Reef-Top Sediment Bodies: Windward O‘ahu, Hawai‘i[1]

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Abstract: Hawaiian fringing reefs display sand bodies on their surfaces that are potentially important components of littoral sediment budgets. This work provides a regional survey of modern reef-top sediment storage and investigated geologic controls on sediment storage potential. Sand bodies are formed when sediment accumulates in topographic depressions that are the result of meteoric water eroding the emerged carbonate reef platform during periods of lower sea level. The relief of some depressions may be modified by Holocene reef accretion. Depression morphology exerts a strong control on volume and internal distribution of sediment. In this study a total of 205 jet probe thickness measurements was collected from 54 major sand bodies on the fringing reef (0–20 m depth) adjacent to 22 km of Southeast O‘ahu coastline (Kailua, Lanikai, and Waimānalo). Volumes were determined and synthesized with previous volume estimates of coastal subaerial and deeper submarine sediment bodies (20–200 m depth), giving the total sediment storage within the coastal system. Sand bodies range from 50 to 2,800 m from shore. Measured thickness varied from 0 to greater than 3.0 m with a mean of 0.95 m. For this study sand bodies were classified into three dominate morphologies: channel, field, and karst depression. The volume of sediment stored in channels was $58{,}253 \pm 618 \times 10^3$ m^3, fields contained $171 \pm 6 \times 10^3$ m^3, and karst depressions contained $1{,}332 \pm 248 \times 10^3$ m^3. Correlation of sediment body distribution with reef and coastal plain morphology revealed potential geologic controls on sand body formation in this region. Meteoric runoff and reef slope are important controls on spatial distribution of sand bodies.

Erosion of Hawaiian sandy beaches threatens important aspects of Hawaiian culture, economy, and ecology. Recreation, sense of identity, ecological stability, and economic prosperity are all closely tied to the existence or perception of pristine white sandy beaches rimming the shoreline. To ensure the longevity and sustainability of Hawaiian beaches, we must recognize carbonate sediment in the coastal zone as an important natural resource to be managed from an informed scientific perspective. In an effort to contribute to management and scientific understanding of sediment flux and storage, this research has three primary objectives:

1. Survey major sediment bodies to identify potential sources of shallow (<20 m depth) beach replenishment material
2. Establish a total storage value for the regional sediment budget
3. Correlate sediment distribution with regional morphology and sea level history to identify potential geologic controls on sediment storage

These goals were applied to a nearshore fringing reef on windward O‘ahu, Hawai‘i, occupying 22 km of coastline in Kailua, Lanikai, and Waimānalo (Figure 1).

Unconsolidated sediment accumulates across the reef surface as it is created either by erosion of reef framework or directly de-

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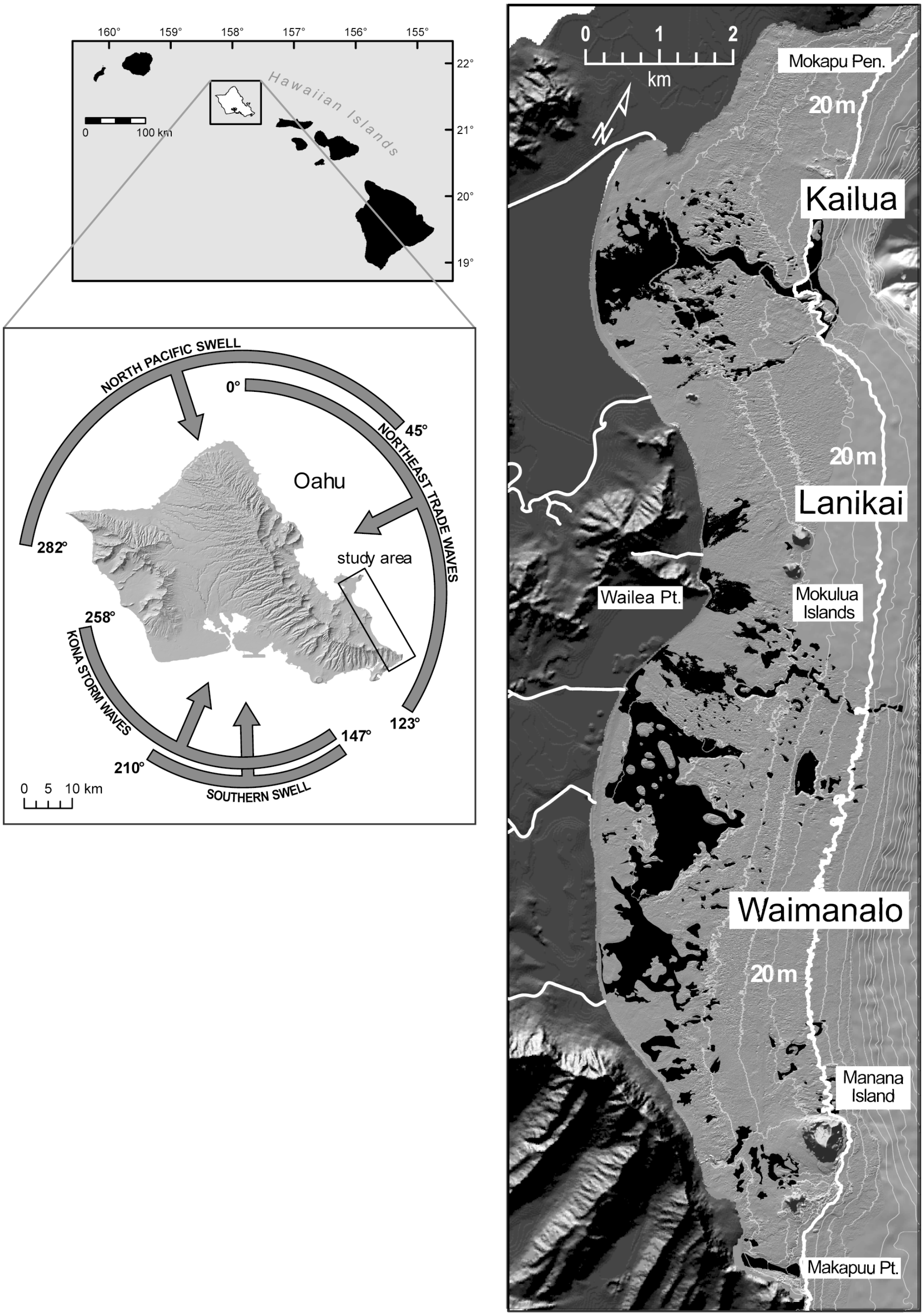

FIGURE 1. *Top left:* Location of study area on the island of O'ahu in the Hawaiian Islands. *Bottom left:* Dominant swell components on O'ahu with study area indicated. *Right:* View of coastal zone topography and bathymetry, showing 5 m depth contours, regional divisions. Sand coverage indicated in black and streams indicated by white lines on land.

posited as skeletal components (Harney and Fletcher 2003). In many cases this sediment fills reef-top depressions, creating discrete isolated sediment bodies. Sediment bodies are conspicuous features on reef flats, displaying large variation in size, shape, and location and easily recognized in remotely sensed imagery (Conger et al. 2005). Sediment bodies also represent a prominent component of the geologic framework of insular shelves and potentially play an active role in littoral sediment budgets. Sediment exchange between sand bodies and the beach face could be an important component of shoreline stability and in some cases can provide quantities of affordable sand for beach replenishment (Moberly and Chamberlain 1964, Casciano and Palmer 1969, Moberly et al. 1975). However, their role in littoral processes needs to be better understood to define best management practices.

The majority of reef-top depressions are relict features incised into the surface of Hawaiian reef platforms via dissolution or fluvial erosion during periods of lower sea level when subaerially exposed limestone is in contact with meteoric waters (Purdy 1974). The resulting channel and karst-doline landscape is drowned by rising sea level and subsequently filled with sediment, unless depressions are closed by new reef accretion (Conger 2005).

Sediment trapping on the reef surface keeps sand potentially available for circulation within a littoral cell rather than lost to offshore sites (Grossman et al. 2006). Most sediment in reef systems is produced on the shallow nearshore platform where carbonate productivity and erosion are the highest. Sediment will remain on the reef platform in storage or as part of the active littoral system unless it is transported seaward of the reef crest and insular shelf (Harney and Fletcher 2003). Once sediment crosses this threshold, the comparatively steep angle of the fore reef slope likely prevents most shoreward transport, effectively removing sediment from littoral circulation. On many islands steep submarine terraces at >20 m depth exacerbate sediment loss by presenting a seaward-facing sharp break in topography (Coulbourn et al. 1974). In some cases large channels are incised, perpendicular to the shoreline and through the reef crest, creating a potential pathway for sediment exchange between inner and outer portions of the reef platform (Grossman et al. 2006).

In this paper, we report findings from 205 jet probe thicknesses from 54 reef-top sediment bodies in shallow (0–20 m) depths (Bochicchio et al. 2006). The study region encompassed 22 km of Oʻahu's windward coast between Makapuʻu Point and Mōkapu Point, including Kailua Bay, Lanikai, and Waimānalo Bay. Volume estimates and uncertainties were extrapolated from thickness data for each sediment body. A synthesis of previously measured subaerial, reef-front (20–200 m depth), and unsampled sediment bodies defined total sediment storage in the study area. Sediment body morphology and spatial distribution were examined in the context of geologic processes to determine potential environmental factors influencing sediment storage potential on the reef platform.

