CHAPTER 1

Antecedent Substrate Underlying the South Molokaʻi Fringing Reef and Implications for Reef Development

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The development and physical characteristics of coral reefs are closely related to the geological evolution of the islands where they form. According to the theory proposed by Charles Darwin (1842), the shape and structure of reefs evolve over geologic time, reflecting the gradual subsidence of tropical oceanic islands balanced by the upward growth of corals. Over shorter time scales, reef evolution is controlled by cycles of falling and rising sea level (Daly, 1915) that are, in turn, driven by the expansion and decay of large polar ice sheets. Erosion during lowstands of sea level, when the reef is subaerially exposed, and renewed coral growth during highstands of sea level modulate reef development.

The fringing reef along the southern shore of Molokaʻi (fig. 1) is a massive geological structure that has developed over thousands of years by the accumulation of corals and other organisms with calcium carbonate skeletons. Corals are colonial animals that inhabit shallow waters along tropical shorelines and require a stable substrate for attachment. Reef-building corals commonly become established on preexisting, hard surfaces, such as old volcanic lava flows or sedimentary rock, which can include ancient reefs.

Geologists consider the antecedent substrate to be an important factor that determines the shape of modern reefs (Purdy, 1974; Grigg and others, 2002). In their view, patterns of coral growth are largely controlled by the configuration of the foundation that lies beneath the reef. Corals need sunlight and so preferentially grow on bathymetrically higher parts of the sea floor. In addition, these bathymetric highs allow corals to grow undisturbed by sediment resuspended from the bottom, which can suffocate, abrade, and kill the reef-building organisms. New reef growth serves to amplify irregularities of elevation and slope that already exist on shallow parts of the sea floor. These irregularities commonly represent features that formed when sea level was lower, such as old stream valleys with raised banks that serve as preferred attachment points for corals. Off the south-central coast of Molokaʻi, for example, corals have encrusted the margins of a former stream channel (Pālāʻau), which meandered across the coastal plain before sea level rose and submerged it (see Storlazzi and others, this vol., chap. 3).

At a broad regional scale, however, subsurface mapping of the Molokaʻi fringing reef shows evidence for a different style of reef evolution that does not preserve or amplify preexisting topographic irregularities. The high-relief pinnacles, mounds, and spur-and-groove features of the modern reef system have developed over a broad, flat-lying platform that exhibits only limited local relief. In this chapter, a conceptual model is presented to explain the possible origin of the antecedent substrate that is buried beneath the Molokaʻi reef.

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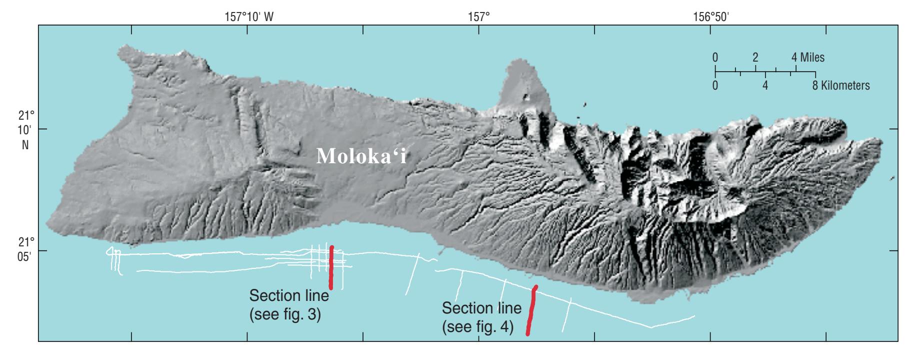


Figure 1. Map of Molokaʻi showing the locations of seismic-reflection profiles discussed in subsequent figures.

Seismic-Reflection Profiling and Reef Evolution

The U.S. Geological Survey used an acoustic technique known as "seismic-reflection profiling" to investigate the long-term development of the Molokaʻi reef. Seismic-reflection profiling relies on sound waves to image the geologic framework of the reef and adjacent areas of the sea floor. The seismic-reflection system consists of (1) a sound source that generates an outgoing pulse of sound and (2) a receiver that records the time required for each pulse to complete a two-way trip through the water column, the materials the reef, and back to the boat (fig. 2). A computer analyzes and plots the returning sound waves on paper as a series of dark and light bands that depict the thickness and geometry of materials making up the ocean floor (figs 3 and 4). These new data have important implications for understanding regional sea-level history and patterns of coastal change (Barnhardt and others, 2005). To ensure that marine mammals were not affected by the sound, we tested the equipment with a calibrated hydrophone and employed independent observers as required under a permit from the U.S. National Marine Fisheries Service.

