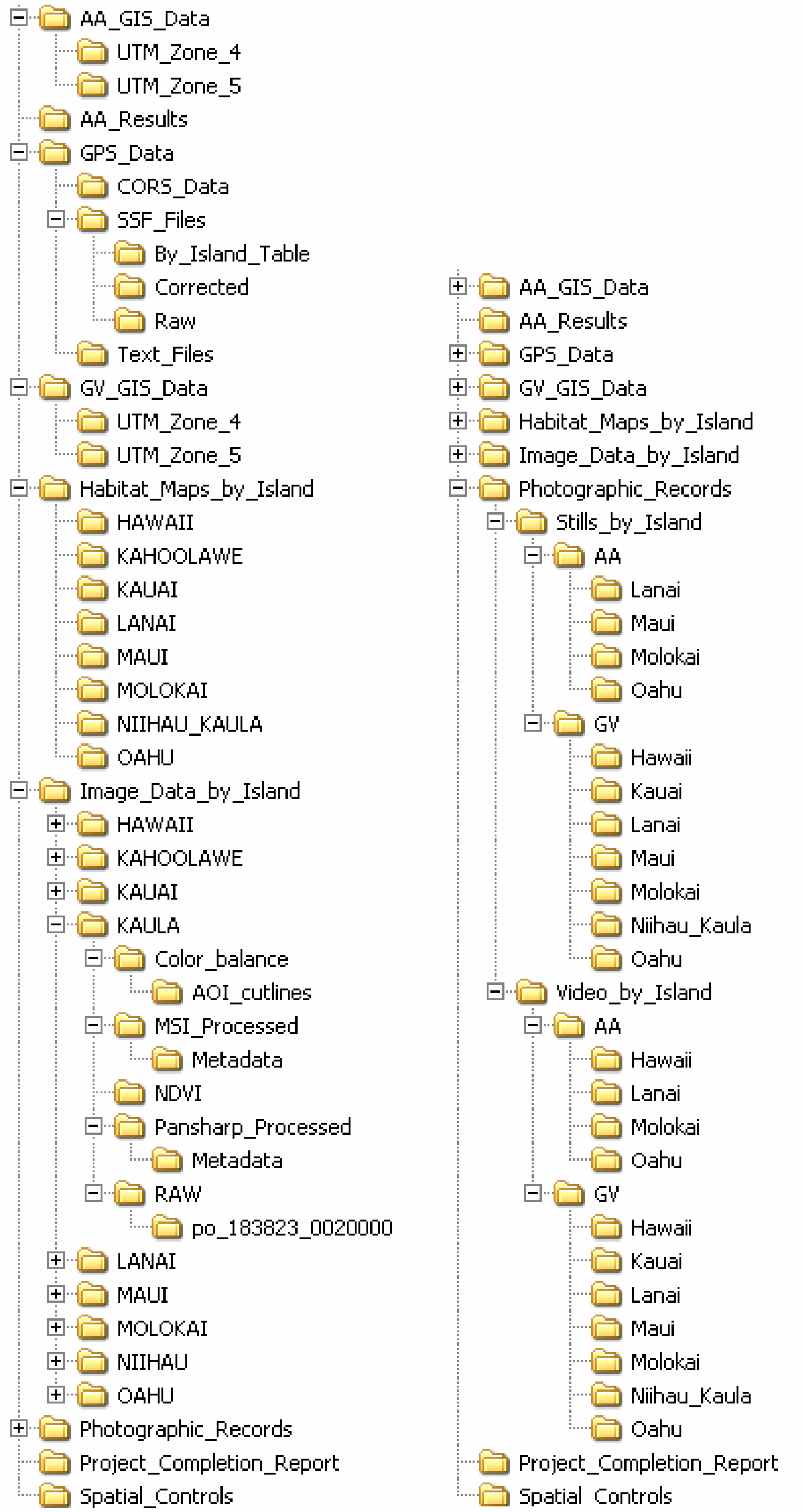

Figure 8. File structure of the deliverable map products

5.2 Deviations from Contract Requirements

A matrix of goals (Table 25) was developed at the beginning of this work that would be completed prior to delivery of the final product (Table 24). This matrix has been used as a check list throughout the project.

Table 25. Goals completed prior to delivery of final product

All GIS polygon data is free of overlapping polygons
All GIS polygon data is free of multipart polygons
All GIS polygon data is built and cleaned
All GIS polygon data is free of adjacency
Minimum mapping restrictions have been met
All GIS polygon data is attributed consistent with the classification scheme
All GIS polygon data has matching unique ids and habitat attributes
All GIS polygon deliverables have valid *.prj files
All GIS polygon deliverables have CSDGM compliant metadata files
All GIS polygon deliverables have consistent fields
All GIS polygon deliverables are checked through QA/QC procedures
All GIS point deliverables have valid *.prj files
All GIS point deliverables have CSDGM compliant metadata files
All GIS point deliverables have consistent fields
All GIS point deliverables are checked through QA/QC procedures
All GPS data is spatially controlled for accuracy and precision
All GPS files needed to recreate the project are provided
All GPS geodetic standards are met including • Horizontal Reference Systems • Vertical Reference Systems • Geoid Model • Projection Time • Minimum mapping units
All Review meetings have been attended
Digitizing has been controlled
Minimum of 25 points have been collected per detailed structure and cover class
All AA test areas have been occupied
Observer objectivity has been maintained
Thematic accuracy meets contractual standard
All original field notes have been delivered
Monthly reports have been provided on time

All objectives were met with the exception of the MMU restriction. Three cases were allowed for delineation of benthic habitats below the MMU of one acre.

1) The minimum mapping unit was for three Marine Life Conservation Districts. Due to requests from the management community all features that could be seen were delineated independent of its size. The Marine Life Conservation Districts are:

- Kealakekua Bay, Island of Hawaii
- Haunama Bay, Island of Oahu
- Honolua Bay, Island of Maui

2) The MMU restriction was removed for shoreline features.

3) The MMU restriction was removed in the event that a similar benthic feature was delineated near a below MMU polygon such as the patch reefs in Kaneohe Bay. This allowance was to remove what would have otherwise been an apparent oversight.

No other deviations have been made from contract requirements.

6 CONCLUSIONS AND RECOMMENDATIONS

BAE Systems, in cooperation with Analytical Laboratories of Hawaii, has completed the data processing, benthic habitat mapping, field validation, and accuracy assessment of the main eight Hawaiian Islands (MEHI). The overall accuracy was high for the class maps, over 90% for major cover and structure and detailed structure, and over 83% for detailed cover. Digital map products of nearshore (<30m) benthic habitats provide a baseline of coral ecosystem extent and type that can be used to structure monitoring programs, provide information for management decisions, establish and manage marine conservation areas, and increase managers' capacity to protect, conserve, and enhance the health of coral reef ecosystems. Because most coral reef resources have not been digitally mapped at a scale or resolution sufficient for assessment, monitoring, and/or research, a large portion of NOAA's Coral Reef Conservation Program has focused on mapping coral reef ecosystems in the U.S. These products for the Main Hawaiian Islands will provide a fundamental spatial framework for implementing and integrating research programs and increase the capability to communicate information and results to coral reef ecosystem managers. This project, which is being developed in collaboration with many U.S. and Main Hawaiian island partners, will produce important map products that will help scientists answer management questions and support management needs.

7 REFERENCES

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4. Hochberg EJ, Andréfouët S, Tyler MR (2003) Sea surface correction of high spatial resolution Ikonos images to improve bottom mapping in near-shore environments. *IEEE Transactions on Geoscience and Remote Sensing* 41: 1724-1729

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8 APPENDIX A

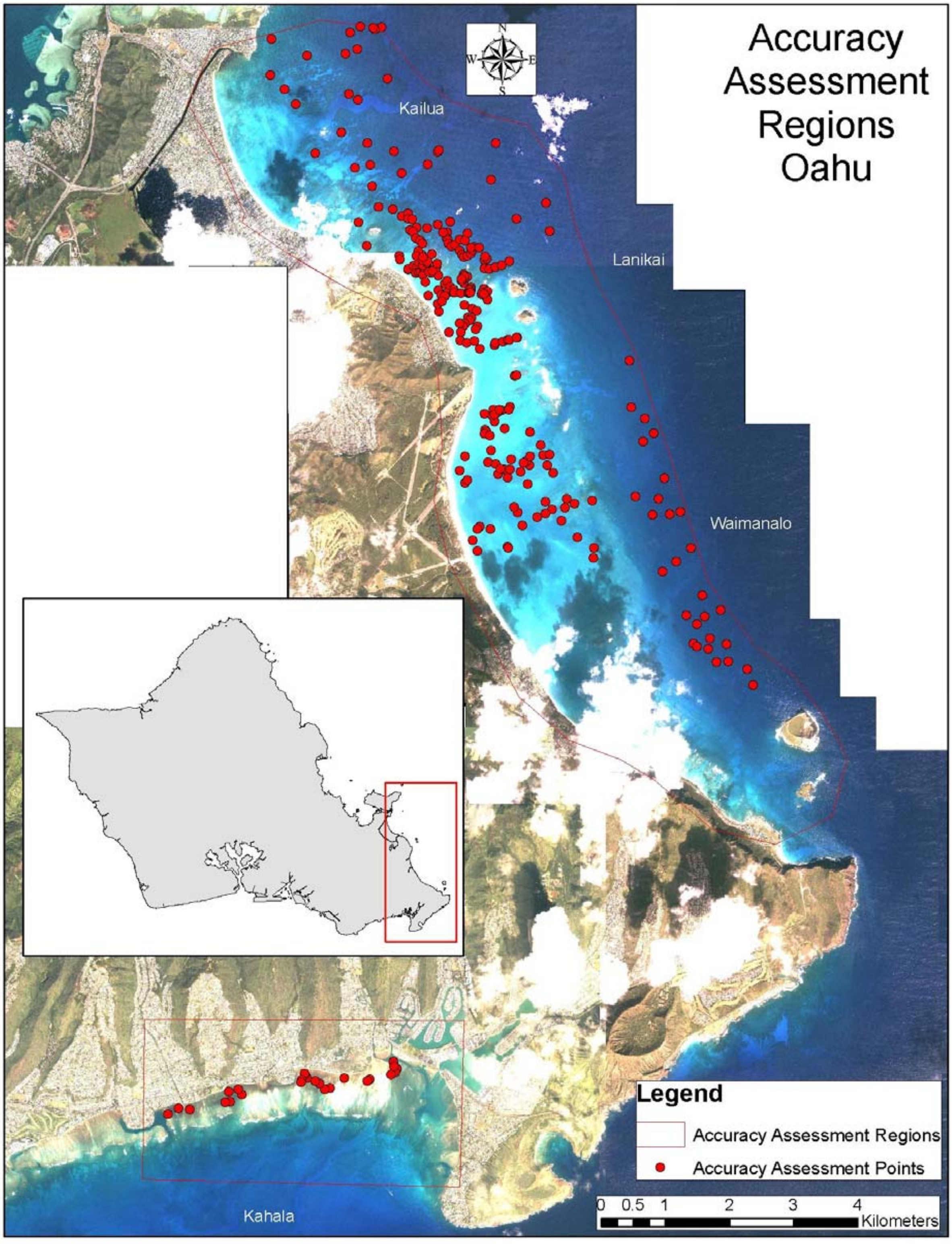

Figure 9. Accuracy assessment data collection points from island of Oahu.

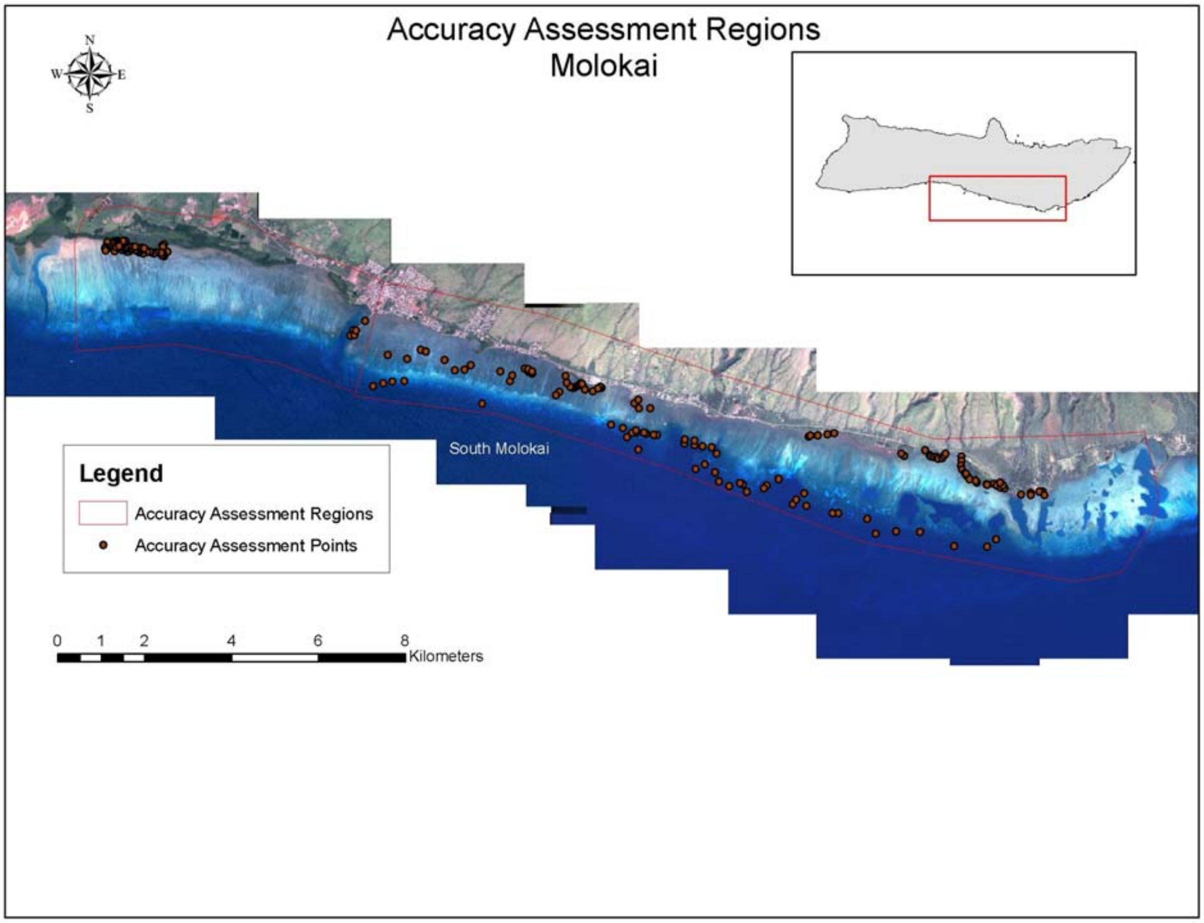

Figure 10. Accuracy assessment data collection points from island of Molokai.

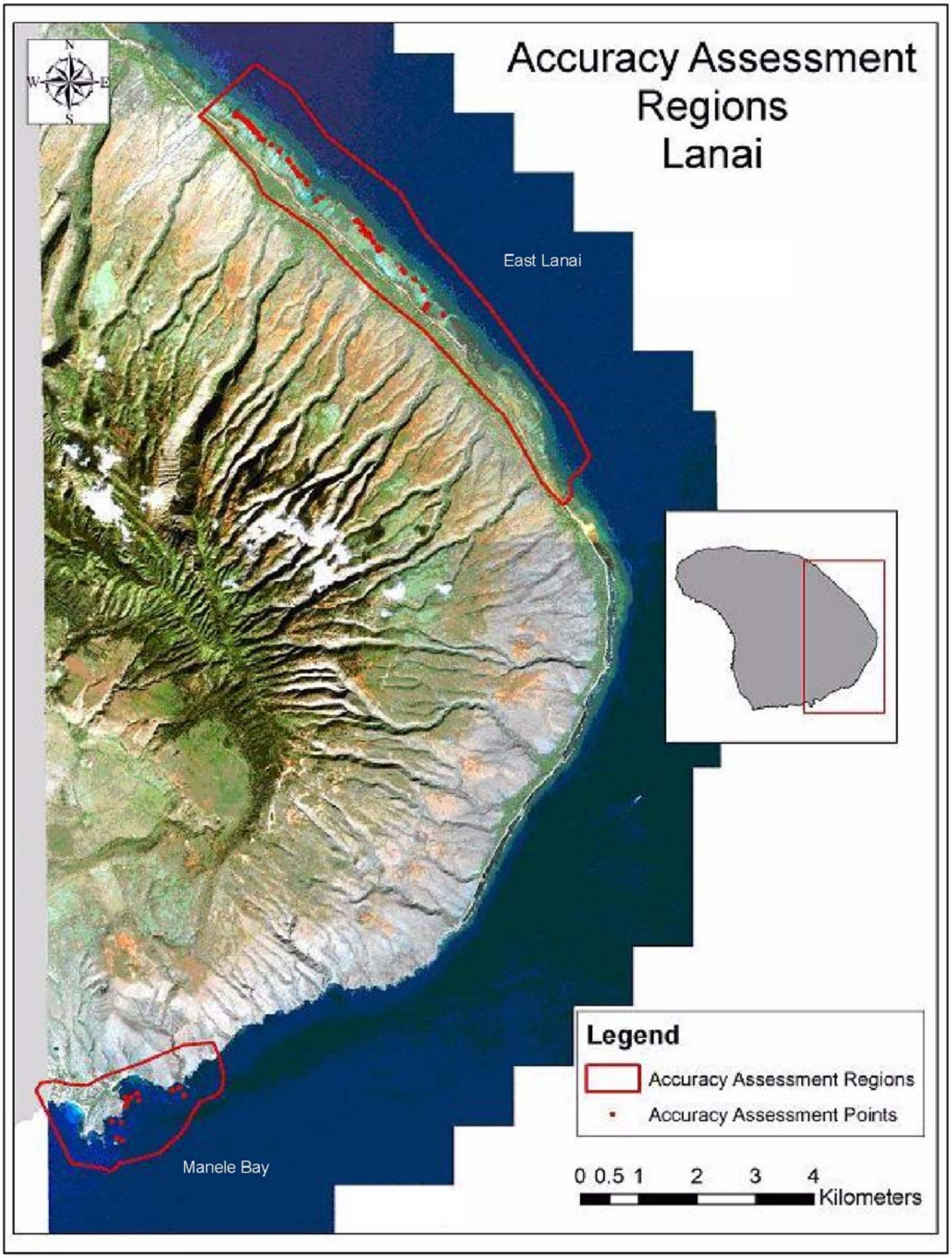

Figure 11. Accuracy assessment data collection points from island of Lanai.

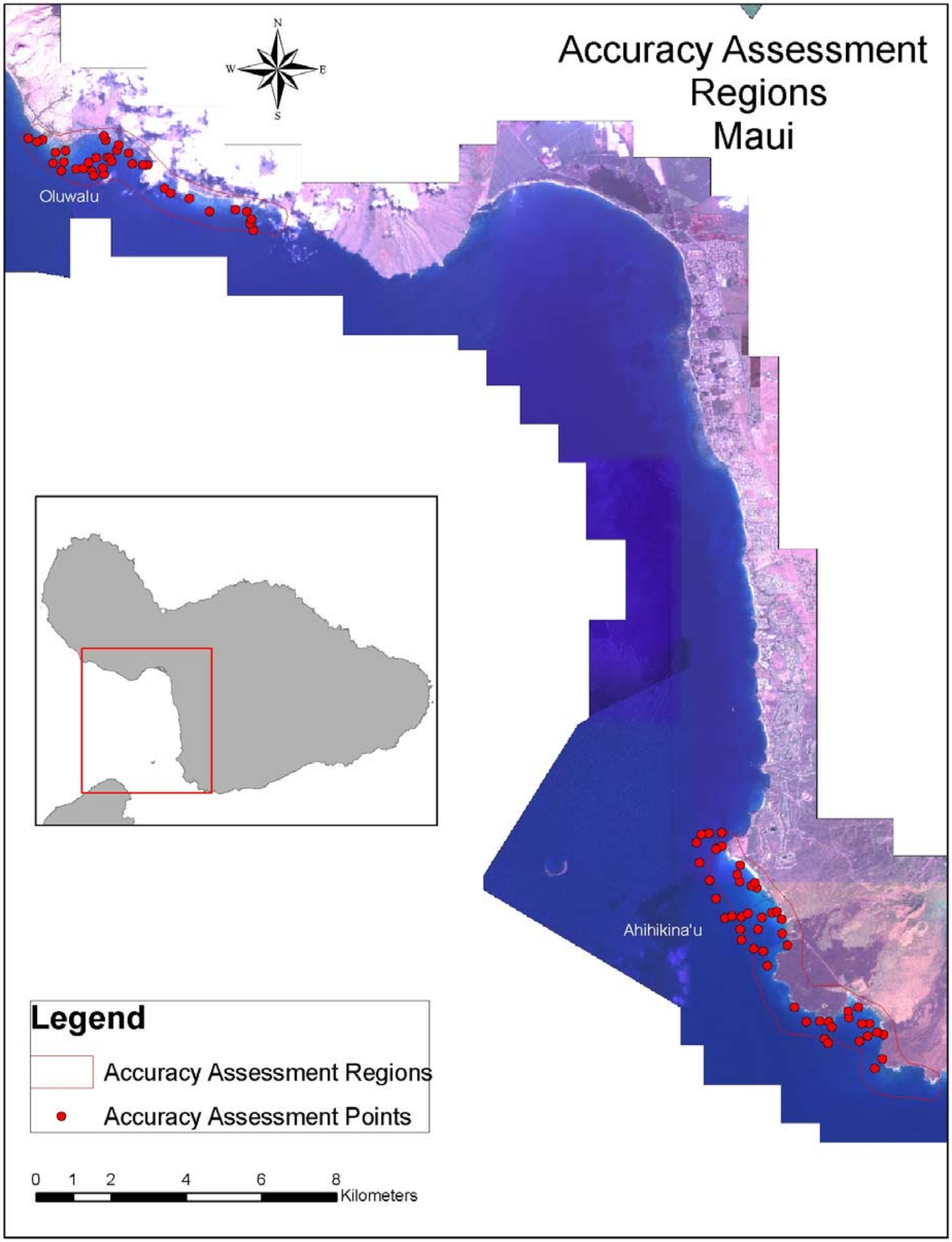

Figure 12. Accuracy assessment data collection points from island of Maui.

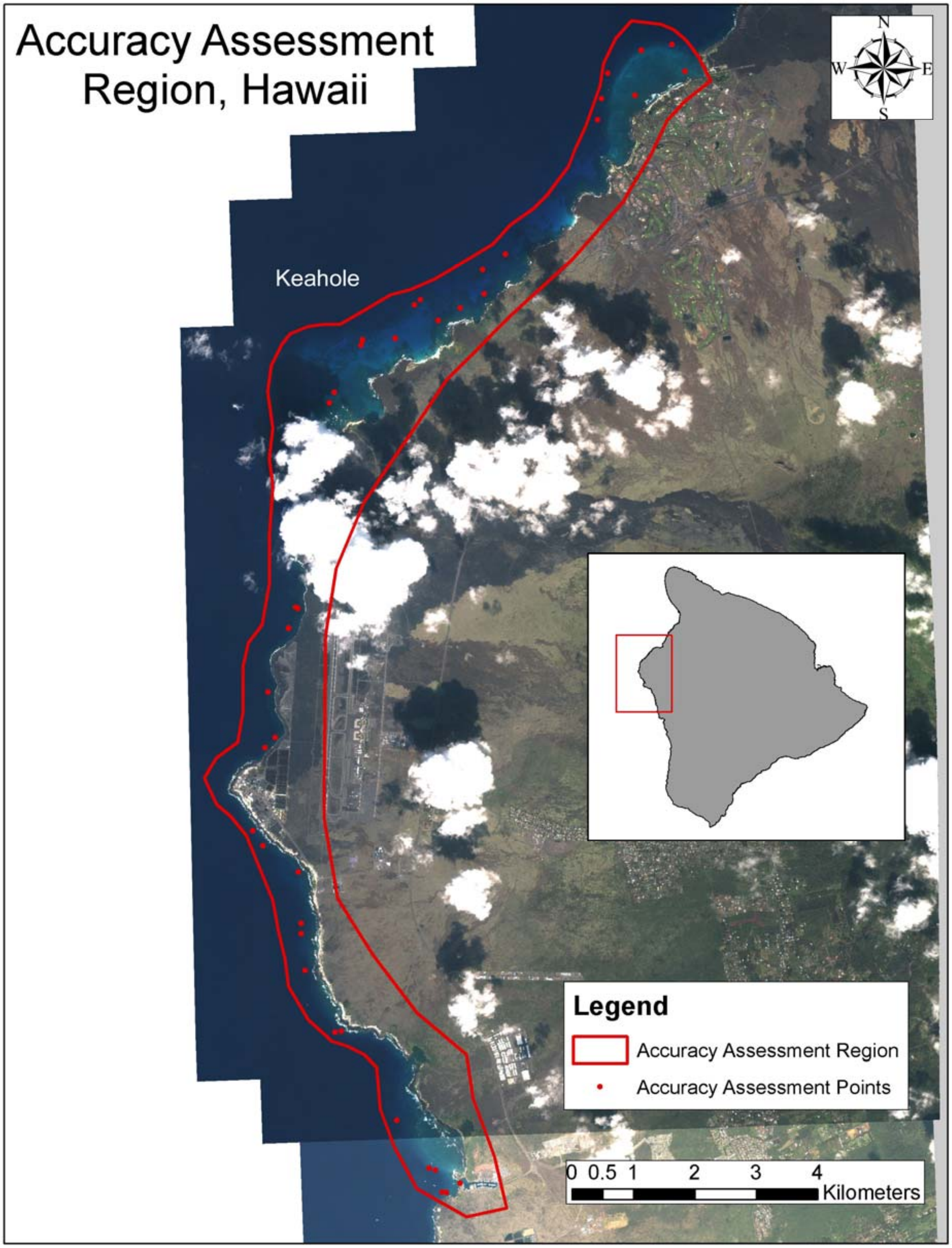

Figure 13. Accuracy assessment data collection points from island of Hawaii.

9 APPENDIX B

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10 APPENDIX C – CLASSIFICATION MAPS

Each island has three maps in this appendix, showing biological cover, geomorphological structure and reef habitat zone. The maps use the NOAA legend files for the classification colors and hatch style.

10.1 East Hawaii (Pahoa)

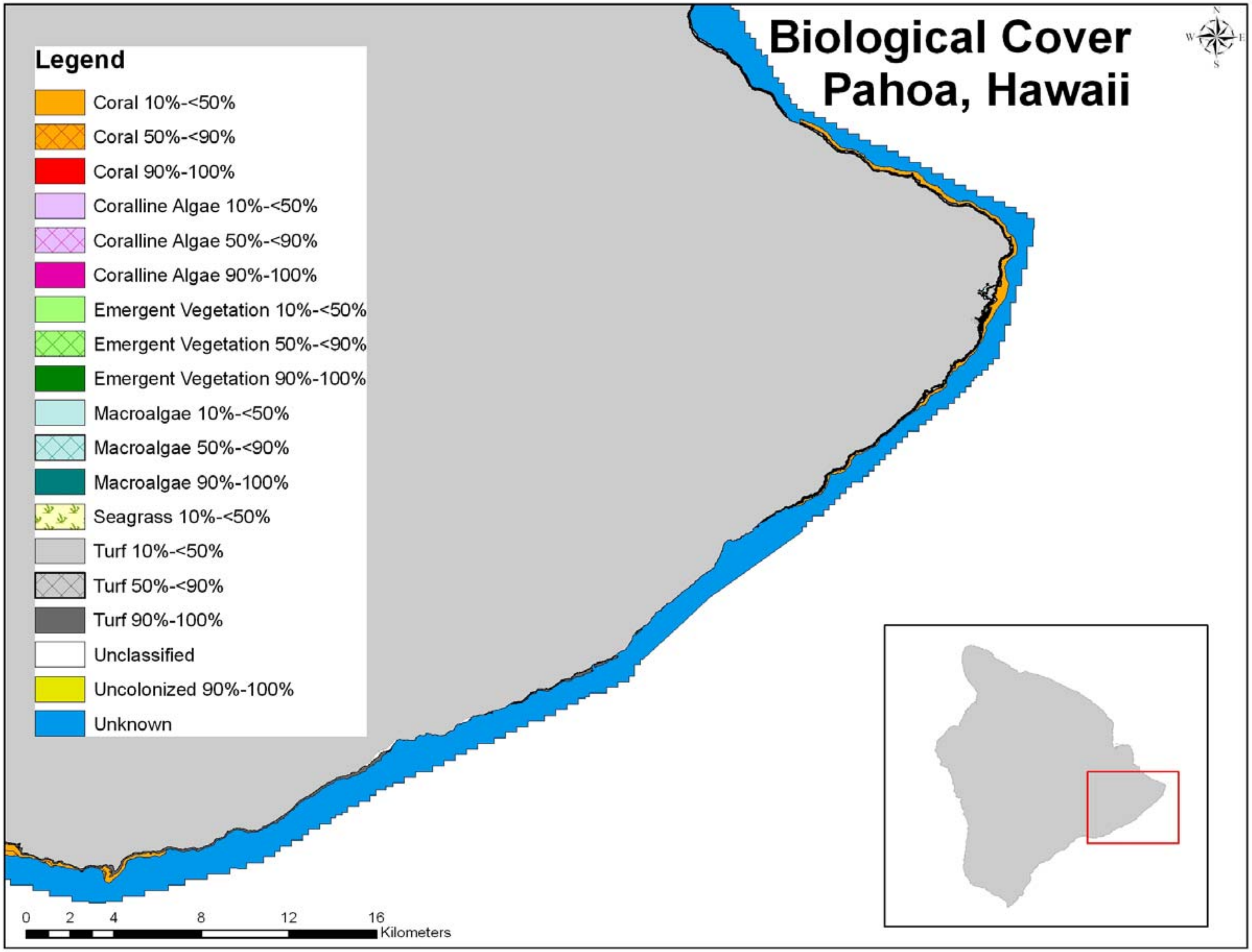

Figure 14. Biological cover map of eastern shore (Pahoa) of Hawaii.