Study Area

A relatively deep fringing reef platform in the study area extends 3–3.5 km from the shoreline to a depth of approximately 20 m where a steeply dipping fore reef slope descends to a lower terrace at approximately 30 m depth. The reef crest shallows to between 0 and 5 m depth at 0.3–1.0 km from shore along 70% of the study region.

Kailua Bay supports a 12 km^2 fringing reef platform that extends from a carbonate sand beach to approximately 20 m water depth. The reef platform is bisected by a sinuous 200 m wide sediment-floored channel, which is likely the extension of drainage from the Kailua watershed during lowered Pleistocene sea level. The channel widens landward into a broad triangular sand body in approximately 5 m depth terminating at Kailua Beach; a similar body is present at the offshore mouth in 20–35 m water depth (Hampton et al. 2004). Sand-filled, reef-top karst depressions of various sizes are present to the north and south of the channel. The fragmented remains of a smaller channel system extend over the reef platform in the southern region of the bay. Holocene reef accretion is likely responsible for closing and fragmentation of the channel. Kailua Beach has shown a trend of accretion (0.5 m/yr) over the last 70 yr (Norcross et al. 2002).

The Lanikai region is a slightly embayed headland with southerly Wailea Point the farthest seaward point and the twin Mokulua Islands located immediately offshore. Three large sand fields, separated by a shallow patchwork of coral heads, extend seaward from shore, diminishing toward a prominent reef crest. South of the Mokulua Islands, a complex of steeply bounded sand-filled depressions and a portion of a channel are incised across the shallow (<2 m depth) back reef.

Waimānalo Bay's reef flat supports a large (~2.9 km^2), steep-walled (~10% slope) basin with a sandy bottom 3–5 m below the reef surface. Within the basin are circular to oval elevated outcrops resembling patch reef, rising from the sandy seafloor. A shallow reef crest occurs 1.5–0.3 km from shore; it is farthest from shore in the northern part of the bay and gradually trends closer to shore to the south, where it is most prominent. Two volcanic islands are present in the southern portion of the bay; Mānana Island is the largest.

Wave Environment

Wave energy influences coastline stability, nearshore sediment transport, and mechanical abrasion on the reef. Hawai'i's regional wave climate was described in four components by Bodge and Sullivan (1999):

1. High-energy swell is created during the winter by storms north of Hawai'i. Waves are incident on west-northwest to north-northeast shorelines with typical heights of 1.5–4.5 m and periods of 12–20 sec.
2. Lower-energy south swell occurs between the months of April and October. Waves are incident on most south-facing shorelines and have typical heights of 0.3–1.8 m and periods of 12–20 sec.
3. Kona storms infrequently produce from the south and west wave heights of 3–4.5 m and periods of 6–10 sec.
4. Trade wind waves consistently approach from the general east to northeast quadrant for 90% of summer months and 55–65% of winter months (Grigg 1998). Trade wind wave heights are 1.2–3 m with periods of 4–10 sec.

In addition, large but infrequent hurricane waves can have considerable impact on the reef (Fletcher et al. 2002).

The primary wave regime for our windward study area is governed by the consistent full strength of trade wind swell. This swell is modified by annual and decadal wave events from the north and south that refract into the study area. Large south swell is less dominant than north swell in this regard. Easterly storms may also impact the study area with high winds and/or high waves approaching on an interannual basis from the northeast, east, or southeast. Calmest conditions in the study area occur during Kona wind conditions as trade winds diminish, frequently producing offshore airflow.

Shelf Geology and Reef Accretion

The underlying carbonate framework of the study area is the product of reef accretion over recent interglacial cycles. Specifically, the primary structural unit of the shallow O'ahu shelf is a fossil reef complex dating from Marine Isotope Stage (MIS) 7 (ca. 190,000–210,000 yr before the present [B.P.] [Sherman et al. 1999, Grossman and Fletcher 2004]). The front of this shelf accreted separately during MIS 5a–d (ca. 80,000–110,000 yr B.P.). Eolianites of late last interglacial age (ca. 80,000 yr B.P. [Fletcher et al. 2005]) are found on the nearshore and coastal plain regions of the study area and greater windward O'ahu.

Holocene accretion is a subject of considerable research. Grigg (1998) showed that high wave stress in Hawai'i has generally limited large regional Holocene reef accretion to sheltered embayments, such as Kāneʻohe and Hanauma Bay. Grossman and Fletcher (2004) showed that in addition to the regional effects of shoreline orientation relative to ocean swell, Holocene reef accretion is controlled by the more spatially and temporally specific interactions of sea level history, antecedent topography, and wave energy. They showed that Holocene accretion tends to occur at topographic depressions on the reef where shelter from wave energy increases accommodation space above or below wave base on the fore reef slope. Grossman et al. (2006) presented high-resolution subbottom seismic reflection data correlated with drill cores that show a distinct erosional boundary marking the beginning of Holocene reef framework growth. From this they confirmed Holocene reef accretion to be a complex and patchy unit emplaced during the period of 8,000 to 3,000 yr B.P. Rooney et al. (2004) demonstrated that Holocene accretion in regions exposed to north swell largely terminated ca. 5,000 yr B.P. They hypothesized that this is related to increased storminess associated with enhanced El Niño–Southern Oscillation dynamics in the middle Holocene.

Much of the sediment in the study area is stored within relic erosional depressions of pre-Holocene age incised during low sea level stands. Once reinundated, these depressions provide accommodation space and shelter from wave energy for reef accretion (Grossman and Fletcher 2004, Grossman et al. 2006). This accretion could potentially reduce available space for sediment storage on the reef (Conger et al. 2005).

General Sediment Characteristics

Moberly and Chamberlain (1964) characterized Kailua Bay, Lanikai, and Waimānalo Bay as having very poorly sorted highly calcareous beach sands and large but thin patches of offshore sediments. Kailua and Lanikai sediments are described as poorly sorted, with Kailua tending toward bimodality (two dominant size classes). Waimānalo sediments are described as coarse- to medium-grained and vary from well sorted to poorly sorted with high Foraminifera fractions. Landward of Kailua and Waimānalo beaches are modern vegetated dunes and older lithified eolianites, consisting of coarse well-sorted sand, in which Foraminifera constitute the highest compositional fraction.

Sediment Production

Harney et al. (2000) analyzed sediment composition collected from beach, channel, and reef-top sand bodies in Kailua Bay. Harney determined that >90% of sediments were biogenic carbonate, dominated by coralline (red) algal fragments. Framework sediments (coral and coralline algae) are produced offshore, and direct sediment production (*Halimeda*, mollusks, and benthic Foraminifera) occurred largely nearshore. Radiometric dating shows most surficial sediments to be middle to late Holocene in age, suggesting relatively long storage times and weak short-term sediment production. Harney et al. (2000) concluded that sand stored in Kailua Bay represents production under a higher sea level stand (+2 m [Grossman and Fletcher 1998]) that retreated during the late Holocene.

Grossman and Fletcher (2004) speculated that a middle Holocene shift in sediment production occurred, caused by movement of the zone of most prolific coral growth from the shallow reef flat to the deeper fore reef. Sediment produced on the fore reef is more likely to move into deeper water, where it is lost to the littoral sediment system. This raises the possibility that sediment stored in many reef-top sediment bodies is a remnant of a more productive sediment system that has been preserved by karst and channel depressions.

Previous Sediment Investigations

Moberly et al. (1975) completed the first intensive survey of offshore sand resources around Oʻahu. Spatial extents of offshore sand fields were roughly mapped by aerial surveys. Major sand bodies from 0 to 18 m depth were mapped for the Kailua and Waimānalo areas; however the survey of deeper sand bodies (18–90 m depth) excluded this study region.

Ocean Innovators, Inc. (1978, unpubl. report prepared for U.S. Army Engineer Pacific Ocean Divison; 1979, unpubl. report prepared for Hawai'i Marine Affairs Coordinator, Office of the Governor, State of Hawai'i, Order No. 163) completed a jet probe survey of the deep (10–20 m depth) Kailua channel and an adjacent sediment body for the U.S. Army Corps of Engineers in 1978. Minimum volumes estimated for the deep channel were $3{,}700 \times 10^3$ m^3, and for an adjacent sand body, 208×10^3 m^3.

Harney and Fletcher (2003) estimated total sediment volume in Kailua Bay from 0 to 40 m of water to be $5{,}425 \pm 289 \times 10^3$ m^3 and $16{,}749 \pm 1{,}809 \times 10^3$ m^3 in the coastal plain deposited during a 5,000 yr +2 m sea level high stand (Kraft 1982, 1984, Athens and Ward 1991, Fletcher and Jones 1996, Grossman and Fletcher 1998). Hampton et al. (2004) mapped sediment thickness near the seaward mouth (20–35 m depth) of the Kailua channel using a tunable, swept-frequency (0.6–3 kHz) acoustic profiler (see Barry et al. 1997 and Sea Engineering, Inc. 1993, Beach nourishment viability study, unpubl. report prepared for the Office of State Planning, Coastal Zone Management Program, Honolulu, Hawai'i) supplemented by analysis of sediment recovered from 14 vibracores in 1997 and 13 vibracores in 2000. The total volume calculated for the reef-front deposit is $53{,}000 \times 10^3$ m^3.