Antecedent Substrate

The most prominent feature observed in the seismic-reflection profiles is a flat-lying, highly reflective surface that lies beneath the fore reef and marginal shelf. The strong reflection, indicated by the red line in figures 3 and 4, was generated by a sharp contrast in physical properties between the material above and below this surface. It might represent, for example, a layer of reef rock overlying volcanic rock or two stacked layers of reef rock that have different porosity or degree of cementation, perhaps due to differences in age and degree of weathering. The low-relief surface dips gently seaward at

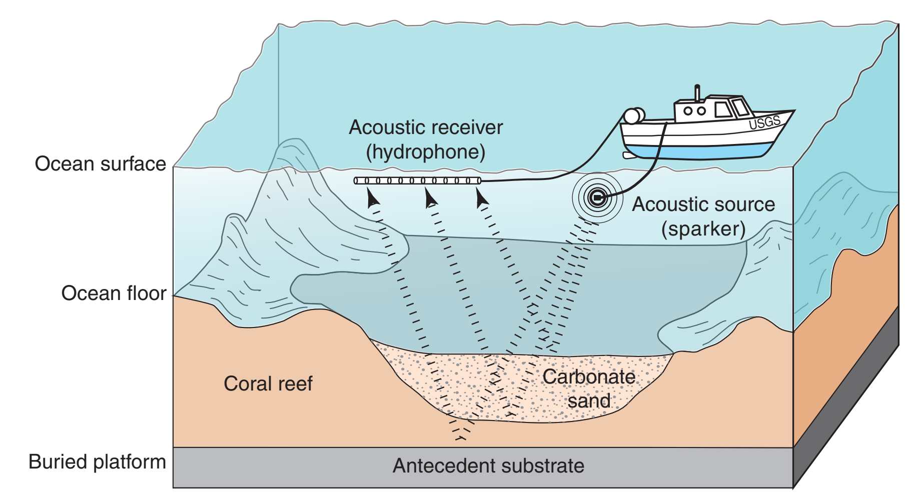


Figure 2. Block diagram showing the basic operation of a seismic-reflection profiling system. Pulses of sound are generated by the system and travel different paths (dashed lines) through water, sediment, and reef rocks. Some of the energy is reflected by the ocean floor back to the hydrophone, which records the timing and strength of each pulse. Some energy also penetrates the ocean floor and is reflected from interfaces between materials of different properties, such as a layer of loose carbonate sand overlying well-cemented reef rocks. Longer ray paths require longer travel times, so reflections from the buried surface that underlies the reef arrive later than reflections that are generated closer to the ocean floor.

