CHAPTER 3

Shape of the South Moloka‘i Fringing Reef: Trends and Variation

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Ever since sailors started mapping the approaches to natural harbors at low latitudes, the complex morphology of coral reefs has been evident. Whereas the shallowest portions of the reef was the most important feature for sailors to map because of its obvious hazard to navigation, it was clear on fringing reefs that the majority of the reef lay seaward, extending into water depths of more than 40 m (132 ft). Although most sandy coasts are relatively straight and gently sloping, carbonate reefs display a wide variety of shapes, including extremely sharp boundaries and nearly vertical faces. The goal of this chapter is to document the morphology of the reef off south Moloka‘i, Hawaii, and from this infer what processes may have led to its present form.

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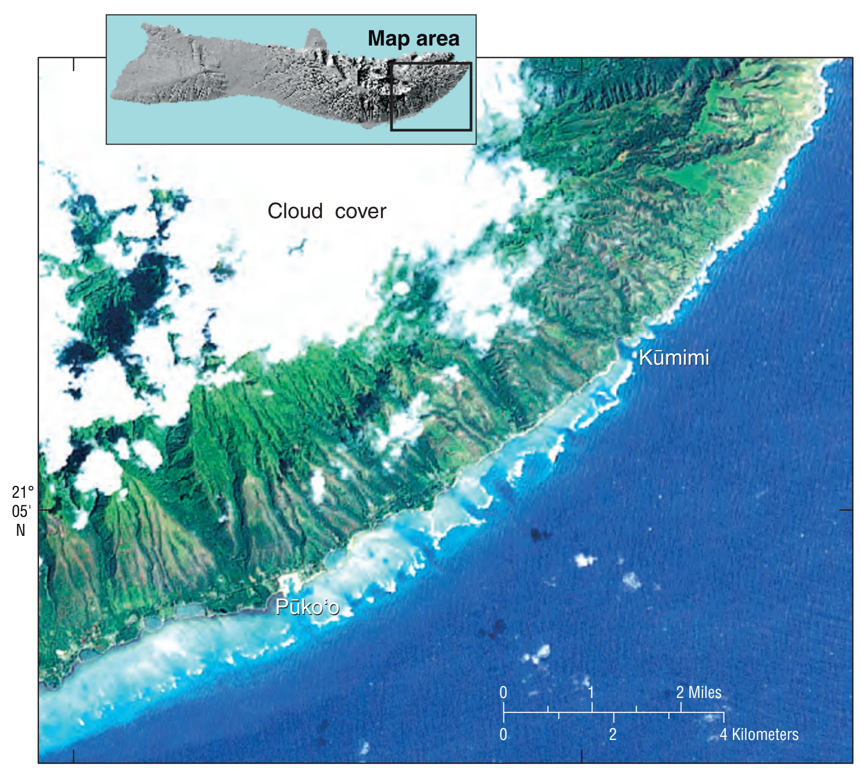

Figure 1. LANDSAT visual satellite image of the east end of the south Moloka‘i reef, showing the tapering of the reef to a narrow band at Kūmimi.

General Reef Morphology

The fringing coral reef lying off the south shore of Moloka‘i extends more than 40 km (24 mi) alongshore. The reef pinches out westward roughly 7 km (4 mi) from the west end of the island and eastward about 20 km (12 mi) from the east end of the island (fig. 1). From the shoreline out to deeper water, the reef can be generalized into three main zones: the reef flat, the reef crest, and the fore reef.

The reef flat is a low-relief, roughly horizontal surface with relatively sparse coral cover (see Cochran, this vol., chap. 9, for all benthic habitat types and coverage percentages) that extends from the shoreline to the reef crest (fig. 2). The reef flat is on average approximately 1 km (0.6 mi) wide and reaches a maximum width of more than 1.5 km (0.9 mi) offshore from the saddle between the two basaltic shield volcanoes that make up the island. The relatively flat inner half of the reef flat transitions into alternating shore-perpendicular low ridges of coral and sand-filled troughs on the outer half of the reef flat. The ridges are on the order of 0.1–1.0 m (0.3–3.3 ft) high and are covered by a variable percentage of live coral, with greater percentages of live coral farther offshore. The intervening depressed channels are mostly filled with sand and some coral gravel; these features have been termed “ridge-and-runnel” structures by Blanchon and Jones (1997).

The water over the reef flat is generally shallow, typically less than 2 m (7 ft) deep. In certain locations, however, there are “blue holes” on the reef flat that have nearly vertical walls and extend to depths of 25 m (83 ft) or greater (fig. 3). Many elongated, shore-normal blue holes correlate to onshore drainages (fig. 4) and are probably related to discharge from the adjacent streams or to submarine ground-water discharge through the reef (see Grossman and others, this vol., chap. 13). Blue holes may have been formed by stream incision or by freshwater-induced dissolution during periods of lower sea level and have subsequently partially filled in by new growth during the recent sea-level highstand. It is not clear, however, which process or processes are responsible for the shapes we see today.