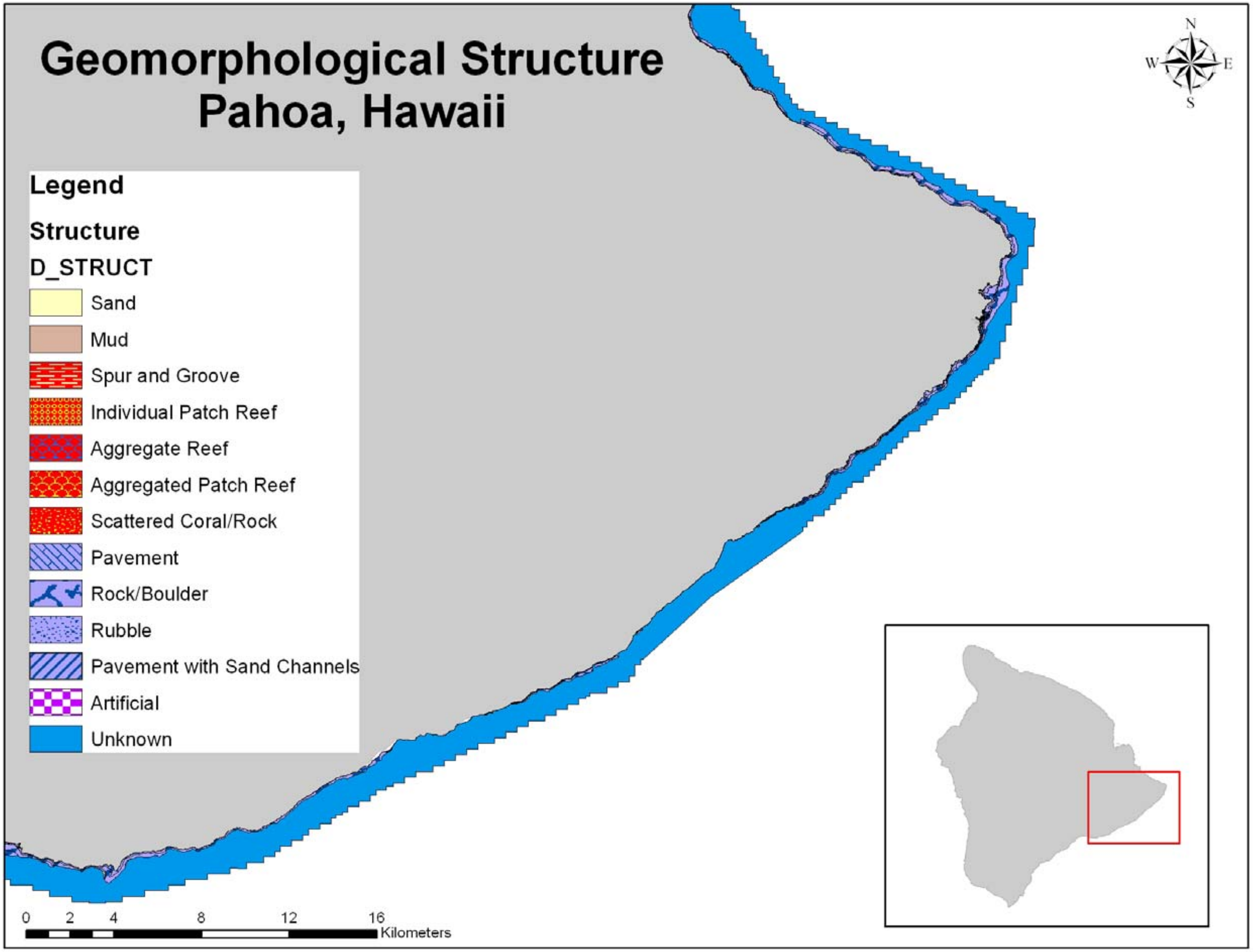

Figure 15. Geomorphological structure map of eastern shore (Pahoa) of Hawaii

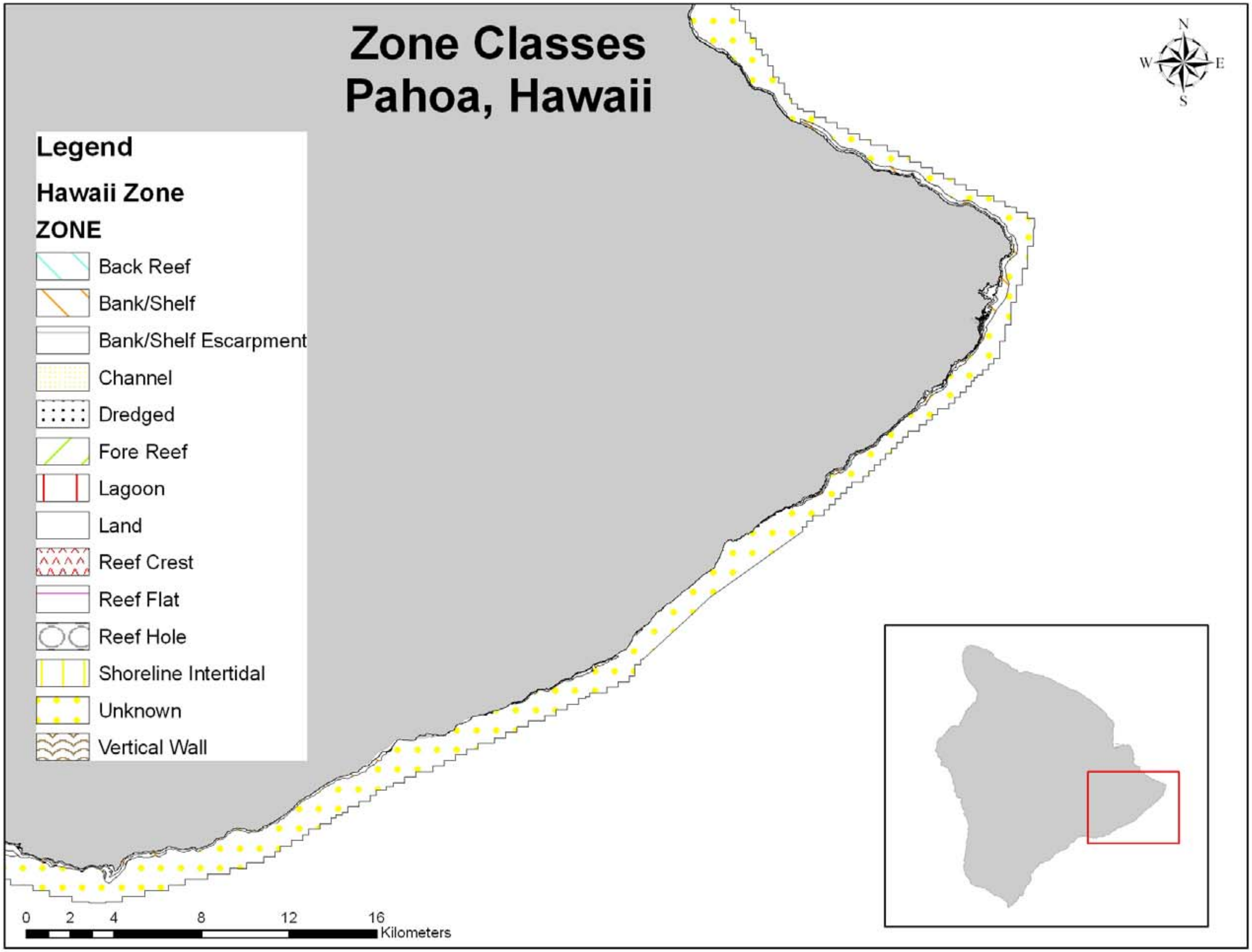

Figure 16. Reef habitat zone map of eastern shore (Pahoa) of Hawaii

10.2 Hilo Bay, Hawaii

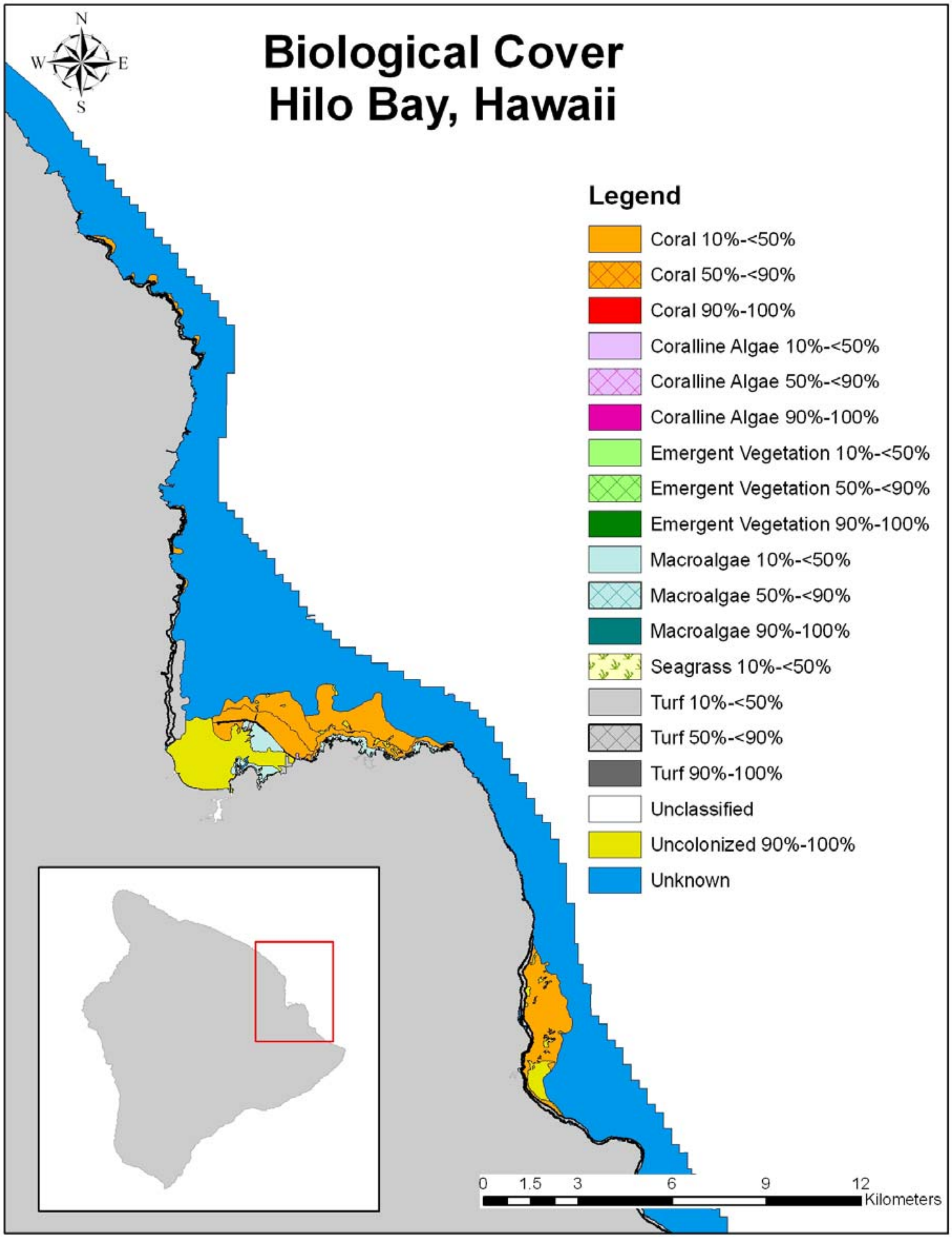

Figure 17. Biological cover map of Hilo Bay, Hawaii.

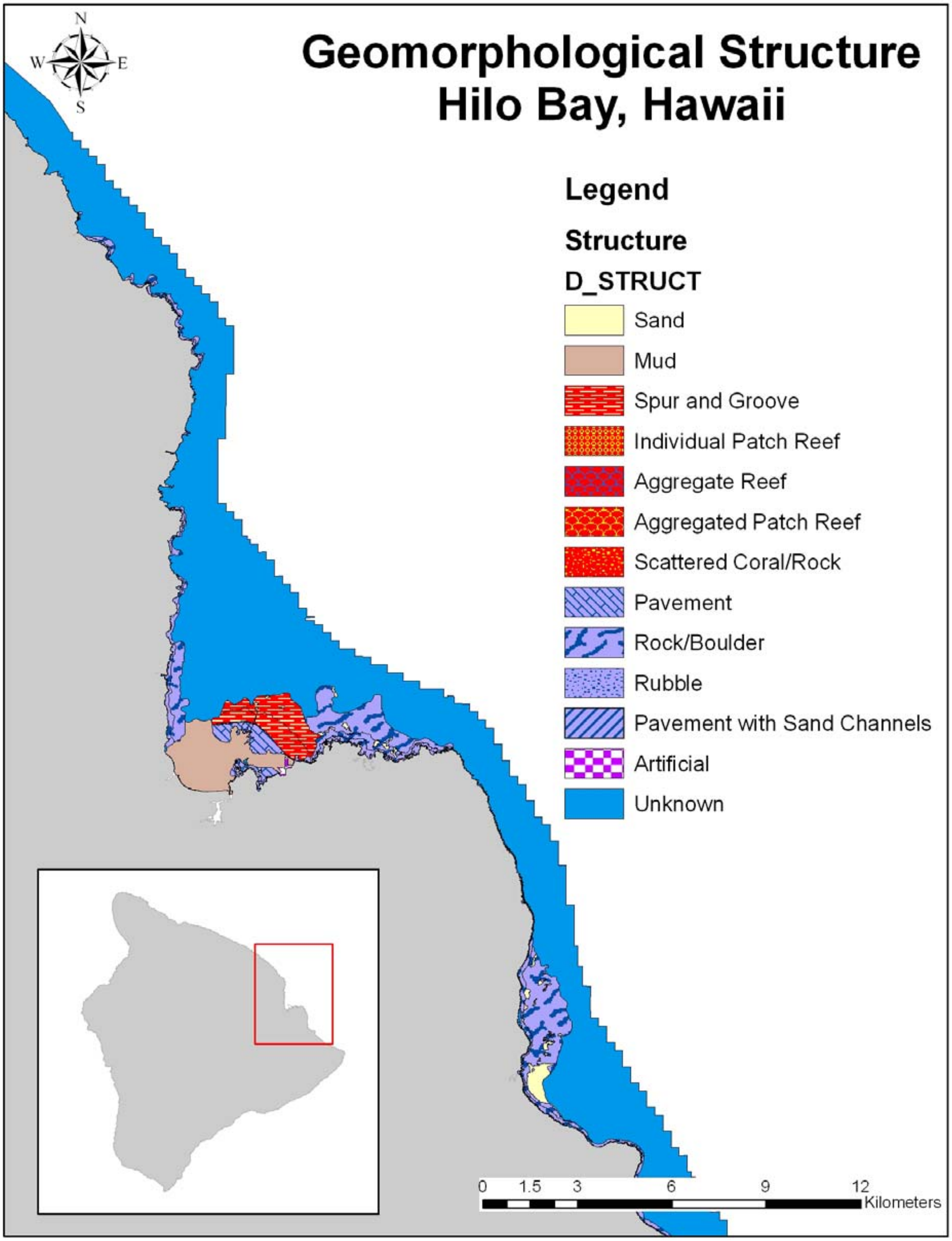

Figure 18. Geomorphological structure map of Hilo Bay, Hawaii.

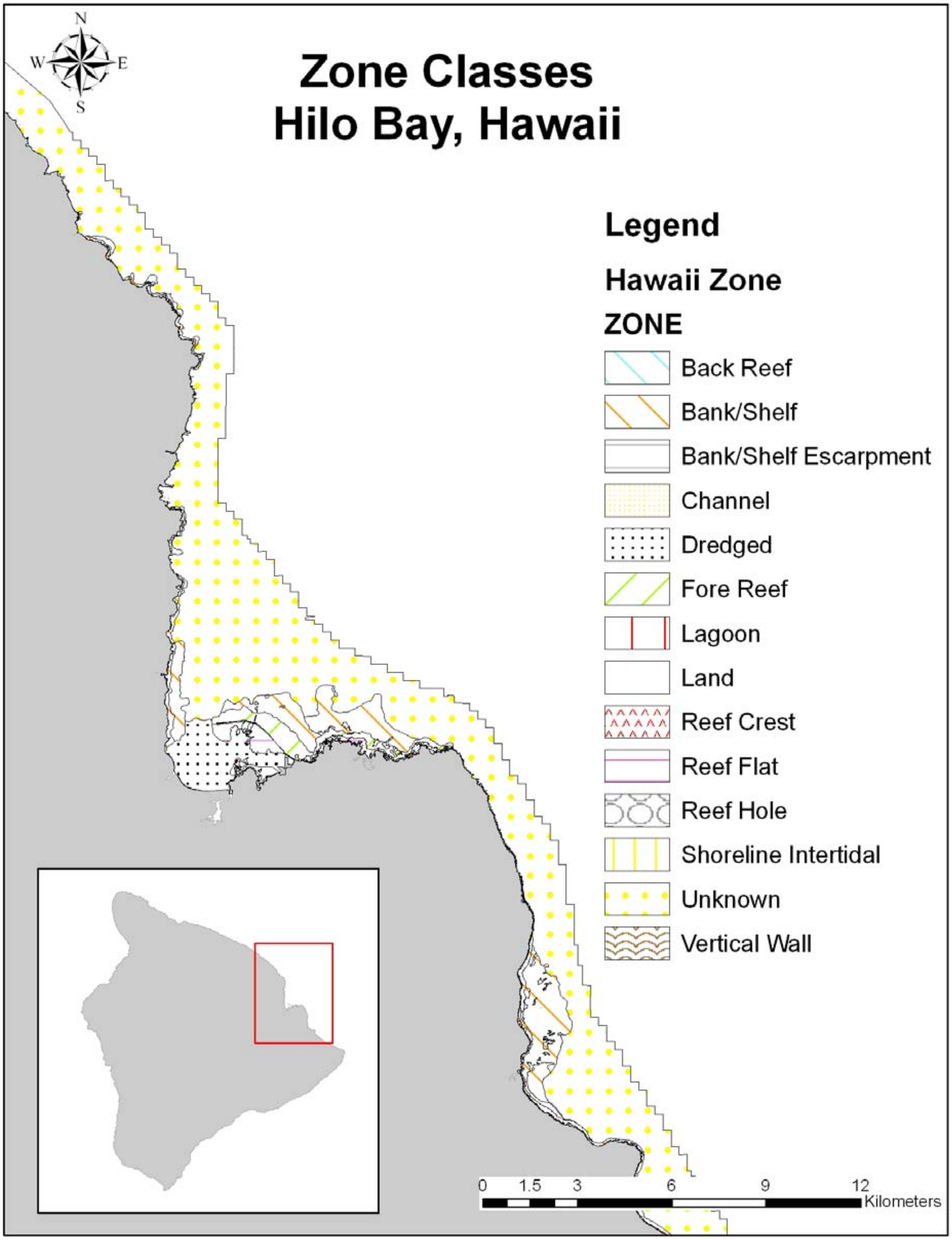

Figure 19. Reef habitat zone map of Hilo Bay, Hawaii.

10.3 Hamakua, Hawaii

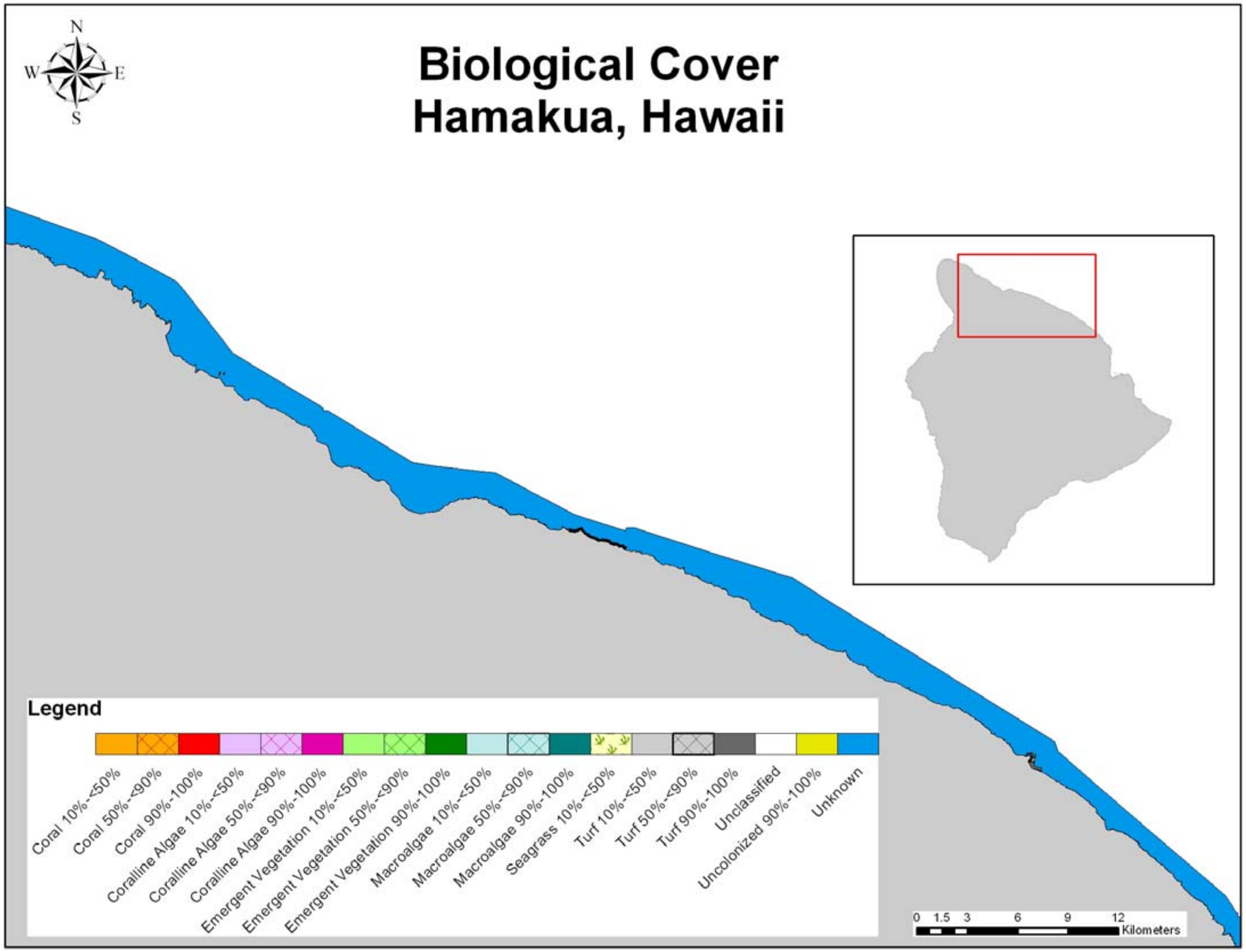

Figure 20. Biological cover map of Hamakua, Hawaii.

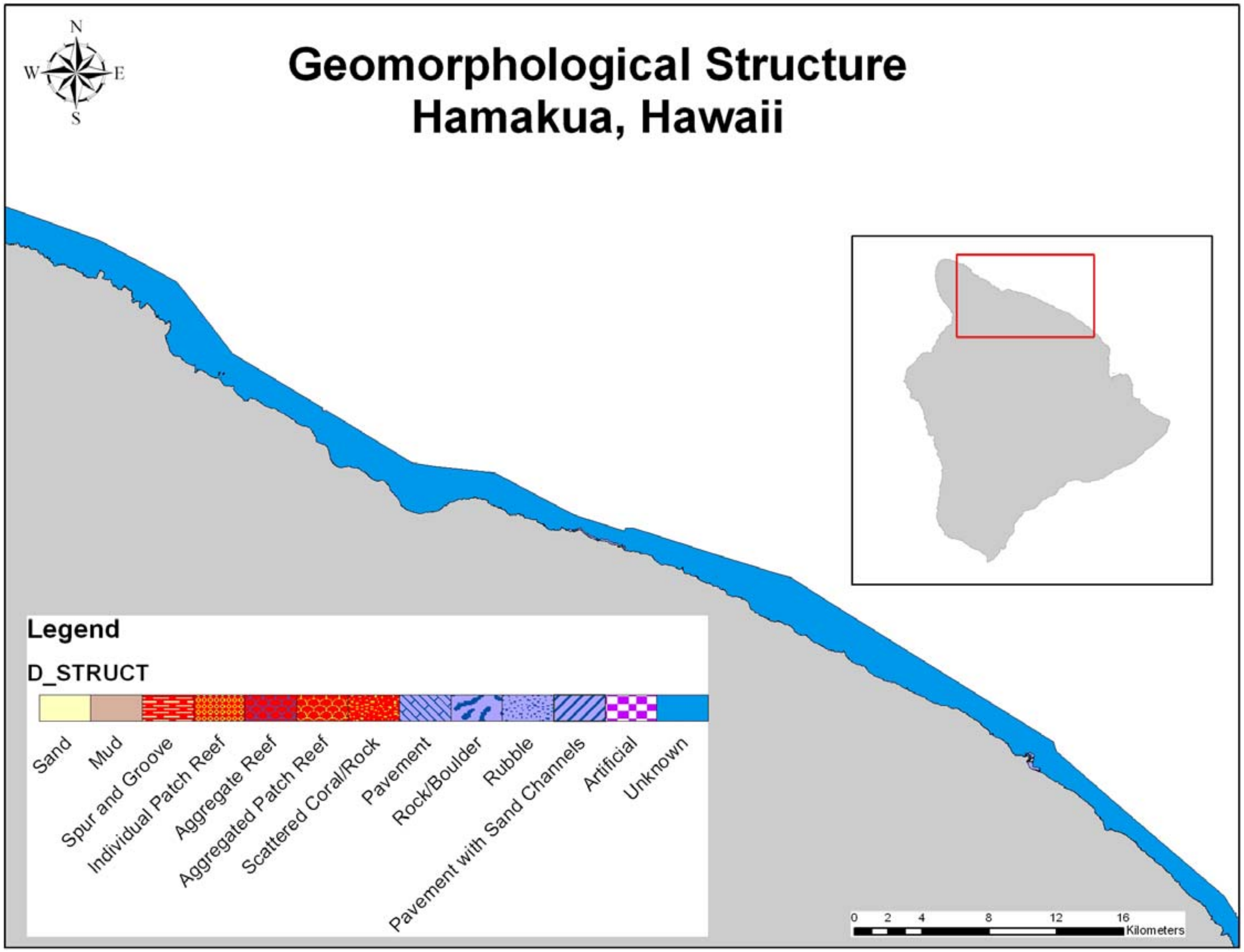

Figure 21. Geomorphological structure map of Hamakua, Hawaii.

