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Shelf stratigraphy and the influence of antecedent substrate on Holocene reef development, south Oahu, Hawaii

E.E. Grossman *, W.A. Barnhardt, P. Hart, B.M. Richmond, M.E. Field

US Geological Survey, Pacific Science Center, 400 Natural Bridges Dr. Santa Cruz, CA 95064, USA

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Abstract

Paired analyses of drill cores and high-resolution seismic reflection data show that development of Holocene framework reefs on the Oahu (Hawaii) shelf is limited to settings of low wave energy and to the period 8000 to 3000 yr BP. A prominent bounding surface that is mapped across much of the Oahu shelf is an erosion surface cut into Marine Isotope Stages 5 and 7 limestones that show extensive loss of primary porosity, aragonite, and $MgCO_3$ owing to meteoric and vadose-zone diagenesis. This acoustic reflector is found exposed at the surface where wave energy is high or in the shallow subsurface below Holocene reef and sand sheet deposits where energy is low. Ship-towed video along 30 km of the shelf reveals a steady decrease in limestone accumulation from offshore of Honolulu southeast to Koko Head where the seafloor is characterized by volcanic pavement and/or thin sand deposits. This may reflect the build-up of late Pleistocene volcanics associated with the Hanauma Bay eruption (30,000–7000 yr BP) that now comprise the substrate in depths shallow enough to limit reef accretion. The absence of significant Holocene reef build-up on the south Oahu shelf is consistent with observations from north-facing coasts that lack Holocene reefs, indicating that Holocene reef formation in Hawaii is complex and patchy.

Keywords: shelf; reef; seismic-reflection; Holocene; Oahu; Hawaii

1. Introduction

Recent studies suggest that in addition to increasing pressure from human activities and climate change, coral reefs on the Island of Oahu, Hawaii, develop within a narrow range of conditions largely controlled by high wave exposure and shallow antecedent topography (Grigg, 1998; Grossman and Fletcher, 2004). Analyses of core samples from two north-facing coasts show that the insular shelf is largely fossil and absent of appreciable Holocene reefs (>1–2 m thick) where it is exposed to open ocean north swell (Rooney et al., 2004; Sherman et al., 1999). Pilot surveys of reef surface ages around the island of Oahu led Grigg (1998) to propose that Holocene reef accretion on Oahu has been insignificant due to long-period swell and has been limited to well-protected embayments such as Hanauma Bay (Easton and Olson, 1976) and Kaneohe Bay.

On the windward coast of Kailua Bay, detailed studies of 32 cores show that a significant Holocene reef developed only between 8000 and 5000 yr BP and only in settings of low wave energy or at depths below wave scour (Grossman and Fletcher, 2004). Additionally, reef development has been uniquely

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* Corresponding author. Tel.: +1 831 427 4725; fax: +1 831 427 4748.

E-mail address: egrossman@usgs.gov (E.E. Grossman).

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linked with antecedent topography, although unlike the Purdy (1974) model where reefs mimic *high* topography. In this wave-exposed setting, reef development occurs only within *low* topography below depths of wave scour. Successful attempts have been made to map and correlate reef distribution to antecedent topography using seismic-reflection profiling (Harvey and Hopley, 1981; Marshall et al., 1998; Searle, 1983), but data quality is generally poor in porous Holocene reefs and coverage is sparse (and lacking in Hawaii). Using high-resolution seismic reflection profiling, ship-towed video, and analyses of core samples, this paper characterizes the substrate of the southern Oahu insular shelf and tests the hypothesis that Holocene reefs across the greater Oahu shelf are restricted to settings of low antecedent topography (below wave scour) and/or areas of dissipated wave energy. The extent to which this model represents recent reef development around the entire Oahu shelf has been unclear; if correct, the few extant reefs warrant greater attention to increased human and climate change-related stress.

2. Setting

Three areas of the inner Oahu shelf (0–40 m) were surveyed (Fig. 1): Kailua Bay on the windward southeast coast of Oahu (Fig. 2) and Mamala and Maunalua Bays stretching along the south–southwest coast between Honolulu and Koko Head (Fig. 3). The Kailua Bay shelf is relatively wide (3–4 km) and deeply embayed (Fig. 2A). It is bounded by the two rocky headlands of Mokapu Peninsula and the Mokulua Islands, which are erosional remnants of the Koolau Basalt comprising the central axis of Oahu (Langenheim and Clague, 1987). Kailua Bay experiences short period (5–8 sec), low (1–3 m) trade wind waves for ~70% of the year as well as high (2–5 m), long (15–20 sec) North Pacific swell during winter months. Occasional passing tropical storms generate moderate period (9–12 sec) swell that break with heights of 2–5 m. A conspicuous meandering channel bisects the central portion of the Kailua shelf and is the drowned expression of the paleo-Kawainui stream (Fig. 2A). It connects a nearshore sediment field with an extensive fore-reef sediment wedge.

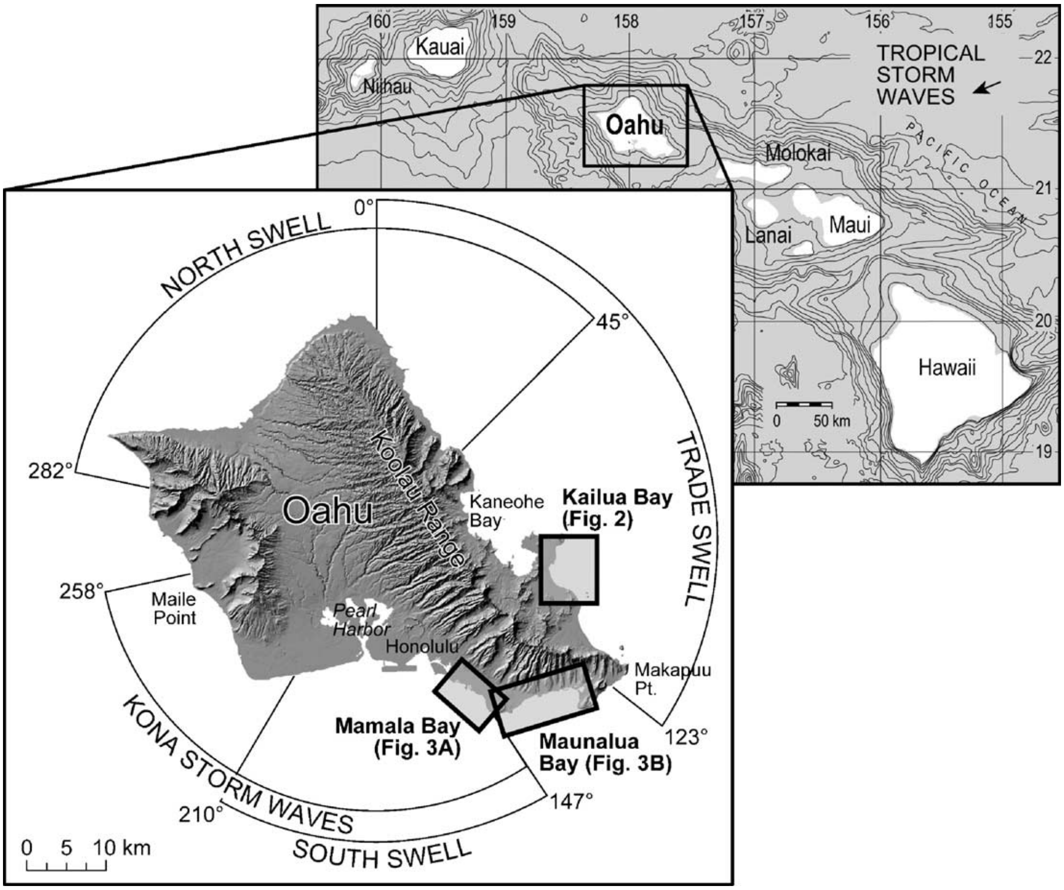


Fig. 1. Map of Hawaiian Islands, study sites on the Island of Oahu and dominant wave regimes influencing Oahu shelf environments.

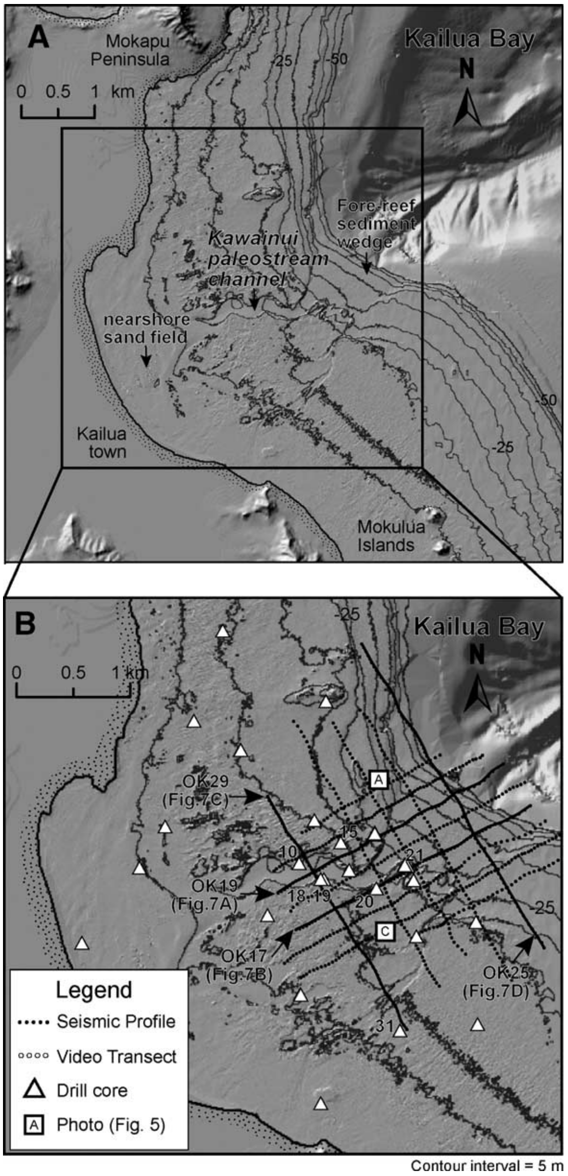


Fig. 2. (A) Map of Kailua Bay and dominant morphological features of the shelf including the drowned Kawainui stream channel connecting a nearshore sand field with fore-reef sediment wedge. (B) Central Kailua reef and location of seismic-reflection profiles (bold lines are presented in Fig. 7), drill cores (triangles, numbered sites shown in Fig. 7), and bottom photographs (squares, Fig. 3). Depth contours in 5-m intervals.