The reef crest, where most deep-water waves break, is well defined along most of the reef off southern Moloka‘i. Lying at a water depth of 1–2 m (3–7 ft), it is characterized by irregular morphology, scattered corals, rubble deposits, and numerous patches of sand. The reef crest is dominated by encrusting coralline algae and robust lobate and encrusting corals.

Offshore of the reef crest, from depths of 5 to 30 m (17–99 ft), lies the fore reef, the zone of highest coral cover. It is generally characterized by

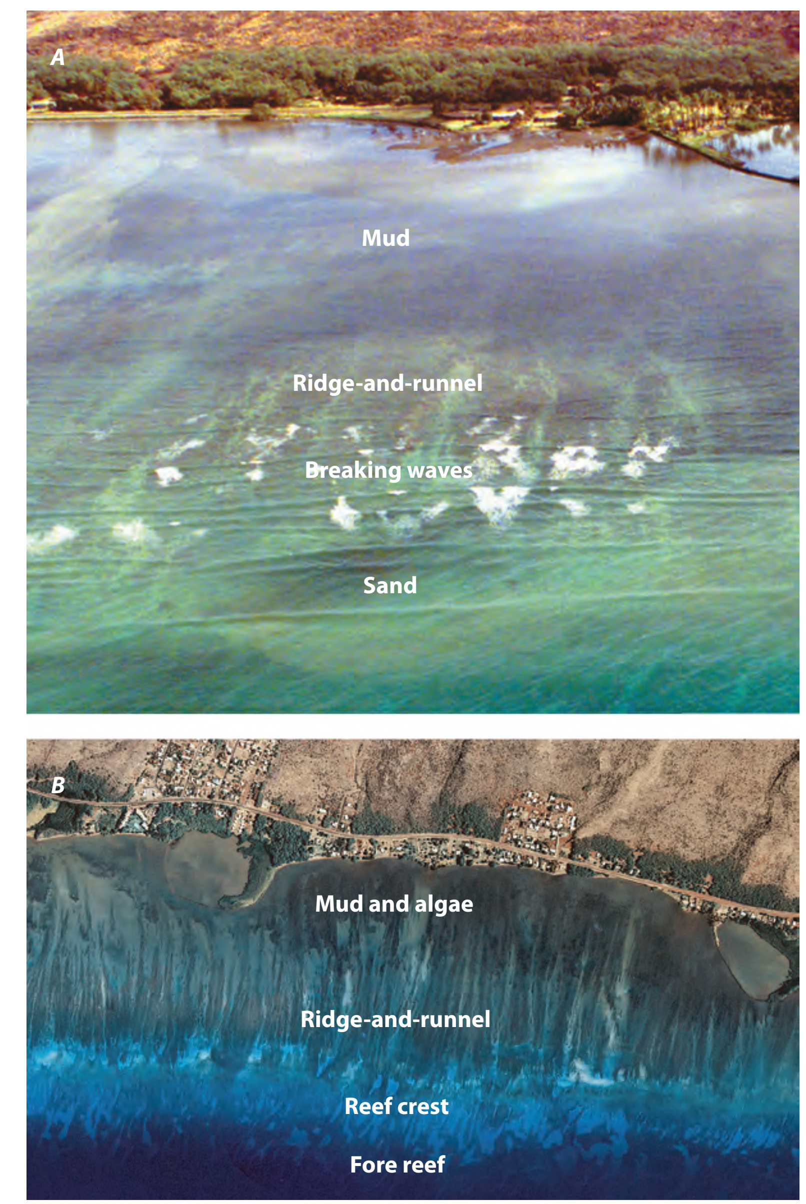

Figure 2. Aerial photographs of the inner reef flat (characterized by mud) and the outer reef flat (characterized by ridge-and-runnel topography) off south-central Moloka‘i. Note the houses for scale in both images. *A*, Oblique photograph of the reef flat just east of One Ali‘i Park. *B*, Vertical aerial photograph of the reef flat off Kamiloloa.

