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Possible modes of coral-reef development at Molokai, Hawaii, inferred from seismic-reflection profiling

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Abstract High-resolution, seismic-reflection data elucidate the late Quaternary development of the largest coral-reef complex in the main Hawaiian Islands. Six acoustic facies were identified from reflection characteristics and lithosome geometry. An extensive, buried platform with uniformly low relief was traced beneath fore-reef and marginal shelf environments. This highly reflective surface dips gently seaward to ~130 m depth and locally crops out on the seafloor. It probably represents a wave-cut platform or ancient reef flat. We propose alternative evolutionary models, in which sea-level changes have modulated the development of reef systems, to explain the observed stratigraphic relationships. The primary difference between the models is the origin of the underlying antecedent surface, which arguably could have formed during either regression/lowstand or subsequent transgression.

Introduction

The geologic development of coral reefs is closely linked to relative sea-level change and the role of island subsidence in the transformation of fringing reefs to barrier reefs and atolls, as proposed already by Darwin (1890). More recently, drilling and dating of shallow-water corals preserved in fossil reefs has elucidated patterns of late Quaternary climate and sea-level change (Macintyre and Glynn 1976; Fairbanks 1989; Macintyre et al. 1992; Grigg et al. 2002). Sedimentologic and petrologic data from drill cores have also increased our understanding of Hawaiian reef architecture, and how faunal and lithologic variations result from changes in wave energy and accommodation space (Engels et al. 2004; Grossman and Fletcher 2004). Cores are relatively short, however, and labor intensive to collect, limiting investigations to the shallow subsurface at a small number of sites. In addition, reef growth is highly variable over small spatial scales, so widely spaced cores may not accurately resolve patterns of coral accumulation. Due to easier access, most stratigraphic investigations have focused on relatively low-energy environments located landward of the reef front. Therefore, little stratigraphic information is available from environments located seaward of the reef front, where higher wave energy and deeper water make coring difficult.

Previous studies have concluded that the surface morphology of Holocene coral reefs is strongly influenced by the morphology of the underlying substrate (MacNeil 1954; Purdy 1974; Purdy and Winterer 2001; Grigg et al. 2002)—that is, the surface of modern reefs resembles more or less directly the shape of the antecedent foundation, on which they formed. Subbottom profiling with seismic reflection can, under appropriate conditions, provide continuous observations of reef structure and elucidate the nature of underlying substrates. Problems with using seismic-reflection techniques in reefal environments include merging of multiple reflections because of shallow water depths, and limited depth of penetration from the hard (i.e., acoustically reflective) and irregular (i.e., highly rugose or rugged) nature of the reef surface. Most studies have focused on stratified channel-fill and lagoonal deposits that are closely associated with the reef, rather than on the coral framework of the reef itself (e.g., Zinke et al. 2001; Fielding et al. 2003).

This paper reports the preliminary results of a single-channel, seismic-reflection survey of coral reefs south of

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Molokai, Hawaii (Fig. 1). The reconnaissance-level survey provides high-resolution observations of shallow subbottom stratigraphy in areas adjacent to, and seaward of the reef crest in water depths up to 140 m. It is part of a multidisciplinary project headed by the US Geological Survey that focuses on the ecosystem health and geological evolution of Hawaiian reefs since the late Pleistocene sea-level lowstand ~21,000 years before present (21 ka b.p.). At that time, sea level was ~130 m lower than today, and has risen at different rates to its present position (Fairbanks 1989). The main objectives of this study are to (1) determine the thickness and geometry of the fore reef and marginal shelf deposits; (2) describe the nature of the underlying substrates, on which the coral reefs formed; (3) consider the possible origins of the antecedent surface, with implications for the interpretation of marine regression and transgression.

Physical setting

More than 60% of coral reefs in US waters are in the Hawaiian Island chain, covering an area of more than 14,000 km^2 (Field et al. 2001). One of the largest coral-reef complexes in the region stretches for ~60 km along the southern, leeward shore of Molokai (Fig. 1). The dense, nearly continuous coverage of live coral is sheltered by the island from large open-ocean swells with periods that can exceed 15 s and wave heights of 8 m or more. Streams draining steep volcanic slopes locally discharge abundant silty sediment onto the reef, thereby posing a serious threat to ecosystem health. Along the central part of the south coast, where wave energy is lowest, terrigenous mud mantles much of the inner reef flat, and corals are severely stressed or absent (Ogston et al. 2004). Agriculture and other historic changes in land use have exacerbated siltation on the reef.