Mamala and Maunalua Bays in contrast, lie in the lee of the Koolau Range and, as a result, trade wind swell is significantly diminished along this portion of the Oahu shelf (Figs. 1 and 3). The Mamala Bay shelf extends seaward of a relatively low-gradient shoreface between Pearl Harbor and the volcanic headland at Diamond Head. The Maunalua Bay shelf between Diamond Head and Koko Head fronts a much narrower and steeper coastal zone but is significantly wider out to the shelf break. The shelf in these bays face directly south and receives wave energy from distant southern hemisphere Pacific swell characterized by long-period (22 sec) and moderate heights (2–4 m). Episodic high energy from tropical storm swell and annual Kona swell (9–15 sec, 2–5 m) passing to the southwest also impacts this coast.

3. Materials and methods

A combination of seismic-reflection profiling, ship-towed video and coring were used in this analysis. Navigation for these data sources was based on differential GPS, which ranged in positional accuracy between 1 and 8 m. An extensive and high-resolution (1–2 m) airborne LIDAR data set (Figs. 2 and 3) collected through a multi-agency effort to characterize coastal habitats and shoreline change was used for initial seafloor classification and for guiding the planning and collection of seismic-reflection data and video-ground truth imagery.

Seismic-reflection profiles were collected along 52 km of the Oahu Shelf in Kailua and Mamala Bays in October 2001 aboard the *RV Wailoa* (Figs. 2 and 3). The sound source for the single-channel seismic-reflection system was a 50-tip mini-sparker operated at 300 J firing at 4 pings per sec. Data were acquired through a 5-m 30-hydrophone streamer and records of 200 msec length were digitized at 16 kHz using Delph Seismic software. Ship speed ranged from 3.5 to 4.5 kts producing an average ping-space of 0.5 m. The digital data were spatially filtered for swell effects by flattening to a smooth seafloor using a 24-sec boxcar filter. This eliminated the effects of the dominant 7-sec trade swell that characterized conditions during data acquisition and had little effect on the morphology of seafloor features examined here which are generally larger than the wavelength filtered. A temporal band-pass filter of 200–800 was applied to the stacked data.

Ship-towed video was collected along ~30 km of the shelf in Mamala and Maunalua Bays between 2000 and 2003 and recorded digitally generally with altimetry data to discern distance off bottom and field of view (Figs. 2 and 3). Two lasers separated at 10 cm provided scale. Morphology, substrate type and coral and algal species/genera were logged real-time and in post-processing following the National Oceanic and Atmospheric Association (NOAA) classification of coral reef benthic habitats (Coyne et al., 2003). GPS positioning was recorded directly onto one of the digital audio tracks using RedHen software/hardware for play-

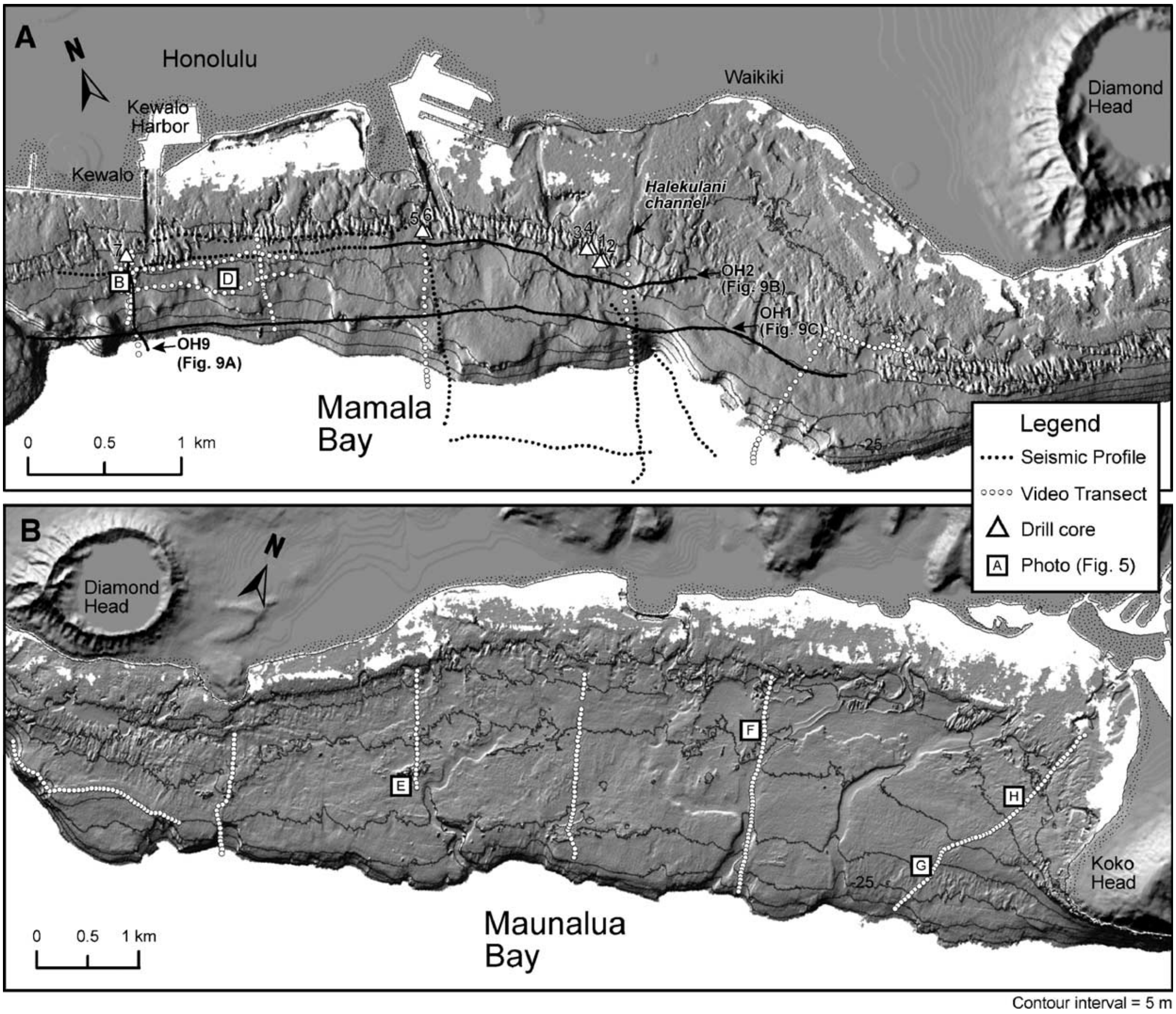


Fig. 3. Map of (A) Mamala Bay and (B) Maunalua Bay showing seismic reflection profiles (solid dotted line, bold lines are presented in Fig. 9), ship-towed video (open dotted line), drill core sites (triangles, numbered sites shown in Fig. 9) and bottom photographs (squares). Depth contours in 5-m intervals.

back and automated ship track generation in ArcInfo. Substrate classifications were made for every GPS location recorded, which under ship speeds of 1–2 kts resulted in a data spacing of 0.5 to 1 m.