Beach face profile data collected by Norcross et al. (2002) gives a volume for Kailua beach of $600 \pm 30 \times 10^3$ m^3. No volume analysis in Lanikai or Waimānalo Bay has ever been reported; this study is the first to provide submarine thickness data for these two regions.

MATERIALS AND METHODS

A total of 54 sand bodies was selected to be representative in terms of size, morphology, and location on the reef. Selection also included bodies that could potentially be convenient source locations for beach replenishment. Boundaries of all 54 sand bodies were delineated using high-resolution (2.4 m) Quick Bird imagery, recent aerial photography, LIDAR bathymetry, NOAA benthic habitat maps (Coyne et al. 2003), sand classification maps produced by Conger (2005), mapping and benthic zonation from Harney and Fletcher (2003), as well as field observations (Figure 2). All sand bodies were classified by a morphology scheme adapted from Conger (2005) (described in the next section). Sampling with a jet probe provided a total of 205 measurements of sediment thickness. Thickness interpolation of point data was accomplished using Kriging and Voronoi methods. Volume estimates calculated from sampled fields were used to approximate volume in adjacent fields of similar morphology.

Sand Body Morphology

Following the work of Conger (2005), a generalized classification for sand bodies has been created for this study. This classification was applied to all 54 sand bodies sampled, 210 not sampled, and two previously sampled (the deeper portions of the Kailua channel). Sand bodies are classified as one of three morphologies (Conger 2005): (1) sand field, (2) fossil channel, or (3) karst depression. Variance in topographic relief, sediment thickness, and shape were used as distinguishing factors to classify sand bodies. Segregating sand bodies in this manner adds a morphology component to the process of interpolating measured thicknesses, thereby increasing confidence in the relationship of volume estimates to sediment body distribution.

In addition to field observations, slope maps generated from LIDAR bathymetry were used to evaluate topographic relief between the adjacent reef flat and surface of the sand body. Table 1 summarizes sand body morphology classifications and location.

Sand Fields

Sand fields are defined here as areas of continuous sand cover deposited over a broad topographic depression in the fringing reef flat. Boundaries have little to no topographic relief and irregular borders. Sand fields are generally found near shore in shallow (0–5 m depth) areas, have broad landward openings toward the beach face that separate and thin into fingers of sand that continue seaward, and terminate on shallow reef locations. The defining characteristic of sand fields is the lack of topographically defined boundaries.

Fossil Channels

Fossil channels are seaward extensions of watershed systems, incised into the carbonate shelf during low sea level stands. Topographic relief allows fossil channels to act as effective littoral sediment traps. Channels in Kailua and Waimānalo are typically oriented perpendicular to the shore and cross the 10 m isobath. Major channels, such as the Kailua sand channel, have steep walls of fossil reef and widen shoreward into broad sand bodies that lack appreciable bounding relief. Large sand channels can contain sediment over 9 m thick (Ocean Innovators, Inc. 1979, unpubl. report prepared for Hawaiʻi Marine Affairs Coordinator, Office of the Governor, State of Hawaiʻi, Order No. 163), often remaining thickest along the axis of the channel and thinning to 1.0–1.5 m at the margins and adjoining landward field.

Karst Depressions

Karst depressions are likely the result of subaerial exposure causing a sinkhole-style feature that has been subsequently filled with sediment. These differ from the shape of fossil channels in that they generally occupy smaller areas, have no dominant orientation, and do not provide connection between sand fields. Karst depressions have steep topographic boundaries, generally dropping 1–3 m below the adjacent reef flat surface to the sand infill, thus distinguishing them from

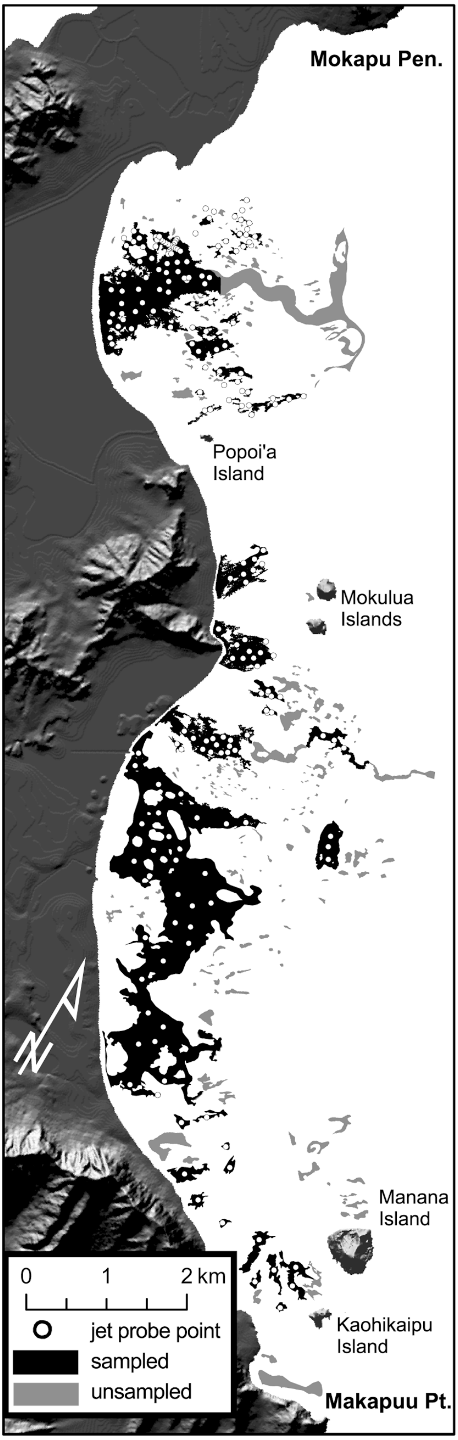

FIGURE 2. Jet probe locations (white circles). All sand bodies are shown. Bodies containing thickness measurements are shown in black (54 total); unsampled bodies are shown in gray (210 total).

TABLE 1

Number of Sand Bodies Organized by Morphology (Columns) and Region (Rows)

Region		Fossil Channel	Karst Depression	Sand Field	Total
Kailua Bay	Direct[a]	7	26	0	102
	Indirect[b]	2	67	0	
Lanikai	Direct	1	3	4	88
	Indirect	2	77	1	
Waimānalo Bay	Direct	0	5	8	74
	Indirect	1	51	9	
Total	Direct	8	34	12	264
	Indirect	5	195	10	
	Combined	13	229	22	

[a] Volume calculation made from thickness measurements.
[b] Volume estimated from known values at adjacent sediment bodies.

sand fields. The measured surface area of all sand bodies is summarized in Table 2.

Thickness Measurements

Sediment thickness measurements were obtained with a jet probe deployed from a small boat and operated by a researcher using SCUBA. The jet probe is built from a small-diameter pipe connected to a shipboard water pump via fire hose. High-pressure water is pumped out of the pipe to displace sediment as the diver pushes it into sandy substrate. A volume of sediment is washed out of the hole by water pressure (called "outwash") affording observations of buried sediment texture, composition, and color. The probe stops penetrating when it contacts a boundary with bedrock or an impenetrable layer of consolidated sediment. Depth of penetration provides a measure of unconsolidated sediment thickness. The probe length is 3.0 m; if sand body thickness exceeds 3.0 m, a value of 3.1 m is recorded. Only 8% of thickness measurements exceeded the 3.0 m length of the probe. These sand bodies could be considerably thicker and contain more volume than reported here, so all thickness interpolation exceeding 3.0 m are labeled as +3.0 m and should be considered a minimum estimate.

At each sample location three thickness measurements were taken within a 20 m radius of the anchored boat and the average

TABLE 2

Measured Sand Body Surface Area Presented as Morphology Class (Column) and Region (Row)

Region		Fossil Channel ($\times 10^3$ m^2)	Karst Depression ($\times 10^3$ m^2)	Sand Field ($\times 10^3$ m^2)	Total ($\times 10^3$ m^2)
Kailua Bay	Direct[a]	8,939	290	0	9,433
	Indirect[b]	8	196	0	
Lanikai	Direct	88	177	754	1,364
	Indirect	117	223	5	
Waimānalo Bay	Direct	0	2,986	235	3,697
	Indirect	85	234	157	
Total (m^2)	Direct	9,027	3,453	989	14,493
	Indirect	209	652	163	
	Combined	9,236	4,105	1,152	

[a] Volume calculation made from thickness measurements.
[b] Volume estimated from known values at adjacent sediment bodies.

thickness recorded for that site. Variation (one standard deviation) between the three measurements is <0.1 m for 75% and <0.5 m for 95% of the sample sites. Variation in the remaining 5% of sample sites showed ranges of 0.7 to 1.2 m, indicating low consistency. Variability in the 0.7–1.2 m range is the result of unconsolidated sediment overlying partially consolidated layers of predominately coral, shell, and *Halimeda* that the probe intermittently penetrates. Thickness of the overlying unconsolidated sediment layer was determined by observing sharp contrasts in jet probe resistance and outwash sediment type. At these sites only the unconsolidated thickness is used in volume calculations.