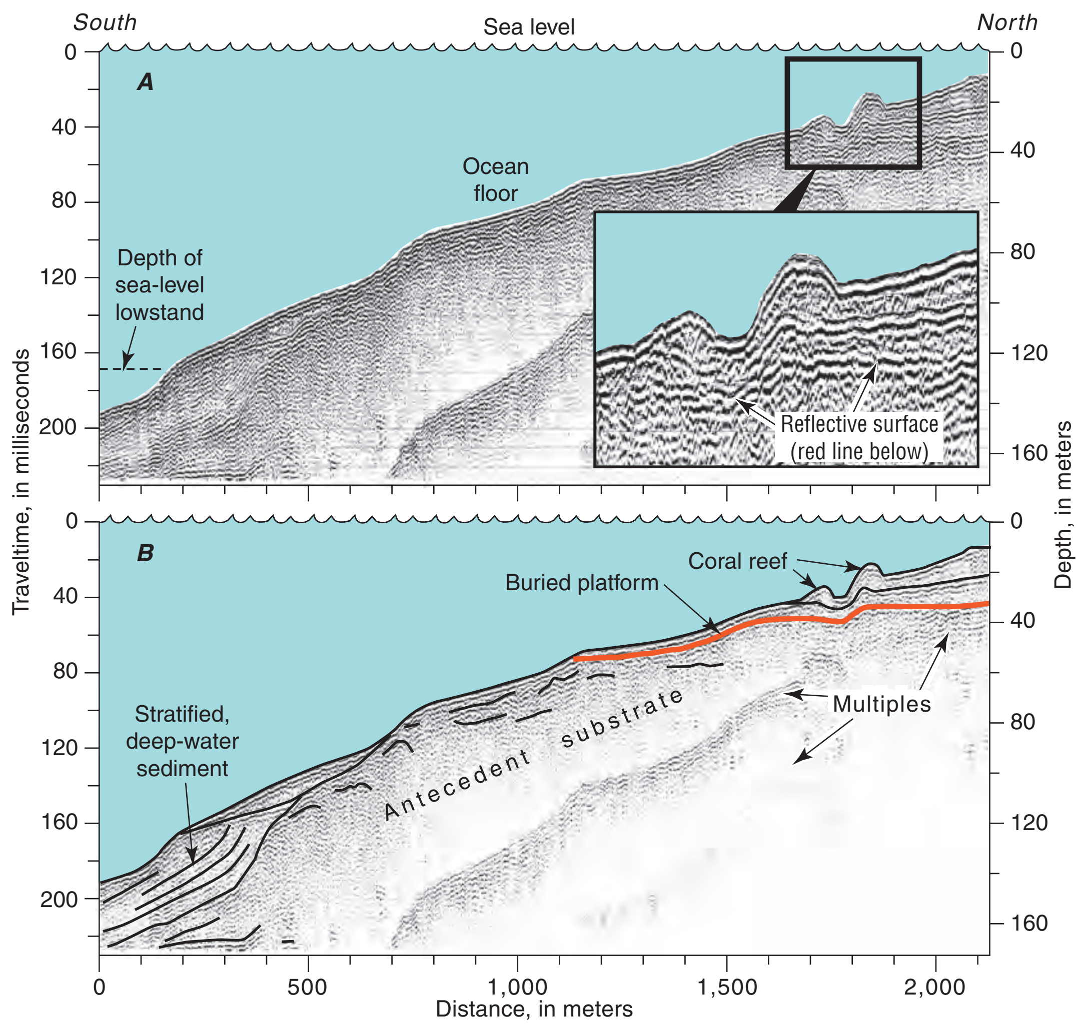
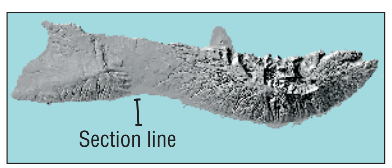


Figure 3. Cross section across the narrow, steeply dipping shelf south of Moloka'i. *A*, Seismic reflection profile, with inset showing modern reef front. The dashed line at lower left indicates the lowstand position of sea level at about –130 m (427 ft) during the last ice age. *B*, Line-drawing interpretation of profile. The red line represents a buried platform, which is etched into the antecedent substrate and extends approximately 1 km (0.6 mi) seaward of the reef crest. The dark lines labeled "multiples" are created by sound pulses that have been reflected more than once; they do not represent geologic structures.