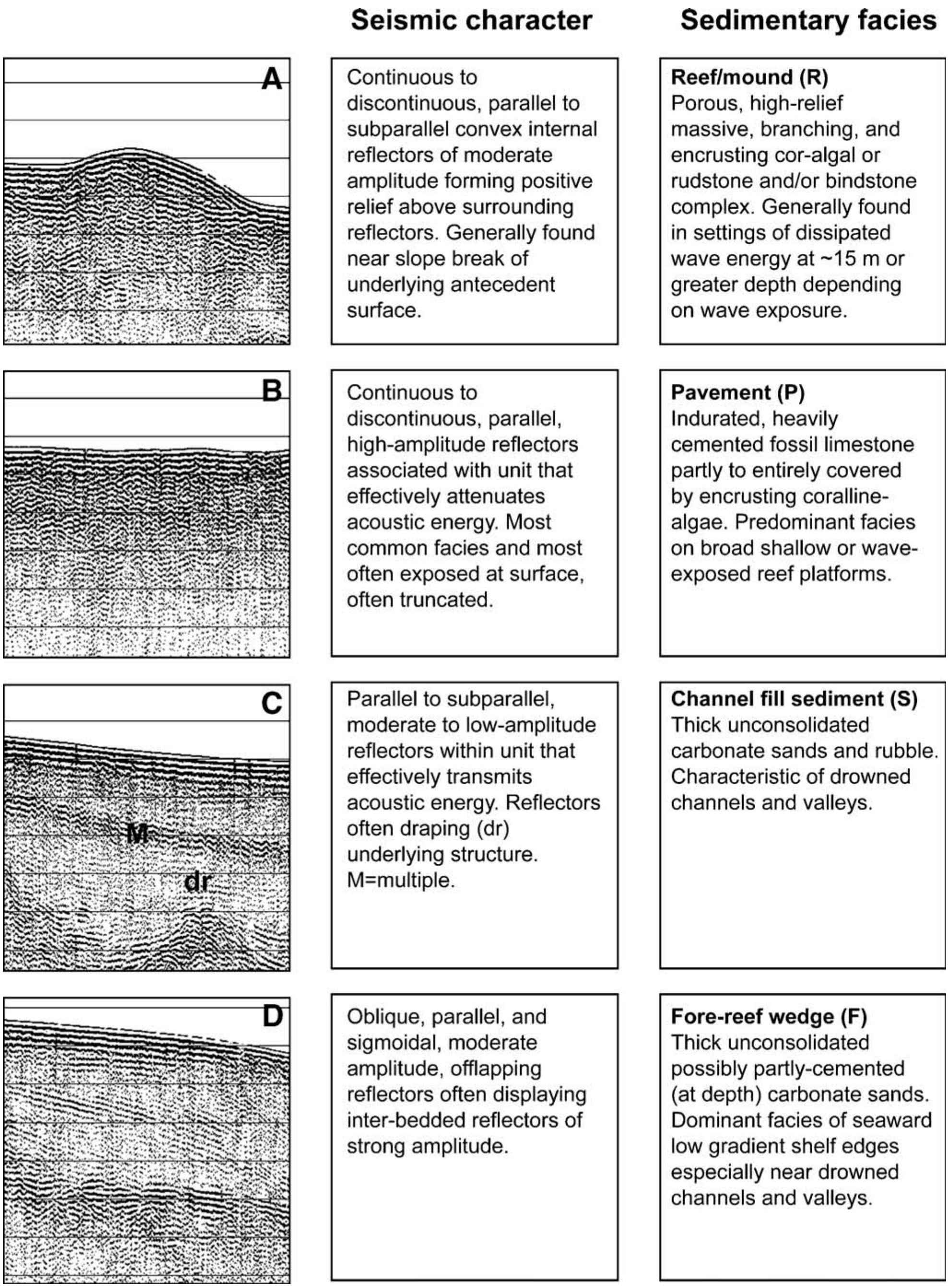
Core samples were collected with a submersible, hydraulic-powered, diver-operated, rotary drill of the open barrel and wireline types (see Grossman and Fletcher (2004) for specifications). Hole depths and recovery lengths were measured with a 1-cm division stadia rod. Cores were logged in the field and stratigraphic reconstructions were generated with detailed lithologic descriptions using standard sedimentologic and petrographic techniques. Samples were screened for radiometric dating using X-ray diffraction (XRD) carbonate mineralogic signatures after thorough cleaning with H_2O_2 and dilute HCl after Grossman and Fletcher (2004). Radiocarbon dates measured by the Center for Accelerator Mass Spectrometry (Lawrence Livermore Laboratory) and the National Ocean Sciences Accelerator Mass Spectrometer (Woods Hole) were calibrated to calendar years using Calib. 4.2 (Stuiver and Reimer, 1993) while U/Th ages were determined at the University of Minnesota following the analytical and reporting conventions of Edwards et al. (1987).

4. Results

4.1. Facies and structural units

4.1.1. Seismic facies and bounding surfaces

Four seismic facies (Fig. 4) are herein identified based on acoustic reflection and geometric characteristics and



	Seismic character	Sedimentary facies
A	Continuous to discontinuous, parallel to subparallel convex internal reflectors of moderate amplitude forming positive relief above surrounding reflectors. Generally found near slope break of underlying antecedent surface.	**Reef/mound (R)** Porous, high-relief massive, branching, and encrusting cor-algal or rudstone and/or bindstone complex. Generally found in settings of dissipated wave energy at ~15 m or greater depth depending on wave exposure.
B	Continuous to discontinuous, parallel, high-amplitude reflectors associated with unit that effectively attenuates acoustic energy. Most common facies and most often exposed at surface, often truncated.	**Pavement (P)** Indurated, heavily cemented fossil limestone partly to entirely covered by encrusting coralline-algae. Predominant facies on broad shallow or wave-exposed reef platforms.
C	Parallel to subparallel, moderate to low-amplitude reflectors within unit that effectively transmits acoustic energy. Reflectors often draping (dr) underlying structure. M=multiple.	**Channel fill sediment (S)** Thick unconsolidated carbonate sands and rubble. Characteristic of drowned channels and valleys.
D	Oblique, parallel, and sigmoidal, moderate amplitude, offlapping reflectors often displaying inter-bedded reflectors of strong amplitude.	**Fore-reef wedge (F)** Thick unconsolidated possibly partly-cemented (at depth) carbonate sands. Dominant facies of seaward low gradient shelf edges especially near drowned channels and valleys.

Fig. 4. Major shelf facies including seismic and sedimentary characteristics.

include (A) coral reef/mound, (B) pavement, (C) channel fill sediment, and (D) fore-reef wedge facies. These facies have been ground-truthed directly through sampling and/or imaged with video and photography. One prominent bounding surface that is pervasive across the Kailua and Mamala shelves is identified as the Holocene unconformity. Description of the acoustic properties and geometry of these facies and bounding surface follows.

The coral reef/mound facies is morphologically distinct on the Oahu shelf, forming mound and/or ridge topography along an otherwise relatively low-gradient terrace (Fig. 4A). It generally has concentric and continuous parallel to subparallel internal reflectors. Reflection amplitudes are moderate in strength and despite the high rugosity and porosity of recent to modern coral reefs, acoustic energy is not significantly attenuated by this facies and is able to image underlying reflectors. The coral reef/mound facies is commonly located near breaks in slope of the underlying antecedent substrate. It is most common in or near drowned depressions of the antecedent topography (valleys, channels) apparently where low-lying substrate provides space below wave scour effects.

The pavement facies (Fig. 4B) is composed of continuous to discontinuous parallel high-amplitude reflectors at or within a few meters of the seafloor that are often truncated. This unit attenuates acoustic energy so effectively that seismic signal is often lost within 5–20 m of the pavement surface. In Kailua and Mamala Bays, this pavement is entirely limestone, although volcanic pavement predominates in Maunalua Bay (see Section 4.1.2). The extremely low Mg-calcite mineralogy of the limestone pavement is responsible for the strong density contrast of the pavement facies relative to the other facies mapped here and the surface ocean (see Section 4.1.3).

The channel fill sediment facies (Fig. 4C) is characterized by parallel to subparallel, moderate to low-amplitude reflectors. Acoustic energy is effectively transmitted tens of meters through this unit. The channel fill facies displays variable internal structure (onlap, offlap, draping) and often reveals complex and strong underlying acoustic reflectors representative of pavement. The channel fill occurs in drowned channels and valleys. Only the upper ~10 m of this unit has been sampled, where it is composed of marine carbonate sands.

The fore-reef wedge facies (Fig. 4D) displays oblique parallel and sigmoidal offlapping reflectors of moderate acoustic amplitude. Variable intensity reflectors suggest interbedded units within the sediment wedge facies that likely represent material of significantly different composition, grain size or cementation history. This is the dominant facies found along the seaward edge of the low-gradient insular shelf and is especially common near drowned channels and valleys. This unit commonly buries steps in the underlying antecedent substrate offshore of the −20 m isobath.

Where the pavement facies underlies the reef/mound, channel fill, or fore-reef wedge facies, a distinct bounding surface is revealed in seismic sections. This surface is marked by the significant density contrast associated with the pavement facies, and where it is exposed at the seafloor, it exhibits pre-Holocene ages reflecting a hiatus in sediment accumulation. This surface is identified as the unconformity between Pleistocene and Holocene deposits.

4.1.2. Modern seafloor substrates

Based on ship-towed video and surface sediment sampling, the modern insular shelf of South Oahu is comprised of three general substrate types: coral reef, pavement (limestone and volcanic), and unconsolidated sediment (Fig. 5).

Coral reef substrates on the south Oahu shelf occur primarily in inner shelf settings (<15 m) and are generally thin veneers except in wave-protected settings. They are generally of high rugosity (Fig. 5A), except where coral community is dominated by encrusting forms (Fig. 5B, C). They commonly display spur and groove morphology. Coral reef substrates are equivalent to the reef/mound facies observed in seismic reflection data. Coral reef substrates are widely believed to be ephemeral features on Oahu. Periodically extensive tracts of surface coral are entirely removed by passing hurricanes and high waves (Dollar and Tribble, 1992; Grigg, 1995).

Pavement substrates occur between 0 and −120 m depth and are low-gradient, smooth surfaces comprised of fossil reef limestone (Fig. 5D) or volcanic basalts. Volcanic pavements commonly display locally high rugosity in the form of ledges (Fig. 5E), pedestals, and meter-size plates (Fig. 5F) or boulders, whereas limestone pavements are typically low relief. The age of volcanic pavements comprising the shelf is poorly known, while limestone pavement ages range ~5000 to 210,000 yr BP (Grossman and Fletcher, 2004; Sherman et al., 1999).

Unconsolidated sediments are primarily comprised of marine carbonate sands found in channels and as sheets (Fig. 5G, H) in mid- and outer-shelf depths (Harney et al., 2000; Harney and Fletcher, 2003). They also are common along the outer shelf in the form of thick sediment deposits (Hampton et al., 2003) commonly supporting dense stands of the green calcareous alga *Halimeda* (Harney et al., 1999).