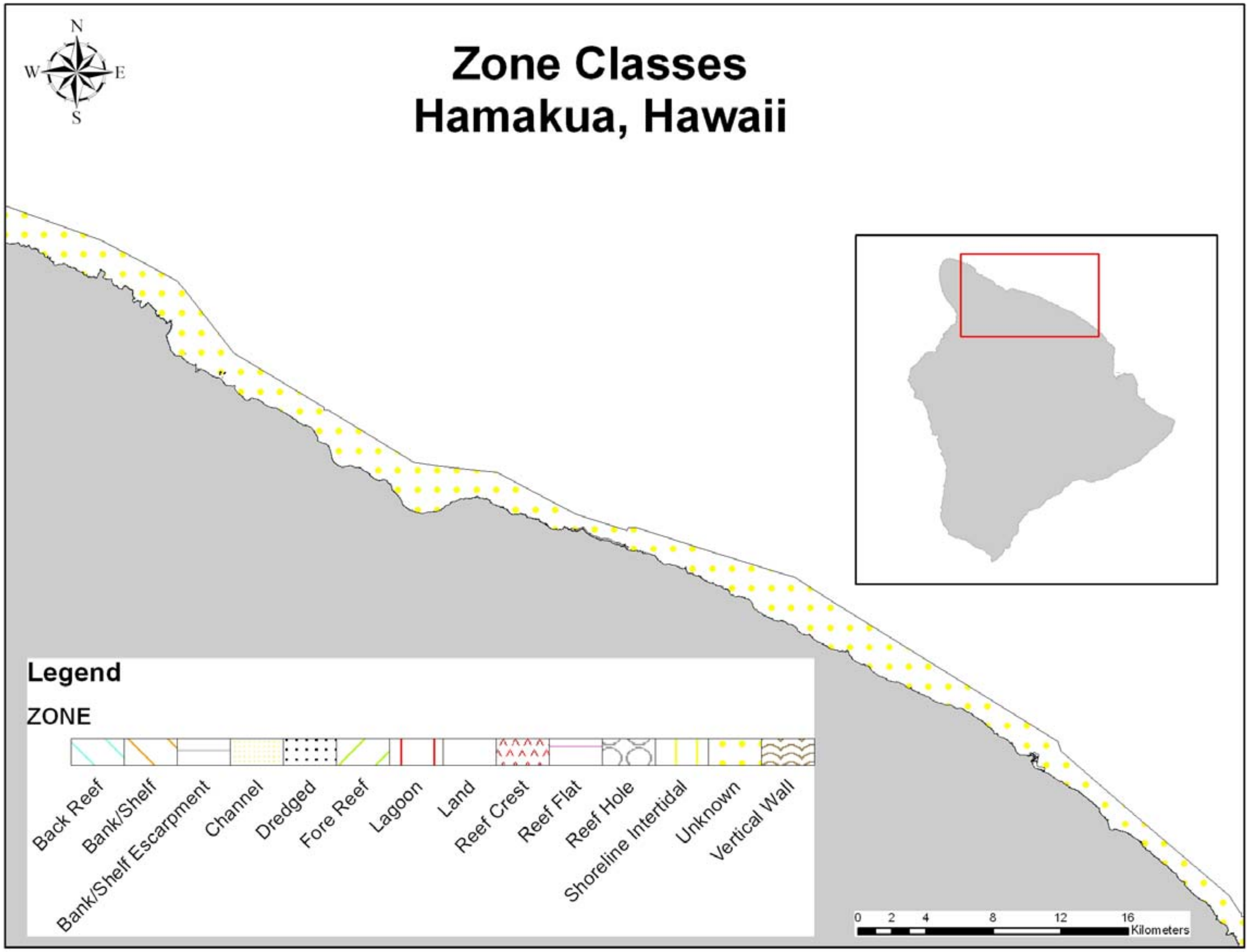

Figure 22. Reef habitat zone map of Hamakua, Hawaii.

10.4 Kohala Coast, Hawaii

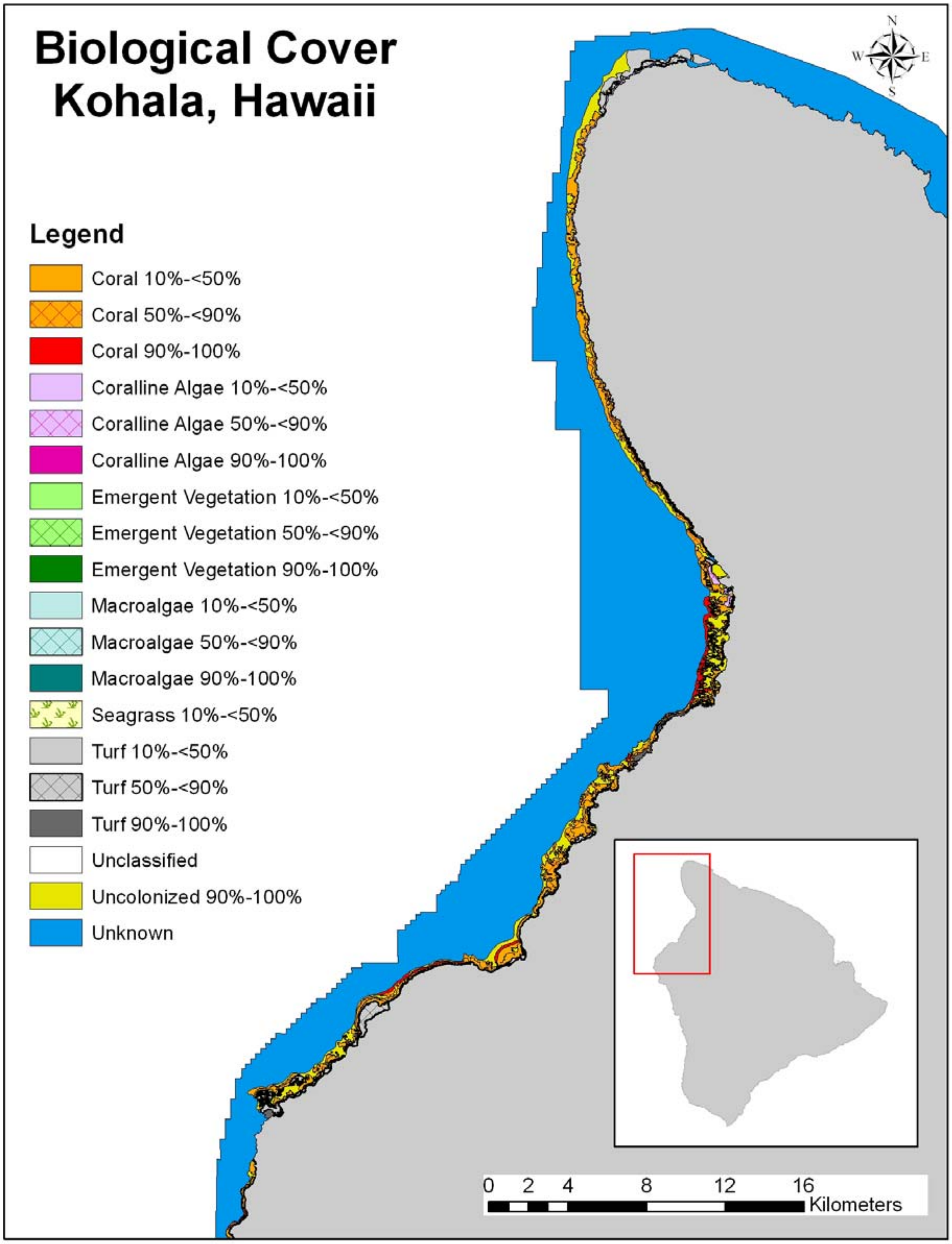

Figure 23. Biological cover map of Kohala Coast, Hawaii.

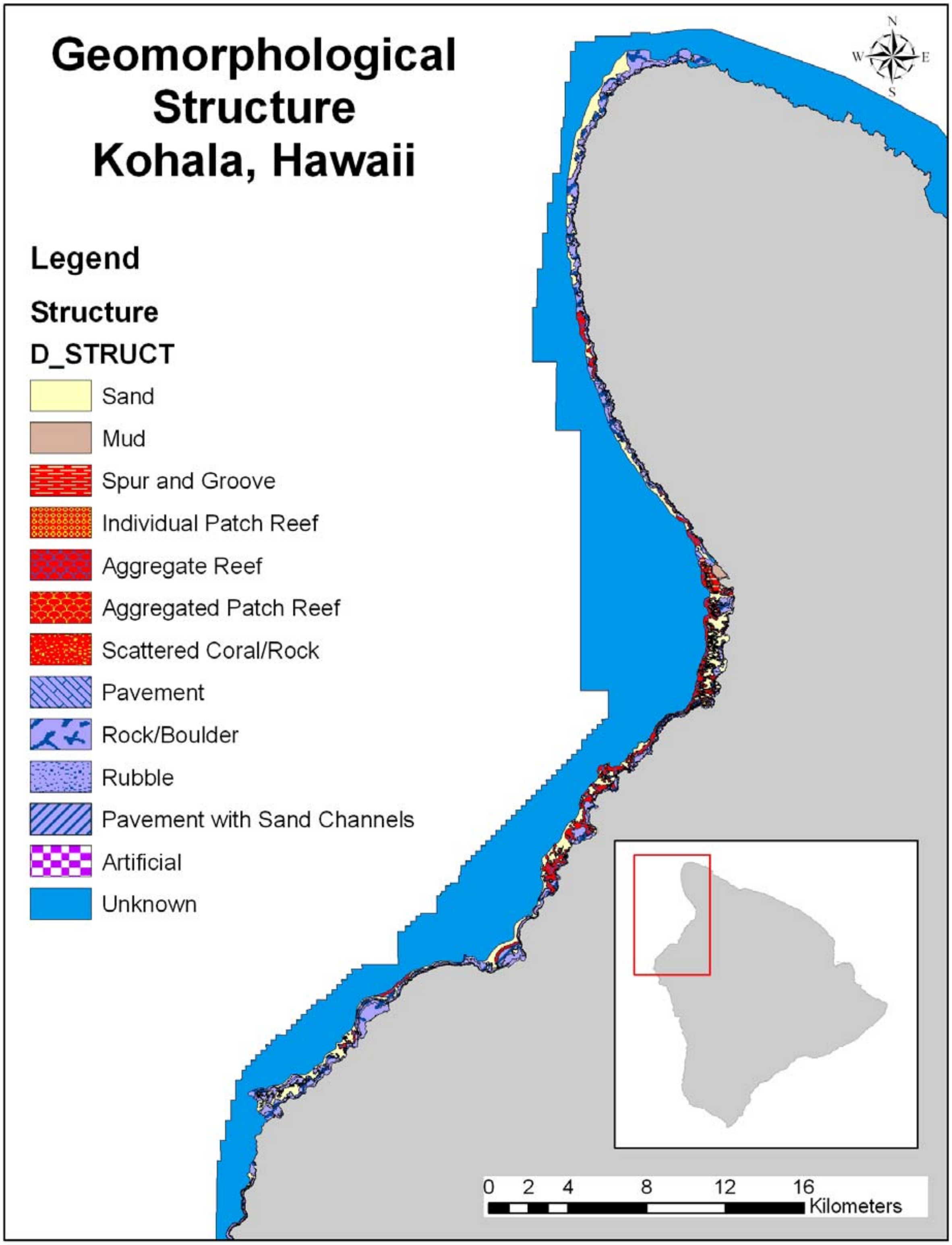

Figure 24. Geomorphological structure map of Kohala Coast, Hawaii.

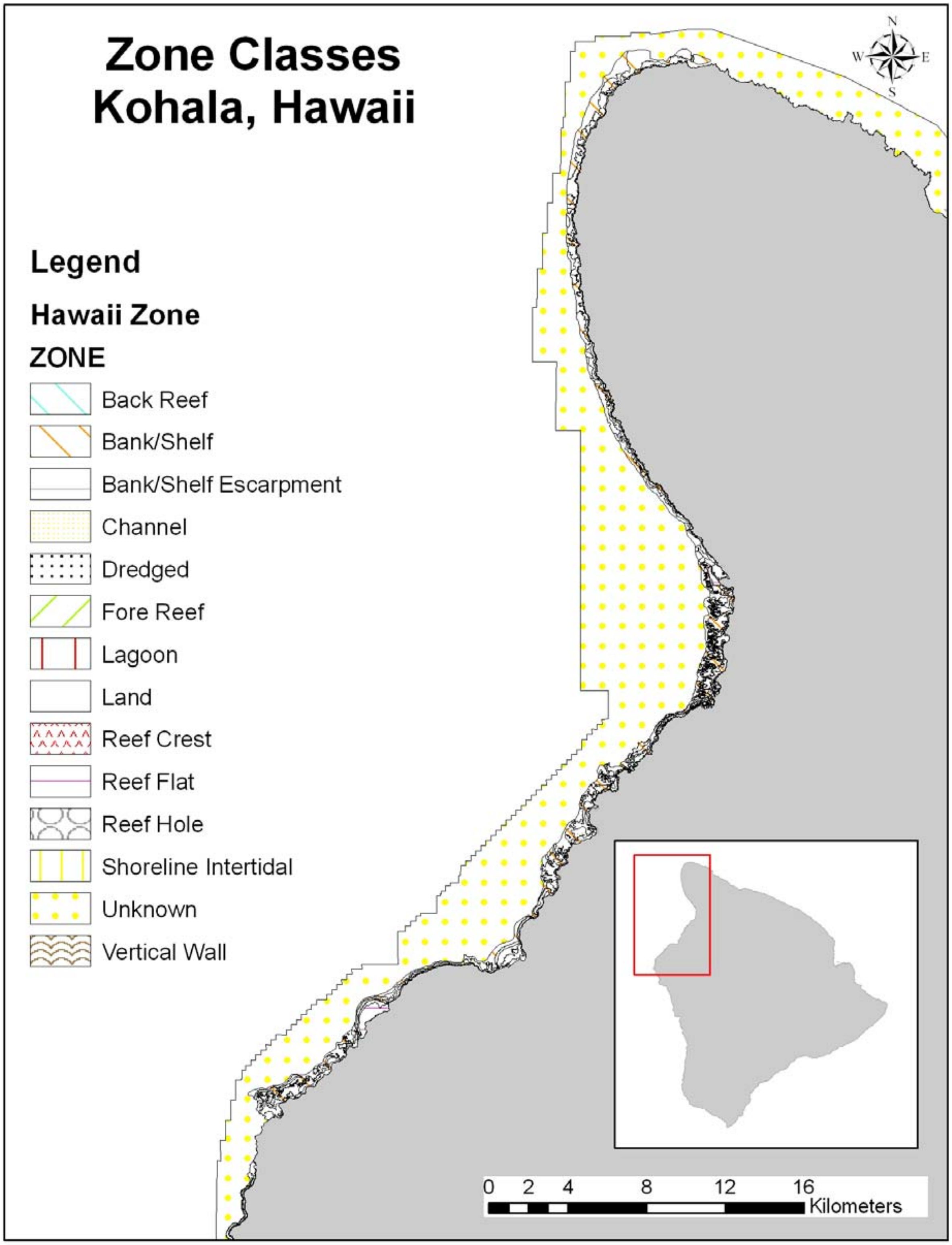

Figure 25. Reef habitat zone map of Kohala Coast, Hawaii.

10.5 South Kona, Hawaii

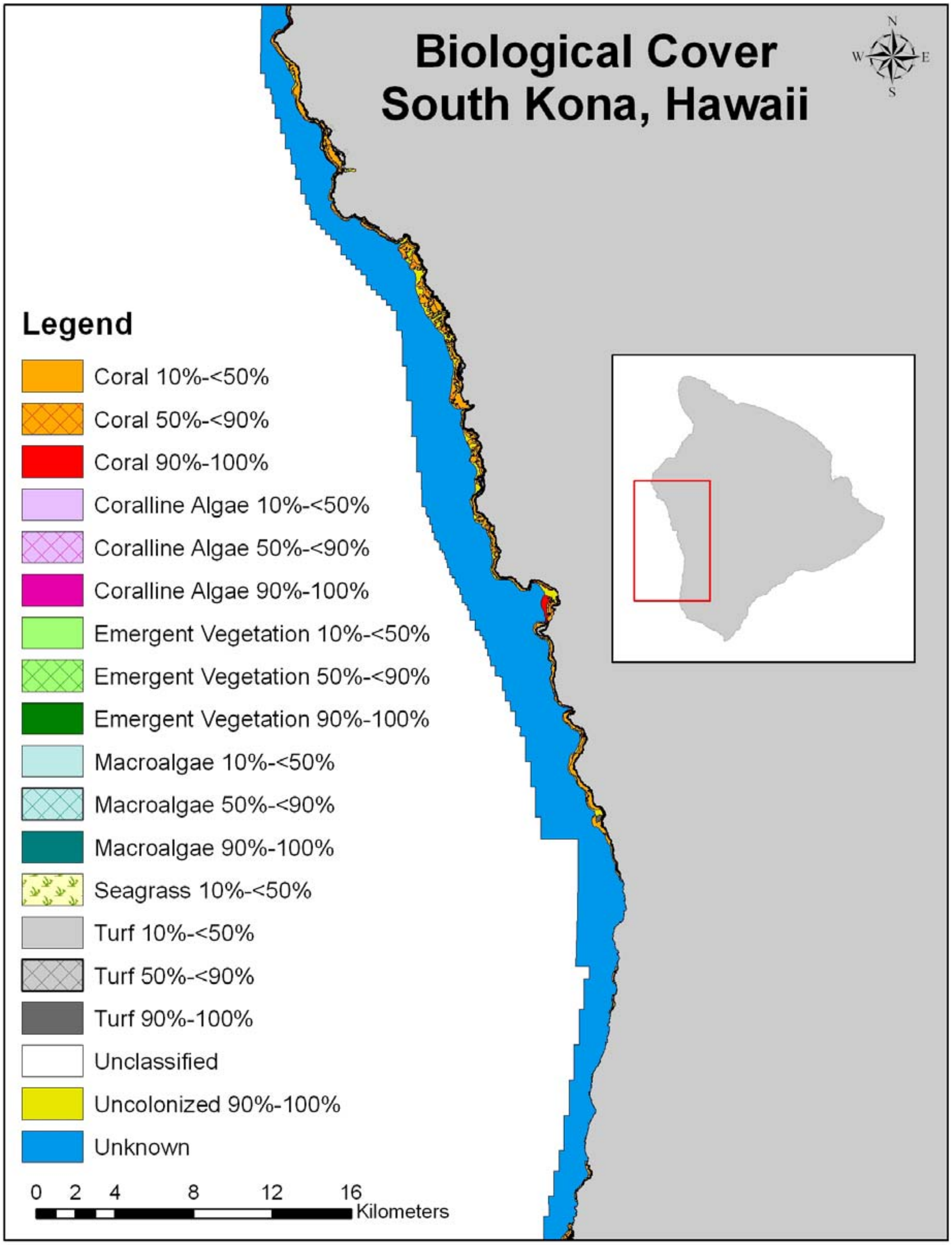

Figure 26. Biological cover map of South Kona, Hawaii.

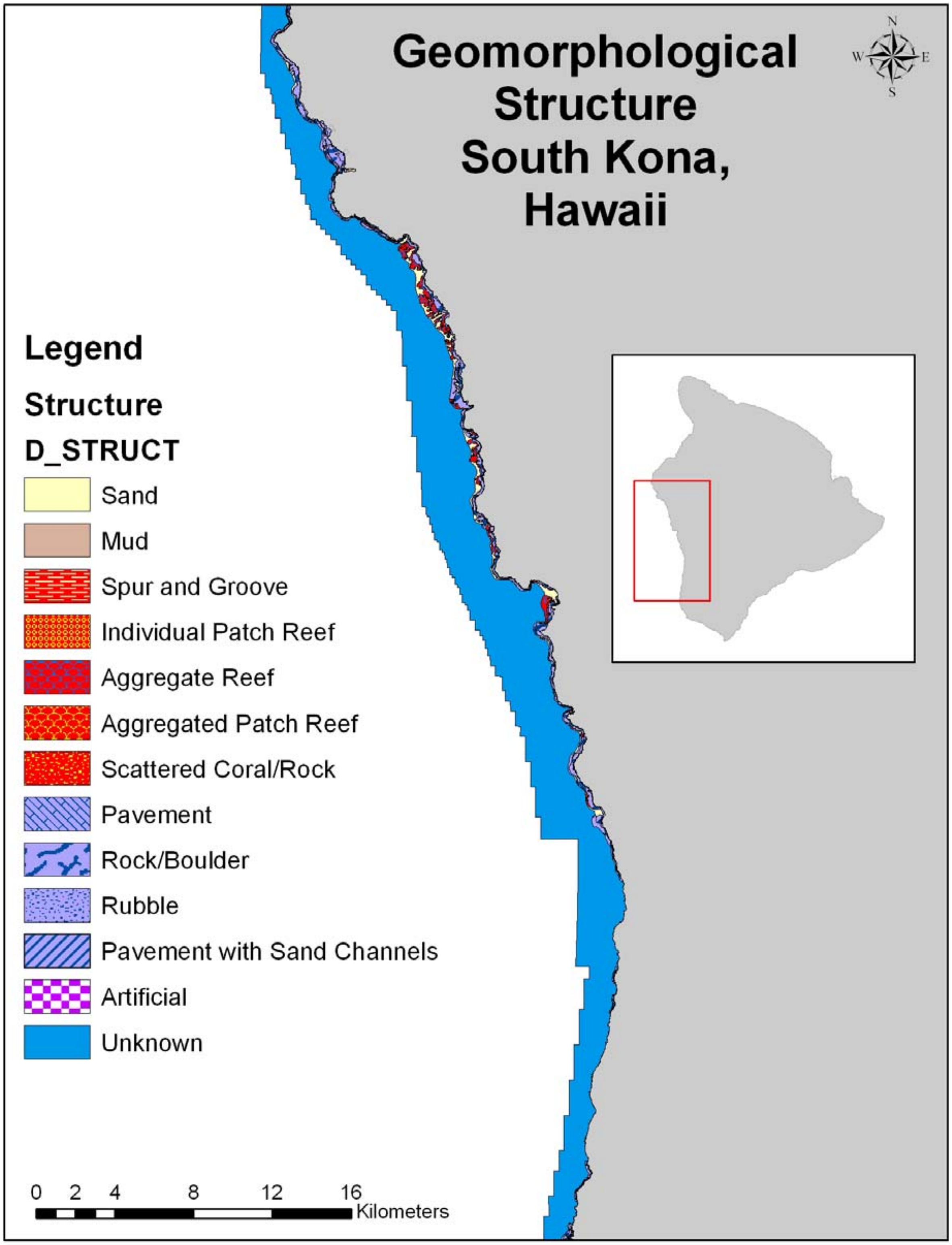

Figure 27. Geomorphological structure map of South Kona, Hawaii.

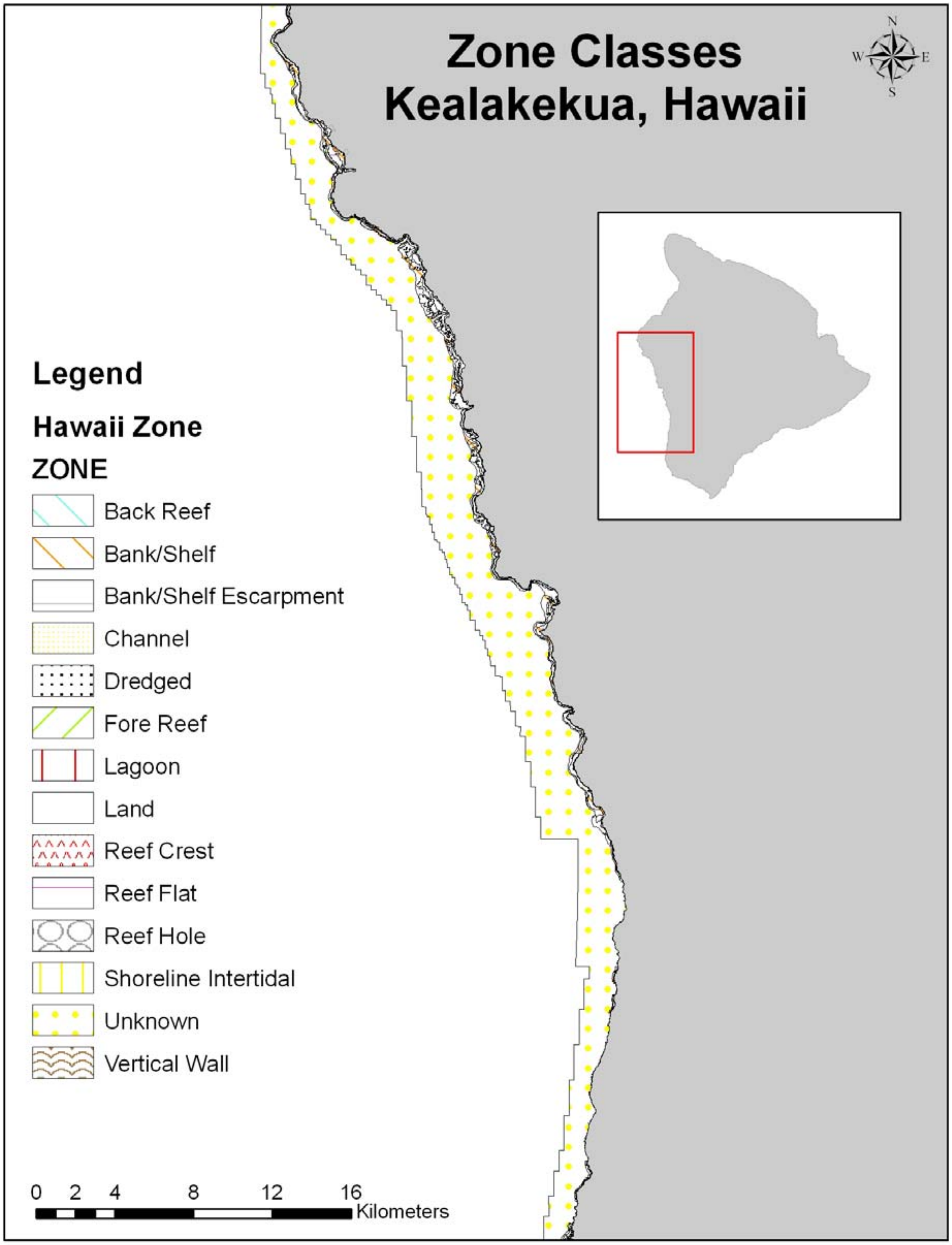

Figure 28. Reef habitat zone map of South Kona, Hawaii.

10.6 South Point, Hawaii

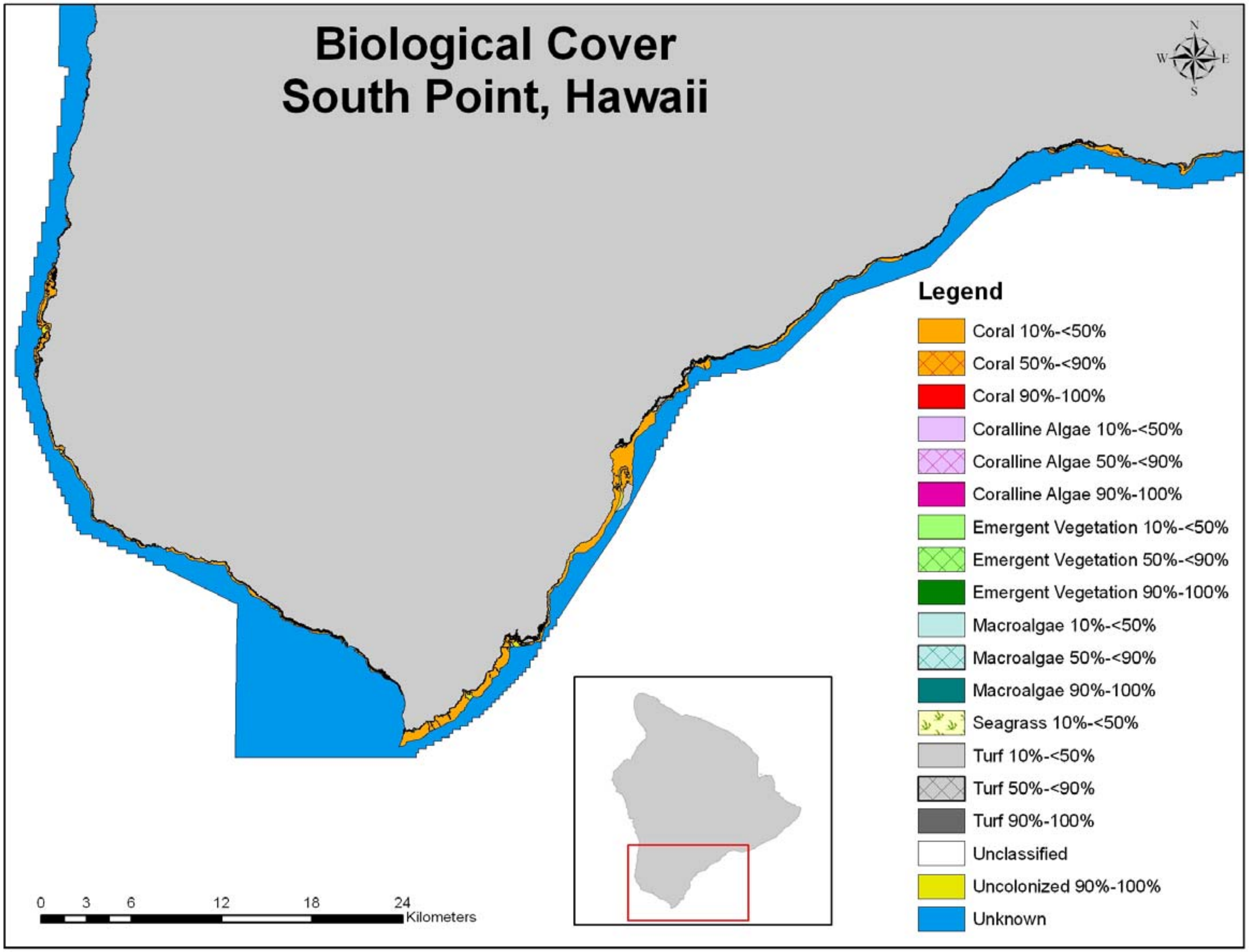

Figure 29. Biological cover map of South Point, Hawaii.