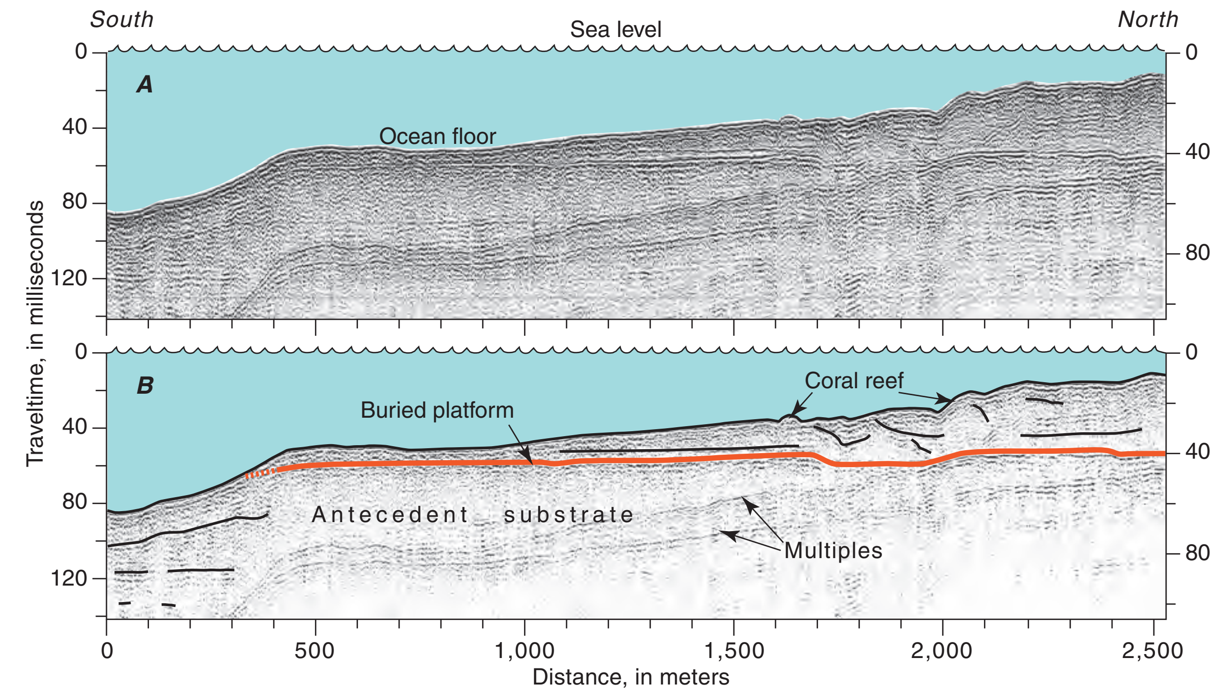
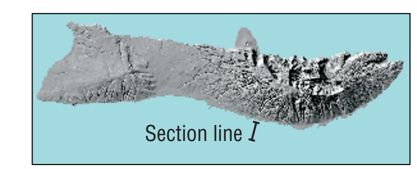


Figure 4. Cross section oriented perpendicular to the coast about midway between Kaunakakai and Kamalō. *A*, Seismic reflection profile. *B*, Line-drawing interpretation of profile. Compared to the profile in figure 3, the buried platform in this area is flatter and extends farther seaward (approximately 2 km or 1.2 mi) of the reef crest.



slopes of 1°–2° and locally crops out on the sea floor in locations offshore of the fore reef. It was traced in the subsurface for about 60 km (37 mi), nearly the entire length of the island.

Judging from its morphology and setting, the buried platform probably represents an ancient reef flat that formed at a previous highstand of sea level or, more likely, a wave-cut terrace that was eroded into the flank of Moloka'i during the last ice age (fig. 5). We believe that erosion by coastal and terrestrial processes produced the wide, flat platform during the long period of subaerial exposure when sea level was lower. During that time, streams flowed across the exposed areas of former sea floor and locally incised deep channels. The platform was later recolonized by corals as glaciers melted and the ocean again rose to its present level. In the course of the sea-level rise, the stream channels were filled with sediment and preserved beneath the modern reef. Note that the uniformly low relief of the buried platform contrasts with the irregular shape of the overlying modern reef, which exhibits rugged pinnacles and mounds.

Deep-Water Sediment

If erosion created the buried platform when sea level was lower than today, we need to account for the large volumes of material that have been removed. Where did all the eroded sediment go? Erosion by waves, currents, and streams probably carried sediment off the reef and deposited it offshore in deep water. Indeed, large deposits of stratified or layered sediment, locally more than 40 m (131 ft) thick, occur in deep water seaward of the modern reef front (fig. 3). The wedge-shaped deposits exhibit a relatively flat top, a sharp break in slope at a depth of about 130 m (427 ft), and a smooth, steep slope that dips farther offshore. Internal reflections dip seaward and are slightly S-shaped. The morphology and depth of the sediment wedge suggests that the deposit was graded to the lowstand of sea level that occurred during the last ice age approximately 21,000 years before present.