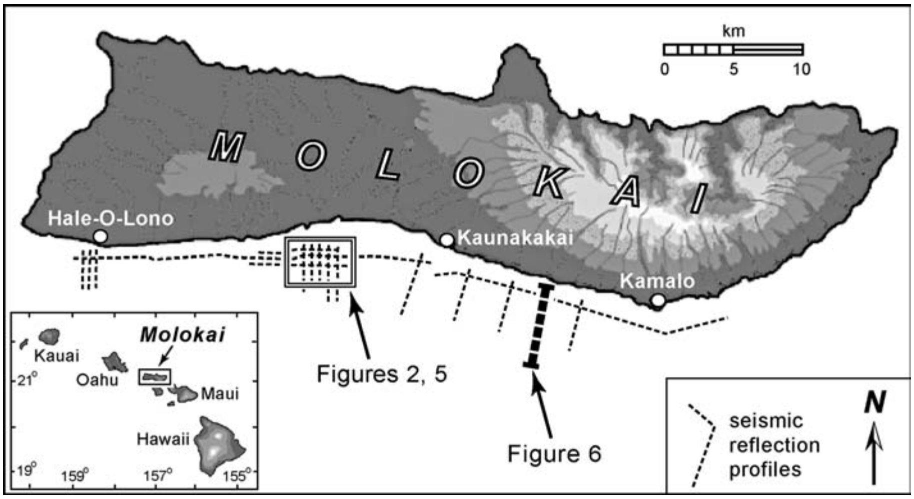
Precise mapping with airborne LIDAR, an airborne laser-based range-finding system, has revealed bathymetric details of the Molokai reef complex (Storlazzi et al. 2003). The reef consists of a shallow reef flat that is 1–2 m deep, and terminates ~1,000 m offshore at the reef crest, a very shallow and energetic zone marked by breaking waves. Narrow channels cross the reef (Fig. 2), and probably represent stream valleys cut when sea level was lower. Sediment in these channels is a mixture of carbonates detritus, derived from the adjacent reef, and terrigenous mud eroded from the volcanic island (Calhoun and Field 2002). The outer reef, or fore reef, extends seaward from the reef crest to depths of ~27 m and exhibits a well-developed spur-and-groove morphology. Beyond the rugged spur-and-groove features of the fore reef, few live corals are observed, and bathymetric contours are smoother and more evenly spaced. This study focused on the fore–reef environment from the reef crest to ~5 km offshore.

Materials and methods

Approximately 100 km of seismic-reflection profiles was collected in water depths of 5–140 m off the south shore of Molokai (Fig. 1) from the RV *Wailoa*, a shallow-draft catamaran well suited for nearshore operations. The acquisition system consisted of a 50-tip mini-sparker source operated at 300 J, a 30-element 5-m-long Benthos streamer, and a Delph Seismic digital recording computer. The fire rate for most lines was four pings (shots) per second, with a 200-ms record length digitized at 16 kHz and recorded in 16-bit integer SEG-Y format. For parts of the deeper water lines, a recording delay of up to 150 ms was used and the fire rate slowed to two pings per second. Ship speed varied between 3.5 and 4.5 knot. Position control was provided by differential GPS.

Prior to the survey, we tested the sparker system using a calibrated hydrophone, as required under a permit from the US National Marine Fisheries Service to ensure that marine mammals are not harmed. Two days of testing determined that the 160-dB safety zone

Fig. 1 Map of study area showing seismic-reflection profiles and locations of Figs. 2, 5, and 6



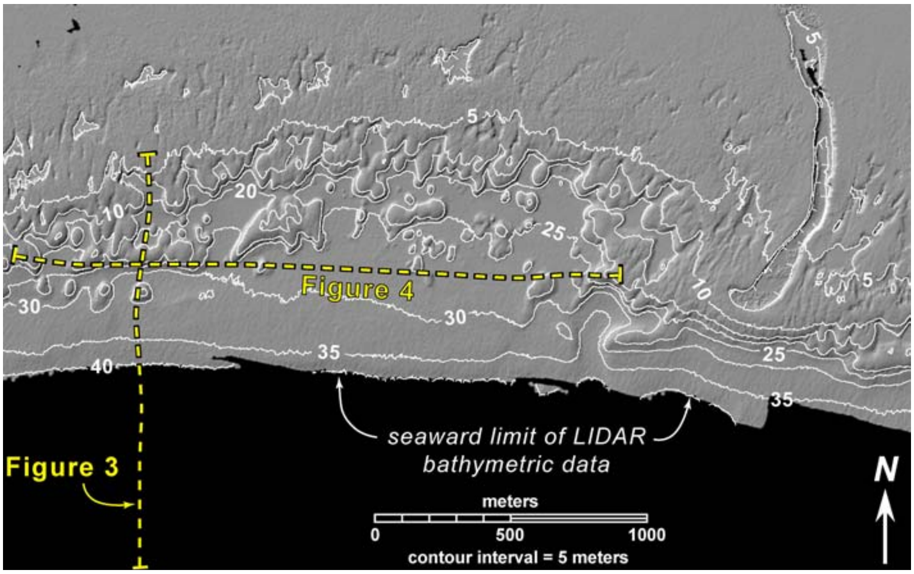


Fig. 2 Shaded-relief bathymetric map overlain with 5-m contours. *Dashed lines* indicate seismic profiles in Figs. 3 and 4. See Fig. 1 for location

(i.e., the distance from the sparker, at which sound-pressure levels decrease to 160 dB) was 100 m. If marine mammals had been observed within a 100-m radius of the sparker, the system would have had to shut down. A team of three independent observers stood watch at all times on the RV *Wailoa*, but no whales were sighted and no shutdowns occurred.

Processing of the data was done with a Cogniseis Focus interactive seismic data processing system. Data were resampled from 16-kHz field sampling frequency to 8 kHz. This reduces file size by half, while still allowing preservation of data frequencies up to 3 kHz. A band-pass filter of 300–2,400 Hz was applied to remove noise outside of the signal bandwidth for useful data; most of the signal content of these data lies between 500 Hz and 1,500 Hz.