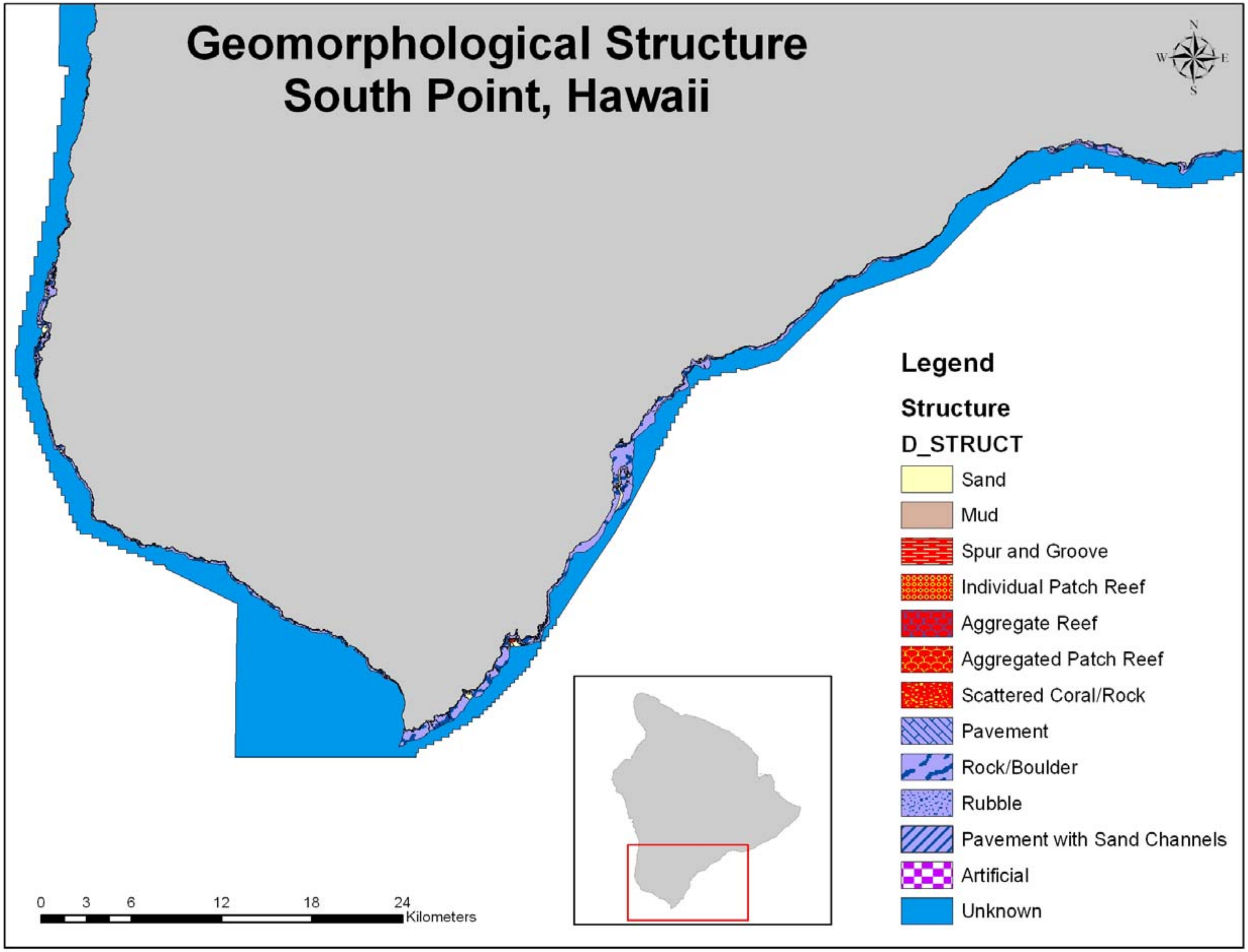

Figure 30. Geomorphological structure map of South Point, Hawaii.

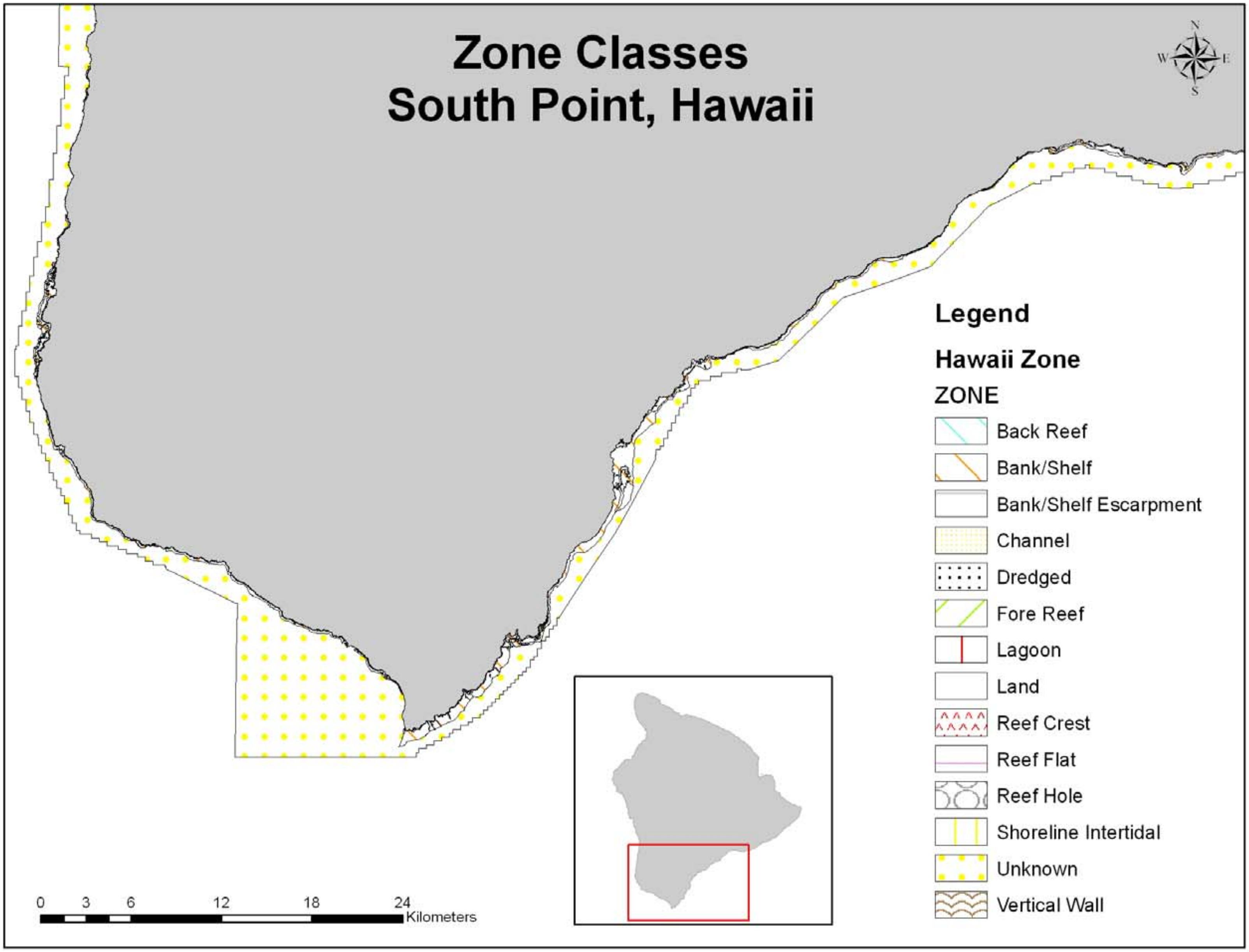

Figure 31. Reef habitat zone map of South Point, Hawaii.

10.7 Kahoolawe

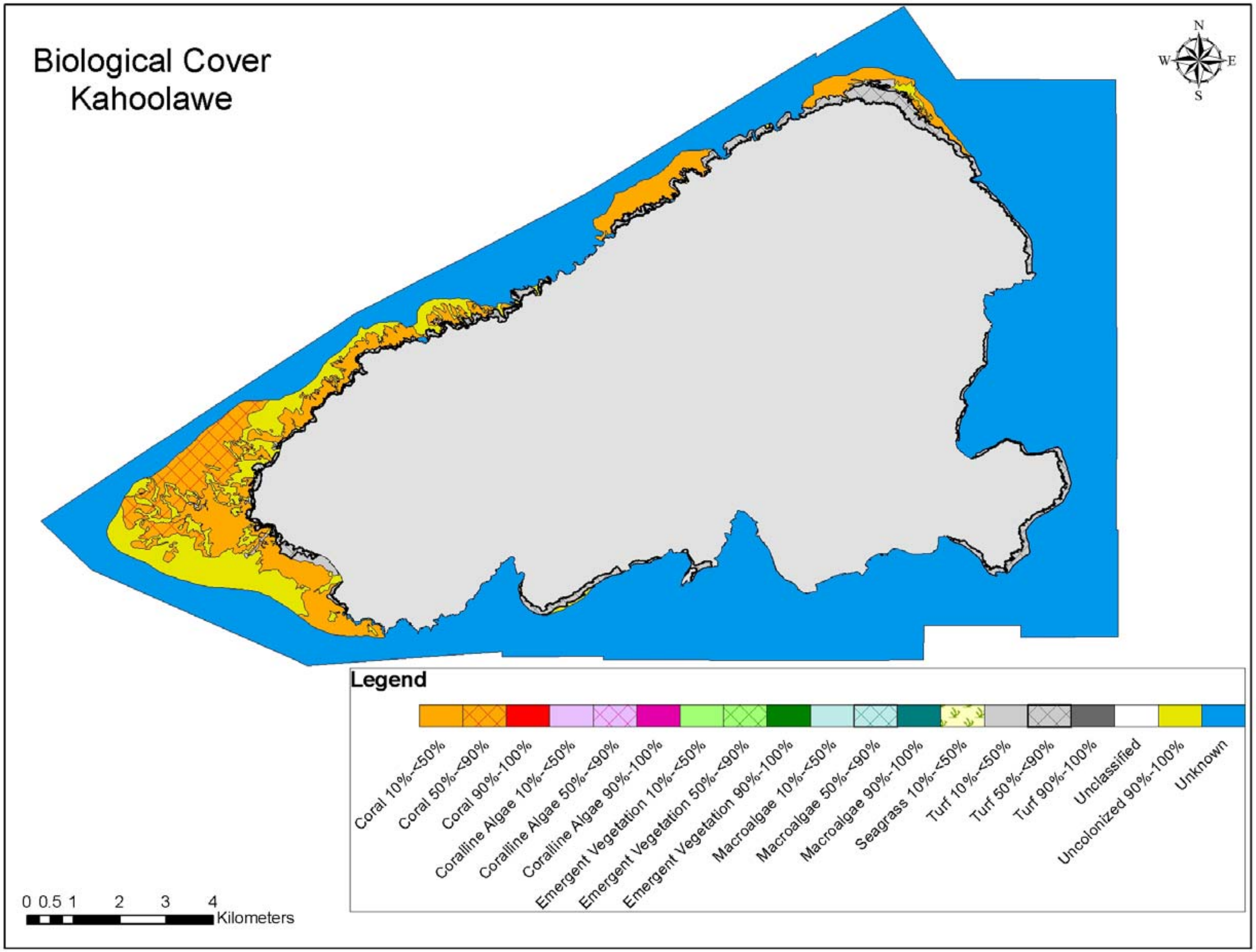

Figure 32. Biological cover map of Kahoolawe.

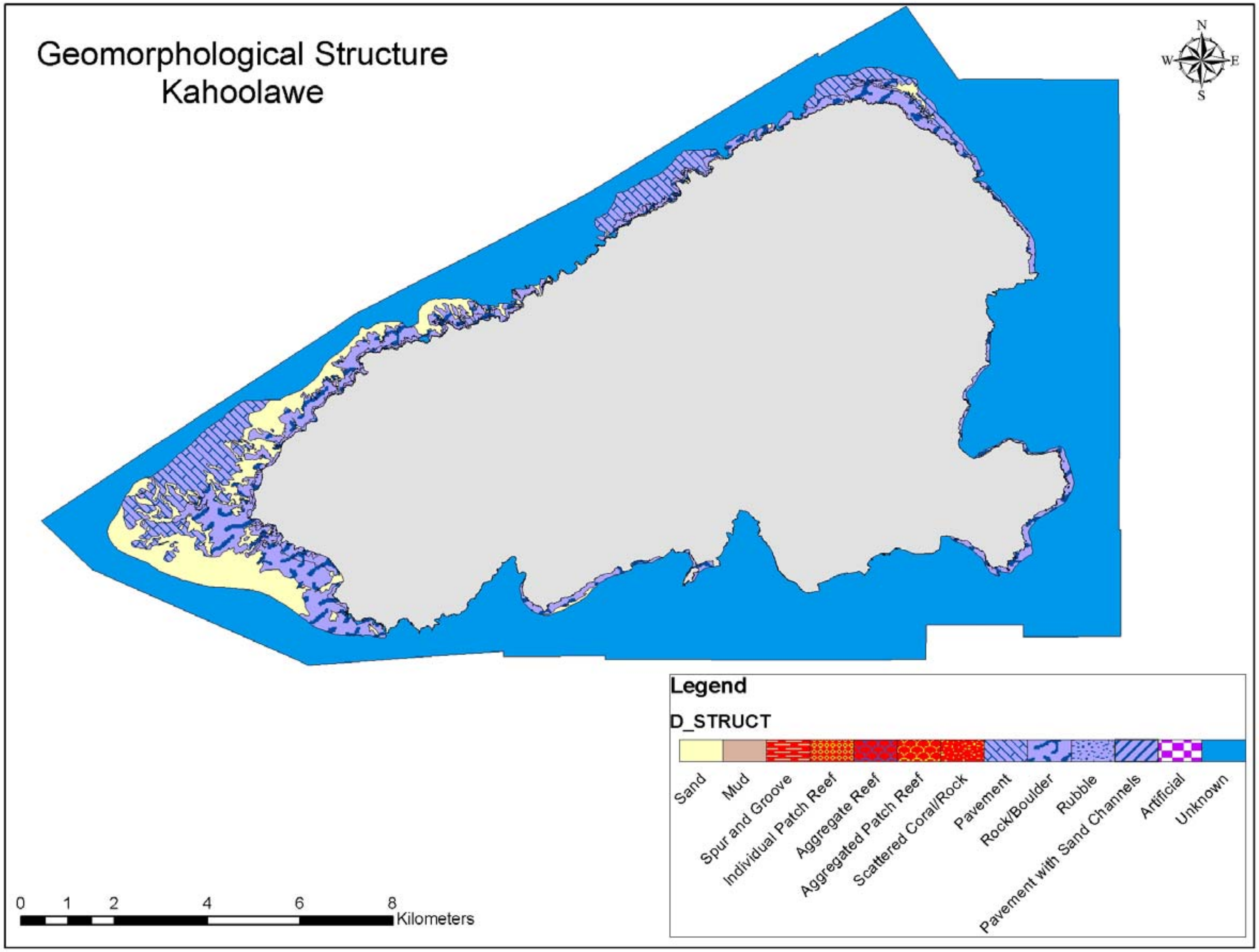

Figure 33. Geomorphological structure map of Kahoolawe.

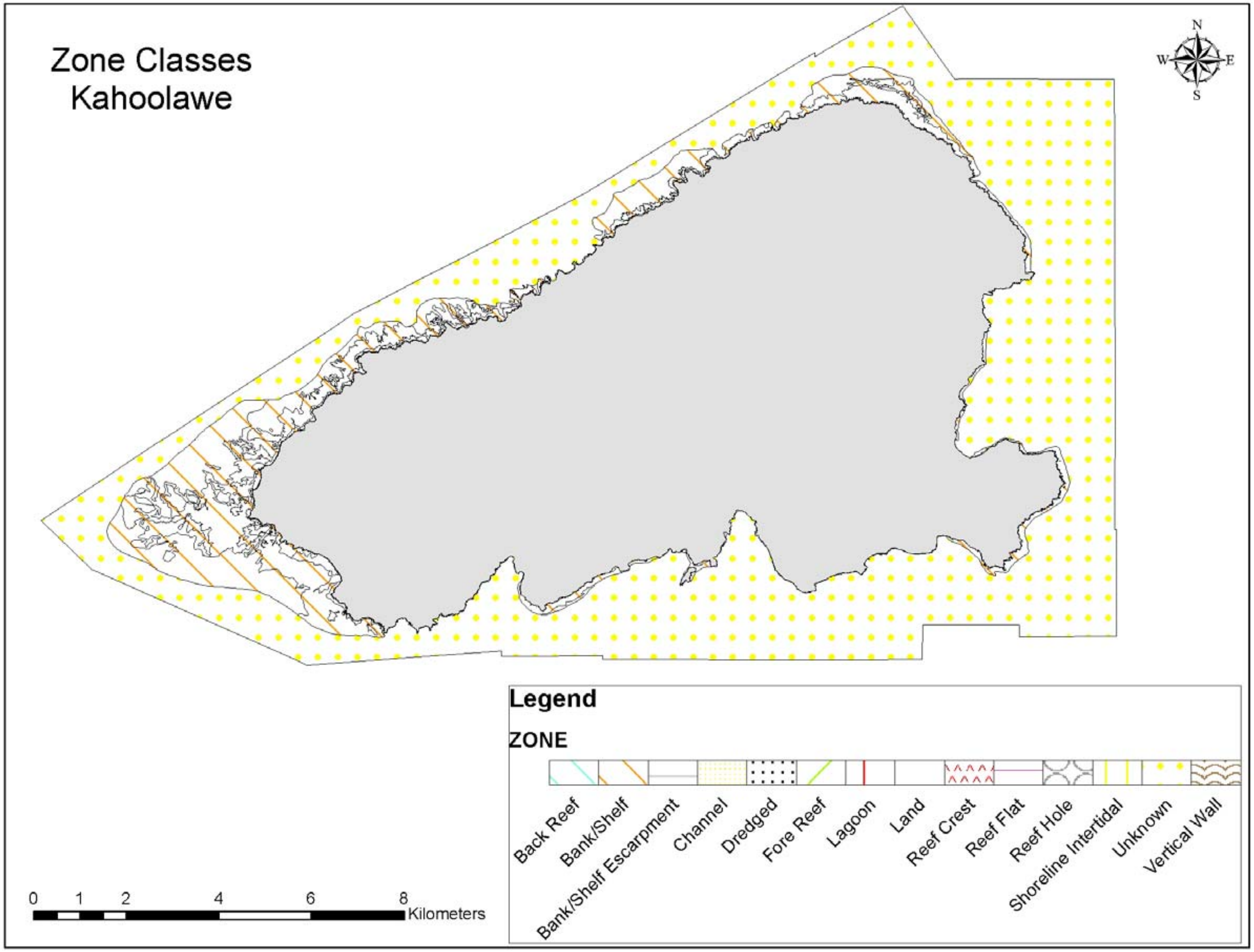

Figure 34. Reef habitat zone map of Kahoolawe.

10.8 East Kauai

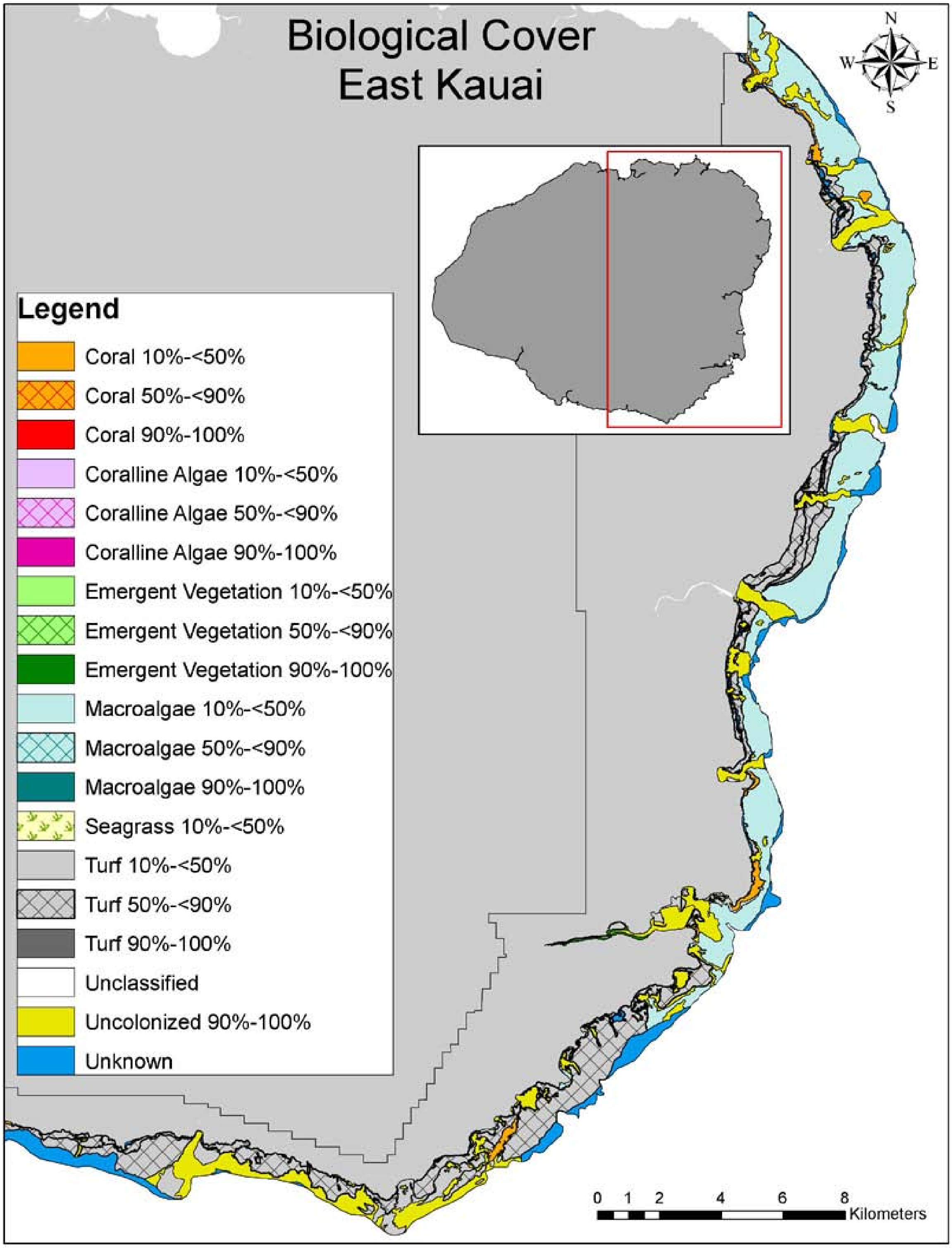

Figure 35. Biological cover map of East Kauai.

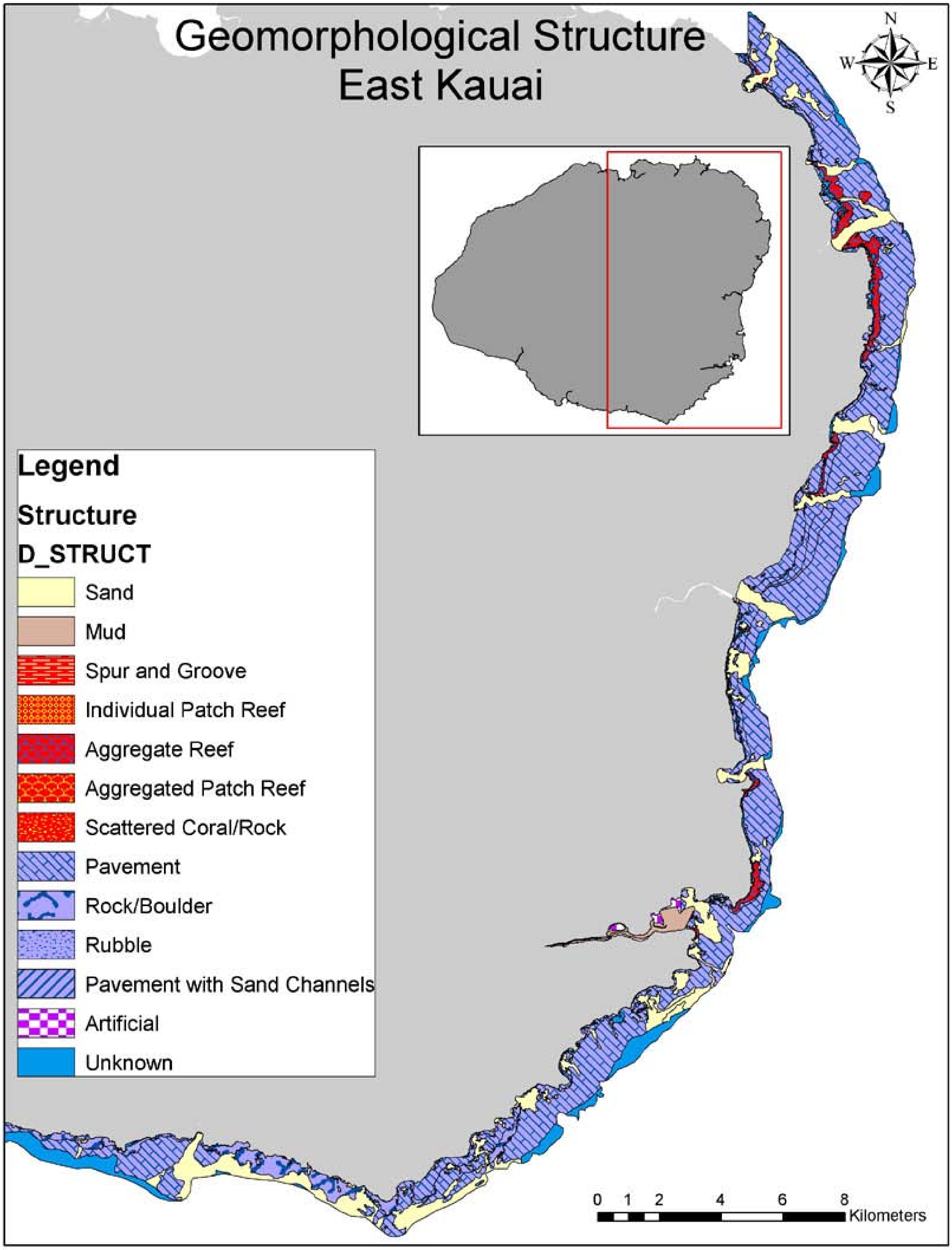

Figure 36. Geomorphological structure map of East Kauai.