Variations to this simple classification result from the temporal colonization of these substrates by coral and algae (coralline and fleshy green and brown algae). Other substrates including volcanic boulder fields are known along portions of the south Oahu shelf (Makapuu Pt.) that were not part of this study.

4.1.3. Biolithofacies

Analyses of core samples from the Oahu shelf reveal three primary reef units (Holocene and Marine Isotope Stage (MIS) 5, and MIS 7 limestones) composed of six biolithofacies: branching coral framestone facies, massive coral framestone facies, mixed coral and coralline algal-dominated grainstone, branching coral-rich rud-

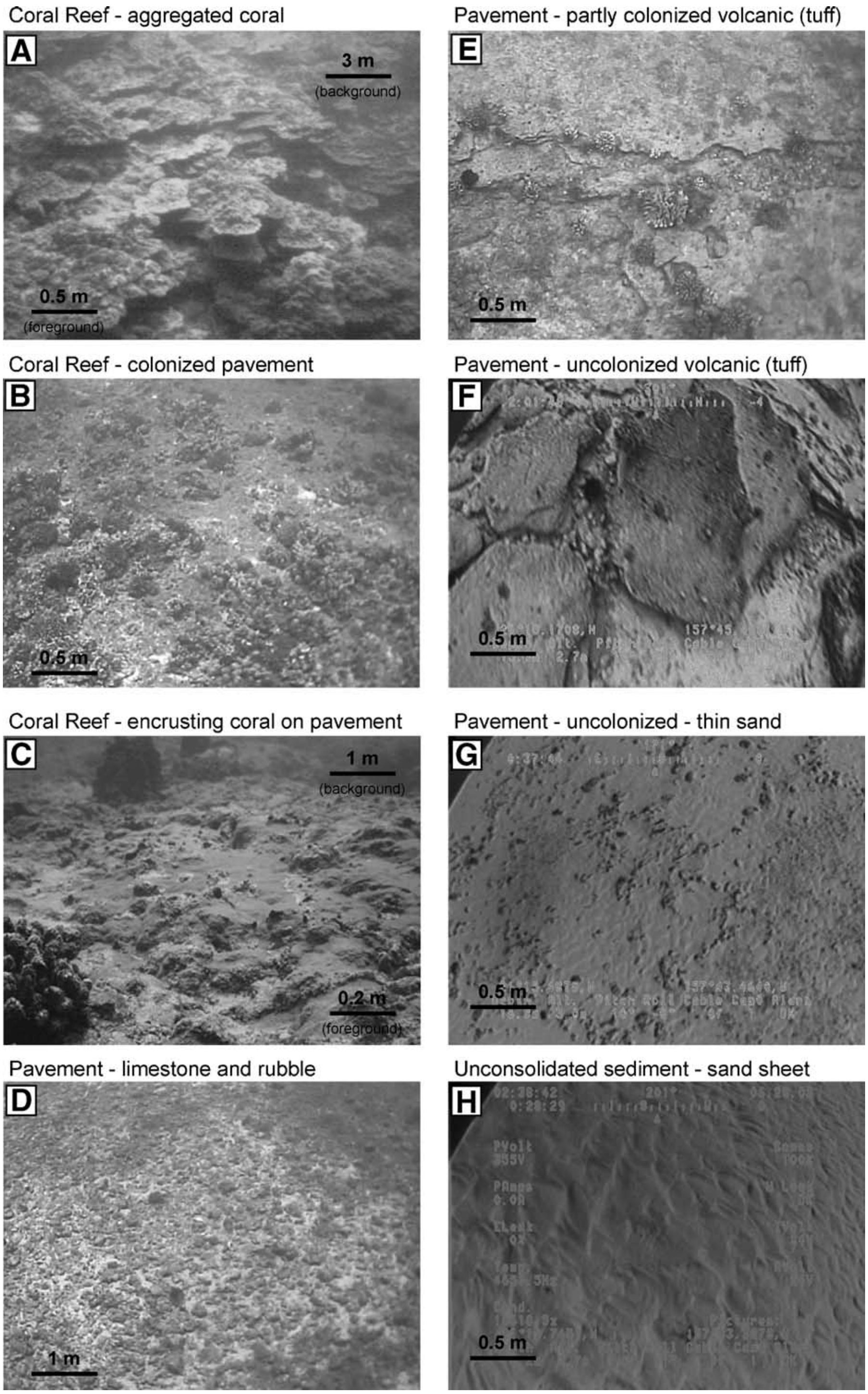


Fig. 5. Seafloor substrate types of the southern Oahu shelf (see Figs. 2 and 3 for locations). (A) Aggregated coral reef, central seaward Kailua Bay. (B) Colonized pavement, offshore of Kewalo, Mamala Bay. (C) Encrusting coral reef on pavement, central south platform Kailua Bay. (D) Limestone pavement with rubble, offshore of Kewalo Harbor, Mamala Bay. (E) Partly colonized volcanic pavement, western Maunalua Bay. (F) Uncolonized volcanic pavement, central Maunalua Bay. (G) Uncolonized pavement central eastern Maunalua Bay. (H) Unconsolidated sediment (sand sheet) outer eastern Maunalua Bay.

stone, encrusting coral and coralline algal bindstone, and a mixed skeletal and pelloidal wackestone. The first five of these facies are discussed in detail by Grossman and Fletcher (2004) and are characteristic of the Holocene reef units in Kailua Bay. All six facies are also found in pre-Holocene MIS 5 (125,000 yr BP) and 7 (210,000 yr BP) reef units (Sherman et al., 1999; Grossman, 2001). The wackestone is restricted to MIS 5 and 7 reef units and composed of well-cemented fine marine carbonate sand and silt often displaying dessication cracks.

Holocene reef facies are differentiated in age from those of MIS 5 and 7 units by radiometric dating (^{14}C and ^{230}Th), carbonate mineralogy, and petrologic texture, namely dissolution and cementation histories (Grossman, 2001). Particularly important to the seismic-reflection imaging and interpretations made here is the difference in $MgCO_3$ mineralogy and cementation history of Holocene and Pleistocene reef units. The Holocene reef units are comprised of porous extant coral, coralline algae, molluscs, foraminifera, and echinoids with pristine mineralogies characterized by marine values of aragonite (90–100%) and Mg-calcite (12–20 mol% $MgCO_3$) (Grossman, 2001). In contrast, the pre-Holocene MIS 5 and 7 reef units commonly retain little aragonite and are comprised of stable forms of calcite (<4 mol% $MgCO_3$) commonly related to calcite spar infills, whisker cements, infilled dessication cracks, and moldic porosity (Fig. 6).

The wholesale loss of aragonite in the pre-Holocene reef units through dissolution and conversion of high-Mg-calcites to stable forms of calcite during meteoric and vadose zone diagenesis (during sea-level low stands) has produced a surface layer of calcrete that in turn yields a strong density contrast and acoustic impedance in seismic reflection data relative to overlying Holocene units. These distinct cementation and alteration histories therefore have produced a distinct reflector that can be continuously imaged over extensive areas with significantly less effort than the widely spaced data points obtained with great effort from cores.

4.2. Shallow stratigraphy of Kailua Bay, Oahu

Seismic-reflection profiles in Kailua Bay show that the shallow stratigraphy of the windward Oahu insular shelf is characterized by reef/mound, pavement, channel fill and fore-reef wedge acoustic facies (Fig. 7). Reef/mound facies are found only in the central portion of the bay and occur in mid-shelf depths (-8 to -15 m below mean sea level; Fig. 7A, B). Core samples show that the Holocene reef at site K21 (Fig. 7B) is >11 m thick. Based on the travel time between the top and base of the reef facies at K21 and the measured thickness of ~11 m in core section, we derive an interval velocity for the porous Holocene reef framework of approximately 1750 m/s, which is lower than previously assumed rates for recent carbonates of 2000 m/s (Esker et al., 1998). Isolated reef and mound structures are also observed buried below modern sediments (e.g. intersection of OK17 and OK24; Fig. 7B). Landward of the fore reef, reef/mound facies are restricted to the central portion of the bay near the central drowned channel and are generally thin (1–4 m) accumulations (Fig. 7C). Cores through the Kailua shelf also show this pattern of Holocene reefs to be restricted to central Kailua Bay (Grossman and Fletcher, 2004).

The pavement facies occurs across the majority of the Kailua Bay shelf. Across the wide reef platforms, it becomes shallower and is ultimately exposed at the surface beyond ~0.5 km north and south of the central drowned channel (Fig. 7C). Results of coring show that the decrease and eventual disappearance of Holocene reef facies north and south away from the central drowned channel is accompanied by a steady decrease and eventual loss of aragonite content within the upper 2 m of the central Kailua reef platform (Fig. 8). A corresponding decrease in the mol% $MgCO_3$ is a characteristic of limestone pavement formed by meteoric and vadose zone diagenesis (Grossman, 2001; Sherman et al., 1999).

The channel fill sediment facies is observed in all of the seismic profiles that cross the central drowned channel and is exemplified by a thick deposit displaying internal structure in Fig. 7D. Although asymmetric bedforms observed migrating seaward under tradewind wave conditions suggest sediment transport is active at the surface of this facies (Cacchione et al., 1999), intricately bedded internal structure within the facies at significant depth (20–30 m, Fig. 7D) indicate variable sediment accumulation has occurred over at least the last several millennia. The channel fill sediment facies is also observed in smaller pockets and karst features across the reef.