Results

Description of acoustic facies

Six acoustic facies were identified on the basis of reflection characteristics and lithosome geometry—*antecedent substrate*, *fore-reef wedge*, *channel fill*, *transgressive sheet*, *nearshore wedge*, and *coral reef*. None of these facies have been directly sampled for ground truthing; interpretations are based entirely on seismic-reflection observations.

The *antecedent substrate* (facies AS) is characterized by internal reflections that are generally scattered and laterally discontinuous (Fig. 3). This facies always occurs at the base of the section and is observed throughout the study area. The low relief, seaward-dipping upper surface is marked by a sharp, high-intensity reflection, and is locally incised by small channel-like features. Facies AS is interpreted as representing older reef deposits that were exposed by sea-level fall and then flooded during the Holocene transgression, forming the foundation for the modern Molokai reef complex. The age is unknown but we assume they belong to marine isotope stage 5 (~125,000 a b.p.) or older.

The *fore-reef wedge* (facies FRW) overlies the antecedent substrate in deeper parts of the study area (water depths >100 m; Fig. 3). This facies is a locally thick (>40 m), sigmoidal-shaped package of stratified material. Internal reflections are characterized by seaward-dipping, slightly *S*-shaped clinoforms. Facies FRW exhibits a relatively flat top with a sharp break-in-slope at ~130 m depth, and a smooth, steep slope that dips offshore. Facies FRW is interpreted to comprise sediment deposited mostly during the late Pleistocene lowstand of sea level approximately 21 ka b.p. The fore-reef wedge probably continues to receive limited amounts of sediment from upslope and perhaps in-situ production (side-scan sonar images show possible *Halimeda* beds on the seafloor). Prominent notches, possibly relic shoreline-erosion features, are buried by the fore-reef wedge at depths >130 m below present sea level (Fig. 3). If the ages of these notches could be determined, they might provide a datum to calculate the subsidence rates of the island.

The *channel fill* (facies CF) lies in long, narrow depressions cut into the upper surface of facies AS (Fig. 4), and is observed only in the central part of the study area. The elongate channel is oriented in a shore-normal direction, and measures up to 8 m deep and 750 m wide. Closely spaced internal reflections are flat-lying and parallel. The top of this facies is truncated by the same highly reflective, relatively flat-lying surface that marks the top of the antecedent substrate (i.e., surface R1; see below). We interpret the channel-fill deposits as a Holocene transgressive backfill of a stream valley cut into older reef deposits during lower sea level.

The *transgressive sheet* (facies TS) is a sheet-shaped or lens-shaped deposit that is observed only in deeper parts of the study area (80–130 m depth). It lacks internal