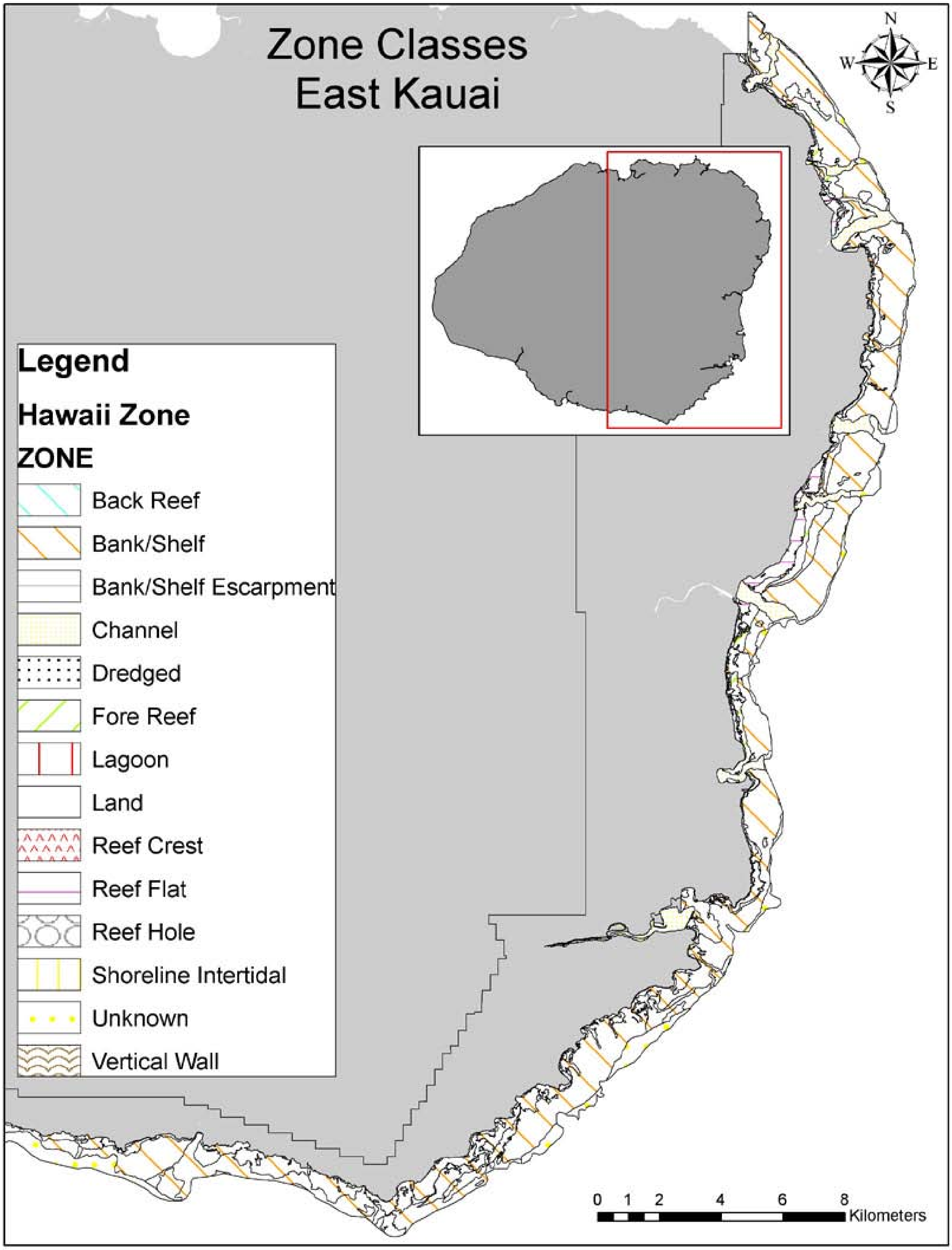

Figure 37. Reef habitat zone map of East Kauai.

10.9 West Kauai

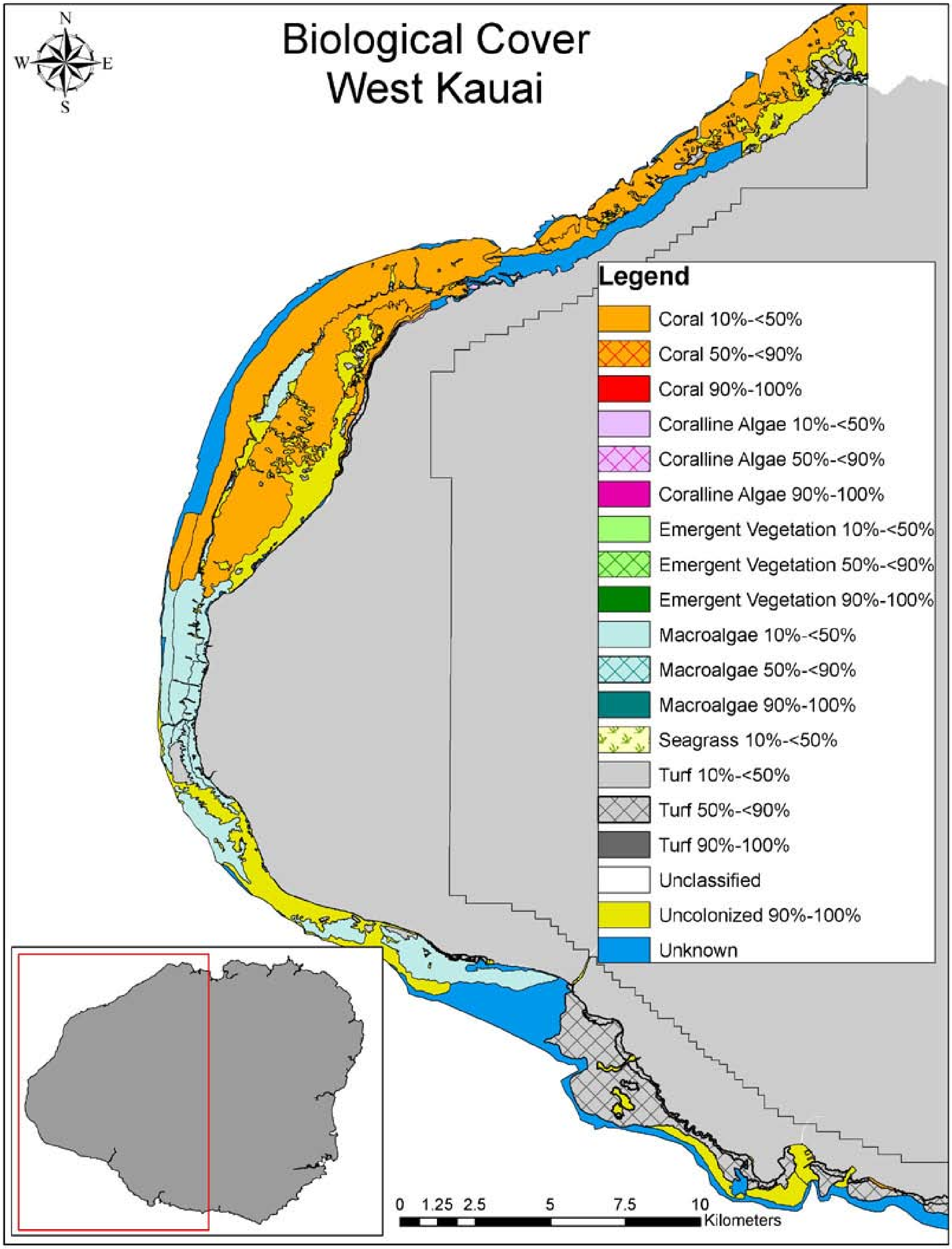

Figure 38. Biological cover map of West Kauai.

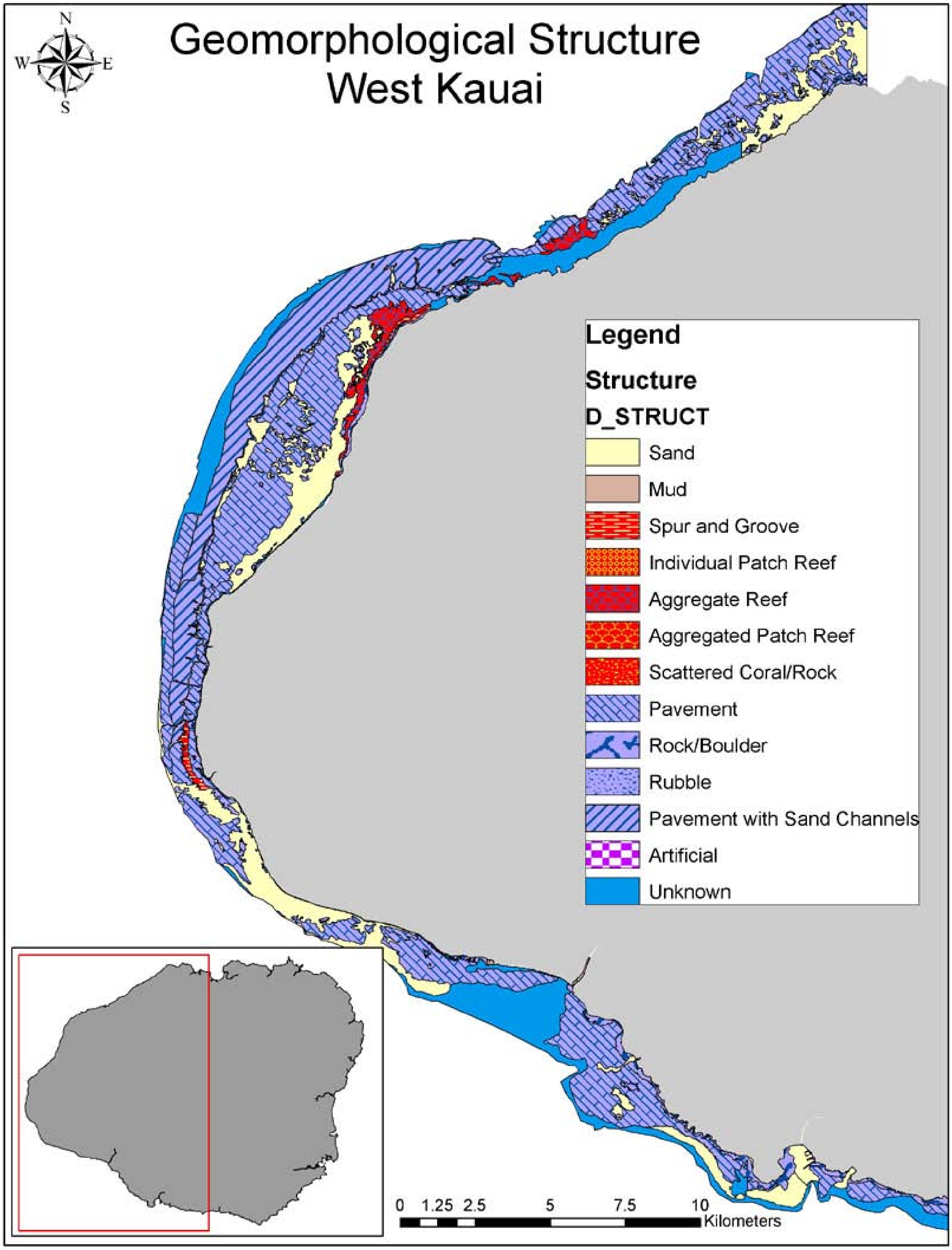

Figure 39. Geomorphological structure map of West Kauai.

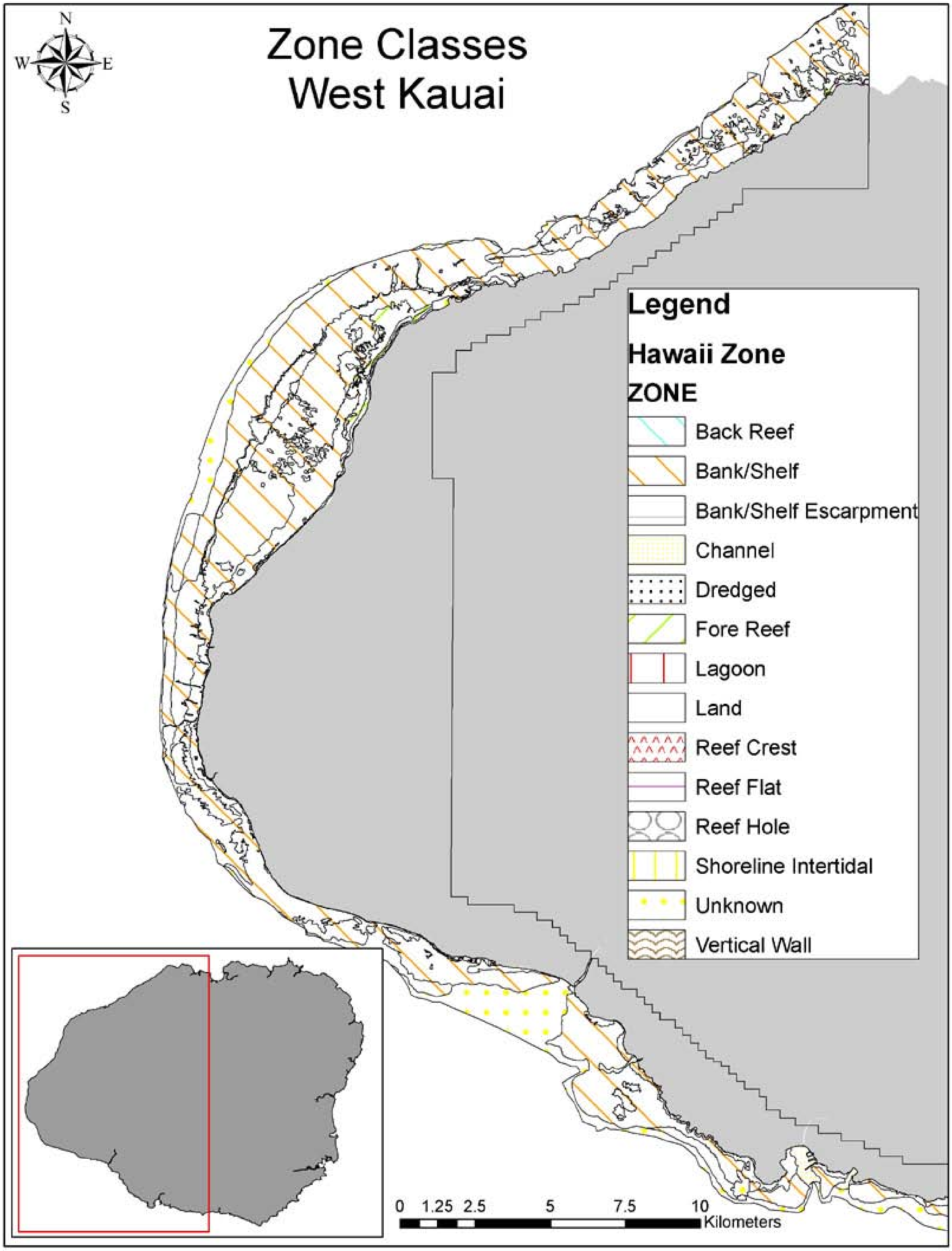

Figure 40. Reef habitat zone map of West Kauai.

10.10 Kaula

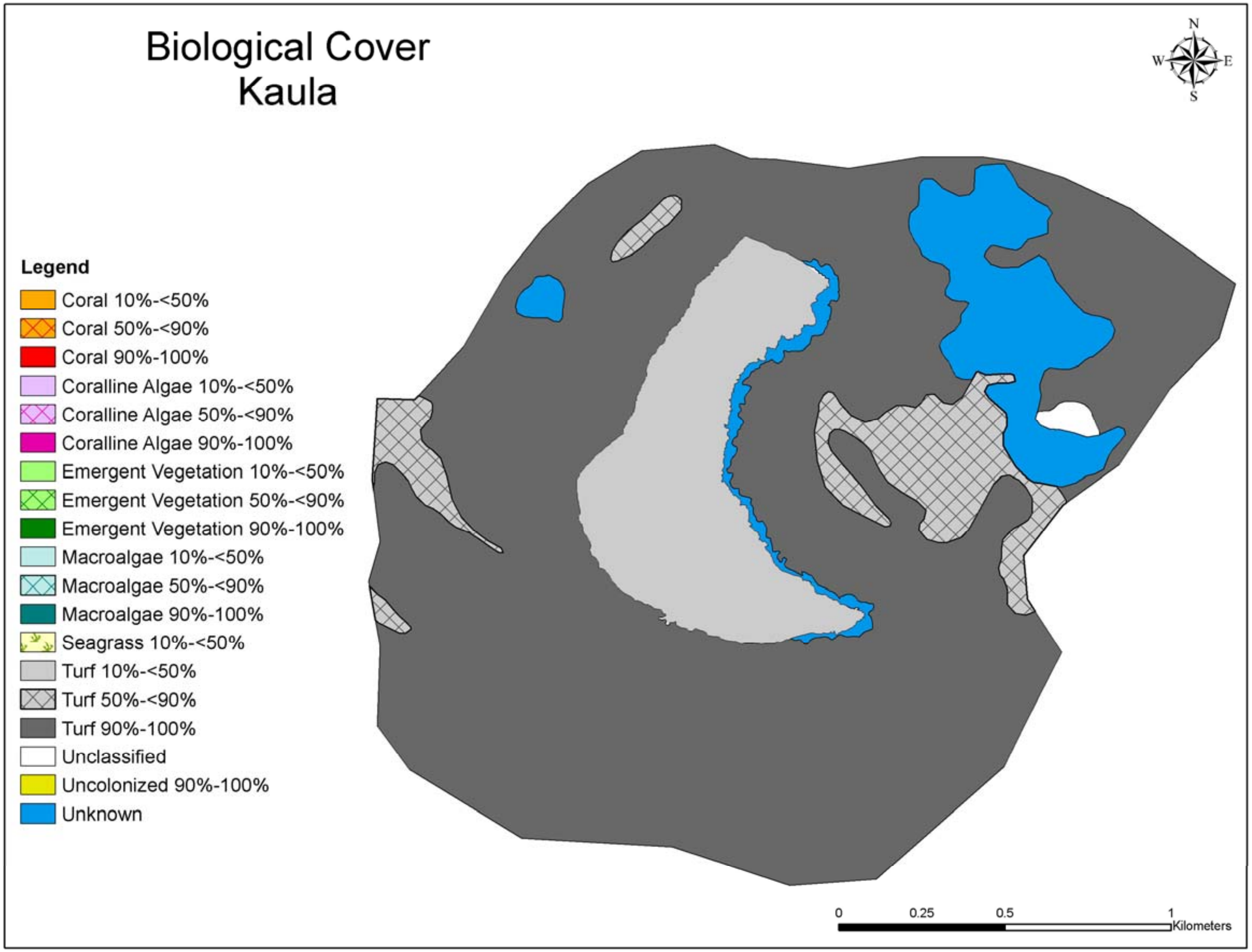

Figure 41. Biological cover map of Kaula.

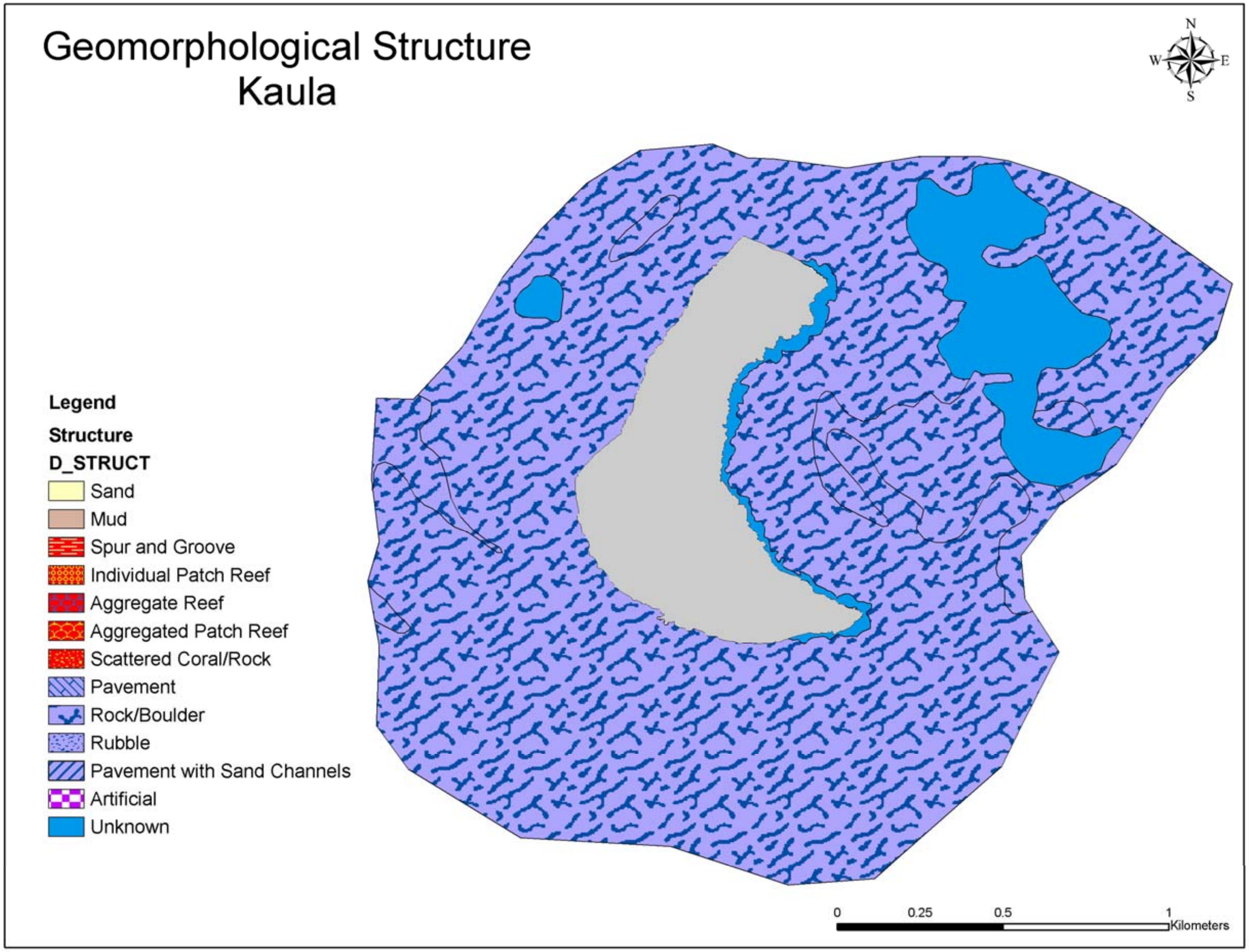

Figure 42. Geomorphological structure map of Kaula.

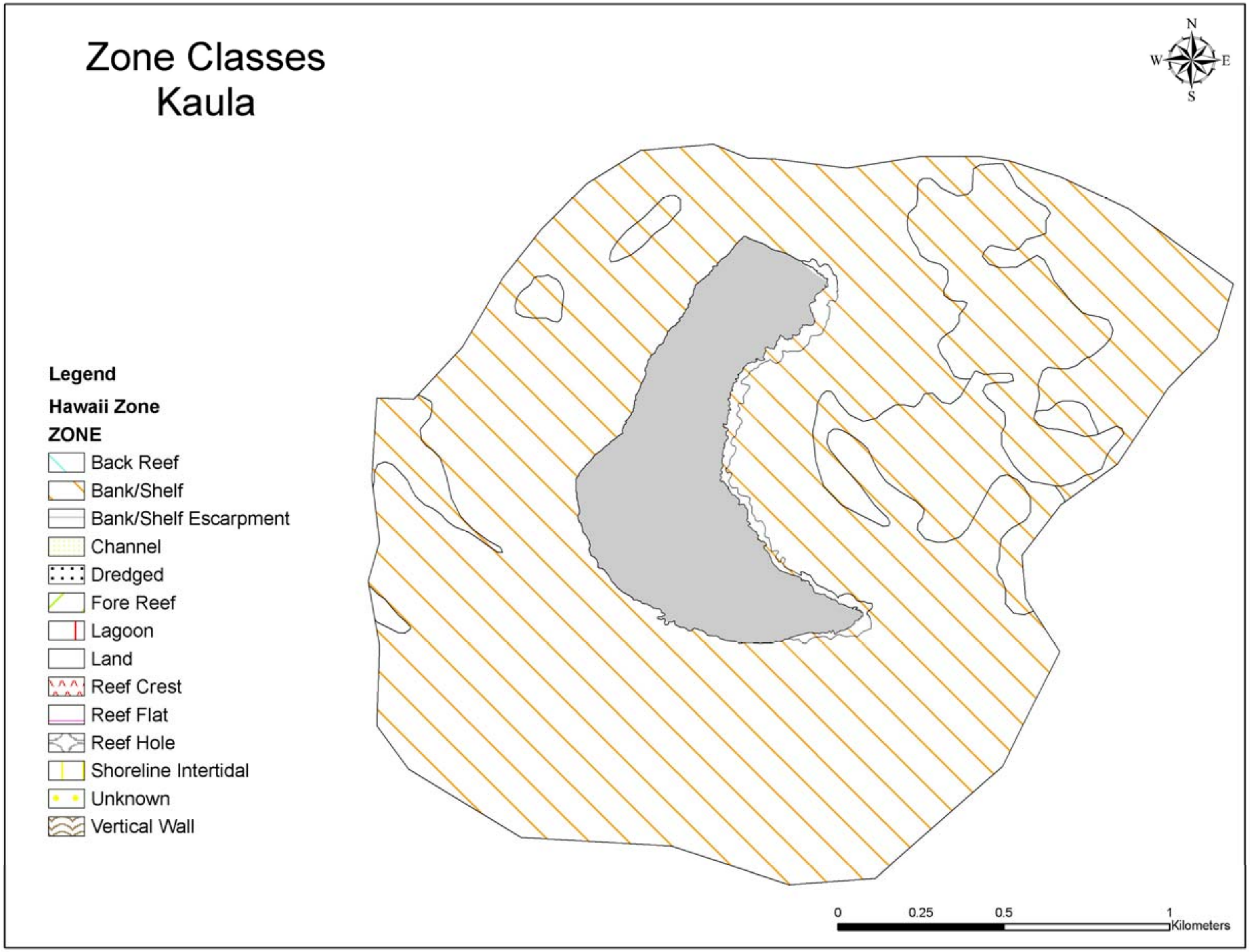

Figure 43. Reef habitat zone map of Kaula.

10.11 Lanai

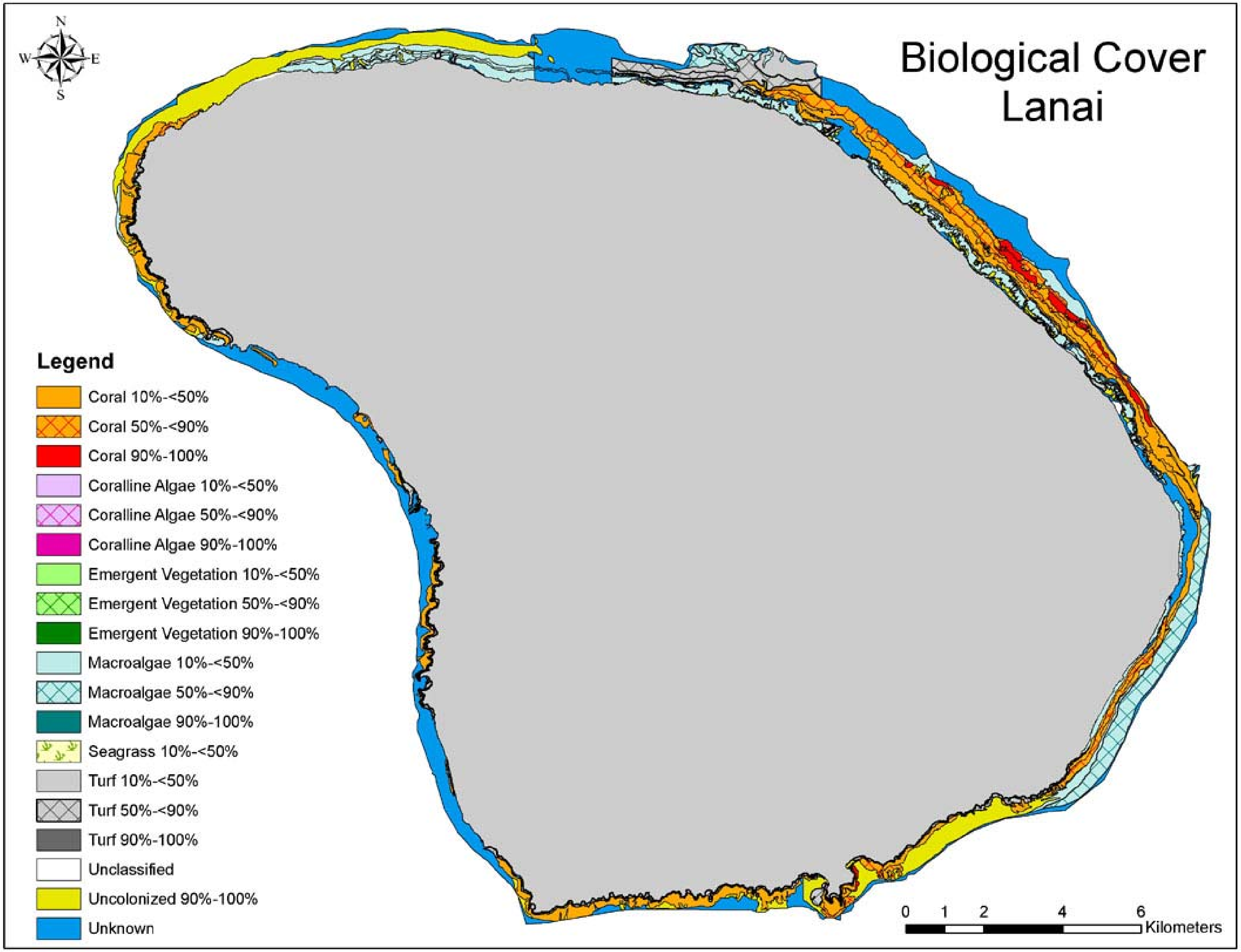

Figure 44. Biological cover map of Lanai.

