Sand Distribution and Statistical Spatial Characteristics on Pacific Reef Platforms

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LONG-TERM GOALS

Our long-term goal was to improve understanding of sand distribution, temporal variability, and response to geologic substrate factors on Hawaiian reef platforms within the depth zone from 20 m to the shoreline.

OBJECTIVES

We analyzed patterns of sand deposit distribution on the reef platform, and documented relationships between sand deposits and reef morphology. Sand deposit patterns, the surrounding morphology, and the environments they are located in are best understood using a combination of statisitics, GIS software, spatial analysis tools, and analyst interpretation. The work consisted of several steps including remote sensing analysis, characterizing and classifying sand deposits, identification of patterns in sand deposit distribution, and interpretation of five general reef types and their ability to store sands.

Our top-level goal was to design and quantify a geologic model of the spatial distribution of carbonate sand on fringing reefs. Fringing reef sands are controlled by a combination of waves and currents (hydrologic environment) on the reefs and geologic factors governing hard substrate relief (i.e., karst bathymetry, spur and groove development, antecedent topography, etc.). These geologic factors exert important controls on the sandy seafloor that work together with dynamic sediment transport processes to determine sand accumulation. We identified several relationships between active sand accumulation and reef geologic factors controlling substrate relief.

There were three sub-goals targeted to facilitate designing and quantifying our geologic model. First, we refined our remotely sensed data processing techniques. This allowed us to prospect for sandy substrate across large areas of the fringing reef, creating sandy substrate maps for nearshore fringing reefs. Second, we developed a means to characterize individual deposits and segment them into functional subgroups. We selected a group of shape measurements that allowed us to characterize individual sand deposits by their 2-D surface shape. Then we developed a supervised class structure for segmenting sand deposits by their relationship between shape measurements and types of depressions. We also segmented sand deposits by depth across the fringing reef. Third, we viewed all sand deposits and segmented sand deposits as they are located on the fringing reef and within the coastal environment to define five general reef types that control sand storage.

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14. ABSTRACT
We analyzed patterns of sand deposit distribution on the reef platform, and documented relationships between sand deposits and reef morphology. Sand deposit patterns, the surrounding morphology, and the environments they are located in are best understood using a combination of statisitics, GIS software, spatial analysis tools, and analyst interpretation. The work consisted of several steps including remote sensing analysis, characterizing and classifying sand deposits, identification of patterns in sand deposit distribution, and interpretation of five general reef types and their ability to store sands.

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The five general reef types are our model for sand accumulation and storage. This model highlights the relationship between hydrologic environment (wave and currents) and substrate geology. Within the model several factors are emphasized: relationship between sand deposit surface shape and types of depressions, depth on the reef, general reef shape, hydrographic environment, and geologic substrate controls.

APPROACH

Step 1 – Remote Sensing Analysis

Methods are focused on developing simple and accurate techniques for sand identification in digital images. Digital images with red, green, and blue components, are the chosen media because they are more common, cheaper, and require less specialized acquisition equipment than hyper-spectral images. A georectified satellite digital image is our base image (Figure 1A).

Red, green, and blue bands all have different attenuation coefficients, with the red band penetrating only a short distance through the water column even in optically ideal conditions. To remove the confounding effects of depth within the water column on reflected data, we fuse individual color bands with a rasterized LIDAR depth band.

LIDAR (USACE SHOALS, *ca* 1999) datasets of the study sites are interpolated into bathymetry surfaces at the same resolution as the image data, and co-registered to the base image (Figure 1B). Modern LIDAR point collection in many sites is at almost the same scale as satellite imagery like that provided by Quickbird. Another useful derivative of the interpolated surface is a slope surface, recorded as increased intensity for steeper slopes it provides detailed information on relief and slope variability.

Attenuation in the water column is logarithmic with depth. Each color band (Figure 2A) is log transformed, creating a linear relationship between the color band and the depth channel, as long as the color band is in optically shallow waters. We assume our interpolated depth channel represents real depths, thus the relationship between light loss in each band and depth can be empirically derived. Each band pair is rotated, according to this relationship, with a Principal Component Analysis (PCA). This maximizes variation in the first component, and leaves all remaining variation in a second orthogonal component. The rotation coefficients are computed using a model that is carbonate sand pixels from all depths, identified within each image. Using a single reflector (bottom type such as carbonate sand) eliminates any variation that would be present from multiple reflectors. Rotation removes any correlation between the color band and depth, leaving a second component that is the color band as if the water column was not present (Figure 2B). In the case of the red band, this will not work when looking beyond its depth of detection, thus the results from rotating the red band beyond 5 m are not useful.