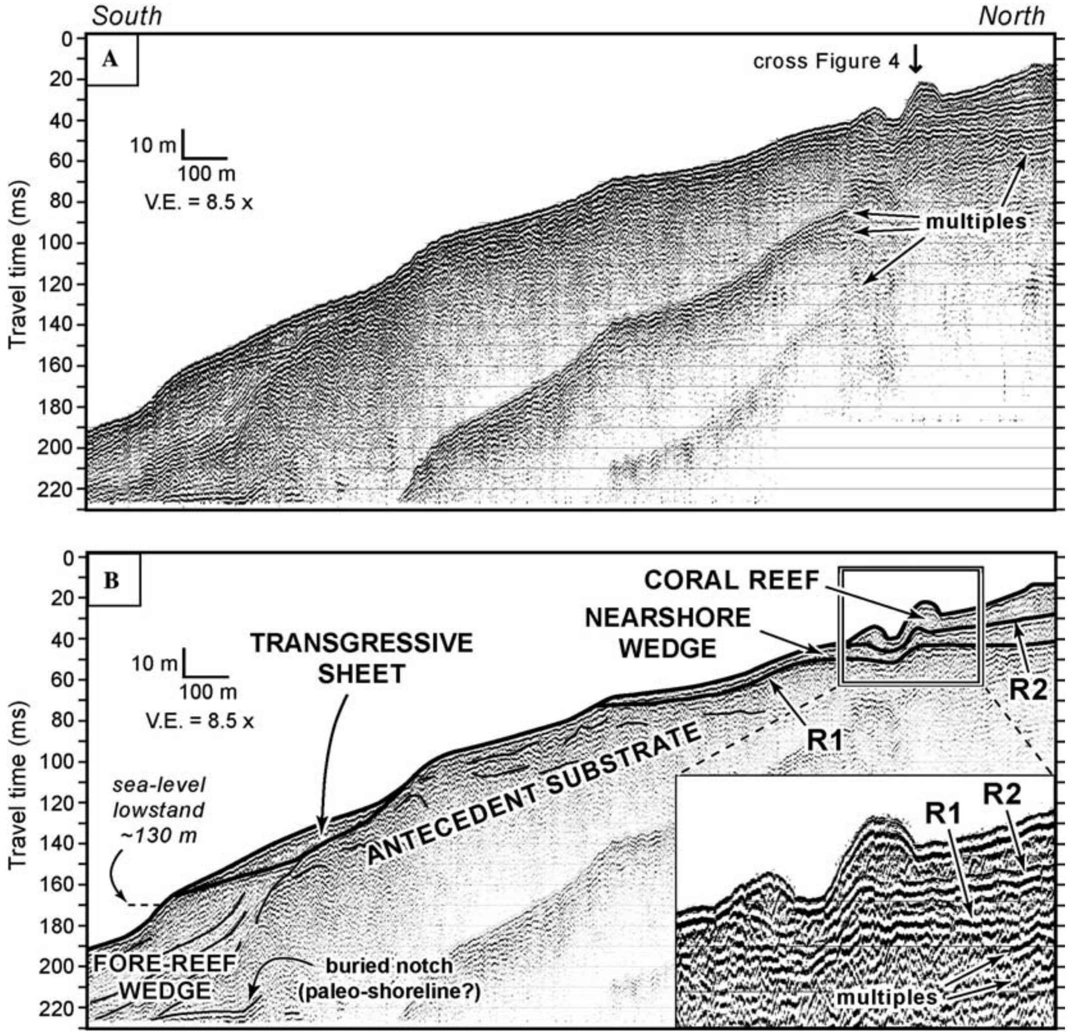


Fig. 3 **a** Mini-sparker seismic-reflection profile across the narrow, steeply dipping shelf south of Molokai. **b** Line-drawing interpretation of profile with inset showing modern reef front. The R1 surface defines a buried platform extending ~1 km seaward of the reef crest. See Fig. 2 for location

reflections, and varies in thickness from 1 to 8 m. Facies TS lies above surface R1, the strong reflection that caps facies AS and CF. This deposit probably formed during the early Holocene transgression as sea-level rose from the lowstand position. The marginal shelf probably still receives some reef-derived sediment.

The *nearshore wedge* (facies NW) is a tabular or slightly wedge-shaped deposit that is 5–10 m thick in nearshore areas, and gradually thins in a seaward direction. It overlies facies AS, and locally crops out on the seafloor beyond the fore reef in depths of 25–50 m. The upper surface of this facies is characterized by a continuous, high-amplitude reflection (surface R2; see below). Internal reflections are discontinuous and rare. Facies NW probably represents transgressive deposits that formed as sea level rose during the Holocene and reworked existing material. However, facies NW might be older, possibly representing truncated regressive or lowstand deposits. Two alternative interpretations for age and origin of this facies are discussed below.

The *coral reef* (facies CR) consists of pinnacle-shaped, mound-shaped, and ridge-shaped deposits that are restricted to water depths of less than ~27 m, and generally thicken in a landward direction (Fig. 3). Internal reflections are incoherent and laterally discontinuous. Facies CR overlies the nearly planar upper surface of facies NW and is, where present, always the uppermost unit, cropping out on the seafloor in a narrow band along the south shore of the island. The thickest part of facies CR is off the east-central coast of the island, where two-way travel time is up to 28 ms. Based on an estimated velocity of 2,200–2,300 m/s in this unit, the maximum thickness is 30–32 m. In the center of the study area, facies CR is 20–21 m thick. Bathymetric relief is high along the fore reef, where spur-and-groove features rise ~2 m above adjacent areas of seafloor, and detached pinnacles are on the order of 10 m high (Fig. 2). We interpret facies CR to represent accumulations of reefal framework materials along with associated sediments that occupy depressions on the reef.

Major bounding surfaces

The most prominent features observed in the seismic-reflection data are the highly reflective R1 and R2 surfaces that underlie the reef complex (Fig. 3). The two surfaces exhibit low relief and dip gently seaward, roughly parallel to each other, forming conspicuous stratigraphic boundaries. Both surfaces crop out on the seafloor in locations seaward of the reef front.

The *R1 surface* is the most extensive of the two surfaces, and marks the top of the antecedent substrate and channel-fill facies (Fig. 4). It is buried by up to 21 m of younger material (facies CR and NW) in areas adjacent to the reef crest (Fig. 3). A small grid of seismic-reflection profiles was used to produce a contour map of the R1 surface (Fig. 5). In the western part of the map, the R1 surface gently dips from elevations of 20–40 m below sea level, and then abruptly steepens as it descends to ~50 m, where it crops out on the seafloor. In deeper water, it marks the top of the fore-reef wedge. Contours in the eastern part of the map depict a channel-like depression that cuts across the top of facies AS and is probably fluvial in origin. The paleochannel is oriented normal to shore, and parallel to an existing channel of approximately the same width. The buried platform beneath the modern reef, as defined by surface R1, extends ~1 km seaward of the reef crest in this area, but is substantially wider in areas off Kaunakakai and Kamalo (Fig. 6).

The contours in Fig. 5 were not created using a depth-dependent velocity function. Instead, a constant velocity of 1,500 m/s was applied through both water and sediment. We estimate a velocity of 2,200–2,300 m/s through the coral reef and transgressive-sheet facies, based on analysis of velocity pull-ups along the margins of sand-filled channels. Actual sub bottom depths to the more deeply buried contours may be up to 15% greater than shown in Fig. 5. In addition, dip angles on the R1 and R2 surfaces may be exaggerated by differences in thickness and velocity structure of overlying material.

The R2 surface marks the top of facies NW, and is less extensive than the R1 surface (Figs. 3, 4, 6). It extends out to depths of ~25 m, approximately the seaward limit of modern coral reef growth (Storlazzi et al. 2003), and merges with the seafloor at the outer toe of the fore reef. The R2 surface is of similar low relief but dips seaward at a slightly steeper angle than R1, such that the two surfaces diverge in a landward direction. Facies NW, which lies between the two surfaces, becomes slightly thicker closer to land.