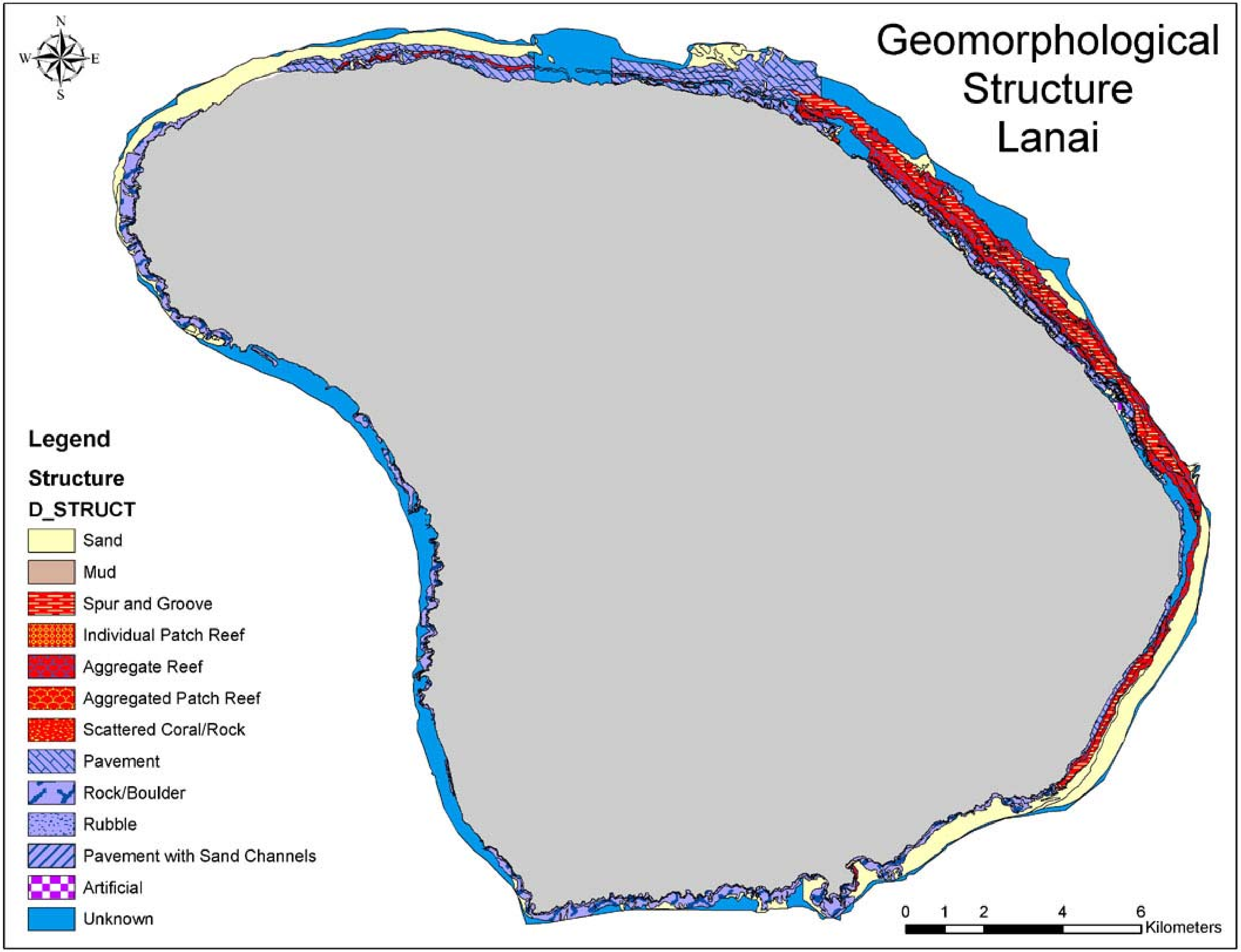

Figure 45. Geomorphological structure map of Lanai.

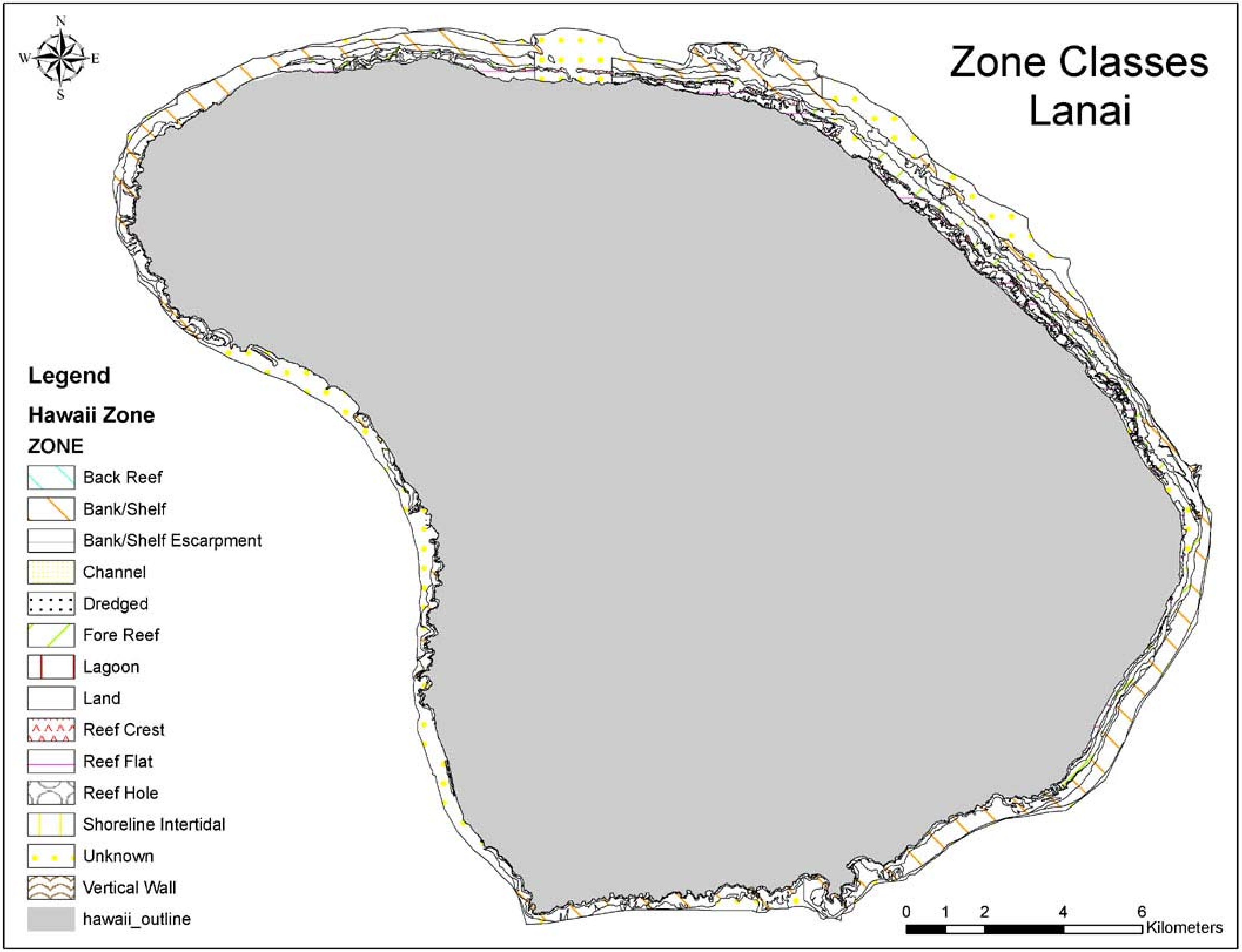

Figure 46. Reef habitat zone map of Lanai.

10.12 East Maui

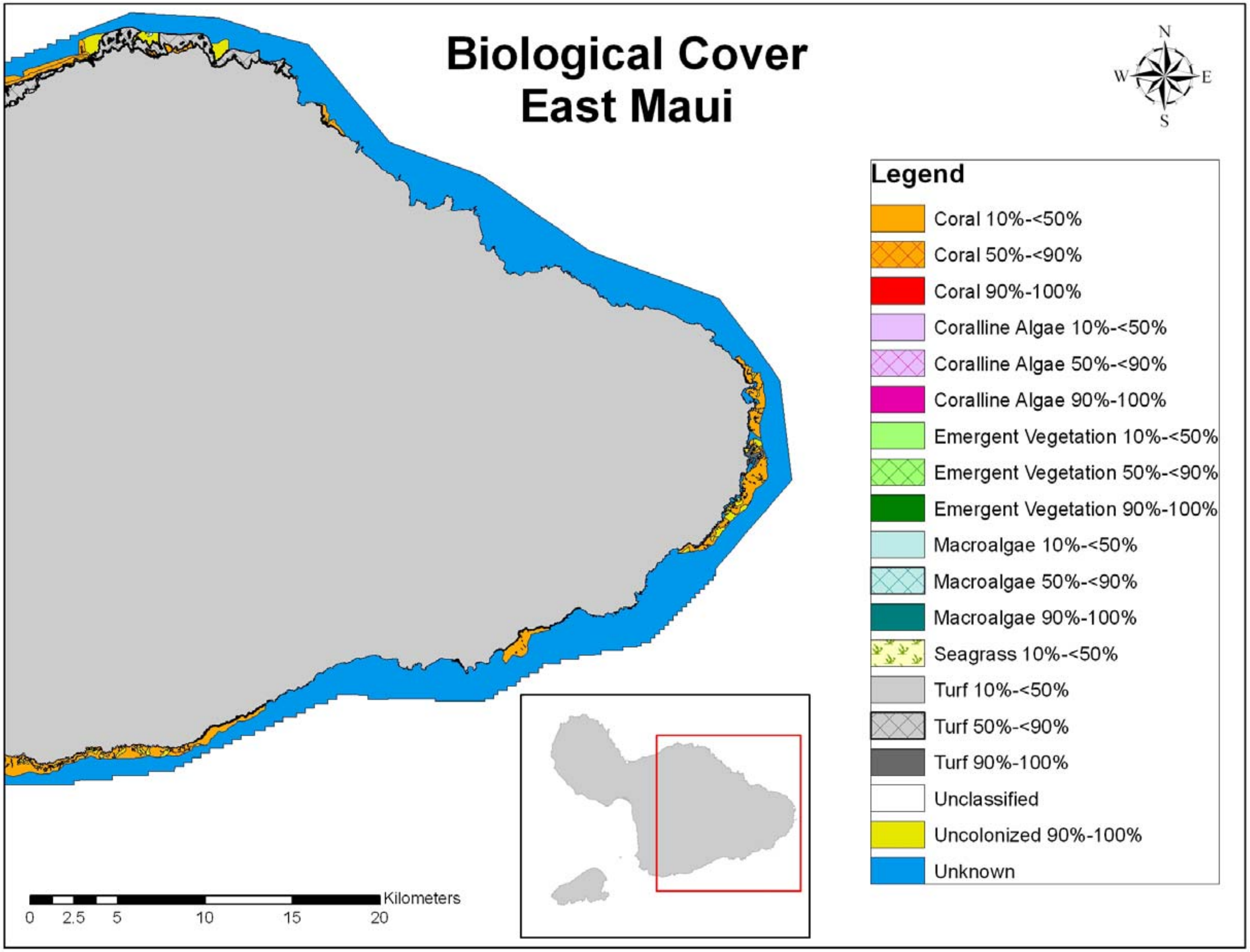

Figure 47. Biological cover map of East Maui.

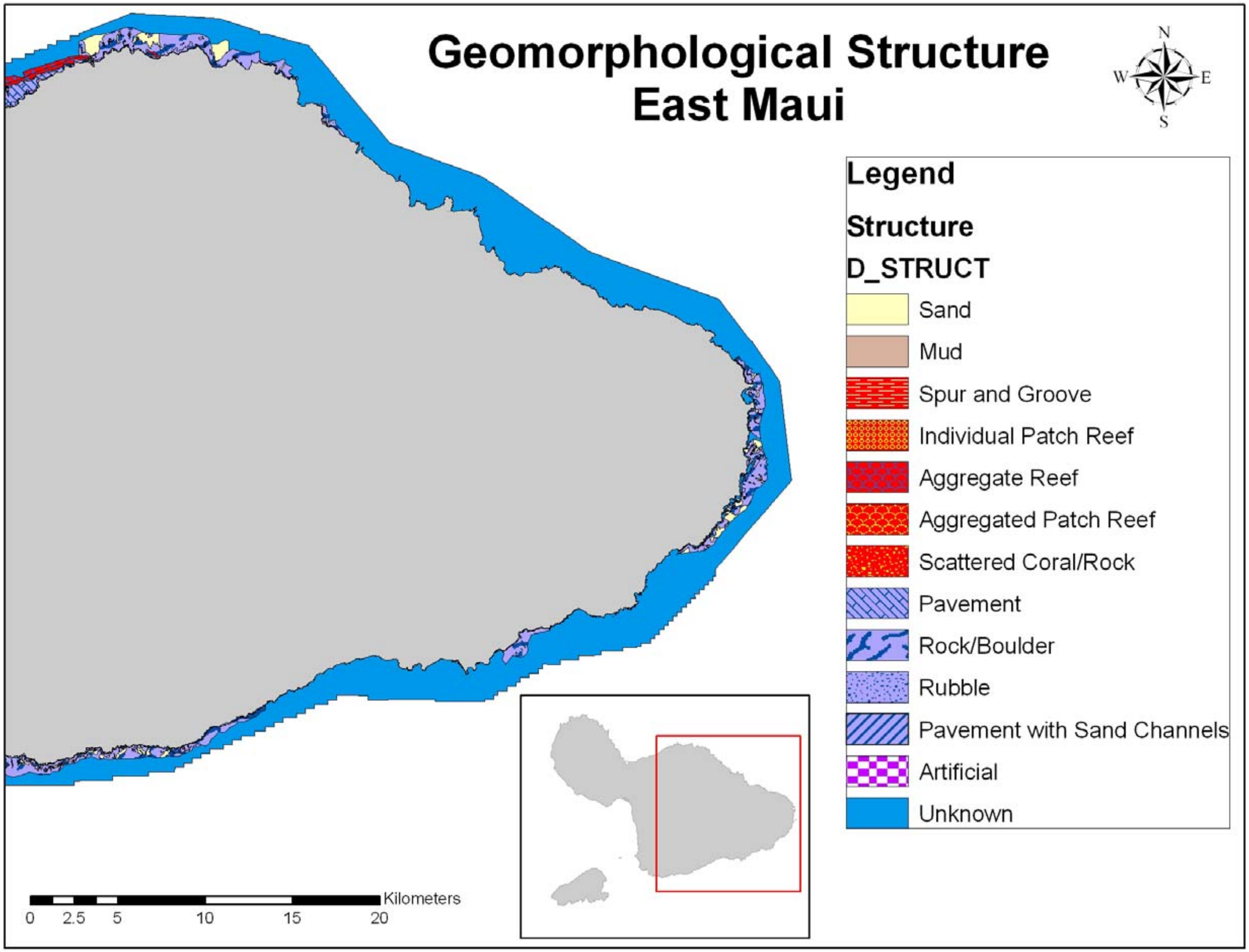

Figure 48. Geomorphological structure map of East Maui.

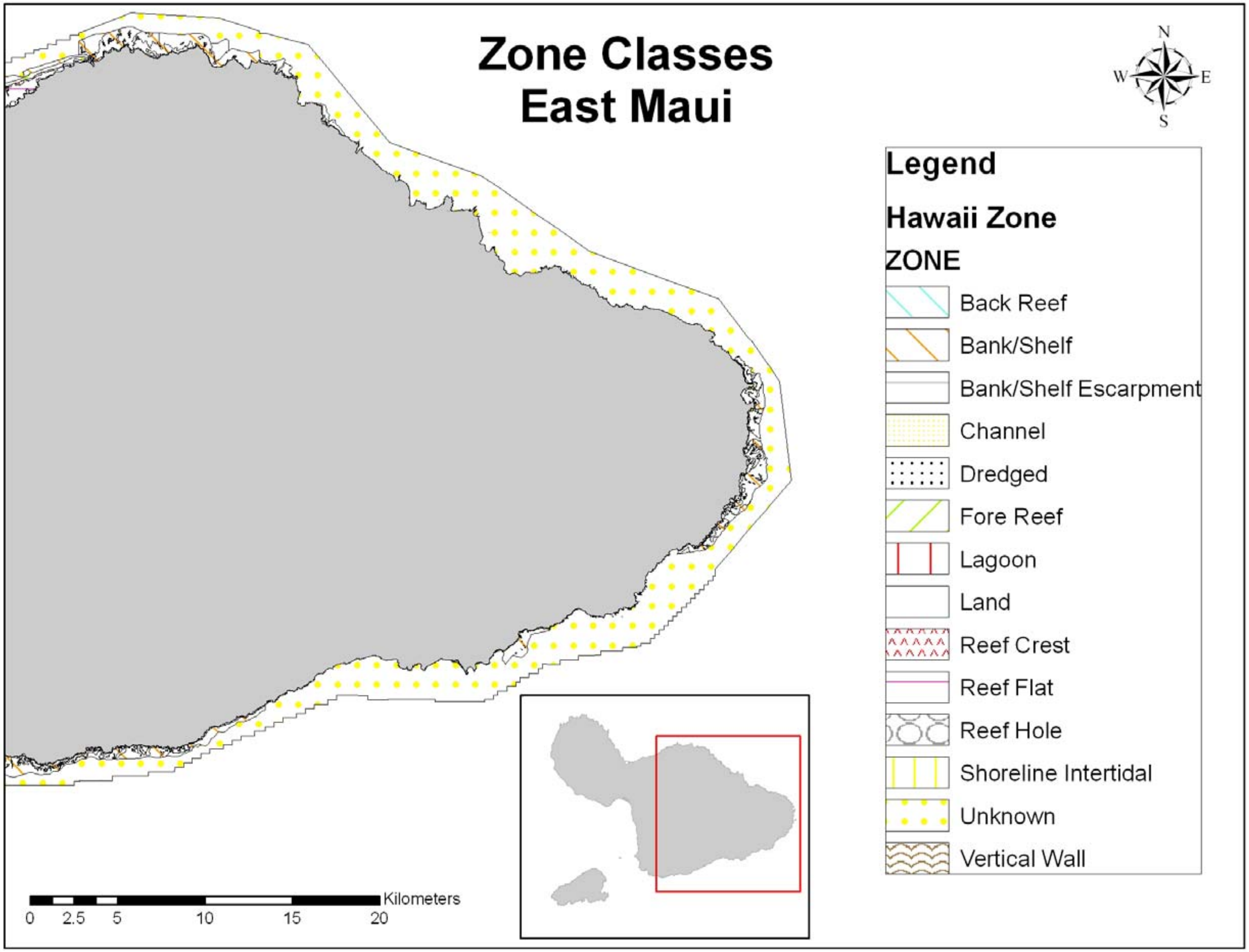

Figure 49. Reef habitat zone map of East Maui.

10.13 West Maui

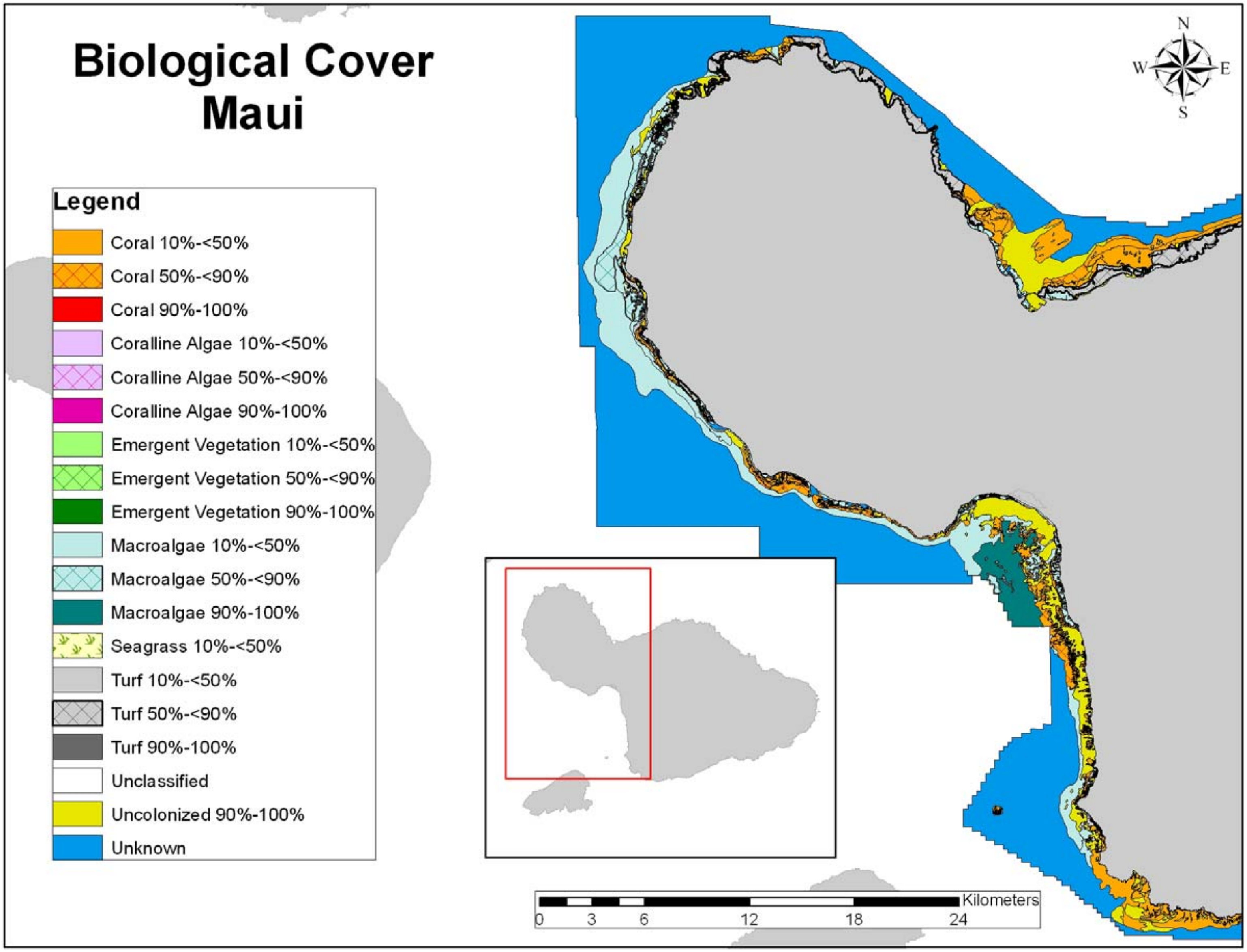

Figure 50. Biological cover map of West Maui.

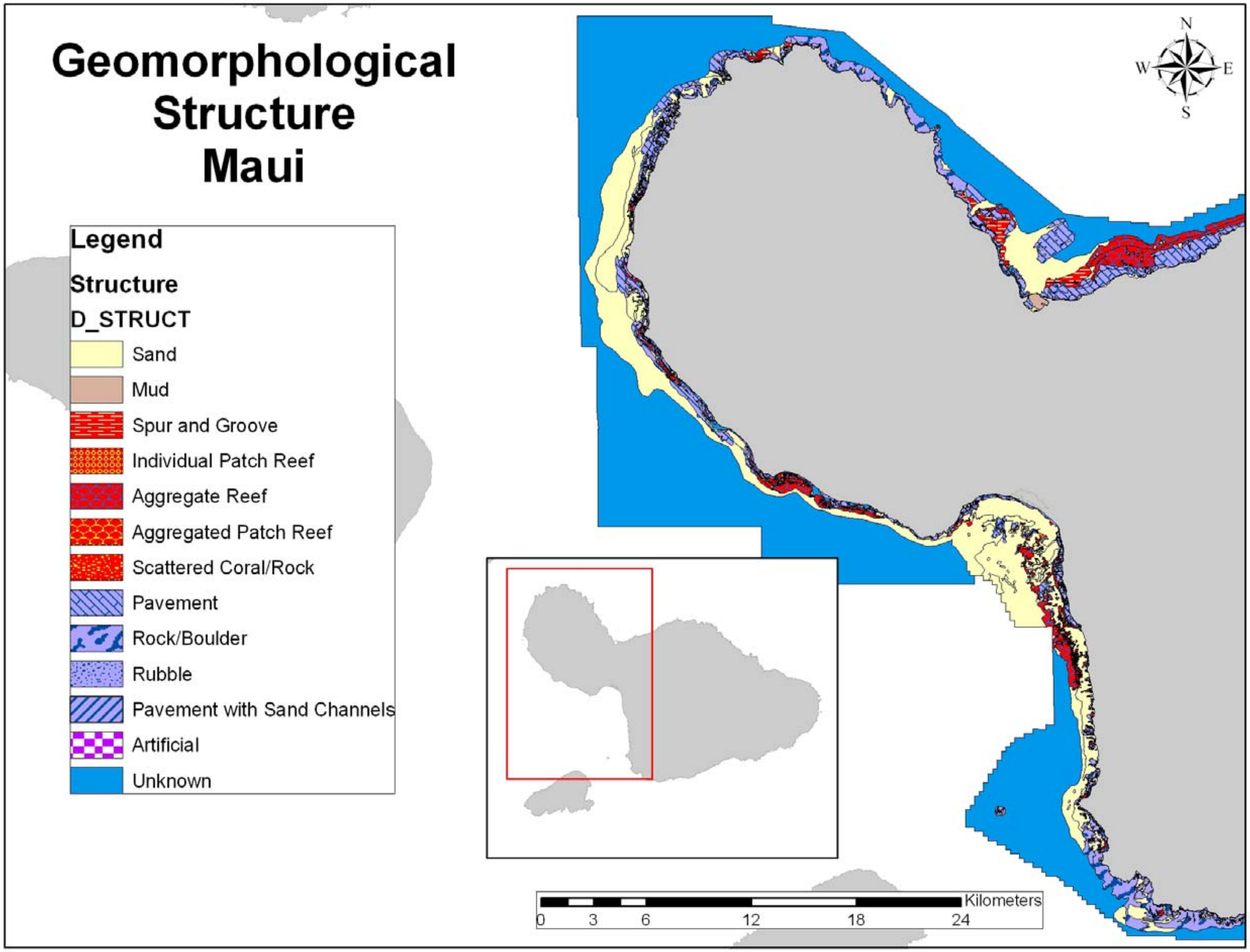

Figure 51. Geomorphological structure map of West Maui.

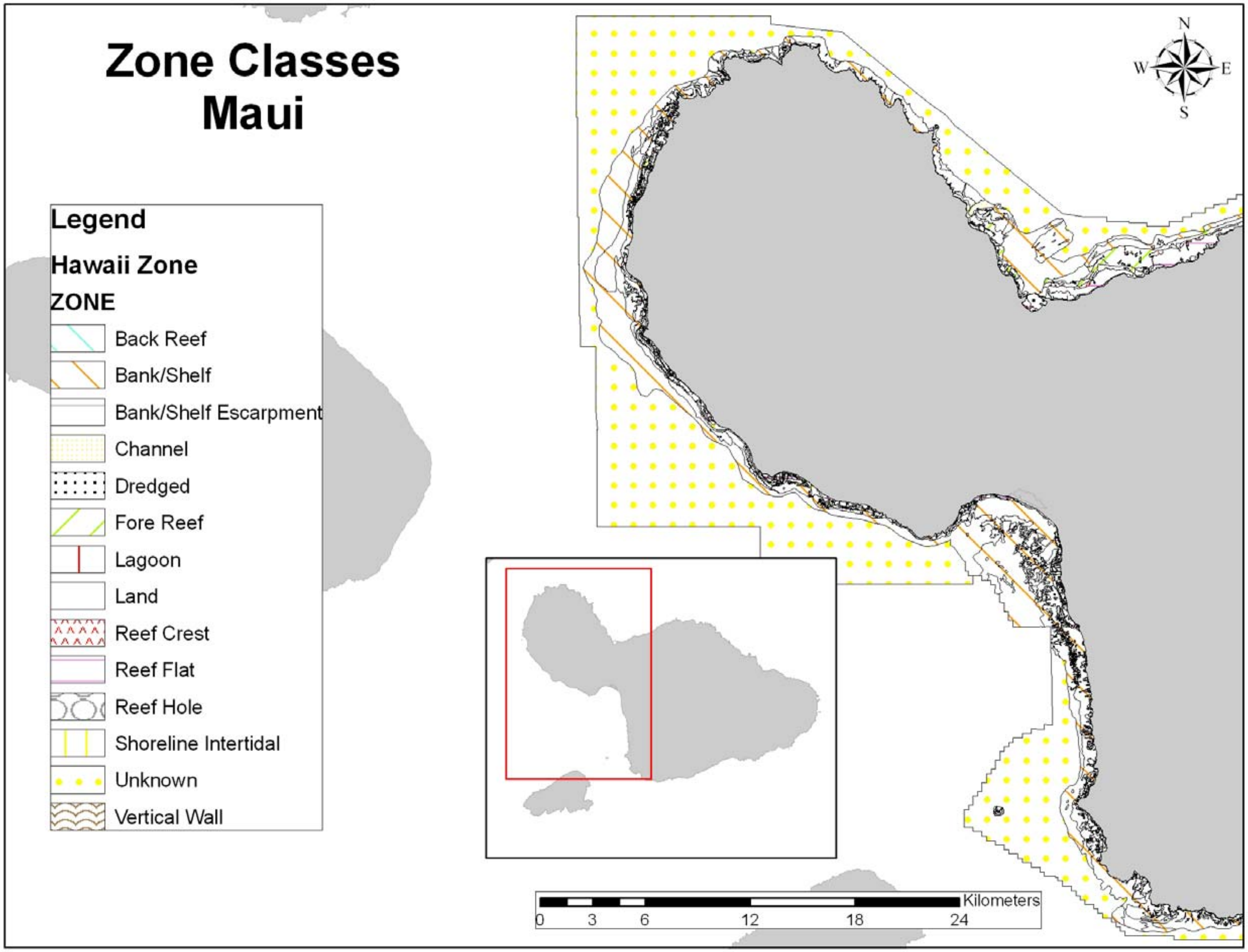

Figure 52. Geomorphological structure map of West Maui.