Sample Locations

Water depth at sample locations was recorded from a hull-mounted fathometer at an accuracy of ±0.5 m. Water depth at sampled sediment bodies varied from 1.5 to 16.8 m, with an average of 5.2 m. General sediment characteristics were noted at each site. The probe was completely removed and inserted multiple times with each measurement to ensure repeatable results. All sample locations were predetermined by examining aerial photos and bathymetry in conjunction with NOAA benthic habitat maps (Coyne et al. 2003) and previous substrate studies in the region (Sea Engineering, Inc. 1993, Beach nourishment viability study, unpubl. report prepared for the Office of State Planning, Coastal Zone Management Program, Honolulu, Hawai‘i; Conger 2005). Survey points were located with a global positioning system (GPS) receiver at an accuracy of ±5 m. Once anchored, drift of the boat was adjusted to match sample location so that a diver could use the boat as a reference point for sampling.

Volume Calculations

Estimates of sand volume were obtained for each sediment body by using one of two methodologies: (1) Kriging (Burrough 1986) or (2) Voronoi (Webster and Oliver 2001) with a volume correction factor. The selection of either methodology was based on the spatial density of available thickness measurements as well as the size and complexity of the given sand body. In instances of good data coverage Kriging was used. Voronoi was used for sand bodies with sparse coverage, where a single measurement must be representative of a large area, because it does not require high data density. Of the 54 sand bodies analyzed, Kriging was applied to nine bodies, and Voronoi was applied to the remaining 45 bodies.

KRIGING METHOD. Kriging is a more statically robust method of estimation than the Voronoi method and is used whenever data density is suitable (Burrough 1986). Boundaries of sand bodies are assumed to be zero thickness and were represented by points of zero thickness generated at 1 m spacing around each sand body. Modeling the variation between measurement points and the edges was accomplished with a semivariogram generated with ArcGIS. A semivariogram model quantifies the relationship between variability of a native data set and spatial location as an equation for a line. The equation for each semivariogram model is used to model the rate of change between points where thickness is known, in this case at the jet probe thickness measurements and edges (Webster and Oliver 2001). A separate variogram equation was produced for each sand body so that the thickness model would be individualized to the unique variability of each body. A spherical semivariogram model was used in all cases. Points of zero thickness along the edge were included when producing a semivariogram. Rasterized thickness estimation maps were gridded at a resolution of 1 m and volume calculated.

VORONOI METHOD. The Voronoi method (Webster and Oliver 2001) assumes that sand thickness is perfectly uniform extending to the edge of the sand body. Perimeters of each sand body and thickness measurements were mapped and entered into ArcGIS. An ArcGIS Voronoi function was used to subset each sand body into a series of smaller adjoining polygons or subpolygons; each subpolygon formed around a single thickness measurement. The Voronoi function draws subpolygon boundaries so that any location within a given subpolygon is closer to its associated measurement point than to the measurement point of any other subpolygon (Webster and Oliver 2001).

Sediment thickness within each subpolygon is assumed to be the same as the thickness measurement it contains. Volume of sediment is calculated for each subpolygon as the product of the area and thickness. The volumes for all subpolygons within a single sand body are summed to calculate a total sediment volume for the entire sand field.

Voronoi Volume Correction

A major source of uncertainty with the Voronoi model is the assumption that the walls of reef-top depressions are at right angles to the base of the depression. A transect of thickness measurements (transect A–A′ in Figure 3) from Kailua Bay suggests that sand bodies are thickest in the center and gradually thin toward the edges.

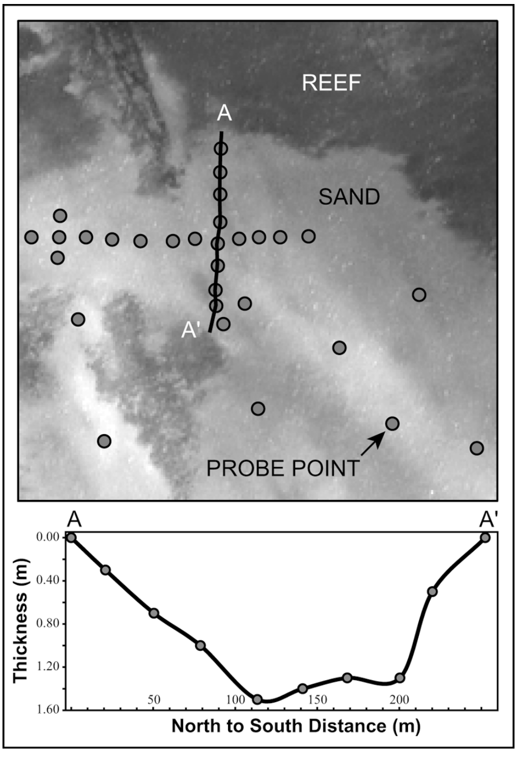

FIGURE 3. *Top:* Aerial photo of seafloor with jet probe locations. Transect A–A′ correlates to graph below. *Bottom:* Cross section showing sand thickness along profile A–A′, illustrating sand thickness variability. See Figure 4 for location.

Given the high range of variability in sand body thickness, failing to account for sand body morphology likely produces an overestimate of sand volume. Correction of overestimated sand volumes is accomplished by calculating an empirically derived reduction factor. Reduction factors are calculated as the average percentage difference between Kriging and Voronoi estimations performed on the same set of sand bodies. Results from comparative volume estimations of 10 sand bodies are segregated by sand body morphology and averaged so as to calculate reduction factors that are morphology-specific to each class. Of the 10 bodies used, four were classified as sand fields, and the remaining six were classified as karst depressions.

The reduction factor calculated for sand fields is 88% ± 8% (i.e., Voronoi estimations are reduced by 88% ± 8%), whereas 64% ± 23% is used for karst and channel morphologies. These reduction factors cause dramatic decreases when applied to the Voronoi-based volume estimates but provide a more informed and realistic estimate.

Prediction Uncertainty

Measurement uncertainties are ±5 cm vertical uncertainty associated with jet probe measurement and ±5 m of horizontal uncertainty associated with accuracy of the GPS receiver. Mean measurement variation of sample sites within each sand body is used to quantify the degree of natural variability in thickness. These uncertainties are taken into account during the Kriging process as a nugget variable (Burrough 1986) and thus are propagated through the interpolation process as a pixel-by-pixel error value. Therefore, every map of estimated volume created via Kriging also has a map of the pixel-by-pixel estimation uncertainty in meters of thickness. Areas defined for volume estimations are used with

TABLE 3

Sediment Volume Organized by Morphology

Morphology		Area ($\times 10^3$ m^2)	Volume ($\times 10^3$ m^3)	Volume/Area Ratio (mean $\pm$ 1σ)	Total ($\times 10^3$ m^3)
Karst	Direct[a]	3,453	1,150 ± 206	0.31 ± 0.22	1,332 ± 248
	Indirect[b]	652	182 ± 42	0.30 ± 0.12	
Channels	Direct	9,027	58,179 ± 601	0.47 ± 0.39	58,252 ± 618
	Indirect	209	74 ± 17	0.36 ± 0.12	
Fields	Direct	989	150 ± 5	0.10 ± 0.07	171 ± 6
	Indirect	163	21 ± 2	0.13 ± 0.00	
Total (m^2)	Direct	13,469	59,479 ± 813	0.29 ± 0.23	59,756 ± 873
	Indirect	1,024	277 ± 60	0.26 ± 0.08	
	Combined	14,493	59,756 ± 873	0.28 ± 0.15	

[a] Volume calculation made from thickness measurements.

[b] Volume estimated from known values at adjacent sediment bodies.

error maps to calculate the error in volume estimation for each area.

Percentage difference between estimated volume and estimated error was calculated for each sand body. These percentage differences were averaged simultaneously with values used for calculating the reduction factors, resulting in the uncertainty values reported for Voronoi estimates.

Indirect Estimation of Sediment Bodies

Volume-to-area ratios and errors were calculated for the 54 measured sand bodies and applied to 210 adjacent unsampled bodies of similar morphology and size. Volumes for unsampled bodies were determined by multiplying the sand body area by a volume-to-area ratio assumed from adjacent sand bodies of similar morphology and depth on the reef. Errors were propagated into unsampled bodies in a similar manner. The estimated volume of each unsampled body was multiplied by an error volume-to-area ratio determined by averaging error volume-to-area ratio values of the adjacent representative sediment bodies.