Discussion

Conceptual models of reef development

Analysis of seismic-reflection data supports two models for the stratigraphic development of the marginal shelf and fore-reef environments off the southern coast of Molokai (Fig. 7, models A and B). These conceptual models are purely deductive, being inferred from seismic-reflection data alone. The timing and elevation of former sea levels used in the models are based on Fairbanks (1989) and Sherman et al. (1993). Each model consists of four phases, which are described below.

Phase 1: last interglacial, approximately 125 ka b.p

Sea level is at, or slightly above the present datum (Sherman et al. 1993). Fringing reefs exist off the southern coast of Molokai, similar to the setting today, and a narrow marginal shelf descends steeply offshore into deep water. Based on seismic-reflection data alone, we cannot differentiate between reefal and volcanic

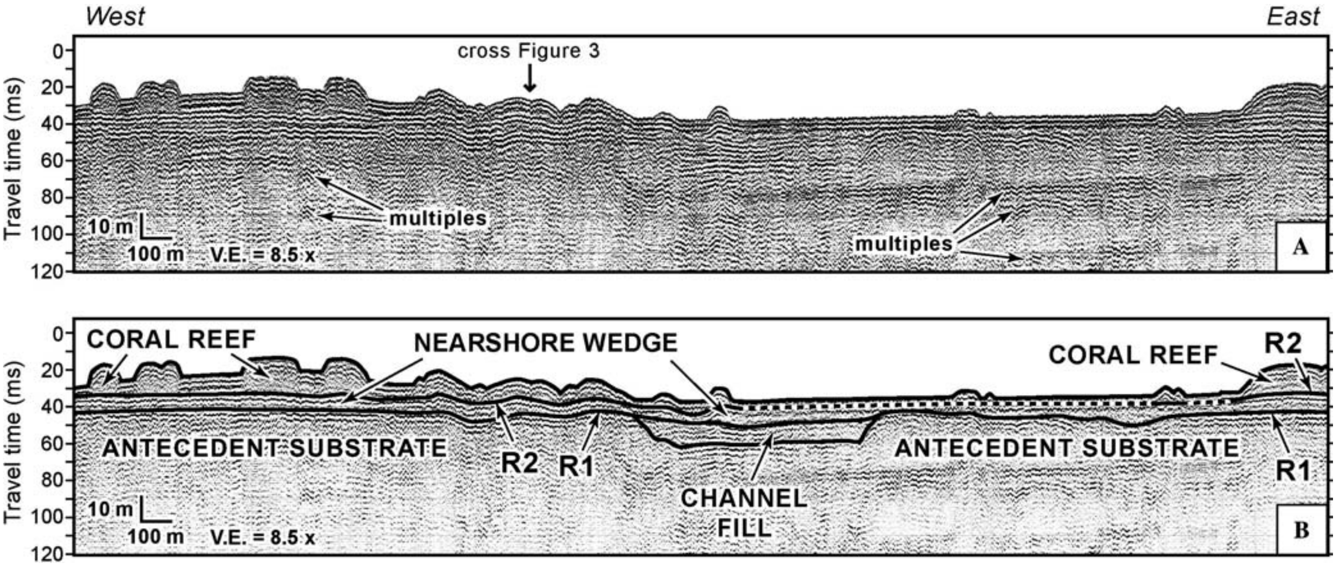


Fig. 4 **a** Mini-sparker seismic-reflection profile oriented parallel to coast. **b** Line-drawing interpretation of profile. See Fig. 2 for location

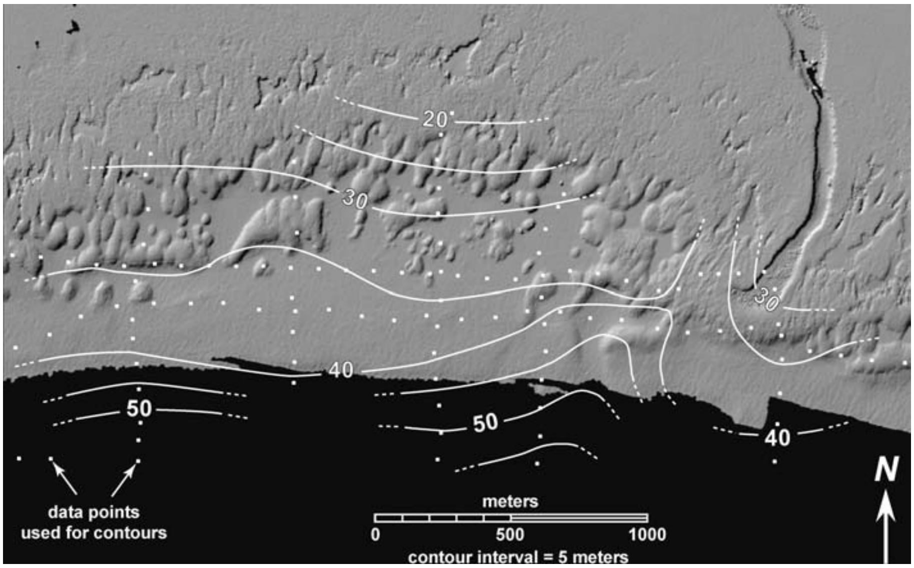


Fig. 5 Shaded-relief bathymetric map overlain with contours of buried R1 surface (same area as Fig. 2). Depths to the R1 surface are based on a velocity of 1,500 m/s in both water and sediment

materials that might comprise the antecedent substrate (facies AS). In phase 1, starting conditions for models A and B are identical—they both begin at the interglacial highstand of sea level.