The new depth decorrelated blue and green bands are then used for sandy substrate discrimination. We used a combination of techniques to accommodate variable water qualities within each image. We began with generic classification algorithms, using which ever had the best initial results. Then we used a band threshold tool to identify the intensity value in each band, above which all brighter pixels were sandy substrate, and below which all darker pixels were not sandy substrate. The final step was hand digitizing to clean up some borders and fill in gaps not accurately represented in the data. We found this combination of techniques to be an effective and efficient method for rapid segregation of

basic substrate information classes, ("sandy substrate class" and "not sandy substrate class"). The result is a two-information class data set, with the primary information class identifying sandy substrate (Figure 2C). After applying this technique to all of data, we had created sandy substrate maps for ~40% of the fringing reefs around Oahu, Hawaii (Figure 3).

Step 2 – Sand Deposit Characterization and Classification

Following sandy substrate discrimination in the base image, we identified all unique sand deposits as continuous shapes within the sand class (14,037 total). These individual sand deposits were then quantified using six unique shape measurements: area, orientation of the major axis, form factor, roundness, solidity, and eccentricity. These six measures provided quantitative values for different characteristics in the sand deposit's surface shape. We then defined a class structure (Figure 4) that identified specific ranges of shape measurements that were related to different types of depressions on the reef's surface. The five sand deposit classes are: Channels and connected fields (97 identified), Complex fields and very large depressions (103), large depressions and fields (1282), linear deposits (1618), and small depressions and simple fields (10,937). This enabled us to compare the types of depressions holding sandy substrate and patterns of sand deposit shape characteristics from one area of the island to another.

After segmenting the data into five sand deposit classes, we also wanted to investigate the effect of the hydrologic environment on sand distribution. We defined three depth controlled sub-environments: shallower than 10 m, deeper than 10 m, and crossing the 10 m contour. These three environments, though generic in nature, were extremely informative into the depth controls on present on Oahu's fringing reefs. Shallower than 10 m is indicative of an environment controlled by antecedent topography and hydrologic shear stress. Deeper than 10 m is indicative of reef accretion's control on morphology. And crossing 10 m is a product of both shallower and deeper controls. We were able to compare sand deposit shape characteristics, class distribution, and percent sandy substrate coverage for the reef, in each of these depth ranges within the different areas of the island.

Step 3 – Identification of Patterns in Sand Deposit Distribution

We divided our study area, the fringing reefs of Oahu, into nine study regions (Figure 5, inset map). These regions were identified by changes in coastline orientation and differences in overall reef shape. Six were located on the east side, one on the west side, and two on the south side of Oahu. To identify patterns in sand deposit distribution we combined all quantifiable and interpretable data and compared the nine regions. We identified four major groups from the percent sandy substrate coverage values. Using sand deposit shape characteristics, presence of sand deposit classes, depth controlled sub-environment data, generalized wave environments, and overall reef shape, we were able to refine the four initial groups into five final groups. These five final groups were representative of distinct sand deposit distribution patterns within specific environments.

Step 4 – 5 General Reef Types

Figure 5 shows the five general reef types and their locations on Oahu, Hawaii. Each general reef type is named with a general reference to annual wave climate and general reef shape. Also listed with each general reef type is the percent of sandy substrate coverage. Energy level are for annual wave climate comparisons between general types. References to shape (wide, variable, and deep) are to whole reef shape interpretation. The most significant sand coverage was in "Low-energy wide reef" with >28%.

This type is exposed to southern Pacific swell (April-October) and occasional Kona storm waves (~9% of the year); has a wide back reef (~0.5 km) and a shallow reef crest (<3 m); and has a strong presence of Channels and connected fields, and Complex fields and very large depressions classes. The next general reef type is "Medium-energy wide reef" with the second highest sand cover at ~26%. This type is exposed to trade wind waves (~90% of year) and north Pacific swell (October-March); has a similar reef shape to "Low-energy wide reef;" and has similar presence of classes. Third is "Seasonally high-energy variable reef" with ~22% sand cover. This type is exposed to north Pacific swell, southern Pacific swell, and Kona storm waves; has a variable width back reef and a variable depth (3-15 m) reef crest; and has strong presence of Channels and connected fields class. "Medium-energy deep reef" has 14-15% sand cover; is exposed to trade wind waves and north Pacific swell; has a narrow back reef (<0.5 km) and a deep reef crest (>8 m); and has a strong presence of Channels and connected fields and Large depressions and fields classes. Similar to "Medium-energy deep reef" is "High-energy deep reef" that has 14-15% sand cover. One difference between the two is that "High-energy deep reef" is exposed to more direct north Pacific swell, as well as being exposed to trade wind waves. It also has a narrow back reef and a deep reef crest, and has a strong presence of Channels and connected fields, Large depressions and fields, and small depressions and simple fields.