10.14 East Molokai

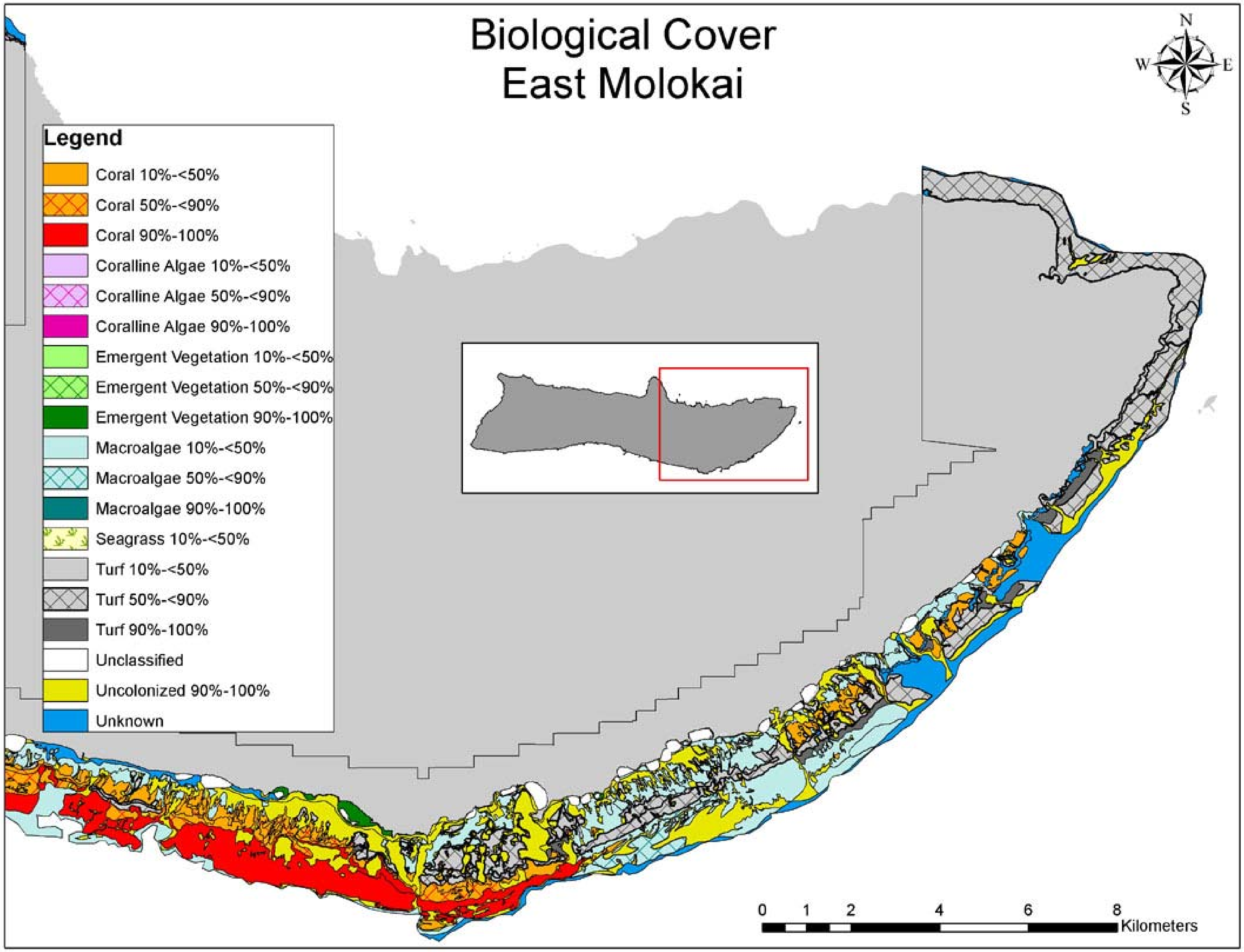

Figure 53. Biological cover map of East Molokai.

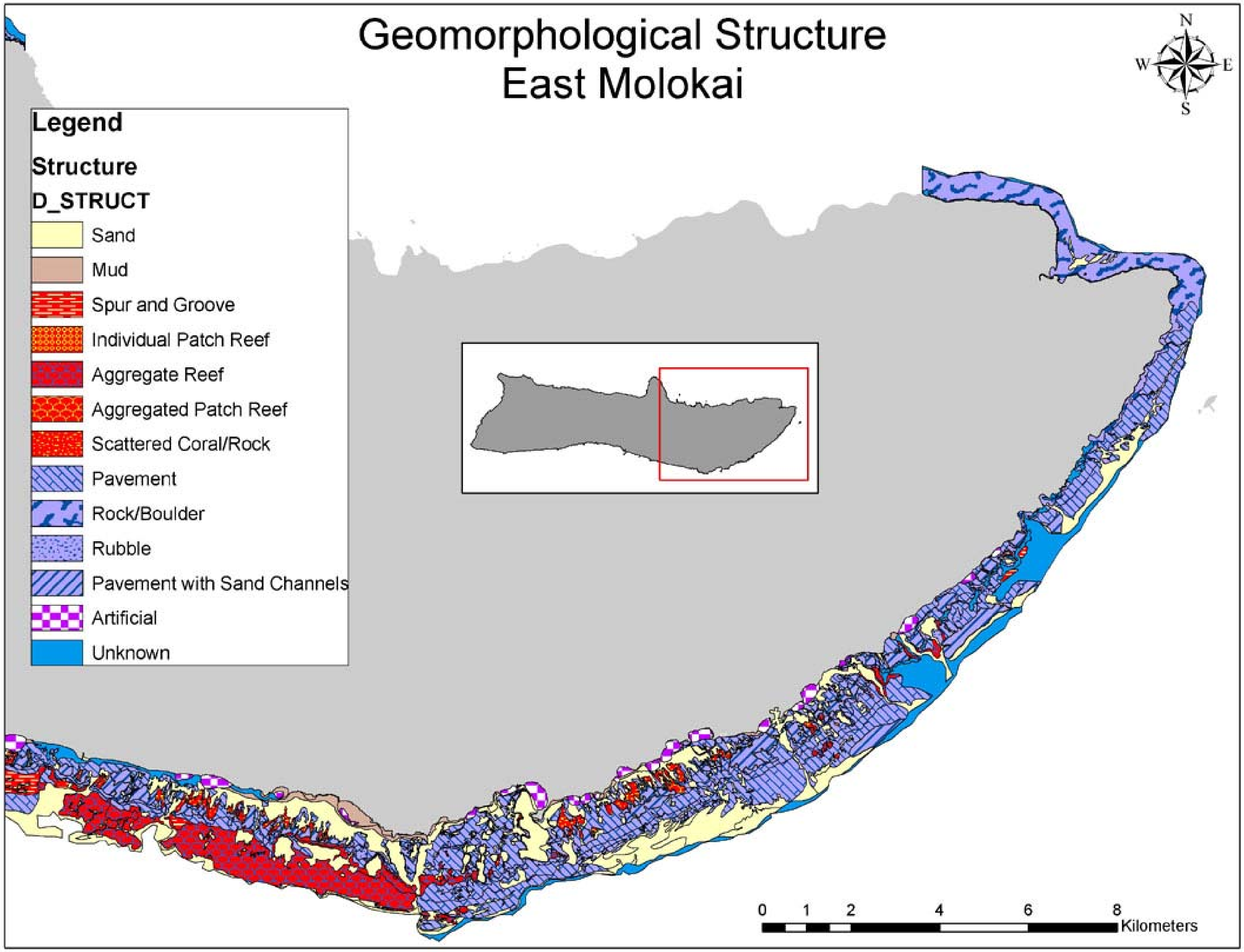

Figure 54. Geomorphological structure map of East Molokai

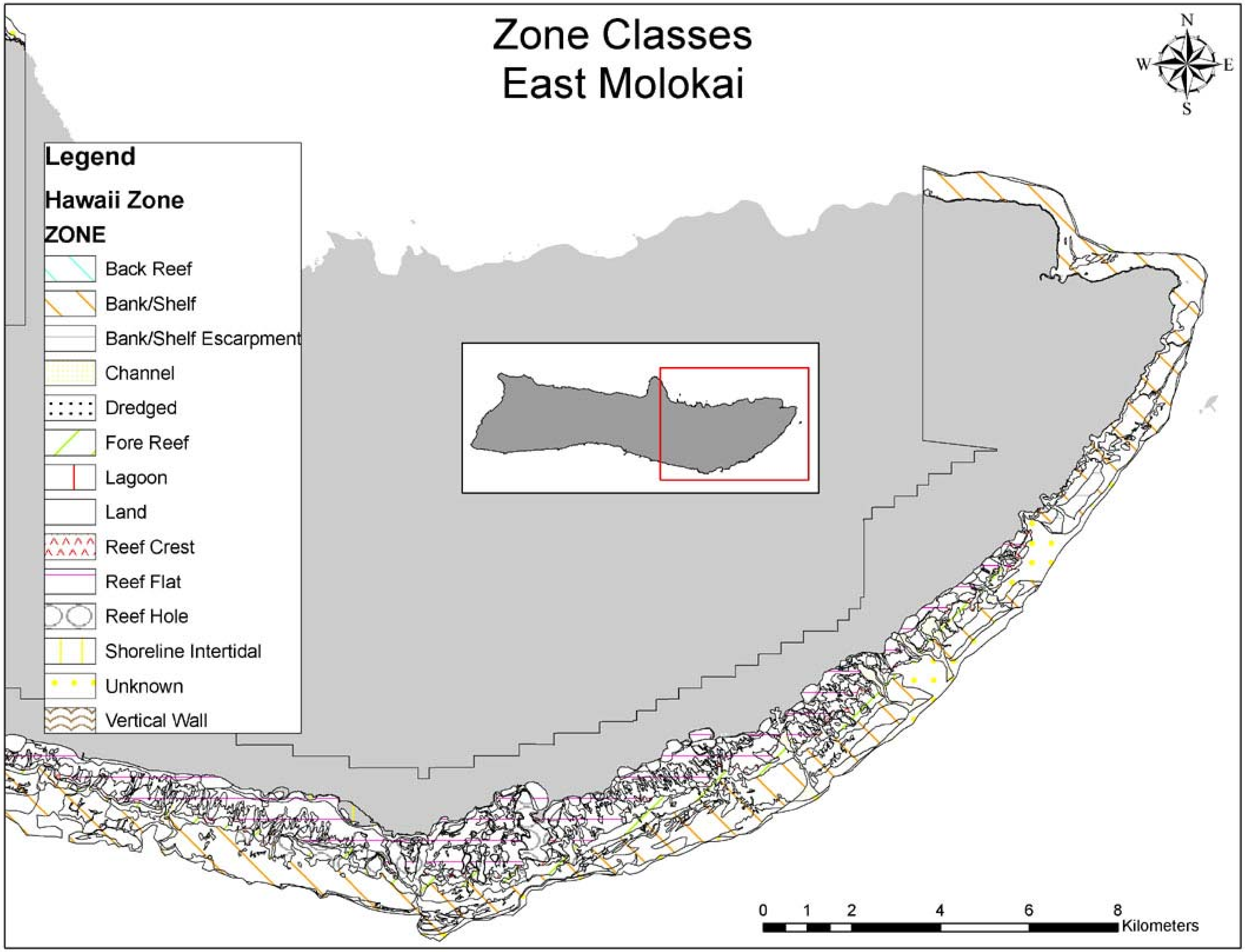

Figure 55. Reef habitat zone map of East Molokai.

10.15 West Molokai

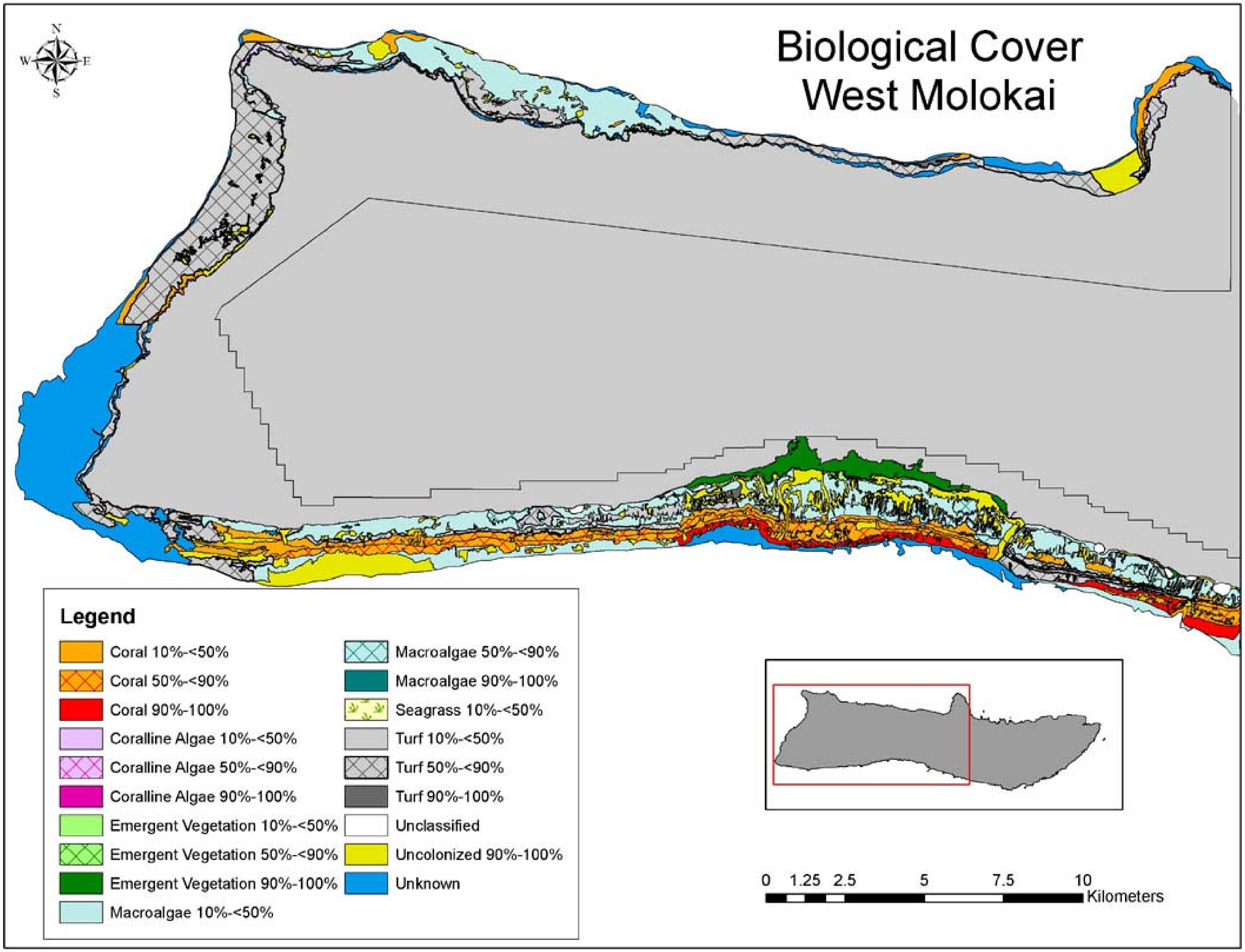

Figure 56. Biological cover map of West Molokai.

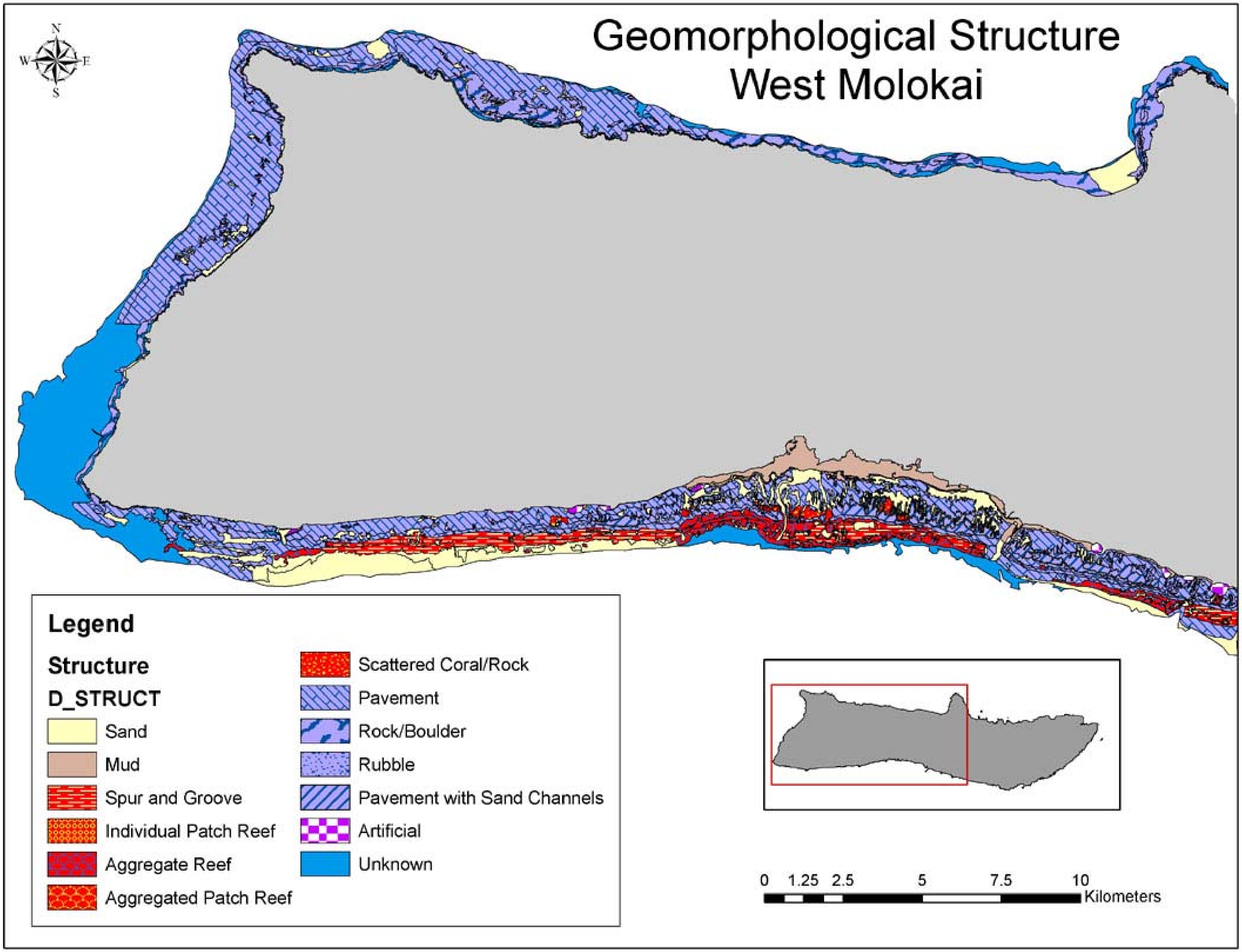

Figure 57. Geomorphological structure map of West Molokai.

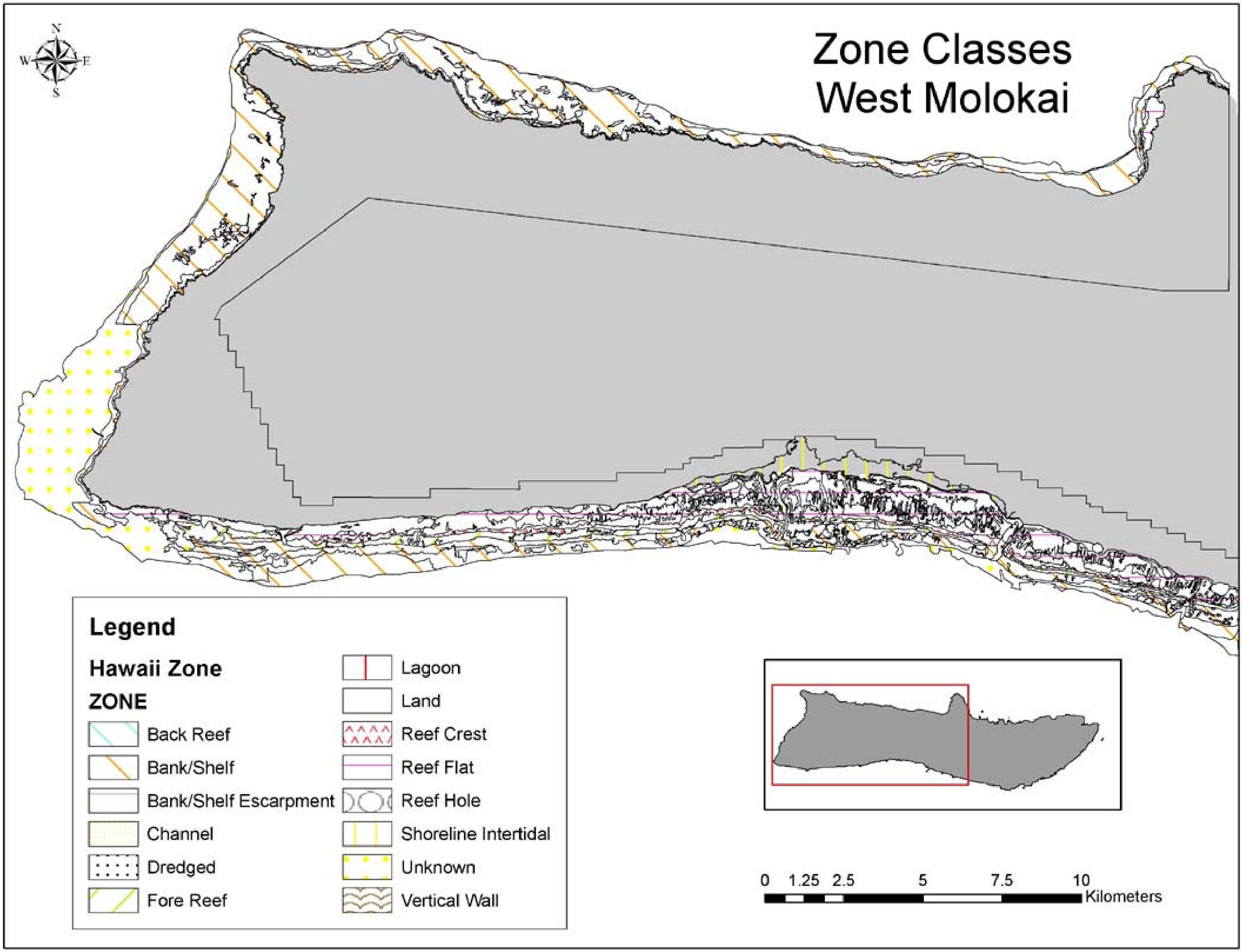

Figure 58. Reef habitat zone map of West Molokai.

10.16 Nihau

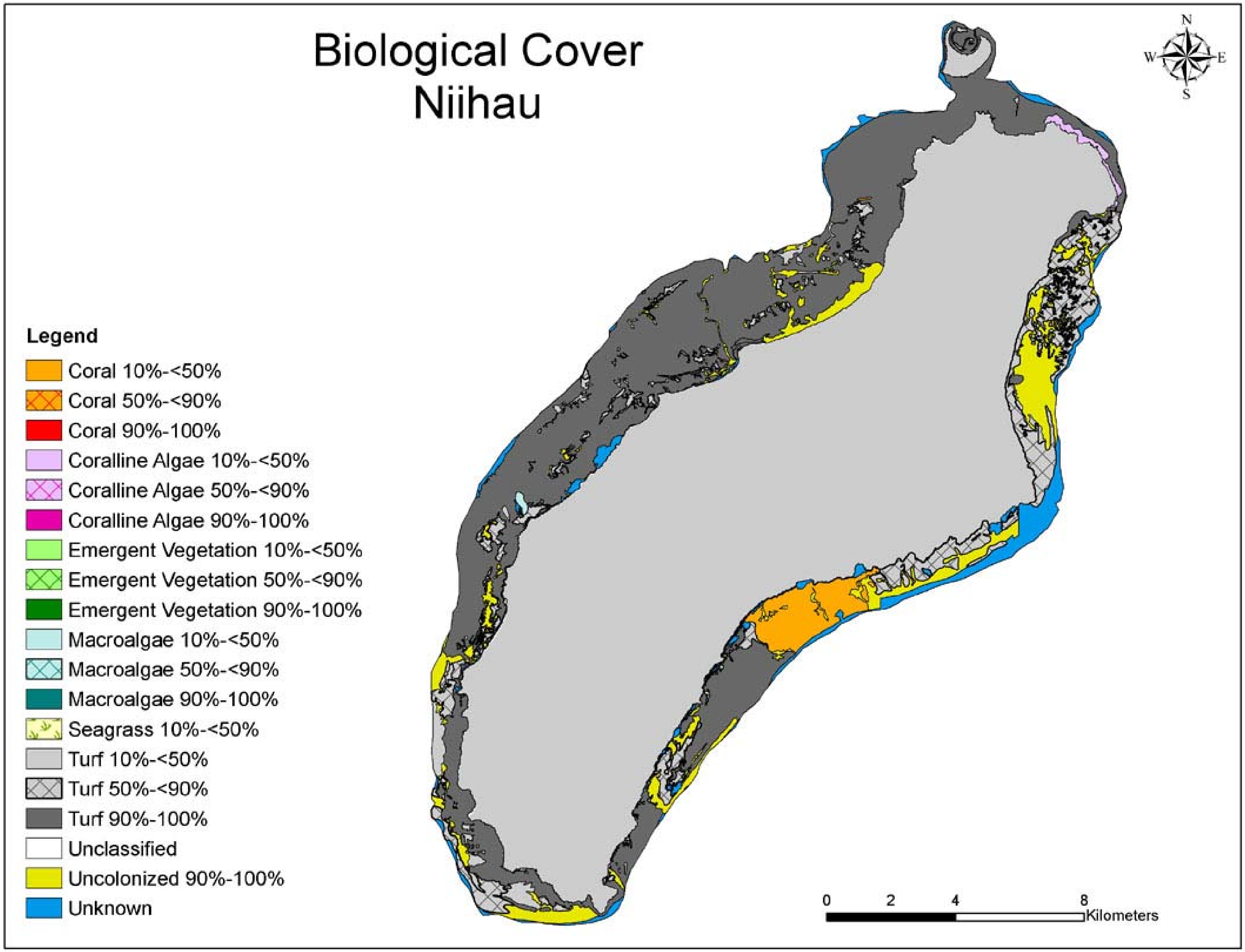

Figure 59. Biological cover map of Niihau.