RESULTS

This study calculated volumes for 54 major sediment bodies from direct measurements of thickness. Volume was also calculated for 210 unmeasured bodies using volume-to-area ratios from adjacent measured bodies of the same morphology class, referred to here as "indirect" measurements. The landward mouth of the Kailua channel was measured in this study, but two previous measurements, the deeper channelized section (Ocean Innovators, Inc. 1979, unpubl. report prepared for Hawai'i Marine Affairs Coordinator, Office of the Governor, State of Hawai'i, Order No. 163) and seaward mouth (Hampton et al. 2004), are used for a complete volume of the feature. Combined submarine sediment volumes are summarized by morphology in Table 3 and by specific sand body formation in Table 4. Note that volume-to-area ratios do not approximate thickness of the sand body at any given point because a majority of the sand body will be either thicker or thinner than the ratio. The volume-to-area ratio provides an indication of the concentration of the deposit and thus partly gauges the usefulness of the body as source material for beach replenishment. A more detailed presentation of the data is published in a technical report prepared for the U.S. Army Corps of Engineers (Bochicchio et al. 2006). ArcGIS shapefiles containing the individual results for sand bodies are available online via the Univeristy of Hawai'i—Coastal Geology Web site (http://www.soest.hawaii.edu/coasts/data/oahu/sandbodies.html).

TABLE 4

Summary of Submarine Sediment Volumes Calculated from Thickness Measurements (Direct) and Inferred from Neighboring Data (Indirect); Organized by Region

Submarine Storage		Volume ($\times 10^3$ m^3)	Area ($\times 10^3$ m^2)	Volume/Area Ratio (mean $\pm 1\sigma$)	n[a]	Total Volume ($\times 10^3$ m^3)
N. Kailua Karst	Direct	19 ± 4	72	0.26 ± 0.21	16	36 ± 8
	Indirect	17 ± 4	56	0.29 ± 0.21	31	
Kailua Channel Mouth (landward)	Direct	1,436 ± 406	1,169	1.23 ± 0.00	1	1,436 ± 406
	Indirect	—	—	—	—	
Kailua Channel[b]	Direct	3,700 ± 185	300	12.34 ± 0.00	1	3,700 ± 185
	Indirect	—	—	—	—	
Kailua Channel Mouth (seaward)[c]	Direct	53,000	7,400	7.16 ± 0.00	1	53,000
	Indirect	—	—	—	—	
S. Kailua Channel Karst	Direct	152 ± 15	288	0.39 ± 0.26	16	201 ± 27
	Indirect	50 ± 11	144	0.40 ± 0.14	38	
Lanikai Sand Fields	Direct	130 ± 3	754	0.13 ± 0.09	4	131 ± 3.15
	Indirect	0.70 ± 0.06	5	0.13 ± 0.00	1	
Lanikai Channel and Karst	Direct	67 ± 15	265	0.17 ± 0.12	4	172 ± 39
	Indirect	105 ± 24	431	0.26 ± 0.06	117	
Waimānalo Karst Basin	Direct	911 ± 171	2,871	0.32 ± 0.00	1	911 ± 171
	Indirect	—	—	—	—	
S. Waimānalo Field and Karst	Direct	64 ± 12	350	0.20 ± 0.21	12	168 ± 33
	Indirect	104 ± 21	384	0.26 ± 0.08	23	
Total	Direct	59,479 ± 813	13,469	2.47 ± 0.10[d]	56	59,755 ± 873
	Indirect	277 ± 60	1,024	0.27 ± 0.10	210	
	Combined	59,755 ± 873	14,493	1.68 ± 0.10	266	

Note: Each region is subdivided into groups of sand bodies by "direct" and "indirect" results. "Direct" refers to volume estimates based on thickness measurements from this or other studies. "Indirect" refers to volume estimates extrapolated from measurements of similar adjacent sampled bodies. Mean and standard deviation of volume/area ratios refer to their respective subdivided sand body groups.

[a] n, Number of sand bodies used in each row calculation.

[b] Ocean Innovators Inc. (1979).

[c] Hampton et al. (2004).

[d] Column total is an average, not a sum.

Fossil Channels

Including all unsampled and previously sampled bodies, 13 were classified as fossil channels. The large Kailua sand channel (Figure 4) is the dominant channel feature in the study area. We divided the channel into three sections: (1) Kailua channel mouth (landward), 0–10 m depth; (2) Kailua channel, 10–20 m depth; and (3) Kailua channel mouth (seaward), 20–35 m depth. Previous volume studies on the deep channel (Ocean Innovators, Inc. 1979, unpubl. report prepared for Hawai‘i Marine Affairs Coordinator, Office of the Governor, State of Hawai‘i, Order No. 163; Hampton et al. 2004) have shown the sediment to be thicker than the maximum probing depth of our equipment (3 m). For this reason, the deep channel and seaward channel mouth were not probed in this study. The preexisting volume measurements used for the deep channel are listed as the Kailua Channel and Kailua Channel Mouth (seaward) in Table 4. In southern Kailua, a group of smaller channel segments form the fragmented remnants of a channel closed by reef growth. Another intact channel exists in northern Waimānalo.

Including all unsampled and previously sampled bodies, fossil channels contain $58{,}253 \pm 618 \times 10^3$ m^3 of sediment and cover an area of $9{,}236 \times 10^3$ m^2. The average volume-to-surface area ratio is 2.33 m^3/m^2, with 1 standard deviation (SD) of 3.9 m^3/m^2,

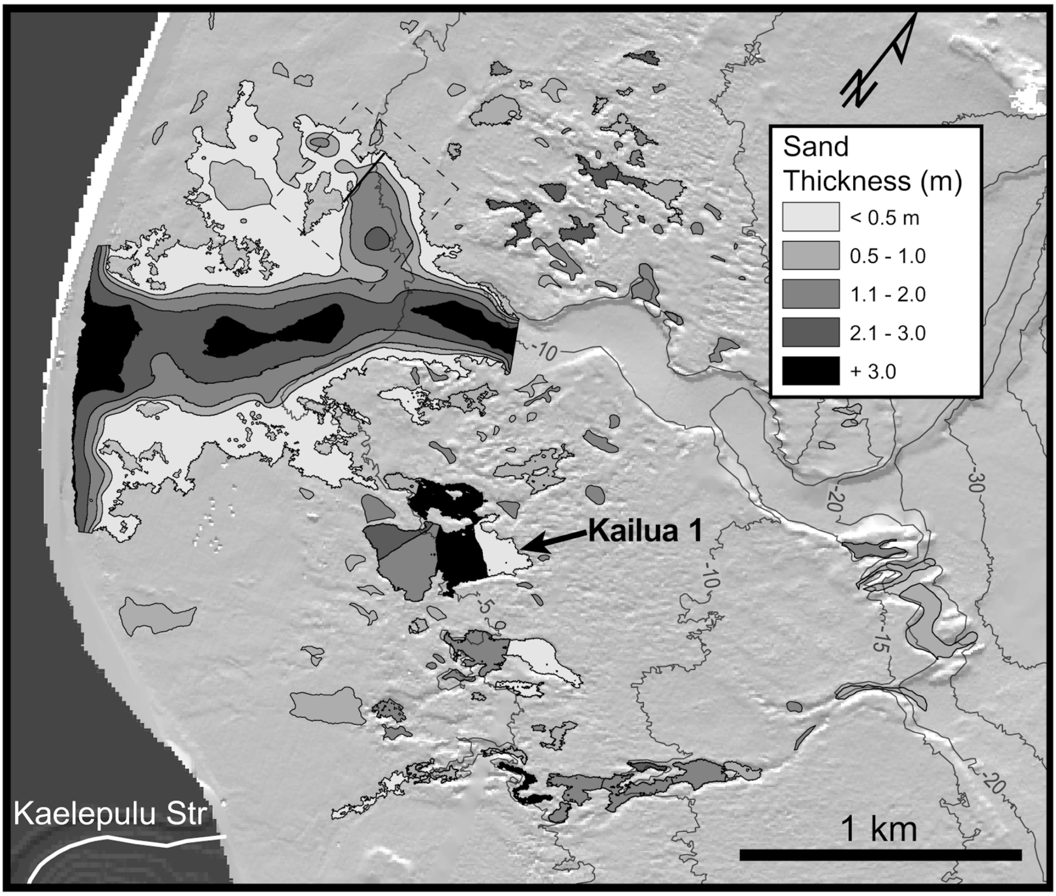

FIGURE 4. Kailua Bay sand body thickness. Bathymetry contours in −5 m intervals. Kailua 1: volume = 103,000 m^3, area = 125,000 m^2, volume/area ratio = 0.82 m^3/m^2. Dashed box and solid line indicate extent of Figure 3.

the highest ratio in the study area. If the deeper Kailua Channel and Kailua Channel Mouth (offshore) portions are excluded, the volume-to-surface area ratio drops to 0.47 m^3/m^2 (SD 0.39 m^3/m^2). Thickness measurements collected for this study in fossil channels had a mean of 1.1 m with 1 standard deviation of 0.9 m and ranged from 0 to over 3.0 m.

Defining a specific morphology for the Kailua Channel Mouth (landward) is difficult because the channel widens landward, loses distinct boundaries, and transitions into an apparent sand field–type morphology with indistinct topographic boundaries. However, a linear trace of high thickness seen in Figure 4 continues landward through the sand field along the central axis of the channel. This indicates that the shoreward portion of the channel has been filled and overtopped by sand, producing a sand body that qualifies as both a channel and a field. For the purpose of estimating sand volume the Kailua sand channel is considered a member of the channel morphology class.