These five general reef types express the interrelationship between hydrologic environment and nearshore geology in controlling the presence on nearshore sands and sand deposit shape and distribution patterns. These five types are a combination of quantifiable measurement data and interpreted environmental and morphology data. The final result provides a first order estimation for amount of nearshore sands and the type of reef depressions holding these features. As stated earlier, our research seeks to understand sand accumulation on fringing reefs and how it is influenced by hard substrate morphology. The steps outlined above provide necessary information for the construction of a geological model that is expressed as five general reef types.

Chris Conger, who completed his Master's of Science for Coastal Geology in the Department of Geology and Geophysics at the University of Hawaii in 2005, is the primary analyst. Chip Fletcher, professor of Geology in the Department of Geology and Geophysics at the University of Hawaii, is the principal investigator.

WORK COMPLETED

The project has been successfully completed. Results have been significant for refining classification techniques for nearshore sands, for developing new techniques for remote sensing data fusion and processing, for creating a classification structure for nearshore sands, and for defining general reef through sand storage, hydrologic environment, and geologic factors. As a result, this work has been presented at three conferences and will be published in three peer-reviewed journals.

RESULTS

Development of new remote sensing data fusion and processing techniques has significantly improved our ability to accurate and effeeiently identify nearshore carbonate sands on the fringing reef. Our selection of 2-D shape measurements allows us to quantify a unique assemblage of data for each sand deposit. Creation of a classification system that relates types and shapes of depressions on the reef's surface to quantifiable ranges in 2-D shape data allows us to unterpret subgroups within our sand deposits and relate them to nearshore geology. Dividing sand deposits by depth ranges allows us to investigate and quantify the effects of hydrologic environment on sand distribution. And finally,

defining general reef types that control sand distribution links hydrologic environmental controls, nearshore geology, and sand deposit storage data to better understand sasndy substrate distribution across the fringing reef, between 20 m depth and the shoreline.

A manuscript describing a portion of this work has been accepted by **Journal of Coastal Research** for publication, and will be published in the Winter 2005 journal. A manuscript describing the reomote sensing data fusion and processing technique has been accepted contingent on revisions by **IEEE's Transactions on Geosciences and Remote Sensing**. A mansucript describing the characterization and classification of sand deposits and the five general reef types controlling sandy substrate distribution is under review at **Marine Geology**. An abstract for the work completed on the Waikiki Test Area was accepted for presentation at the **Geological Society of America Annual Meeting** in 2003. A poster for spatial analysis work completed in Waikiki and Kailua was presented at the **American Geophysical Union's** annual meeting in 2004. The remote sensing data fusion and processing techniques were presented at the 6th annual **Joint Airborne LIDAR Bathymetry Technical Expertice Center (JALBTEC)** conference in 2005.

IMPACT/APPLICATIONS

This research has improved understanding the relationship of sandy and hard substrate on fringing reefs, and sandy substrate is controlled by a combination of hydrologic environment and geologic factors. This research has also defined a new method to decorrelate color band data from depth, a significant improvement in current techniques.

RELATED PROJECTS

We are collaborating on bottom characterization with the ONR funded mine burial study. We collaborated with the Department of Land and Natural Resources in a sand resource study on Oahu, Hawaii.

PUBLICATIONS

Conger, C.L., Fletcher, C.H., Barbee, M., 2003. Marine Carbonate Sand Location and Substrate Morphology Analysis Using PCA and Neural Networks on RGB Images. GSA Annual Meeting, Seattle, WA.

Conger, C.L., Fletcher, C. H., Hochberg, E.J., 2004. Identification and spatial distribution of remotely sensed sand on fringing reefs of Oahu, Hawaii. AGU Annual Meeting, San Fransisco, CA.

Conger, C.L., Hochberg, E.J., Fletcher, C.H., Atkinson, M., 2005. Decorrelating remotely sensed color bands from bathymetry. JALBTCX 6th Annual Conference, Philidelphia, PA.

Conger, C.L., Fletcher, C.H., Barbee, M., 2005. Artificial Neural Network Classification of Sand in all Visible Submarine and Subaerial Regions of a Digital Image. Journal of Coastal Research, scheduled for print Winter 2005 issue.

Conger, C.L., Hochberg, E.J., Fletcher, C.H., Atkinson, M., 2005. Decorrelating remotely sensed color bands from bathymetry in optically shallow waters. IEEE Transactions on Geoscience and Remote Sensing Letters, submitted and revised.