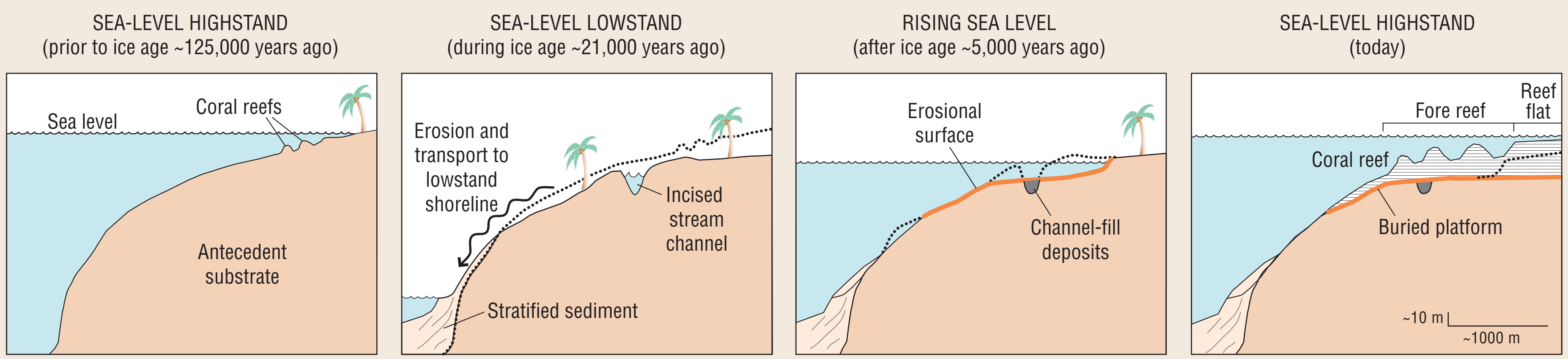
Summary

The geologic development of coral reefs is closely linked to sea-level change. Fluctuations in sea level are well documented in the Hawaiian Islands and, without doubt, have considerably influenced the development of coral reefs (see Grossman and others, this vol., chap. 10). The internal structure of the Moloka'i reef records a complex history of reef building that was modulated by changes in global sea level and erosion by oceanic and terrestrial processes. As submarine volcanoes grew out of the sea to form the island, corals and other carbonate-secreting organisms colonized the shallow nearshore environment. High-resolution seismic-reflection data have enabled us to accurately map the morphology of the antecedent substrate on which the reef complex formed. The buried platform underlying the modern reef probably represents a wave-cut terrace that developed at some past time; a full understanding of its origin and age will require direct sampling with cores.

The rugged surface of the modern fore reef bears no resemblance to the planar morphology of the buried platform beneath. The pinnacles and spur-and-groove features (see Storlazzi and others, this vol., chap. 3) have high local relief, but the underlying platform is smooth and gently sloping. In more seaward locations, the shelf steepens and dips down at a high angle, restricting the potential area for reef growth during sea-level highstands to a narrow band that is, on average, about 1.5 km (0.9 mi) wide.

Deeper parts of the sea floor off Moloka‘i have received carbonate sand and rubble from reworking of coral reefs and terrigenous sediment from erosion of the island’s volcanoes. Although the relative contributions are poorly understood, a significant volume of sediment has accumulated in a thick, wedge-shaped deposit. This stratified sediment was probably transported across the steep shelf and sequestered offshore, mostly during the last ice age as sea level fell and remained lower than the present shoreline for thousands of years.

Figure 5. Diagrams showing a conceptual model of four steps in the development of the Moloka‘i reef in response to sea-level changes. Thin dashed lines represent island profiles in the preceding panel.



STEP 1

Previous interglacial period approximately 125,000 years ago, before the last ice age began. Sea level is at or near the present highstand elevation. Coral reefs grow in shallow waters along the margins of the island, similar to the modern setting. These reefs and/or underlying volcanic rocks form the antecedent substrate that was mapped with seismic-reflection profiles.

STEP 2

Last glacial maximum approximately 21,000 years ago (late Pleistocene). Global sea level drops to depths of about 130 m (427 ft), exposing older reefs and marginal shelf areas. The shoreline migrates in a seaward direction. Coastal and terrestrial processes erode and rework the antecedent substrate. Pālā‘au and other streams incise their channels deeply into the emergent landscape. Stratified sediment is deposited at the lowstand shoreline and in deeper water offshore.

STEP 3

Postglacial period approximately 5,000 years ago. Ice sheets are melting and sea level is rising. Shoreline migrates landward across formerly exposed areas of the island. Waves and currents further erode the antecedent substrate, creating a relatively broad, flat platform (red line). Incised stream channels fill with sediment.

STEP 4

Present conditions. The rate of sea-level rise has decreased, allowing coral reefs to develop in shallow water near the coast. Reef deposits bury the wave-cut platform (red line), which is observed in seismic-reflection profiles beneath most of the Moloka‘i reef complex.

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