Sand deposits in fossil channels tend to be consistently thick and yellow to white in color. Surface sediments in these channels appear medium- to coarse-grained; however subsurface sampling in the Kailua channel has shown significant fine-grained sediment (U.S. Army Engineer District 1978).

Sand Fields

Including all unsampled bodies, 24 sand bodies were classified as sand fields. Sand fields are estimated to contain $171 \pm 6 \times 10^3$ m^3 of sediment and cover an area of about $1{,}152 \times 10^3$ m^2. The average volume-to-surface area ratio is 0.10 m^3/m^2 SD 0.07 m^3/m^2, the lowest ratio in the study area.

Sediment bodies have a mean thickness of 0.96 m with 1 standard deviation of 0.86 m. The largest sand fields in the study area are connected to the shoreline in the vicinity of Wailea Point, visible near the upper portion of Figure 5. Thickness measurements across these fields generally range from 0.2 to 0.8 m; measurements within zones of high thickness range 1.7–>3.0 m. Sediments are fine to medium sand with a mixture of sandy and gravelly substrata. Nearshore sand fields are generally connected to the adjacent beach, where they potentially function as sediment storage and source locales participating in volume fluctuations on the beach.

Karst Depressions

Including unsampled bodies, 229 bodies were classified as karst depressions. Thirty-four sand bodies are classified as karst depressions. Karst depressions are estimated to contain $1{,}332 \pm 6 \times 10^3$ m^3 of sediment in an area of $4{,}105 \times 10^3$ m^2. The average volume-to-surface area ratio is 0.31 m^3/m^2 SD 0.22 m^3/m^2, the midrange ratio in the study area. Measurements in karst bodies are generally thick with a mean measurement of 0.87 m, 1 standard deviation of 0.73 m. Thick and thin karst bodies show little spatial grouping.

Sediments in karst depressions are observed to contain one or both of two characteristic strata: (1) medium to coarse light-colored sand, and (2) coral gravel of various sizes between 5 cm fragments and hand-sized branches of coral. Sediment bodies in karst depressions consist of either 1.0–2.0 m thick deposits of sand, 0.5–1.0 m sand overlaying coral rubble, or an absence of sand with coral rubble outcropping on the surface. Coral rubble deposits were not included in thickness and volume calculations. Sand bodies without coral rubble tend to lie directly on fossilized reef platform.

An expansive system of interconnected, sand-filled karst depressions dominates the topography of the central-South Waimānalo area (Figure 5). This feature, referred to as the Waimānalo Karst Basin in Table 4, resembles a sandy lagoon that runs parallel to shore between a fringing reef and outcropping back reef in 4–7 m of water. Sediment thickness is greatest in two isolated semicircular areas. Thickness measurements near the edge of this feature are <0.5 m. Two areas show a progressive thickening toward the interior of the feature, forming semicircular "bull's-eye" thickness patterns increasing to >3.0 m thick near the center. The lack of any linear zones of thickness exclude this feature from consideration as a channel feature.

DISCUSSION

New data acquired in this study provide, for the first time, a regional volume estimate to be made for the Kailua-Waimānalo region. Conger (2005) showed that a majority of sand body surficial coverage is in <10 m of water depth. Volume data can be used to test whether this relationship holds true for the volume as well. Figure 6 divides total volume by depth zones; 0–10 m, 10–20 m, and 20–>30 m. Because the Kailua channel is singularly responsible for contributing a majority of the sediment volume in the deeper two zones, a second set of bars in Figure 6 displays total volume minus contribution from the Kailua channel. The Kailua channel represents an increasingly large faction of sediment storage at greater depths. If the Kailua channel is included, the deepest zone contains more sediment than the shallower two zones. If the channel is excluded as an unusually thick outlier, Conger's relationship holds, with most of the sediment residing in the shallow 0–10 m zone.

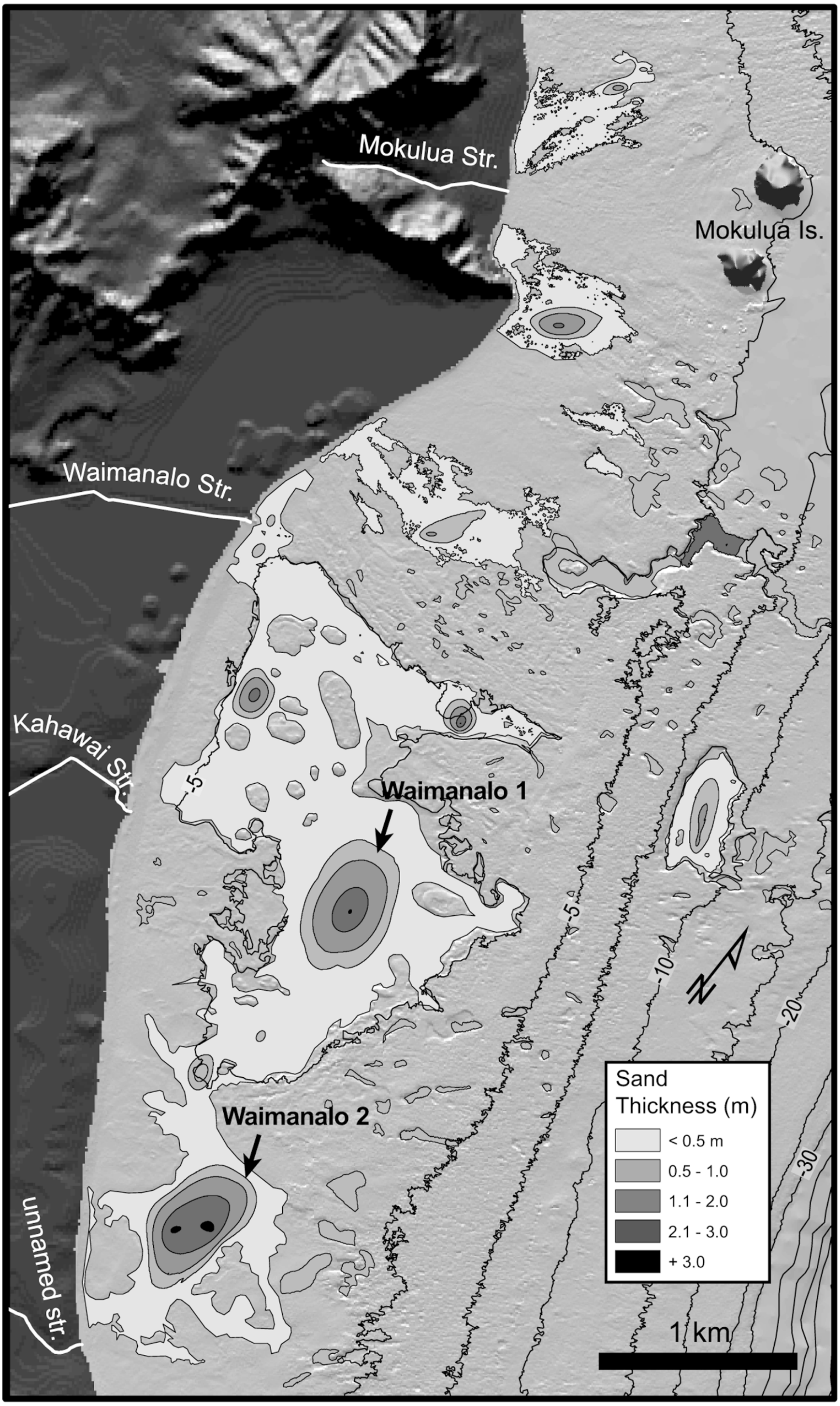

Figure 5. Sand thickness, Lanikai and North Waimānalo. Bathymetry contours in −5 m intervals. Waimānalo 1: volume = 174,000 m^3, area = 241,000 m^2, volume/area ratio = 0.72 m^3/m^2. Waimānalo 2: volume = 243,000 m^3, area = 221,000 m^2, volume/area ratio = 1.10 m^3/m^2.