Seaward of the fore reef the Kailua shelf grades into an expansive sediment wedge that we have classified as the fore-reef wedge seismic facies (Fig. 7A, B). Seismic-reflection data indicate that it reaches a maximum thickness of ~40 m near transect line OK25 (Fig. 7A). The extent to which this sediment body represents Holocene sedimentation is uncertain and has been the focus of a number of studies (Casciano, 1979; Hampton et al., 2003; Harney et al., 2000; Harney and Fletcher,

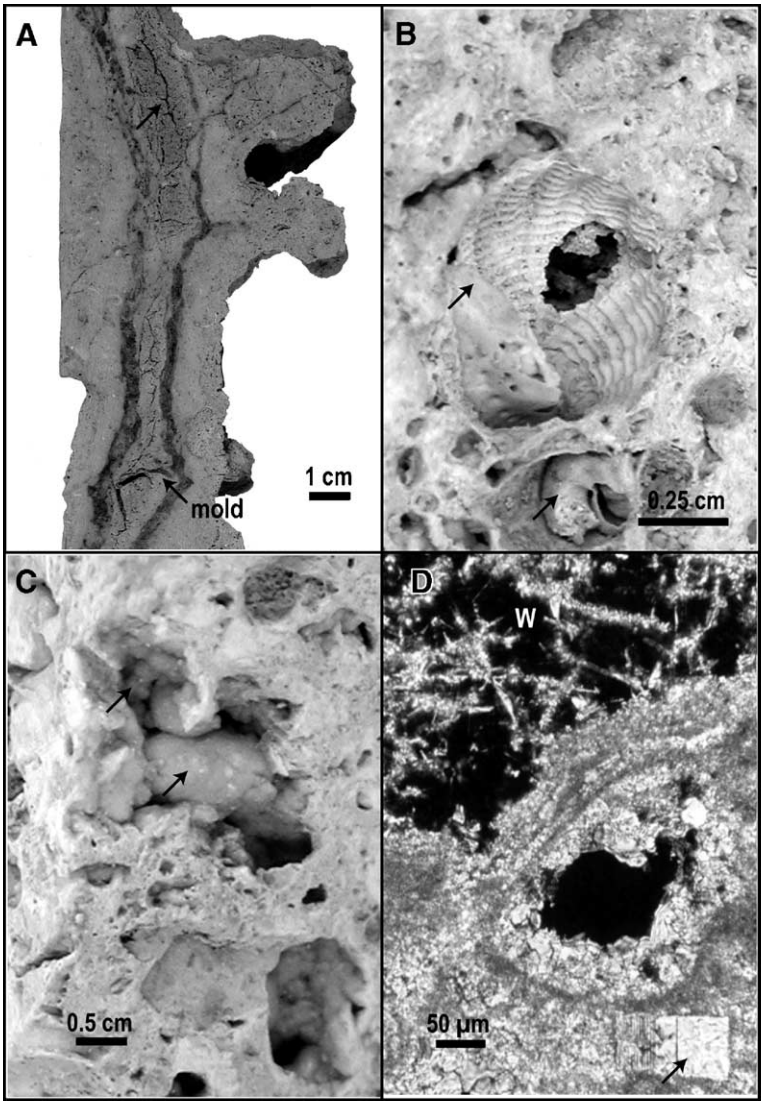


Fig. 6. Diagenetic products in MIS 5 and 7 reef units. (A) Mudstone/wackestone showing dessication cracks lined by coralline algae and infilled with skeletal debris and pelloidal micrite all of which has been converted to calcite. Molds are common. (B) Moldic porosity (arrows) in cor-algal bindstone “algal ridge”. Bindstone is entirely converted to calcite, only molds remain. (C) Dripstones of calcite (arrows) are common in MIS 7 cor-algal bindstone. (D) Blocky calcite spar (arrow) and whisker cements (W) indicate diagensis of cor-algal bindstone within the meteoric phreatic and vadose zones, respectively (polarized light).

2003). Intricate internal structure characteristic of bedded sediment/rubble units (Fig. 7A, D) is observed in this facies but has not been sampled to discern its age and composition. The lack of a continuous reflector characteristic of a flooding surface or surface of erosion in the fore-reef wedge facies of most transects (including OK19; Fig. 7A) suggests the entire package may be Holocene in age. Alternatively, the reflector within the fore-reef wedge facies of transect OK17 (Fig. 7B) may be the marine flooding surface associated with the last transgression. Determining the age and origin of this surface will have important implications for the amount of sediment produced and stored within the fore-reef wedge facies during the Holocene.

A broad set of flat terraces (~1.25 km wide) flanking both sides of the channel is buried within the central drowned Kawainui paleostream channel (Fig. 7D). Although its origin is probably fluvial, it is likely that wave-erosion also helped shape it. Two periods of channel incision are indicated by the (1) narrow central channel cut within the (2) broader cut terraces flanking the sides. It is likely that the central deeper incision was cut by the last glacial maximum sea level low stand 21,000 yr BP.

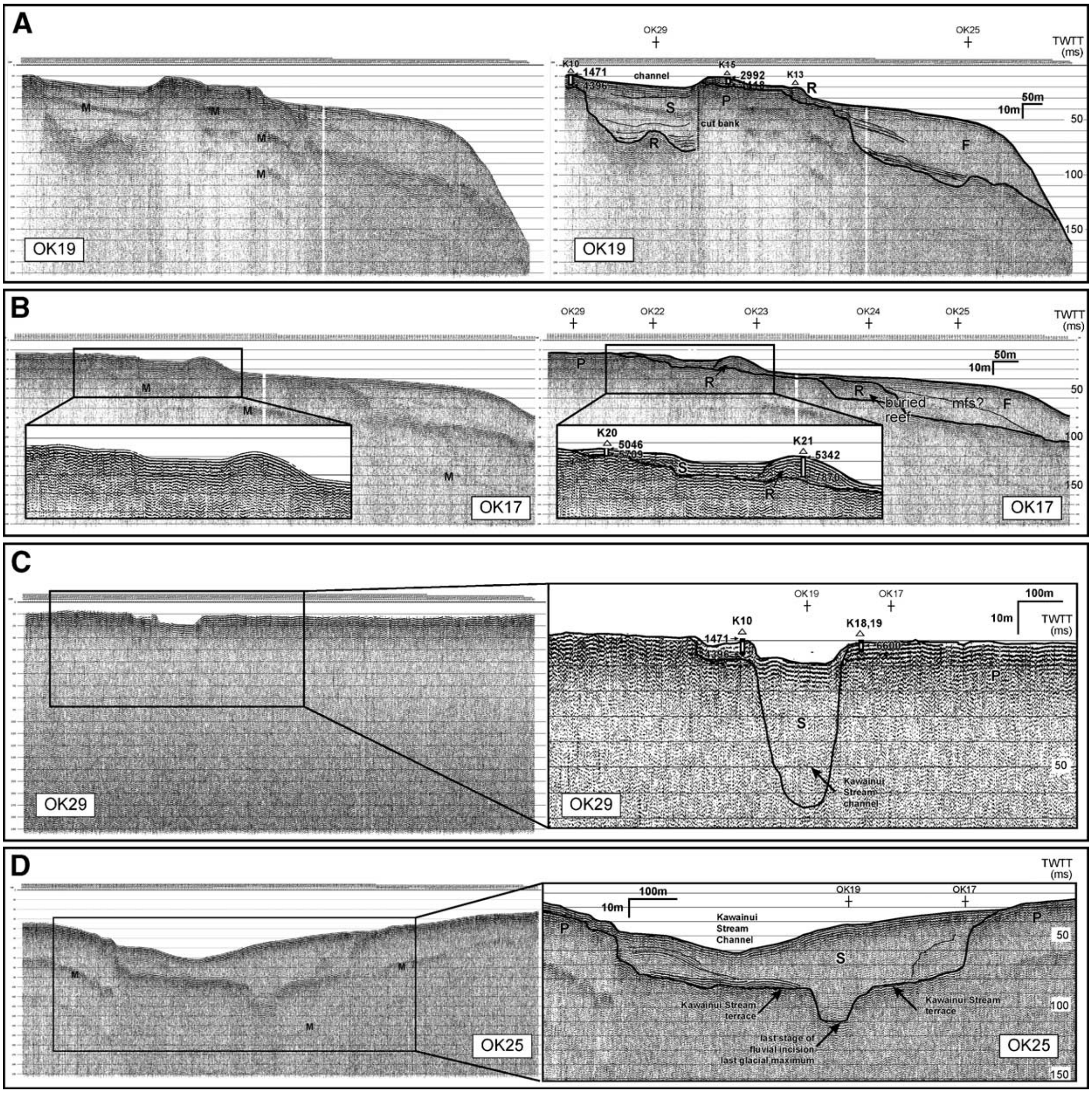


Fig. 7. Seismic reflection profiles of the Kailua Bay shelf showing both uninterpreted (left) and interpreted (right) sections for line OK19 (A), OK17 (B), OK29 (C), and OK25 (D), locations noted in Fig. 2. Drill core sites (triangles) are shown with radiometric age results (Grossman and Fletcher, 2004), multiples (M), line crossings (crosses), reef facies (R), pavement facies (P), channel fill sediment facies (S), and fore-reef wedge facies (F).