Phase 2: last glacial maximum, approximately 21 ka b.p

Global sea level is at lowstand ~130 m below present. In both models A and B, shoreline regression subaerially exposes the highstand reefs and adjacent shelf areas. Streams, in response to falling base level, incise and deeply erode the emergent landscape, forming a lowstand surface of erosion. Voluminous sediment is transported offshore to the lowstand shoreline, and deposited as a thick fore-reef wedge (facies FRW). The sigmoidal stratal pattern in this unit indicates lateral outbuilding or progradation into deeper water.

During phase 2, models A and B differ in two important ways: (1) the magnitude of erosion during regression and lowstand (model A > model B), and (2) the accu-

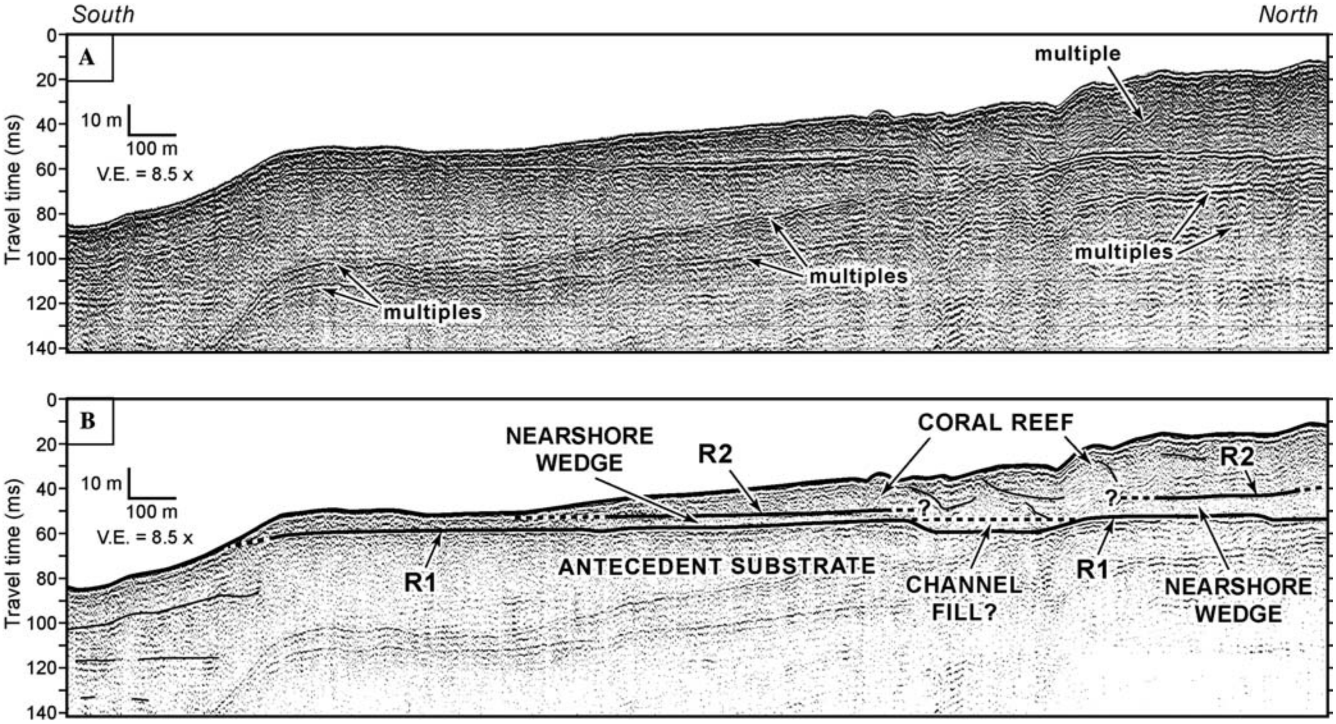


Fig. 6 **a** Mini-sparker seismic-reflection profile oriented normal to coast about midway between Kaunakakai and Kamalo. See Fig. 1 for location. **b** Line-drawing interpretation of profile. Compared to the profile in Fig. 3, the R1 surface in this area is flatter and extends farther seaward (~2 km) of the reef crest