Conger, C.L., Fletcher, C.H., Hochberg, E.J., Frazer, N., Rooney, J.J., 2005. Patterns of sand distribution across fringing reefs on Oahu, Hawaii. Marine Geology, Submitted.
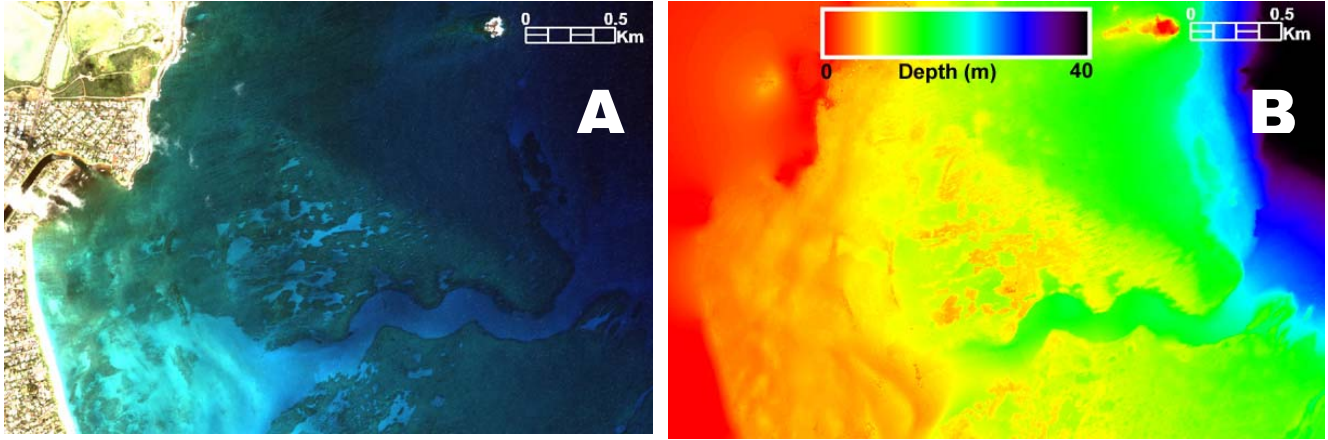
Figure 1. A) Color satellite image of Kailua Bay, Hawaii. This is a georectified Quickbird Satellite image with 2.4m pixel resolution. Blue, Green, and Red bands are used for image analysis. B) Bathymetry raster (image) for test section of Kailua Bay, Hawaii. Red areas are shallowest, black areas are deepest. This depth image was interpolated at the same pixel resolution and orientation as the digital color image.
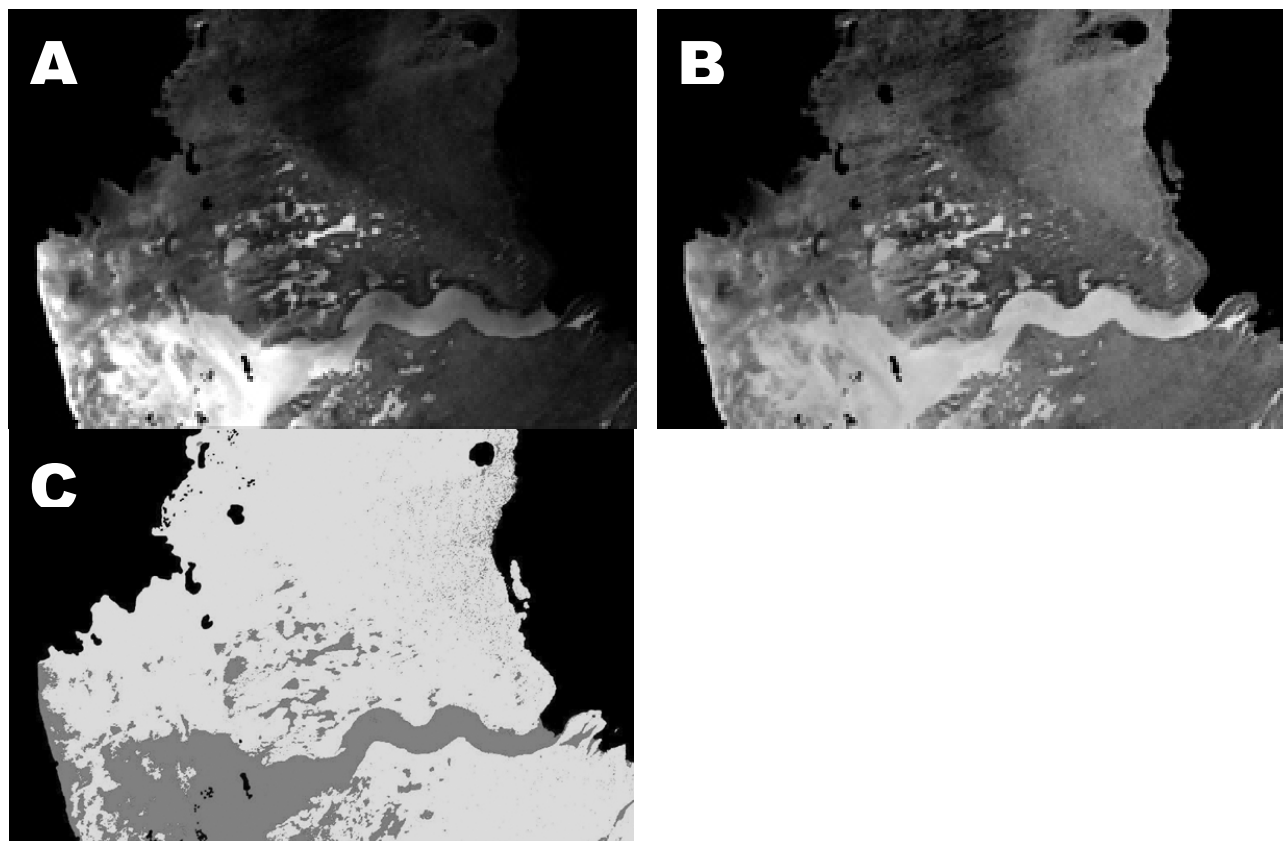
Figure 2. A) Original Kailua Bay, Hawaii, Quickbird blue band displayed in gray scale. B) The depth decorrelated color image, produced by rotating the blue color band and the depth band together, thus removing the confounding effects of the water column. C) Classified sand map created by application of substrate discrimination techniques on depth decorrelated color bands. Gray pixels are identified sandy substrate, black pixels are masked from the scene, and white pixels are marine substrates that are not sand.