4.3. Shallow stratigraphy and seafloor substrate of Mamala and Maunalua Bays

Seismic-reflection profiles of the Mamala Bay shelf (Fig. 9) are dominated by pavement facies (Fig. 4) and in general show considerably less variability than the Kailua shelf (Fig. 7). The Mamala shelf is dominated by limestone and volcanic pavement substrates with isolated channel-fill sediment bodies or facies “S” (Fig. 9). The extensive coverage of pavement is supported by coring results at sites M1–M6 that are characterized by strongly cemented rudstones dating 7263–2419 yr BP commonly bound by coralline algae of similar age (Table 1). Near the shelf edge, fore-reef wedge facies are common in seismic profiles and reach up to 16–20 m thick (Fig. 9A).

Near Kewalo Harbor isolated features displaying reef/mound facies occur in depths ranging 10–20 m. A shore-normal seismic-reflection profile (OH9; Fig. 9A) crosses one such isolated mound that was cored

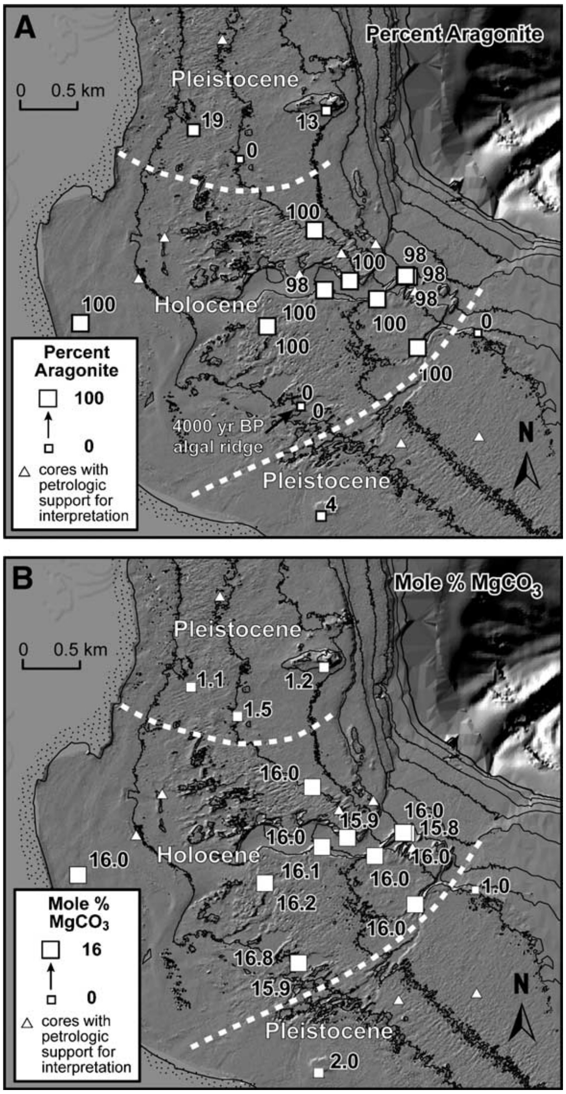


Fig. 8. Map showing aragonite content (A) and mol% $MgCO_3$ (B) remaining in surface samples (<2 m) across the Kailua shelf (size of symbols proportional to content, values in bold text). A steady decrease in aragonite and $MgCO_3$ with distance away from the central drowned channel where Holocene reefs accreted, reflects pervasive expanse of recrystallized fossil MIS 5 and 7 reefal limestone that produces a prominent subsurface acoustic reflector.

(M7). The 5.5 m core is comprised of branching coral framestone underlying a thin veneer of rudstone. Radiocarbon dating (Table 1) shows that these corals ranged in age between 8000 yr BP at the base (− 18.5 m) and 3000 yr BP at the surface (− 13 m). The only other reef/mound facies observed in seismic-reflection profiles occurred as isolated spur and groove features near core sites 5 and 6 (Fig. 9C). The majority of the Mamala and Maunalua shelves is comprised of pavement facies exposed at the surface as exemplified in Fig. 9B.

Ship-towed video along cross-shore and along-shore transects on the Mamala (Fig. 10) and Maunalua Bay shelves (Fig. 11) show that the surface substrate is dominated by pavement facies (P) with lesser amounts of unconsolidated sediment facies (F and S). Modern coral reef cover is relatively scarce and limited to isolated patches within deep embayed and channeled sections near shore (Fig. 10). Of the 20 km of video, less than 2% is characterized as coral reef, whereas pavement and unconsolidated sediment comprised ~58% and ~40% of surveyed seafloor, respectively (Figs. 10 and 11). A distinct transition occurs seaward of Diamond Head at which point limestone pavement that characterizes Mamala Bay is replaced to the east by pavement comprised of volcanic tuff (Fig. 5E). Although a shallow fringing reef dominated by coralline algae occurs along the inner shelf along the entire Maunalua Bay coast, this is likely a fossil late Pleistocene reef based on 125,000 yr BP ages of correlative reef units exposed at the shoreline (Szabo et al., 1994). It grades offshore into a relatively barren wave-abraded volcanic pavement intermixed with thin sand sheets (Fig. 11). Isolated pedestals and erosional remnants support patchy distributions of small (10–15 cm diameter) stout branching (*Pocillopora meandrina*) and lobate (*Porites lobata)* coral colonies (Fig. 5E) indicative of frequent disturbance. Several drowned stream channels bisect the Maunalua shelf and are shown in the LIDAR and video data to be filled with sediment of unknown thicknesses.

5. Discussion

5.1. Extent of Holocene reef development

The pervasive cover of pavement and unconsolidated sediment on the south Oahu shelf strongly supports the hypothesis that Holocene reef development on Oahu has been significantly limited in space and time. Seismic-reflection data, coring results, and seafloor imagery show that Holocene and modern reefs are patchy and isolated in settings of low-wave energy. Primary locations of observed Holocene reef accretion occur in low antecedent topography of drowned stream channels and valleys (Kewalo (Fig. 10A), Kailua (Figs. 2 and 5A) and within deep embayments that experience dissipated wave energy as wave rays diverge (central Kailua Bay). On the Kailua shelf, Holocene reef accretion is clearly imaged above a strong acoustic reflector characterizing the erosion surface cut into recrystallized fossil MIS 5 and 7 reefal limestone observed in core samples. Where pre-Holocene limestone units are less

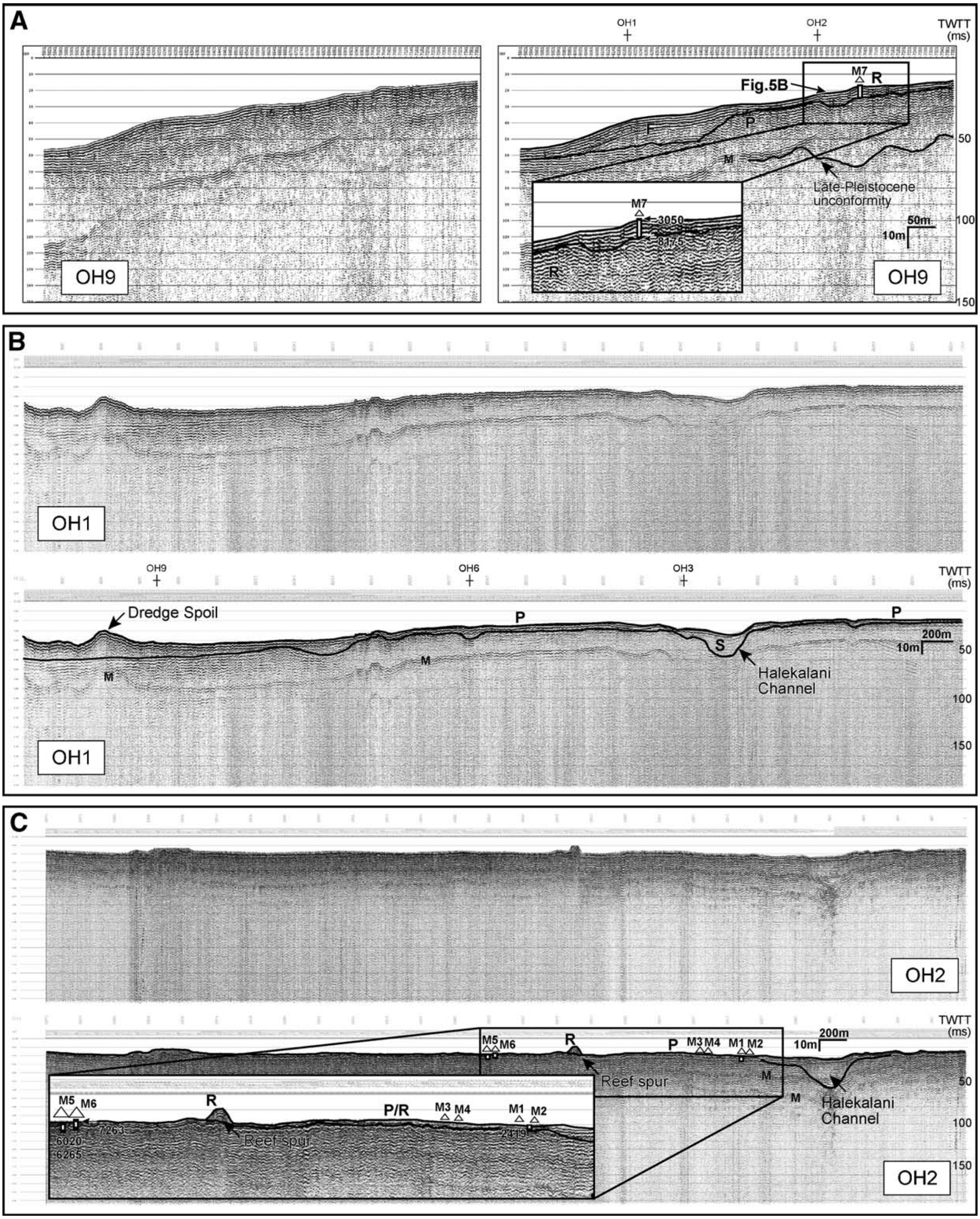


Fig. 9. Seismic reflection profiles of the Mamala Bay shelf showing both uninterpreted (left or upper) and interpreted (right or lower) sections for lines OH9 (A), OH1 (B), and OH2 (C). Drill core sites (triangles, locations noted in Fig. 3) are shown with radiometric age results (Table 1), Multiples (M), cross-lines (crosses), reef facies (R), pavement facies (P), channel fill sediment facies (S), and fore-reef wedge facies (F).