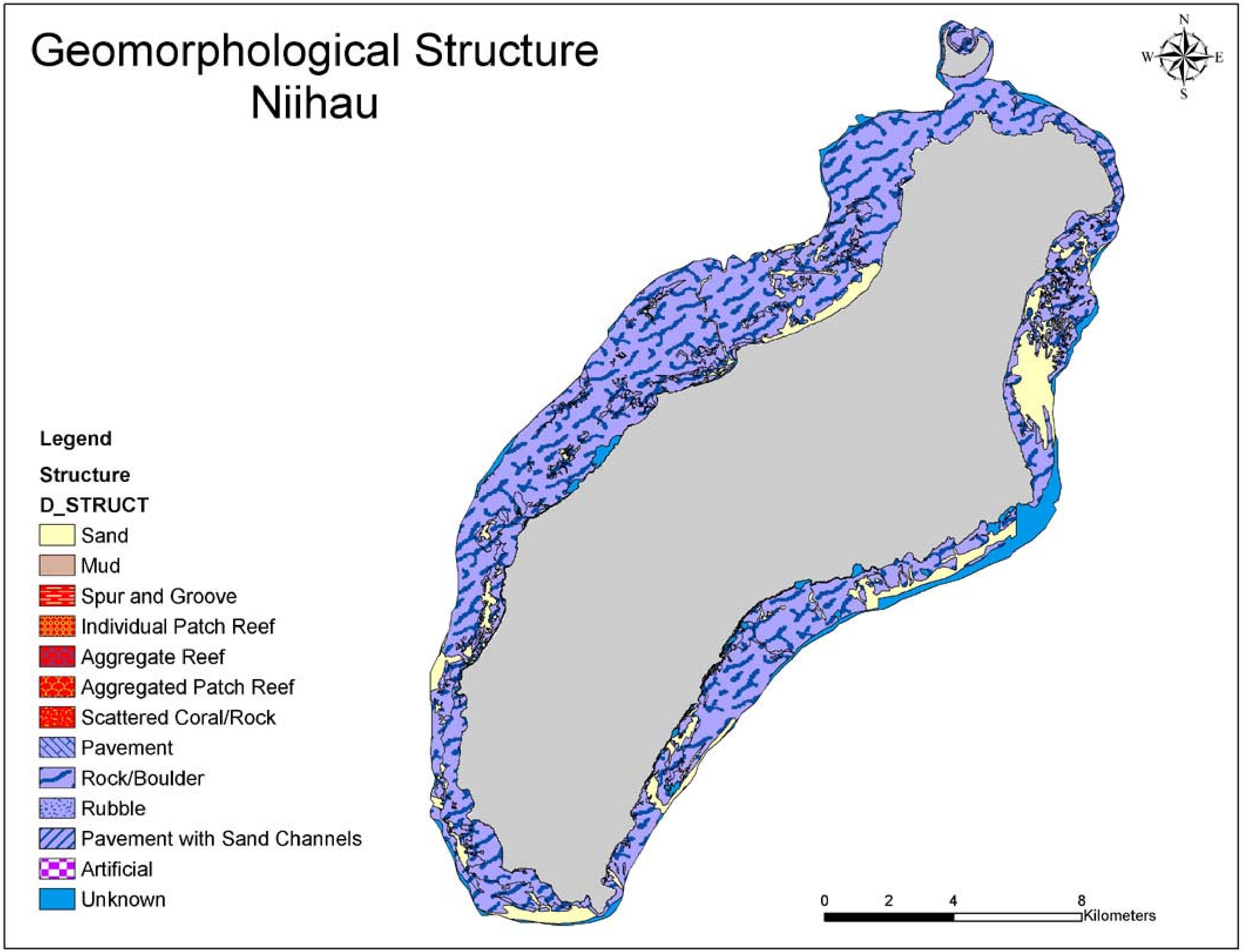

Figure 60. Geomorphological structure map of Niihau.

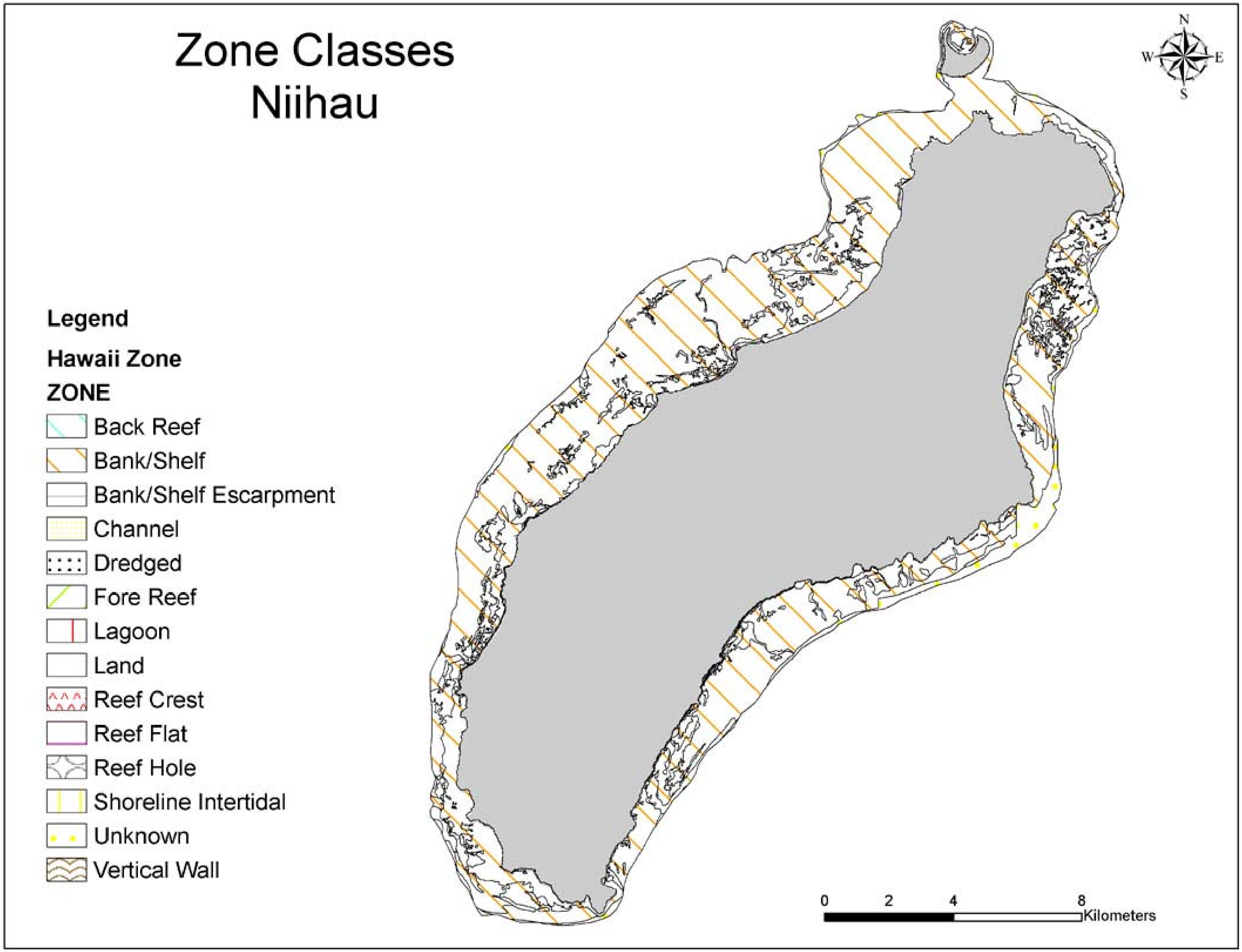

Figure 61. Reef habitat zone map of Niihau.

10.17 East Oahu

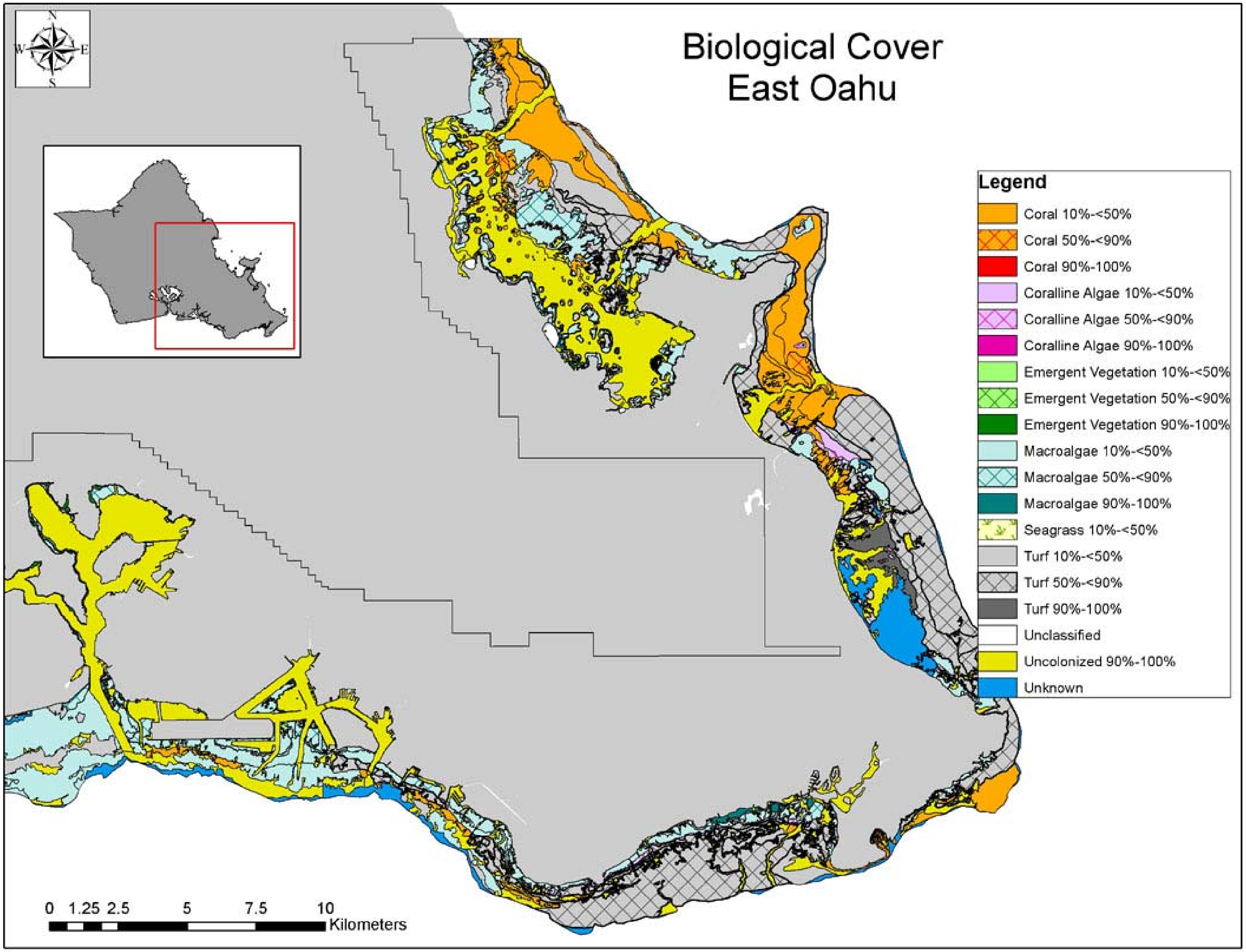

Figure 62. Biological cover map of East Oahu.

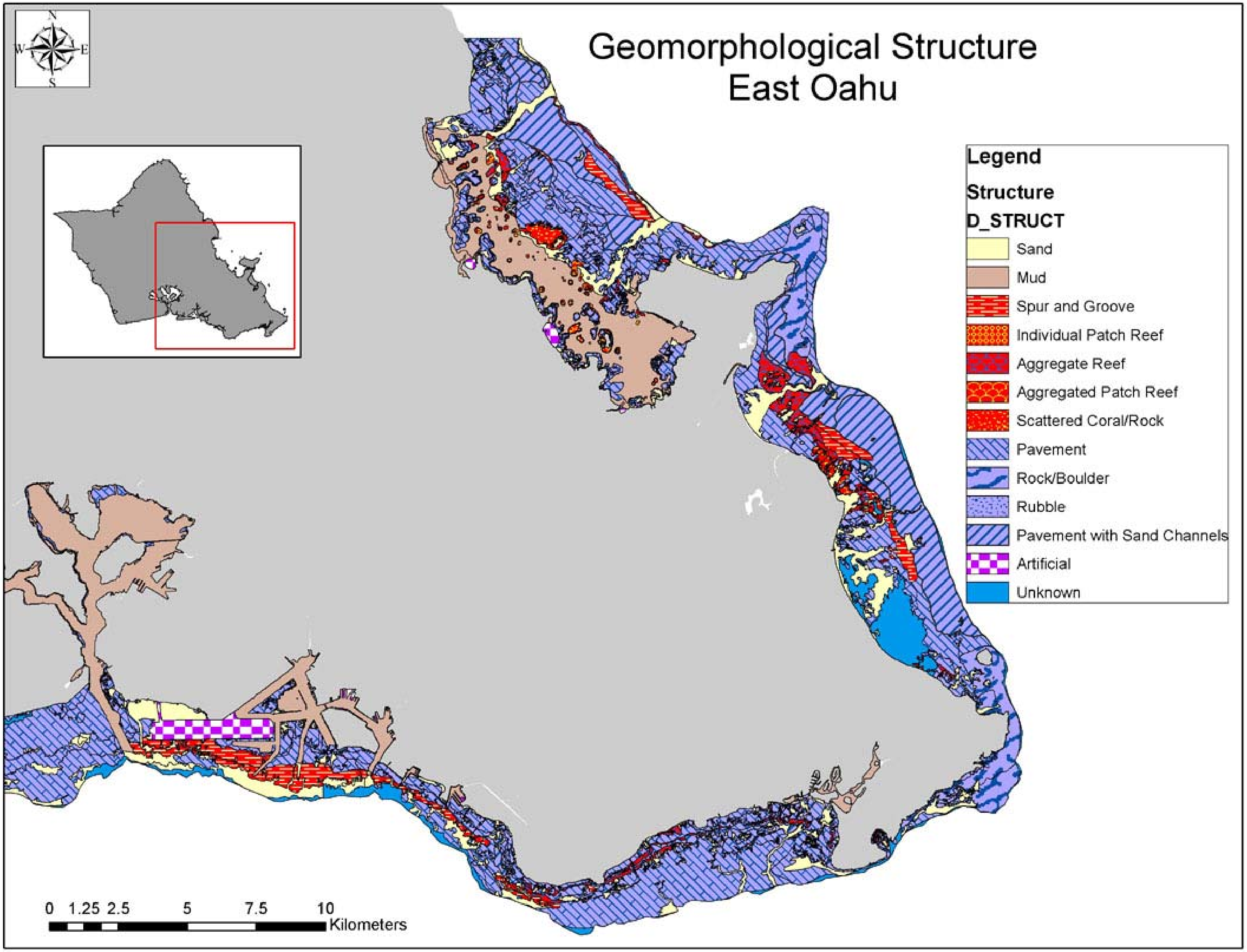

Figure 63. Geomorphological structure map of East Oahu.

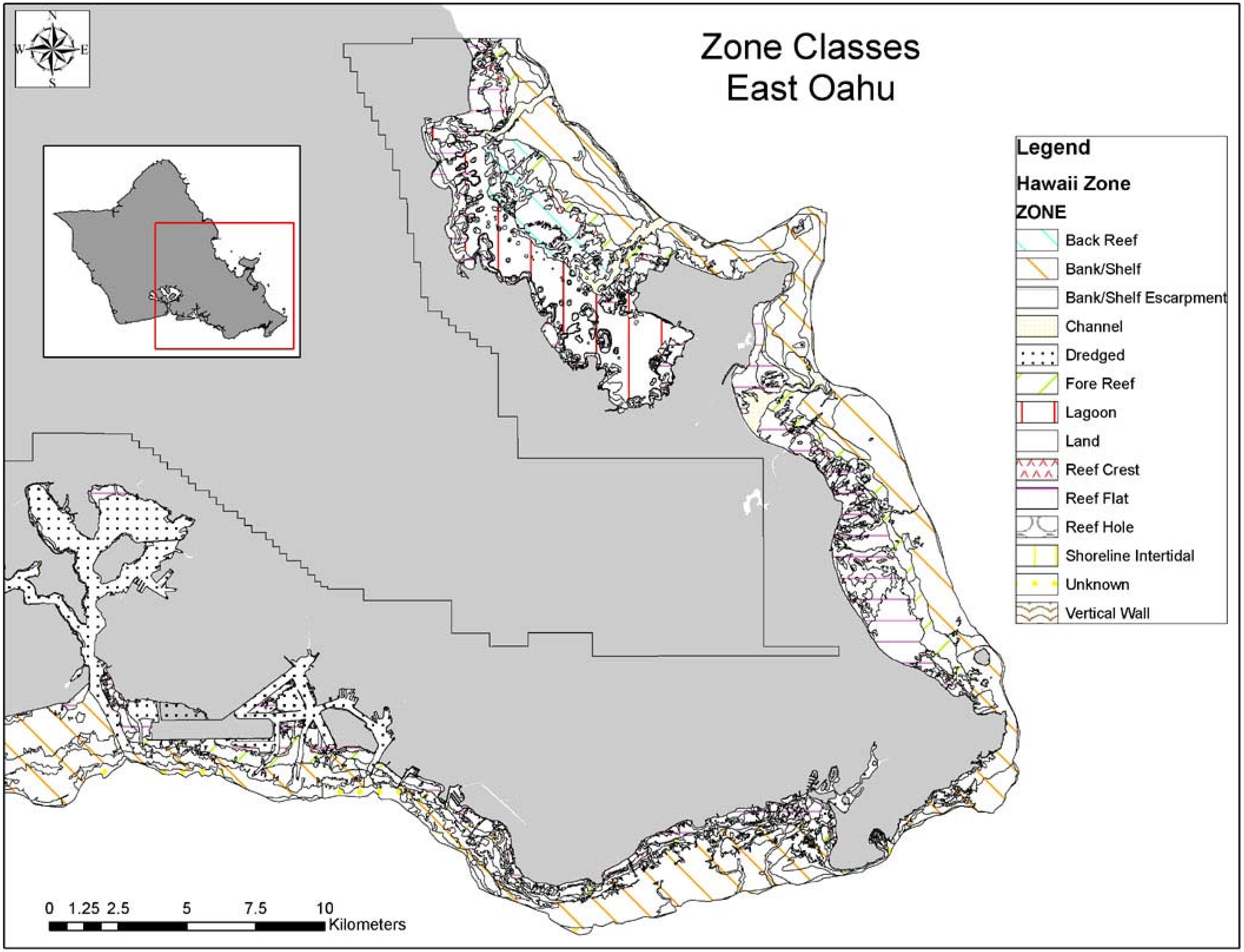

Figure 64. Reef habitat zone map of East Oahu.

10.18 West Oahu

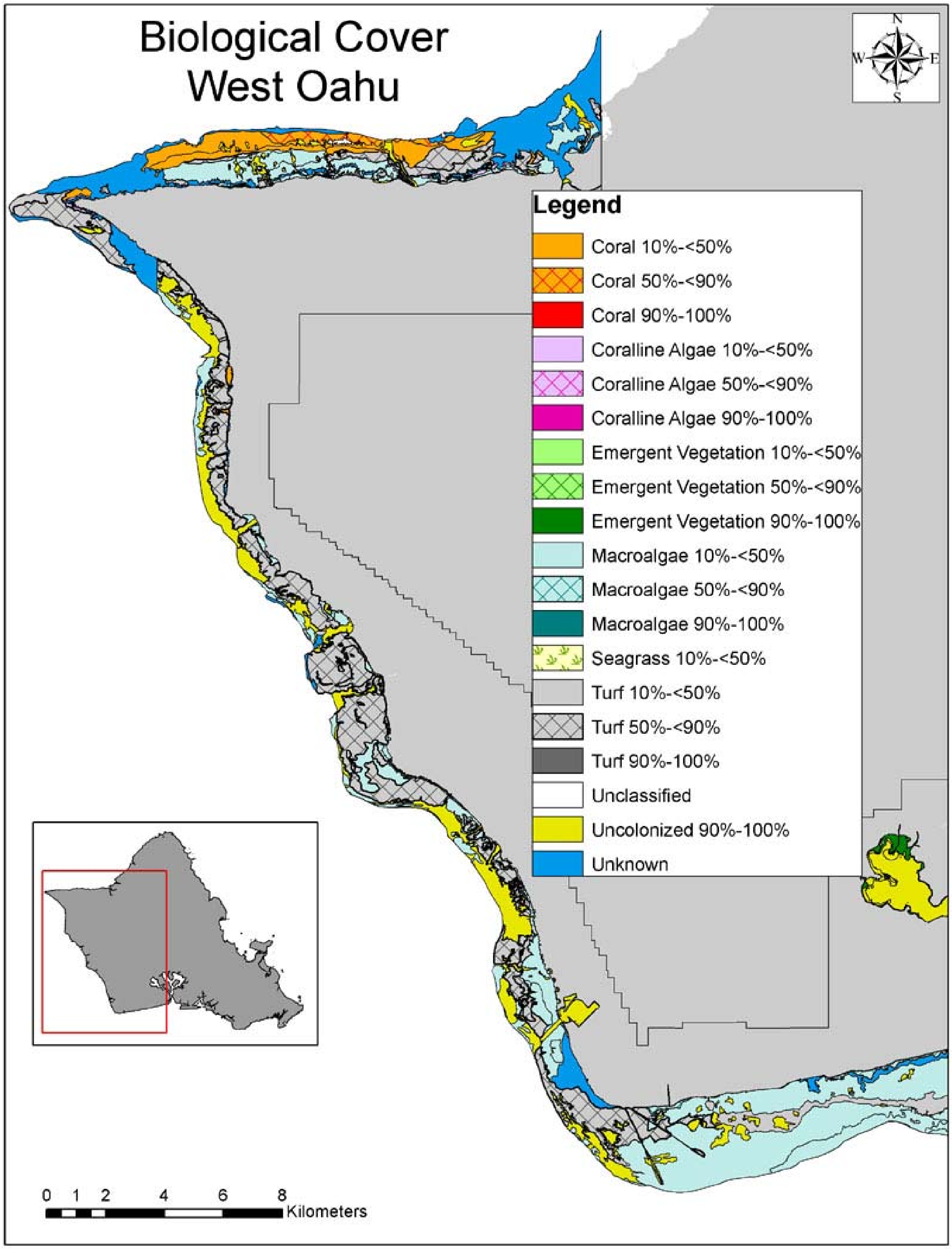

Figure 65. Biological cover map of West Oahu.

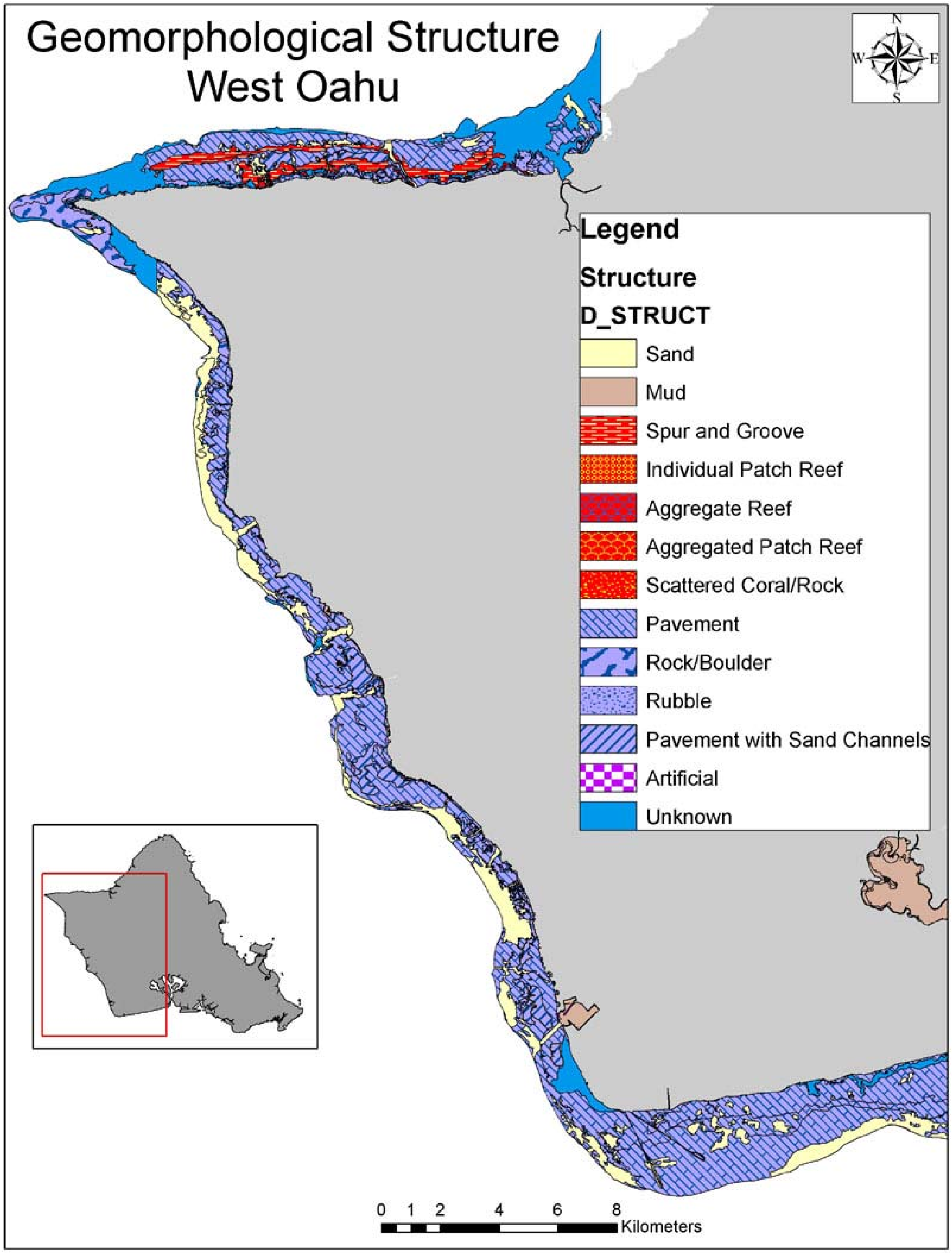

Figure 66. Geomorphological structure map of West Oahu.

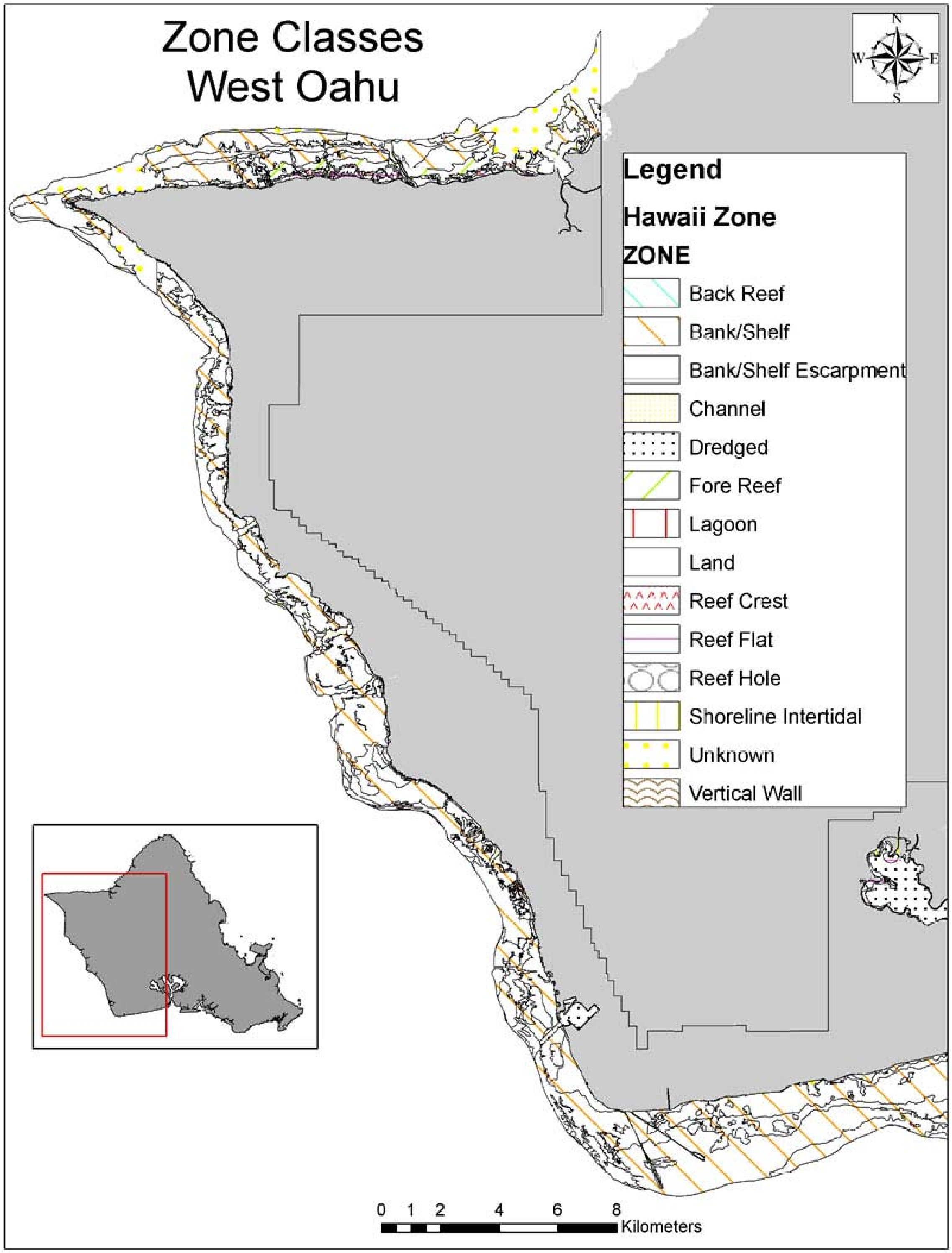

Figure 67. Reef habitat zone map of West Oahu.