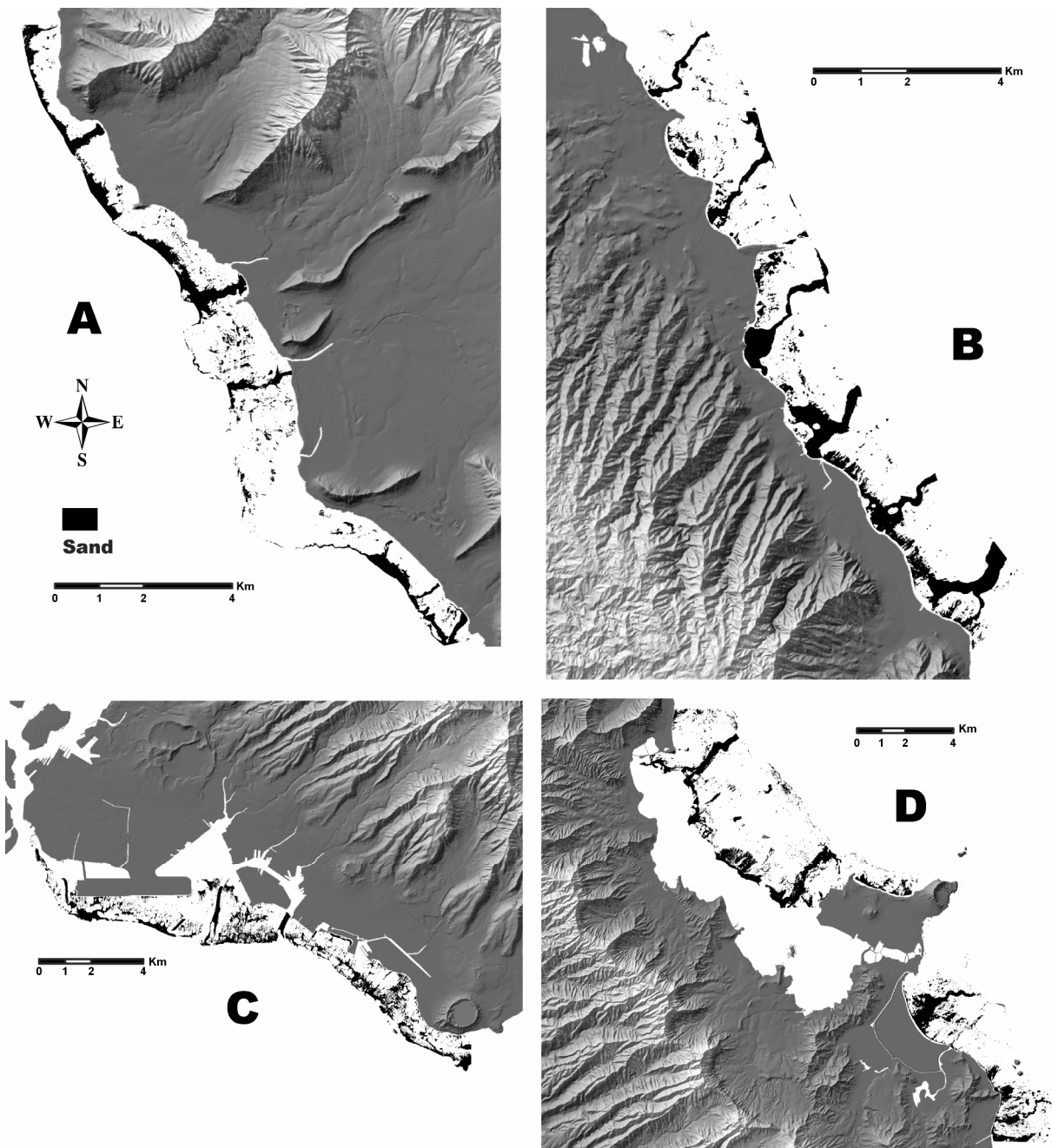
Figure 3. Identified sandy substrate on the nearshore fringing reefs of Oahu, Hawaii. These four areas (A-D) comprise ~40% of the nearshore fringing reef of Oahu. All black pixels are identified sands, Oahu is represented by a gray scale topographic map. A) Nearshore sands along the Waianae coastline on western Oahu. B) Nearshore sands along the north-eastern coastline of Oahu, from Punaluu in the south to Kahuku in the north. C) Nearshore sands along the southern coastline of Oahu, from Diamond Head in the east to Pearl Harbor channel in the west. D) Nearshore sands along the eastern coastline of Oahu, from Waimanalo Bay in the south through Kaneohe Bay in the north.
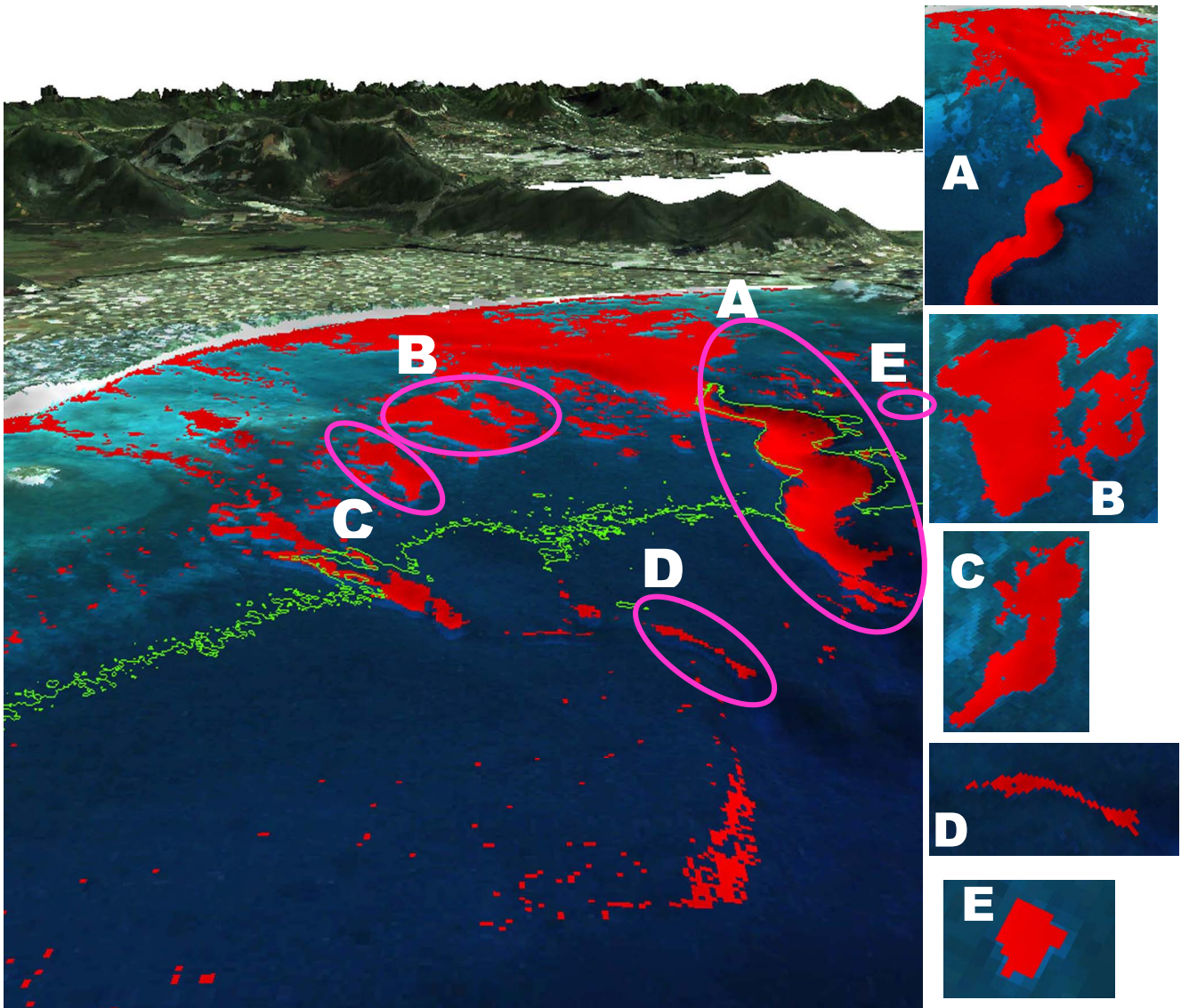
Figure 4. Image of coastal zone for Kailua Bay, Oahu. Red pixels are identified carbonate sands. Magenta ovals identify regions used as examples for each sand deposit class. Each class example is labeled in both the scene on the left, and the blown up image on the right. A) Channels and connected fields class. These sand deposits are winding and elongate shapes with complex borders