Table 1
Radiometric ages of Mamala Bay core samples

Sample	Site	Description	Depth (m)	%Ar	$MgCO_3$[a]	$\delta^{13}C$	^{14}C	1(σ)	Cal age (yr BP)	2(σ)
M1–15	Waikiki	*P. lobata*	−11.90	100	–	0.023	2742	40	2419	2666–2312
M5–20	Waikiki	Coralline algae	−10.51	[b]	15.83	0.100	5643	50	6020	6189–5892
M5–20	Waikiki	*P. lobata*	−10.49	100	–	0.332	5847	50	6265	6400–6100
M6–15	Waikiki	*P. lobata*	−10.67	100	–	−0.377	6796	50	7263	7387–7159
M7–160	Kewalo	*P. compressa*	−13.79	100	–	−0.500	3350	55	3050	3243–2841
M7–505	Kewalo	*P. lobata*	−17.24	100	–	−0.980	7850	60	8175	8343–8017

Sample number format (xx−yyy): xx=site, yyy=depth of sample in core in cm.
Depth=meters below mean sea level.
%Ar=percent aragonite.
[a] In mol% $MgCO_3$.
[b] 91% $MgCO_3$ and aragonite.

than ~5–8 m below mean sea level and exposed to moderate wave energy, this reflector (major bounding surface) is exposed at the seafloor (Fig. 7) or draped by a thin veneer of Holocene and/or modern encrusting coral and coralline algae (bindstone) (Figs. 5C and 7). The only accumulation of framework reefs during the Holocene is within the antecedent topography of the drowned paleo-Kawainui stream channel and below wave base between 8000 and 5000 yr BP, indicating that accommodation space was a primary factor for development.

The same pattern characterizes the Mamala and Maunalua Bay shelves, with only small patchy reef development in the vicinity of drowned low antecedent topography (e.g. Kewalo paleostream channel; Fig. 10A). Whereas Holocene coral framestone accretion terminated on the windward Kailua shelf at ~5000 yr BP (Grossman and Fletcher, 2004), it was maintained until 3000 to 2400 yr BP on the Mamala Bay shelf near Kewalo Harbor and offshore of Waikiki (Table 1). Seismic-reflection data and video imagery collected in this study indicate that few other settings provide the necessary conditions for appreciable reef accretion and that, where reefs are found, they are likely transient features. Extensive coral reef gardens that were documented offshore of Waikiki were shown to be entirely scoured from the seafloor during Hurricane Iwa in 1982 (Grigg, 1995), exhuming fossil mid-Holocene pavement dating 2500 to 6000 yr BP (Table 1; Figs. 5D, 9 and 10A)). Little coral growth has occurred since. The lack of accretion despite coral colony growth rates that average 1 cm/yr on Oahu (Grigg, 1983) suggests that regular and periodic wave scouring associated with wave base has been a primary control on reef accretion on the Mamala and Kailua Bay shelves since the mid-Holocene.

The near absence of Holocene reef development and sparse colonization of volcanic pedestals by small (10–15 cm diameter) robust branching *Pocillopora meandrina* colonies on the Maunalua Bay shelf (Figs. 5E and 11) indicates that frequent disturbance controls modern accretion and that a lack of accommodation space has been a primary limiting factor on accretion. It also suggests that either (1) antecedent low topography in the form of channels and valleys were not as well developed on the Maunalua shelf prior to the Holocene sea-level transgression as along other coasts, (2) shallower substrate afforded less accommodation space, and/or (3) Maunalua Bay experiences a more energetic wave regime than Kailua and Mamala Bay. High-resolution LIDAR bathymetry and video imagery show that channels on the Maunalua shelf have less relief above channel fills relative to similar features on the Kailua and Mamala Bay shelves (Fig. 11). The thickness of Maunalua shelf channel fills is unknown. Holocene reefs may be buried in them; however, their development would have likely terminated ~5000 yr BP due to wave abrasion and sediment deposition as in Kailua and Mamala Bays.

The shallower Maunalua shelf may also have limited Holocene reef accretion more than in Kailua and Mamala Bays, as near-bottom friction stresses would be accentuated during wave shoaling over the shallower Maunalua shelf topography. In addition, it is likely that wave-scour may be greater on the Maunalua Bay shelf, which is exposed more directly to long-period southern hemisphere swell and energetic wave energy associated with Kona storms.

Another likely explanation for lower reef development on the Maunalua Bay shelf relative to Kailua and Mamala Bays is a shallower and younger substrate comprised of recently deposited (late Pleistocene) volcanic tuff (Fig. 11). The Haunama Bay eruption is thought to have formed 30,000–7000 yr BP (Easton and Olson, 1976) during lower sea level. The fact that this tuff shows little stream incision and extends across

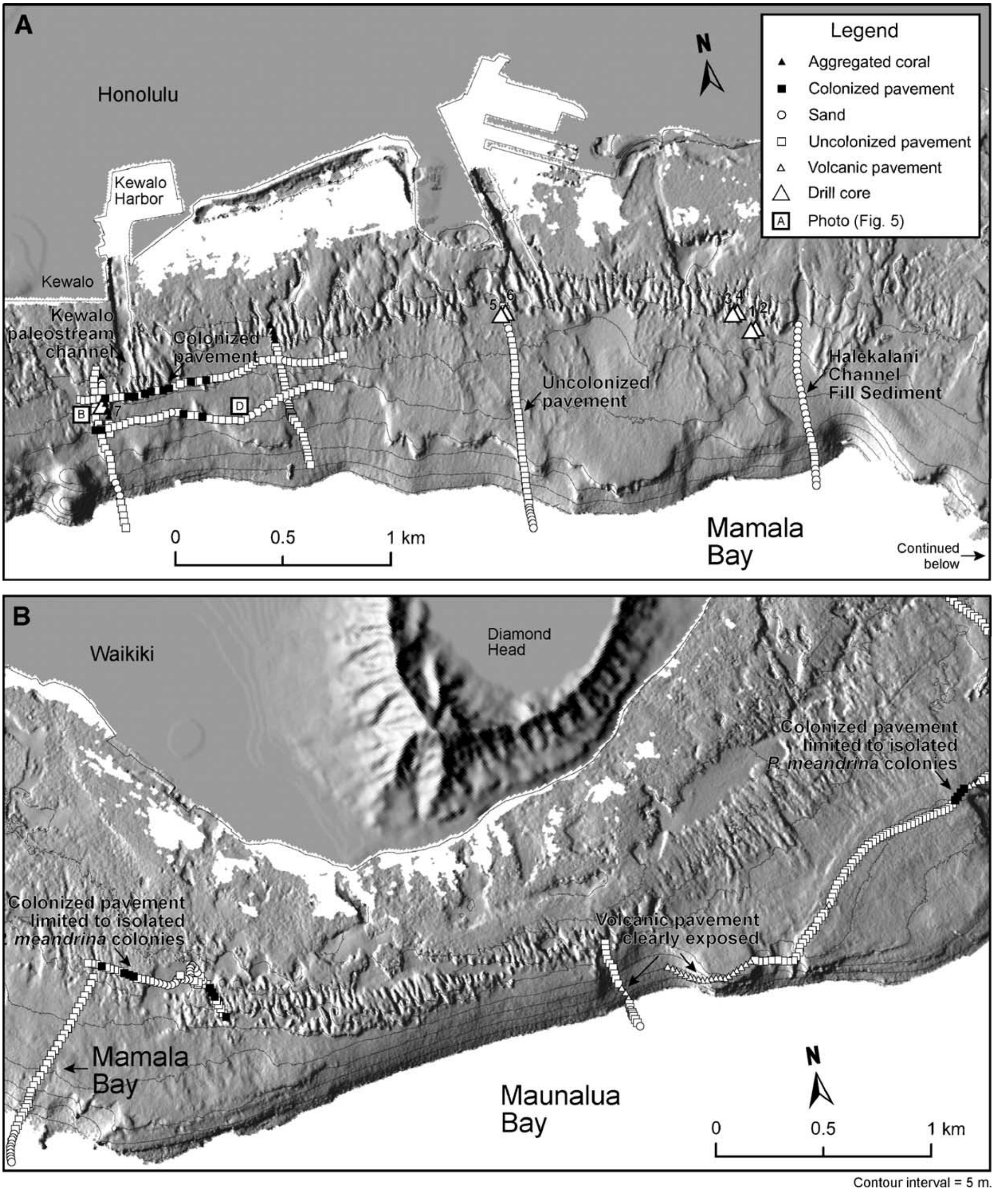


Fig. 10. Substrate types observed in ship-towed video from the western (A) and eastern (B) portion of the Mamala Bay study area. Substrates include aggregated coral (solid triangles), colonized pavement (solid squares), unconsolidated sediments (open circles), uncolonized pavement (open squares), and volcanic pavement (open small triangles). Also shown are locations of drill cores (large triangles) and bottom photographs (lettered squares). Depth contours in 5-m intervals. Dominant substrate type is uncolonized pavement. Colonized pavement occurs in isolated patches near the Kewalo paleostream channel and seaward edges of select spurs with low coral cover (10–20%) of *Pocillopora meandrina*, and *Porites lobata* in encrusting and lobate forms. While volcanic pavement is only clearly exposed in select regions near the lower flanks of Diamond Head, it likely comprises a large proportion of the uncolonized pavement viewed in video in the form of abraded volcanic tuff and ash.