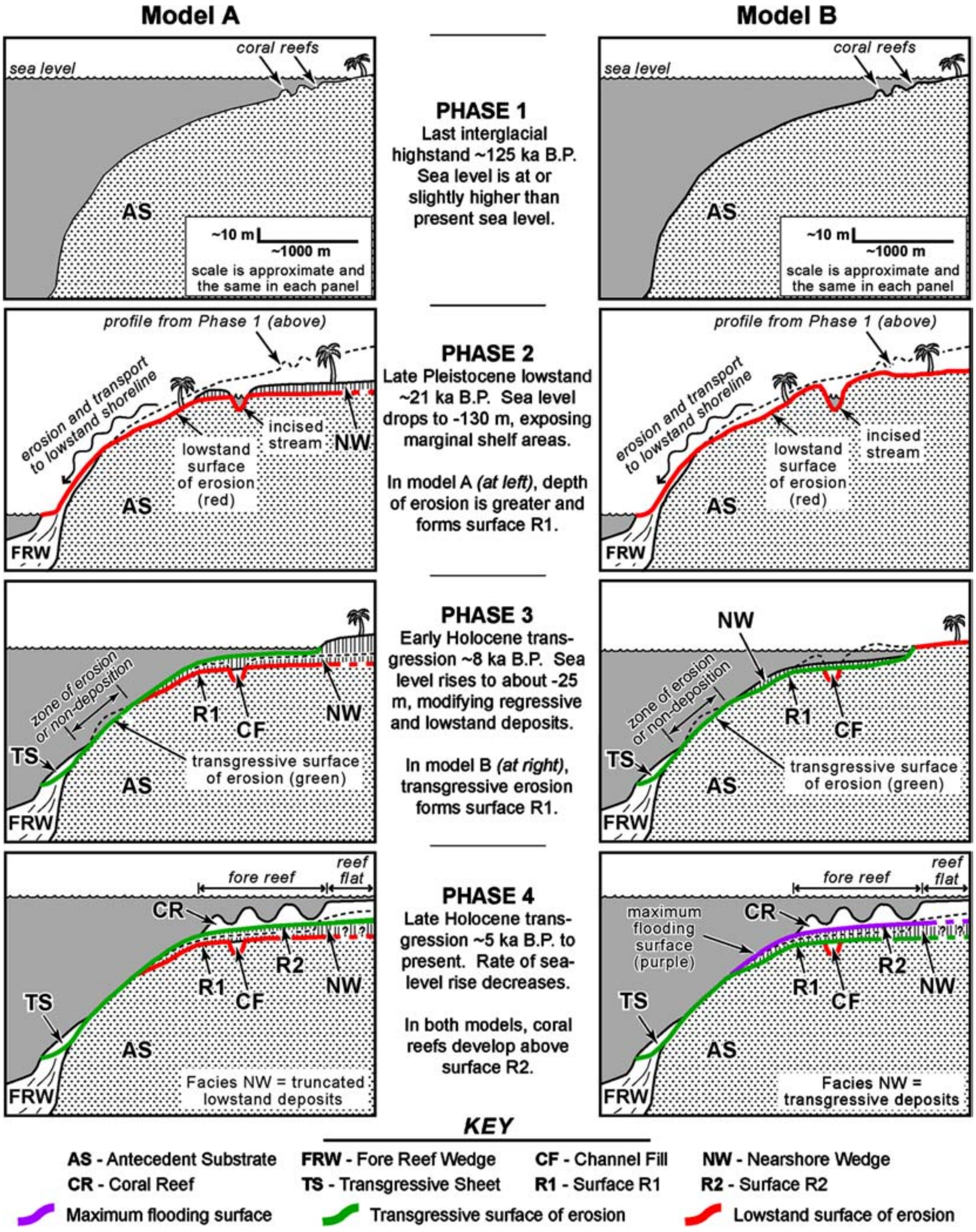


Fig. 7 Conceptual models **a** and **b** depicting two possible modes for development of shelf stratigraphy in response to sea-level changes. *Colored lines* represent different interpretations of buried surfaces observed in seismic-reflection data. *Thin dashed lines* represent island profiles in the preceding panel. See text for explanation and comparison of models

mulation of sediment over the lowstand surface (thin to absent in model B). At this point in model A, erosion has lowered the island topography to approximately the same elevation as the R1 surface (Figs. 3, 6). The eroded shelf in model A exhibits the same flat-lying morphology as the R1 surface. By contrast, the lowstand surface that develops in model B lies stratigraphically higher—that is, the lowstand surface in model A correlates in space with the R1 surface, but in model B it does not.

Phase 3: early Holocene transgression, approximately 8 ka b.p

Sea level has risen to ~25 m below present. Exposed parts of the shelf are flooded, and incised channels are filled with sediment. Erosion beneath the shoreface has reworked coastal sediment that was deposited during regression and lowstand (or earlier), and creates a transgressive surface of erosion that extends landward from the lowstand shoreline and climbs up the steep marginal shelf. Accommodation space increases with rising sea level, and transgressive sediment locally accumulates above the lowstand shoreline and in near-shore areas. Antecedent substrate material apparently crops out on the seafloor in mid-shelf areas (50–80 m depth), which have no discernible cover of transgressive sediment and probably represent a zone of erosion or non-deposition.

During phase 3, models A and B differ in the degree of preservation of the lowstand surface (model A > model B). The main difference involves interpretation of the R1 surface—does it represent the lowstand surface of erosion (i.e., *basal unconformity*), or is it the transgressive surface of erosion (i.e., *ravinement unconformity* of Swift 1968)? An important control on the preservation of the lowstand surface is the relative thickness of sediment that has accumulated above it. Thus, stratigraphic preservation is a function of the depth of burial relative to the depth of transgressive erosion that follows (Belknap and Kraft 1985). Sediment above the lowstand surface is thicker in model A, increasing the preservation potential of that surface. In model B, however, sediment cover is thinner and transgressive erosion has largely exhumed the lowstand surface, which is only preserved in low-lying areas of antecedent topography. Preservation is primarily restricted to the base of incised channels.