and lots of open space. They typically fill paleo-stream channels and have connected nearshore and/or offshore sand fields. B) Complex fields and very large depressions class. These sand deposits are rounded with complex borders and lots of open space. They typically fill multiple depressions linked through sand and large terraces or back reefs. C) Large depressions and fields class. These sand deposits are elongate with moderately complex borders and minor open space. They typically fill single depressions and isolated sections of terrace or back reef. D) Linear deposits class. These deposits are very elongate with simple borders and fill almost all open space. They typically fill very elongate and narrow depressions or are sediments strung out across flat bottom. E) Small depressions and simple fields class. These deposits are very rounded with very simple borders and fill almost all open space. They are typically filling small circular depressions or shallow and small swales on the reef's surface.
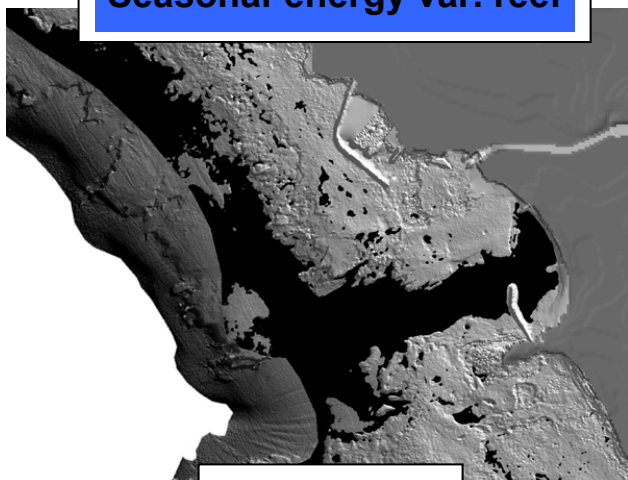
Low-energy wide reef
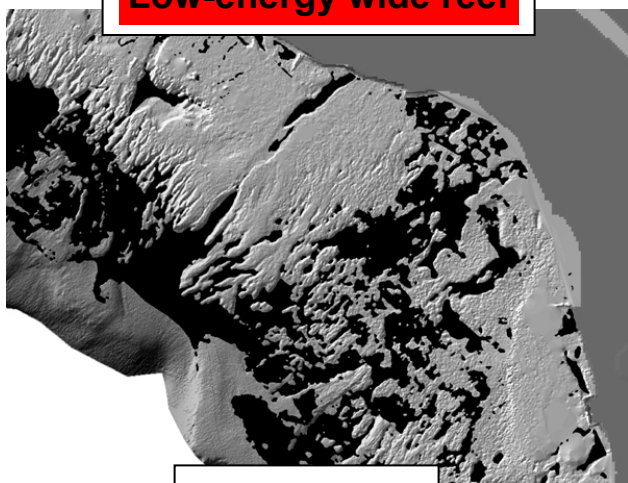
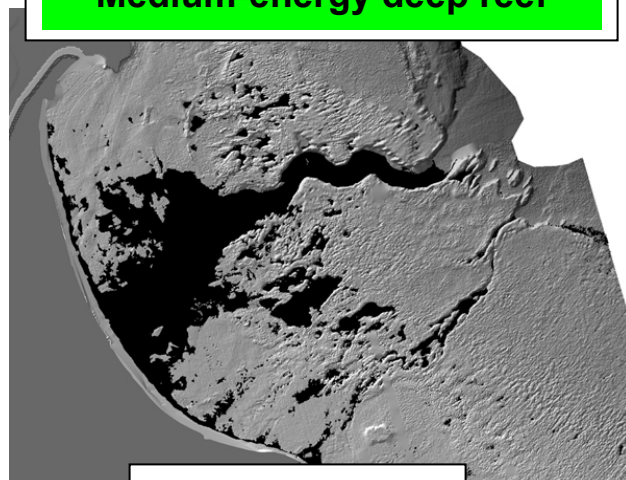>28% Sand