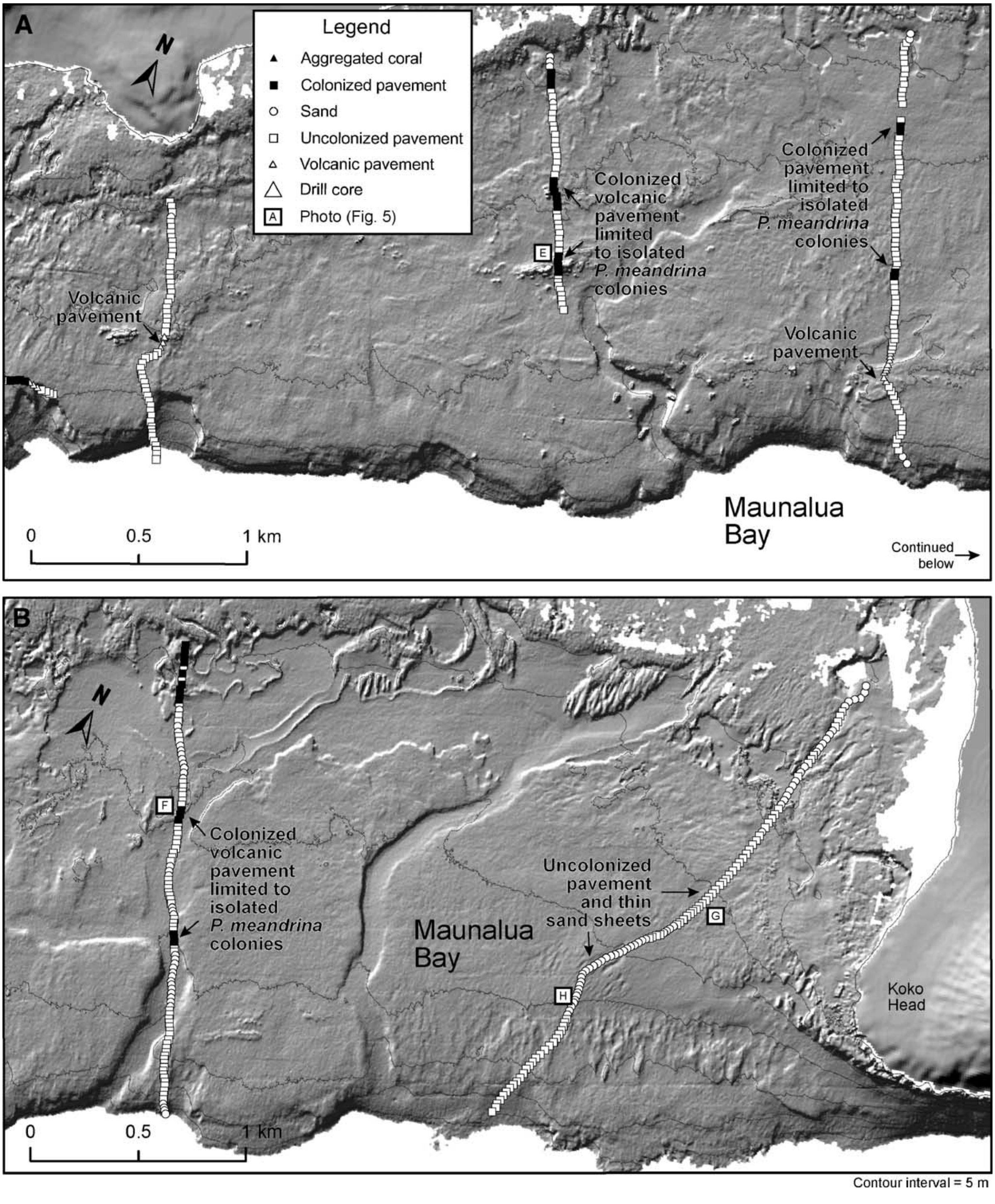


Fig. 11. Substrate types observed in ship-towed video from the western (A) and eastern (B) portion of the Maunalua Bay study area. Symbols are the same for Fig. 10. Dominant substrate type on the Maunalua shelf is uncolonized volcanic pavement and thin sand sheets. Colonized pavement is limited to isolated volcanic pedestals and ridges with low cover (10–20%) of small (10–15 cm) *Pocillopora meandrina* colonies, indicative of little accretion. *Porites lobata* is sparse but occurs in mid-shelf settings as isolated mounds.

a broad and shallow portion of the shelf suggests that it post-dates the last highstand (MIS 5e) reef deposits found along the shore (Szabo et al., 1994). If correct, this volcanic pavement may have filled accommodation space, and prevented subsequent Holocene reef accretion in Maunalua Bay. A test of this hypothesis would include evidence of MIS 5 and/or 7 reefal limestone (like that found in Kailua and Mamala Bays) buried beneath the volcanic pavement observed across the Maunalua shelf in this study.

Although the importance of wave base in controlling space for reef accretion and in modifying reef structure has long been realized (Lowenstam, 1957; Purdy, 1974), it has been difficult to quantify the role of wave base relative to other processes that modulate reef development. Important conceptual models have been developed to illustrate accretion patterns and morphological and coral colony response to gradients in wave forcing and accommodation space (Adey, 1978; Chappell, 1980; Hubbard, 1997; Montaggioni, 2000). For example, where annual and/or episodic high waves scour reefs as in hurricane-prone settings such as the Caribbean, wave base is observed to directly control reef architecture (Blanchon and Jones, 1997). A comprehensive review of fringing reef development histories shows how accommodation space set by sea-level position influences a variety of reef morphologies (Kennedy and Woodroffe, 2002). Along with this study of reef accretion on Oahu, these models provide important starting points for refining our understanding of the role of wave base in modulating accommodation space for reef development.

5.2. Late Quaternary deposition on the Oahu shelf

A general model of seaward progradation of the shelf during sea-level highstands by small, isolated reef units and thick fore-reef sediment wedges characterizes constructive shelf processes on the Island of Oahu. Sherman et al. (1999) and Fletcher et al. (submitted for publication) describe fossil MIS 5 and 7 marine and eolian facies found on the north-facing shelves of Maile Point and Kaneohe Bay and the windward Kailua shelf. The data presented here support the concept that insufficient accommodation space was also a limiting factor for reef development since MIS 7 on the insular shelf of south Oahu. In addition to the scarcity of Holocene reefs, the reoccupation of stream valleys by fluvial systems like Kaiwainui Stream (Fig. 7D) indicate that the wide reef platforms surrounding the channel were of sufficient relief to control stream processes and therefore reef accommodation since at least MIS 5. Where framework reefs have developed, they form patchy, local accumulations of reefs and reefal mounds near breaks in slope, in settings of dissipated wave energy near drowned stream channels and valleys (Figs. 7A and 9A), or in embayed settings where wave energy is reduced by divergence. Periodic high waves from storms and annual open ocean swell appear to have restricted reef accretion below wave base since the mid-Holocene. This is observed by a clear transition from vertical to lateral reef accretion as Holocene sea-level rise slowed and stabilized 5000–3500 yr BP (Grossman and Fletcher, 2004, 1998) even in wave-protected settings like Hanauma Bay (Easton and Olson, 1976). This has resulted in high sediment production that fills channels and progrades seaward, extending the shelf seaward during highstands (“F” in Figs. 7A, B and 9A). The extent to which these unconsolidated deposits will be lithified through meteoric and vadose cementation during subaerial exposure is unknown. The Holocene appears to be the first significant period of time in the late Quaternary in Hawaii lacking accommodation space for framework reef development such that sediment production and progradation have become increasingly important in shelf constructional processes.

6. Conclusion

A combination of high-resolution seismic reflection profile data, ship-towed video and analyses of core samples indicate that, like north-facing coasts exposed to large ocean swell, the south Oahu shelf lacks significant Holocene reefs and is dominated by fossil pre-Holocene pavement. A strong acoustic reflector is clearly identified across the Kailua and Mamala Bay shelves and is apparently formed by the density contrast that exists between porous reefs and sediments of Holocene age and pre-Holocene low-porosity, mineralogically stable calcite-filled limestones. The top of the older, diagenetically altered limestone is exposed at the surface where wave energy is high. This reflective surface dips below thin Holocene reef packages and unconsolidated sediment sheets where lower wave energy accommodates accumulation. The south Oahu shelf is comprised of a complex mix of reefal material originating during the Holocene, last interglacial (125,000 yr BP), and penultimate interglacial (210,000 yr BP) as well as late Pleistocene volcanic tuff (30,000–7000). The volcanic substrate, likely originating from a Hanuama Bay eruption, appears to have filled accommodation space for subsequent reef growth in the moderately high wave-energy setting of Maunalua Bay. A decrease in accommodation space through time has resulted in an increase in sediment production that feeds extensive prograding fore-reef sediment wedges along the outer shelf.

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