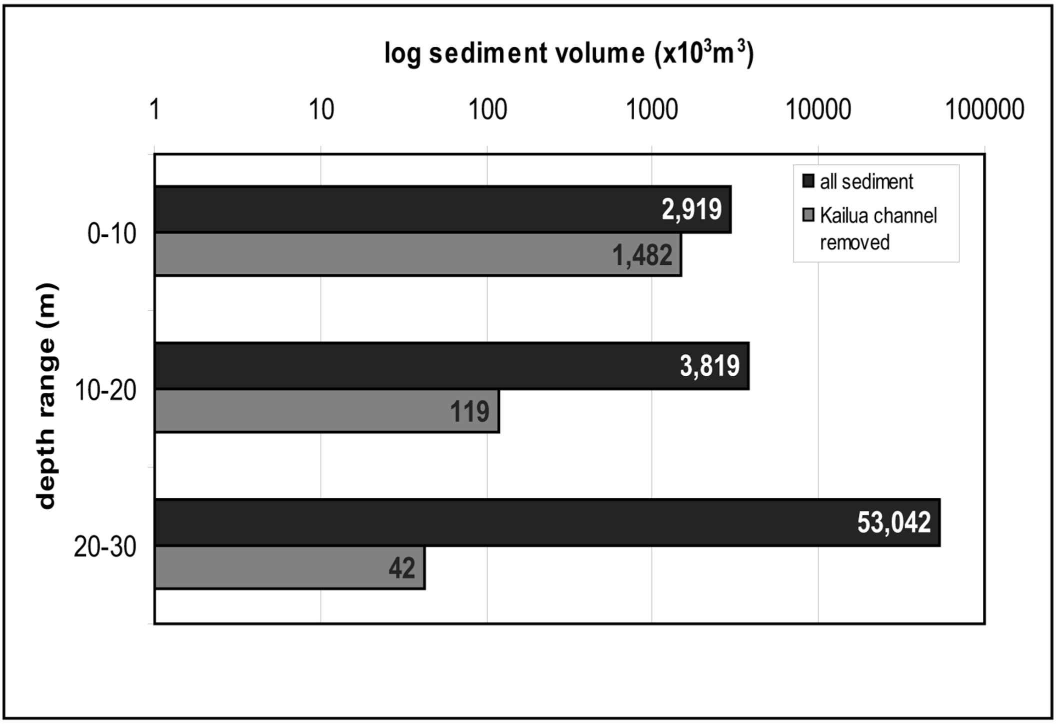

FIGURE 6. Volume of sediment by depth zone. Dark bar shows all sediment. Light bar excludes the Kailua channel.

Comparison with Previous Volume Estimates

This study updates volume data for sand bodies previously sampled by Harney and Fletcher (2003). Volume predictions made for Harney's sediment budget were based on 14 jet probe measurements. More detailed jet probing presented in this paper increased the estimated volume for the shallow Kailua channel mouth (landward) section from 475 ± 29 × 10^3 m^3 to 1,436 ± 406 × 10^3 m^3. This change likely results from a more detailed

TABLE 5

Comparison of Kailua Volume Predictions Made in This Study and by Harney (2004)

Feature	This Study		Harney (2004)	
	Area ($\times 10^3$ m^2)	Volume ($\times 10^3$ m^3)	Area ($\times 10^3$ m^2)	Volume ($\times 10^3$ m^3)
North Kailua Karst	128	35 ± 8	132	242 ± 15
Kailua Channel Mouth (landward)	1,169	1,436 ± 406	1,000	475 ± 29
South Kailua Channel Karst Complex	432	201 ± 22	295	1,007 ± 60
Total	1,730	1,672 ± 437	1,427	1,724 ± 104

Note: Addition of a larger data set significantly increases the volume predication for the Kailua channel mouth, suggesting a broader subsurface channelized zone than previously assumed.

subsurface delineation of the thick channel axis within the nearshore mouth. Table 5 compares results of this study calculated as part of Harney's sediment budget.

Norcross et al. (2002) estimated the volume of sediment stored in Kailua beach to be 600 ± 30 × 10^3 m^3 of sediment. The domain for beach volume data in Norcross et al. was the berm crest to 40–80 m offshore; this study calculated volume 65–80 m from shoreline. Predictions for sediment volume in the shallow sand bodies of Kailua Bay are estimated here to be 1,672 ± 437 × 10^3 m^3, over 1,000 × 10^3 m^3 greater than the total volume predicted for Kailua Beach by Norcross et al. (2002). The large volume of sand residing offshore indicates that the subaerial beach is not the primary storage site for carbonate sediment, and a majority of the sediment storage exists in the nearshore submarine region.

Combining the total submarine volume estimates made in this study (3,055 ± 688 × 10^3 m^3) with previous estimates of the deep Kailua channel (56,700 ± 185 × 10^3 m^3), estimated volume of Kailua beach (600 ± 30 × 10^3 m^3), and estimated volume of the Kailua coastal plain (16,749 ± 1,809 × 10^3 m^3) gives a total system storage of 77,104 ± 2,712 × 10^3 m^3. This estimate does not include the currently undetermined volumes of subaerial sediment in Lanikai and Waimānalo.

Four sites of notable sediment volume are identified as reasonably compact and accessible sources of beach sand that could warrant further investigation as beach sand sources. In Kailua Bay, the most voluminous source of isolated sand is the largest karst depression labeled Kailua 1 on Figure 4. The Waimānalo Karst Basin contains two zones of high thickness that warrant attention; they are labeled Waimānalo 1 and 2 in Figure 5. Lanikai contains a large deposit directly off Wailea Point that could potentially be used for nourishment. However, proximity to the shoreline and previous studies (Noda and Associates, Inc. 1989, Lipp 1995) suggest that the sediment not be moved out of the Lanikai littoral zone because it potentially exchanges sediment with adjacent beaches. However, this study has only provided a reconnaissance of these sites and a more focused study must be completed before they can be considered for mining.

Geologic Controls on Sediment Distribution

Our results indicate that a majority of the shallow reef-top sediment storage occurs in depressions likely eroded during periodic subaerial exposures of fossilized reefal limestone. Therefore, the potential for modern sediment storage is, to some degree, a function of pre-Holocene erosion (increasing storage space) and post-Holocene reef accretion infilling of eroded features (reducing storage space). Controls on post-Holocene accretion in Hawai'i have been thoroughly studied (Grigg 1998, Grossman and Fletcher 2004, Rooney et al. 2004, Grossman et al. 2006). To better understand sand body distributions, we speculate as to factors controlling the pre-Holocene karst and fluvial erosion that formed the reef-top depressions.

To date, only one study has examined O'ahu reef-top sediment distribution in context of reef morphology and wave energy. Conger (2005) correlated regional variations in sand bodies (number, shape, and size) with regional geomorphic settings (deep versus wide reef) and wave climate (high, medium, or low energy). Conger concluded that distribution of reef-top sediment is strongly influenced by large-scale reef geomorphology and, to a lesser extent, wave energy, with the highest sand cover being "wide low-energy reef" and the lowest being "narrow high-energy."

In this study we can suggest two additional environmental controls on sediment distribution: (1) availability of freshwater drainage, and (2) topographic slope of the reef.

Our observations imply that proximity to an onshore watershed is a major control on depression formation and consequently offshore sand storage. Figure 7 shows the study area with sediment bodies and stream outlets identified. Black dashed lines in Figure 7 delineate the Lanikai offshore region with a conspicuous lack of sand bodies. The lack of sand bodies correlates with the presence of the Ka‘iwa Ridge, which divides Kailua and Waimānalo watersheds. Diversion of surface runoff would have created an arid region of the reef associated with the onshore interfluve where exposure to meteoric waters was reduced or less concentrated. Reduced meteoric water on the reef would lead to reduced karst and fluvial erosion in the region, resulting in reduced sediment storage.

Extending this effect seaward, consider the relative convex offshore shape of the Lanikai reef, which would have acted as a seaward extension of the Lanikai headland by diverting water to the north and south at times of subaerial exposure. These combined effects can in part account for the dearth of sediment storage in the Lanikai region.

A majority of the karst depression complexes occur in areas with a relatively low slope or "reef platforms." Comparison of profiles AB and CD on Figures 8 and 9 shows central Kailua Bay to have a reef platform that is not present in northern Kailua Bay (feature 1). Similarly, karst complexes are limited to reef platforms in Lanikai (profile GH; feature 6) and Waimānalo (profile IJ; features 11, 12, 13, and 14). The occurrence of these "platform karst" complexes suggests that platforms are more susceptible to karstification than areas with higher slope. There is one low-slope platform that lacks any karstified features (profile EF; "vacant platform"). This platform illustrates the aforementioned effect of the Lanikai "arid" reef zone. Though a reef platform is present, it is possible that a lack of freshwater runoff has pre-