Medium-energy wide reef
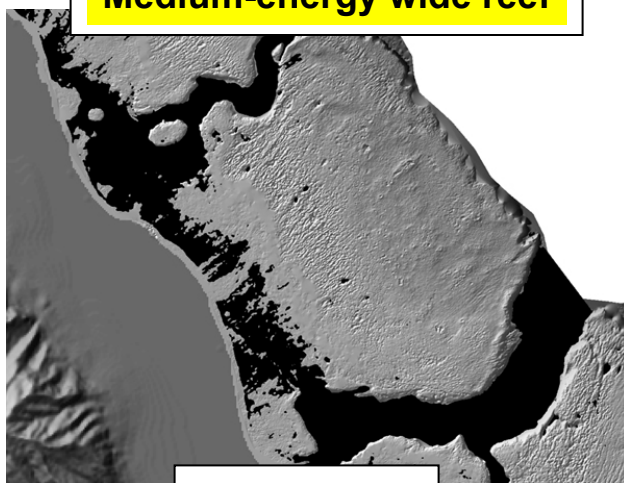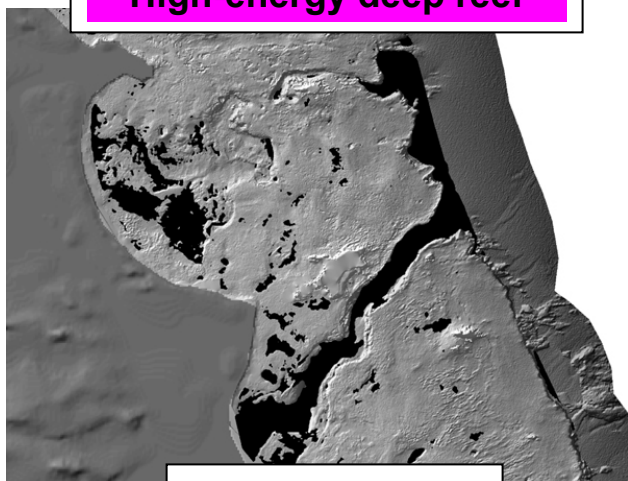
~26% Sand