Phase 4: late Holocene transgression, approximately 8 ka b.p. to present

By 5 ka b.p., the rate of sea-level rise has decreased, allowing coral reefs (facies CR) to develop in shallow water near the coast. The reefs lie above surface R2, which marks the top of facies NW. During phase 4, models A and B are again identical—they both end at the modern stand of sea level.

Inferred origins of stratigraphic elements

Models A and B illustrate different interpretations of key seismic-stratigraphic elements (Fig. 7). In particular, the models differ on the relative age of facies NW, and the origin of the R1 and R2 surfaces that bound it at the top and bottom. It is not entirely clear whether these elements formed during regression and lowstand, or during the subsequent transgression.

If facies NW formed during regression and lowstand (model A), it would probably consist of coastal plain and littoral sediment that aggraded and/or prograded over the R1 surface. The R1 surface, in this case, represents the lowstand surface of erosion (red line in Fig. 7). The transgression that followed then truncated facies NW and produced the R2 surface, interpreted here as the transgressive surface of erosion (green line in Fig. 7). However, we see no evidence for progradation in the seismic data (i.e., internal downlapping or prograding clinoforms are absent), nor does facies NW exhibit evidence of stream incision that commonly occurs at lowstand.

If facies NW formed during transgression (model B), it would consist of more recently deposited sediment that was reworked by waves and tides, and probably not exhibit evidence for progradation—as, indeed, it does not. The underlying R1 surface, in this second case, represents the transgressive surface of erosion (green line in Fig. 7), which truncates channel-fill deposits (facies CF). The incised channels are topographically low, and have preserved lowstand-age sediment beneath the depth of transgressive erosion. The upper boundary of facies NW, surface R2, is tentatively interpreted as the maximum flooding surface. By definition, the maximum flooding surface separates the transgressive from the highstand systems tracts, and marks the time when the shoreline is at its maximum landward position (Posamentier et al. 1988). Our data do not show it, but the maximum flooding surface is commonly expressed as a downlap surface in seismic-reflection data. In this scenario, sea-level rise is continuing, but has slowed enough to allow coral reefs to aggrade or “catch up” (Neumann and Macintyre 1985). Highstand behavior might just be starting with the growth of reef pinnacles and ridges along the reef front (Fig. 2).

Both models A and B are problematical, however, because they depict exceedingly large accumulations of material above the antecedent substrate. Consider, for example, the volume of material in Fig. 3 that lies above the R1 surface, regardless of its age and origin. A vertical slice 1 m thick (i.e., extending 1 m out of the plane of the profile) represents ~35,000 m^3 of sediment along that shore-normal profile alone. Extrapolating this relationship (35,000 m^3 per linear meter of shoreline) along the entire 60-km length of the island yields a volume exceeding 2 km^3 of material that has accumulated since either the late Pleistocene (model A) or the early Holocene (model B).

A third alternative, not considered in Fig. 7, is that facies AS, CF, and NW are much older (greater than 125 ka) and did not form during the late Pleistocene and Holocene. Instead, sediment accumulation off Molokai was much slower in the Holocene, and reef growth during that time may be too thin and spatially discontinuous to be resolved by the seismic equipment. A definitive answer will require direct sampling and radiometric age ating of materials directly above and below the R1 and R2 surfaces.

Conclusions

This study provides general guidelines on the application of seismic-reflection techniques in coral-reef environments, and insights about the geologic evolution of the Molokai fringing reef.

- High-resolution, seismic-reflection profilers are capable of imaging the subsurface structure of coral reefs, even at relatively low power (300 J). Most of the useful signal was in the frequency range of 500–1,500 kHz.

- Pre-survey testing of sound levels was needed to establish a safety zone of 100 m around the sound source. Harassment of marine mammals was avoided with close monitoring by a team of observers.
- The antecedent substrate beneath the Molokai reef is a low relief, areally extensive surface that generates strong acoustic reflections. Seaward of the reef front, the reflective surface crops out on the seafloor in water depths of about 50 m. In more landward areas, it is locally buried by more than 20 m of sediment.
- The planar morphology of the antecedent substrate bears no resemblance to the rugged surface of the modern fore reef. The buried platform shows evidence of stream incision, but shows no evidence of karst topography, such as rim-bounded solution basins.
- The results of this study suggest that the stratigraphic response of a mixed carbonate–siliciclastic margin to sea-level change (i.e., the formation of lowstand deposits at Molokai) is similar to the response of terrigenous margins. Deeper parts of the marginal shelf received carbonate sand and rubble from reworking of coral reefs, and terrigenous sediment from erosion of the island. The relative contributions are not known, but a significant volume of sediment accumulated offshore in a thick fore-reef wedge. The sediment was probably transported across the steep shelf during periods of lower sea level, and sequestered below the depth of the sea-level lowstand.
- This pattern of sediment dispersal is antiphase with the "carbonate highstand shedding" concept of Schlager et al. (1994), who postulated that sediment production on carbonate banks is many times higher at sea-level highstands relative to lowstands. The geologic setting at Molokai, however, includes a proximal source of terrigenous sediment (i.e., a volcanic island) that is absent from carbonate banks.

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