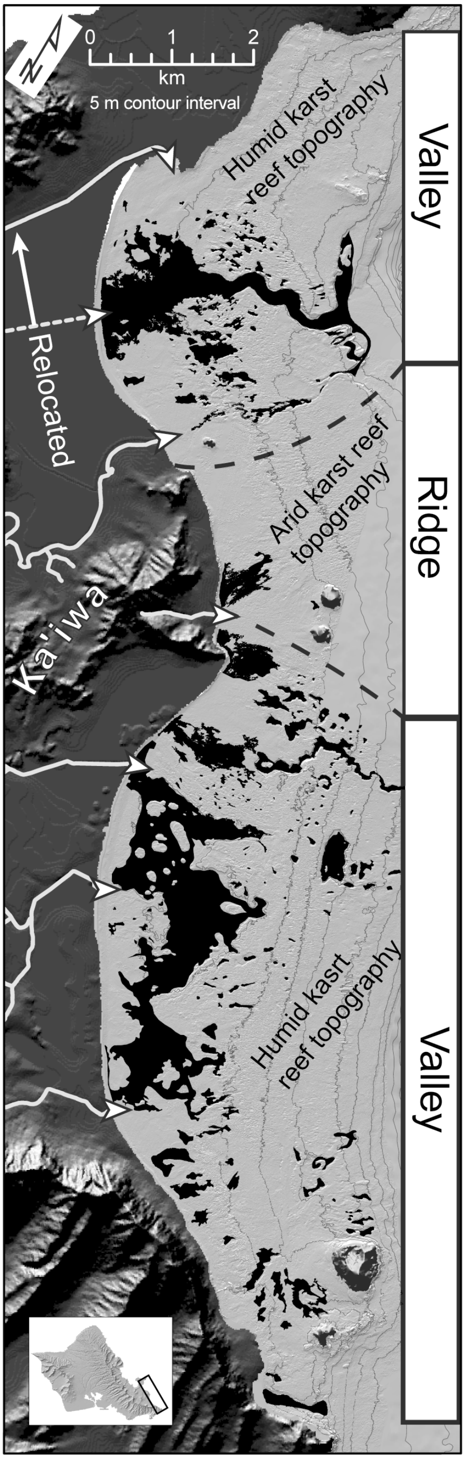

Figure 7. Shaded relief topography and bathymetry. Sand bodies are shown in black on seafloor. Bathymetry contours are in −5 m intervals. Streams are shown as lines over topography. Stream outlet location is represented by white arrows on shoreline. Ka‘iwa Ridge (labeled) divides the Kailua and Waimānalo valley watersheds, approximated by "Valley" and "Ridge" bar on right of figure. Dashed black lines illustrate diversion of meteoric waters by the ridge, creating two different types of karst topography on the reef: arid (minimal karst) adjacent to the ridge, and humid (extensive karst) adjacent to the valley.

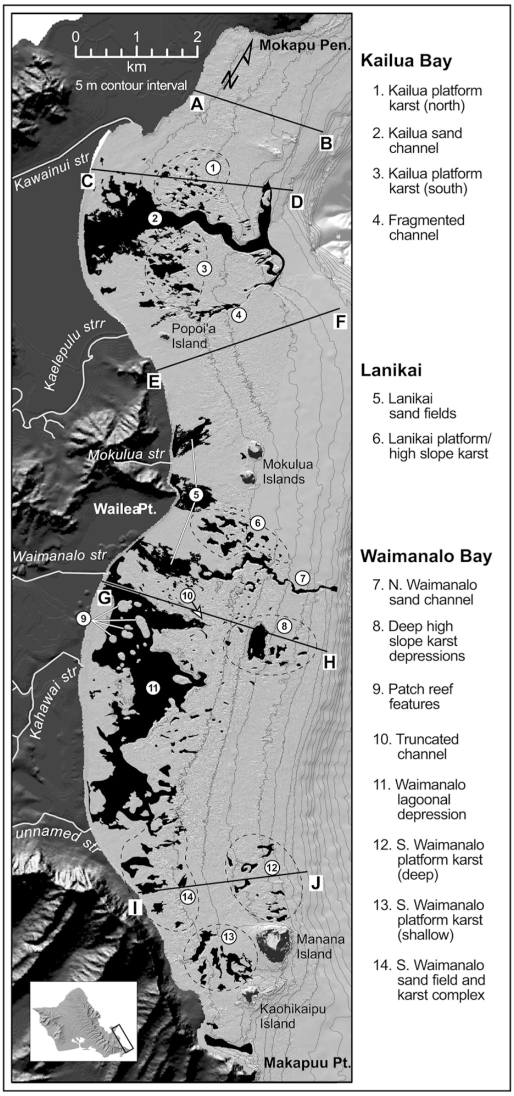

Figure 8. Shaded relief topography and bathymetry. Sand bodies are shown in black on seafloor. Bathymetry contours are in 5 m intervals. Streams are shown as white lines over topography. Sand body features (some delineated with black dashed lines) are labeled with numbers corresponding to the index on right side and referred to in the text. Profile lines correlate with graph in Figure 9.

vented karstification on this reef surface and thus reduced its sediment storage potential.

Karst complexes on high-slope reef areas are visible in two locations: the seaward portion of the feature labeled "Lanikai high slope karst" (profile GH; seaward portion of feature 6) and the feature labeled "Deep high slope karst" in northern Waimānalo (profile GH; feature 8). It is likely that adjacent Mokulua and Waimānalo streams contributed to the creation of the high-slope karst depressions.

In Lanikai, the sand field directly offshore of Wailea Point is thicker than adjacent sand fields to the north and south (Figure 5). This could be the result of Mokulua Stream passing through this sand field and either incising a channel or leaching a cave system with a collapsed roof, thus creating the high-slope karst depressions in feature 6, and possibly converging with the Lanikai channel (feature 7). The elongated shape of the larger karst depressions in feature 6 suggests that they might be channel fragments. Modern reef in the vicinity of feature 6 has accreted unusually high (<1 m water depth), further suggesting that feature 6 has been closed by Holocene accretion. It is feasible that the Mokulua Islands to the north of feature 6 have shielded the area from strong northern swell, allowing more reef accretion.

Similarly, in Waimānalo, the deep high-slope karst complex (feature 8) could be the result of enhanced freshwater flow from Waimānalo Stream. Upslope from the high-slope complex is a linear extension of the Waimānalo Karst Basin (feature 11) that resembles a truncated channel (feature 10). Freshwater flowing from Waimānalo Stream could have incised a partial channel (feature 10) before percolating through the reef, eventually creating the large karst depressions (feature 8).

Though strictly circumstantial, these observations imply that the distribution of sediment storage is controlled to some degree by variation in the onshore supply of meteoric waters and the slope of the fringing reef. Another factor to consider is the enhanced orographic effect during periods of lowered sea level, which could increase the amount of freshwater available to drive the karstification process (Gavenda 1992, Fletcher et al. 2005).

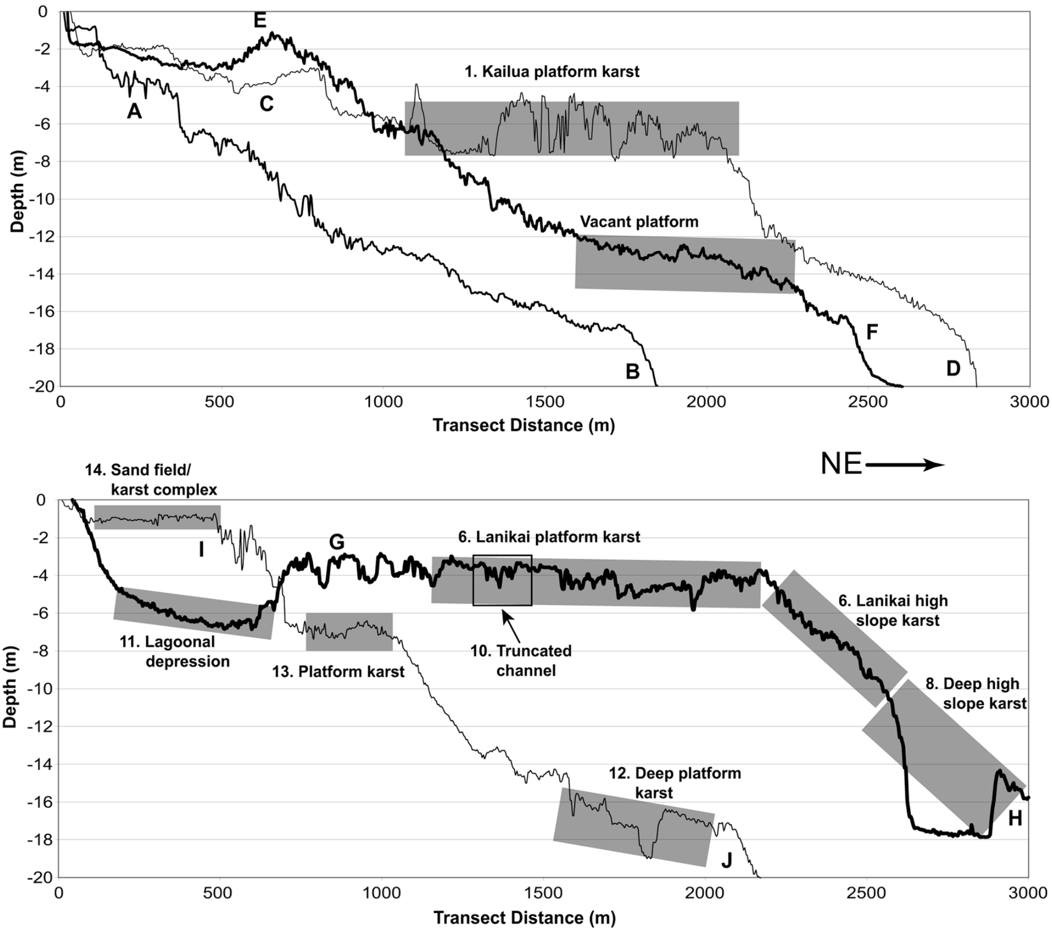

FIGURE 9. Bathymetric profiles corresponding to lines indicated in Figure 8. Gray boxes show location on profile of adjacent sand body features referred to in text and Figure 8. Lines are displayed in different thickness to enhance visibility. Vertical exaggeration = 50.

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