Seasonal-energy var. reef

~22% Sand

Medium-energy deep reef

14-15% Sand

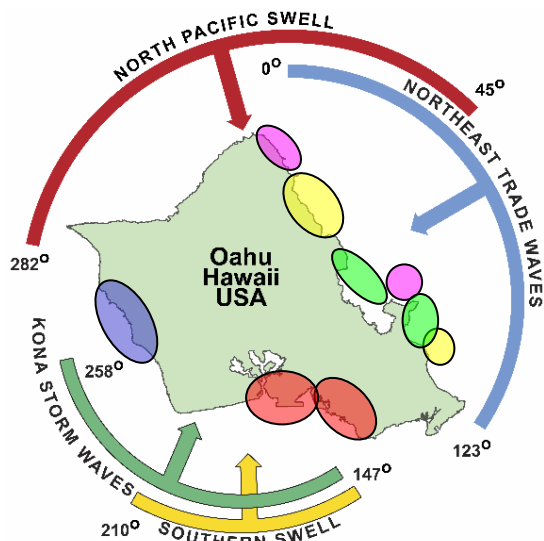**High-energy deep reef**

14-15% Sand

NORTH PACIFIC SWELL

NORTHEAST TRADE WAVES

KONA STORM WAVES

SOUTHERN SWELL

Oahu
Hawaii
USA

0°
45°
123°
147°
210°
258°
282°

Figure 5. Display of 5 general reef types and their locations on the nearshore fringing reefs of Oahu, Hawaii. These general reef types were identified by combining percent reef covered by sand data, shape measurement data on individual and groups of sand deposits, sand deposit classification data, depth controlled sub-environment data, regional distribution data, whole reef shape interpretation, and annual wave climate information. References to energy level are for annual wave climate comparisons between general types. References to shape (wide, variable, and deep) are to whole reef shape interpretation. Bottom number on each reef type is the percent of reef covered by sandy substrate. The color in each type's label matches the colored ovals on the map of Oahu, Hawaii, marking regions of nearshore reef that are identified as that general reef type. A) Low-energy wide reef has the highest percent sand cover (>28%); is exposed to southern Pacific swell (April-October) and occasional Kona storm waves (~9% of the year); has a wide back reef (~0.5 km) and a shallow reef crest (<3 m); and has a strong presence of Channels and connected fields, and Complex fields and very large depressions classes. B) Medium-energy wide reef has the second highest sand cover (~26%); is exposed to trade wind waves (~90% of year) and north Pacific swell (October-March); has a similar reef shape to A; and has similar presence of classes. C) Seasonally high-energy variable reef has ~22% sand cover; is exposed to north Pacific swell, southern Pacific swell, and Kona storm waves; has a variable width back reef and a variable depth (3-15 m) reef crest; and has strong presence of Channels and connected fields class. D) Medium-energy deep reef has 14-15% sand cover; is exposed to trade wind waves and north Pacific swell; has a narrow back reef (<0.5 km) and a deep reef crest (>8 m); and has a strong presence of Channels and connected fields and Large depressions and fields classes. E) High-energy deep reef has 14-15% sand cover; is exposed to trade wind waves and north Pacific swell; has a narrow back reef and a deep reef crest; and has a strong presence of Channels and connected fields, Large depressions and fields, and small depressions and simple fields.