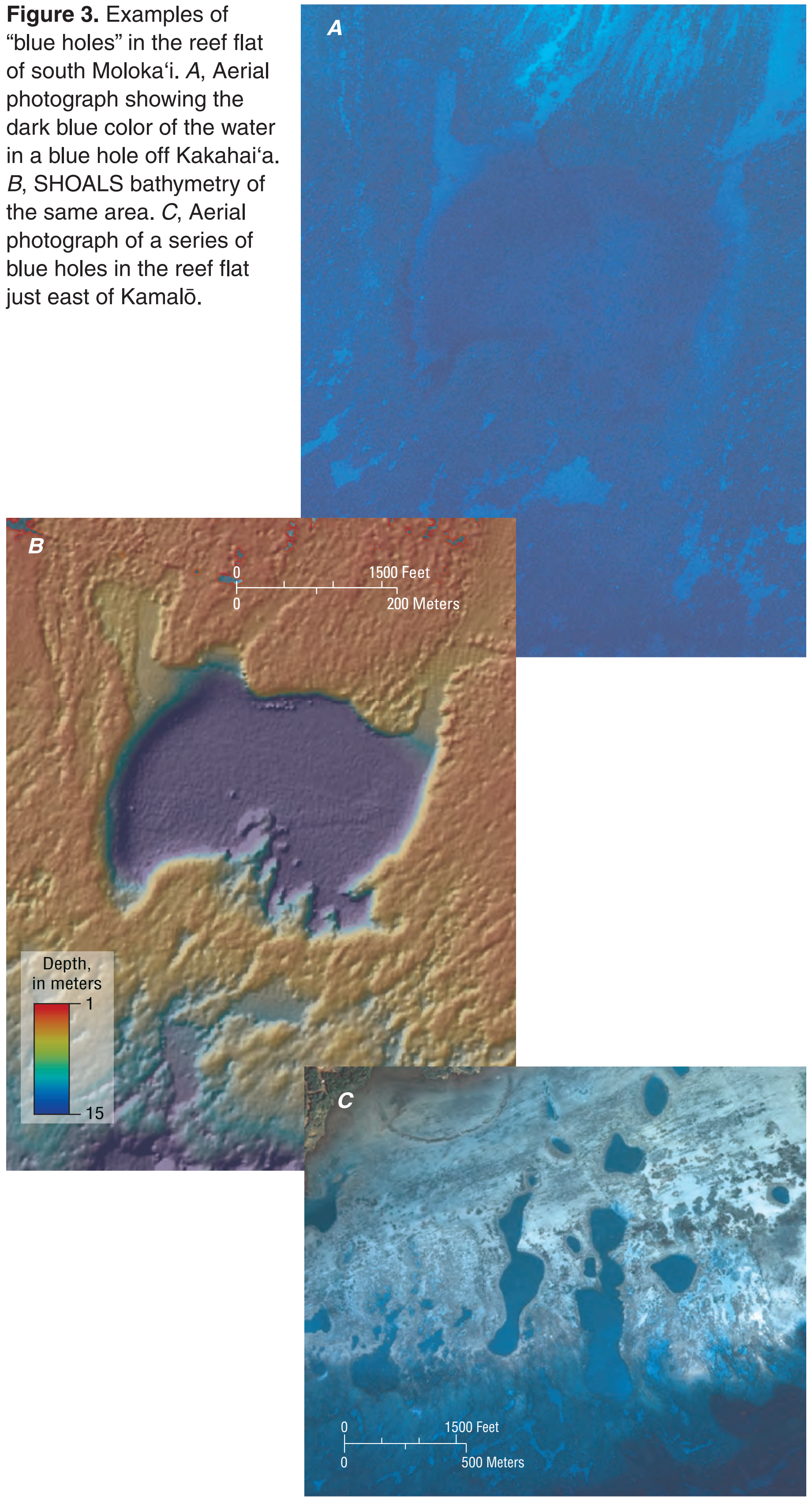

Figure 3. Examples of “blue holes” in the reef flat of south Moloka‘i. *A*, Aerial photograph showing the dark blue color of the water in a blue hole off Kakahai‘a. *B*, SHOALS bathymetry of the same area. *C*, Aerial photograph of a series of blue holes in the reef flat just east of Kamalō.

shore-perpendicular ridges of coral (coral “spurs”) that are separated by shore-perpendicular patches of sand (sand “grooves”). These features are common along wave-exposed reefs and have been termed “spur-and-groove” (SAG) structures (fig. 5). Coral cover on the fore reef is typically between 70 and 90 percent (see Jokiel and others, this vol., chap. 5, for descriptions of all corals). The reef typically ends at a depth of about 27 m (89 ft), with hard corals giving way to sand flats dominated by patches of calcareous *Halimeda* algae, similar to what was observed by Dollar (1982) on other reefs in Hawai‘i.

Large-Scale Morphology (1–10 km)

In order to understand the large-scale shape of the reef, 36 shore-perpendicular depth transects were made extending from the shoreline out to the base of the present reef. The transects were spaced at roughly 1.5-km intervals and were constructed from SHOALS bathymetric data (see Logan and others, this vol., chap. 2, for a further discussion of SHOALS). The locations of the profiles and selected depth profiles of the reef along these transects are shown in figure 6. For reference, the projected slope of the land surface beneath the reef is extended through the reef profiles to provide some insight to the likely cross-sectional area of the reef complex. No shallow reef flat is present at the ends of the island, as shown in profiles 2 and 36; field observations show a very thin veneer of live coral overlying volcanic substrate. Along the central portion of the fringing reef between Pālā‘au and Kamalō (profiles 13 through 27), a well-defined reef flat extends more than 1,200 m (3,960 ft) offshore. The reef along this stretch of coast has a steeper slope from just above 20 m (66 ft) to the 30 m (99 ft) isobath, which corresponds to the toe of the present-day living reef observed during scuba transects, similar to that observed by Dollar (1982). Intermediate between these areas of no clearly defined reef crest and well-defined reef flat are transitional regions, as shown by profiles 6 and 33. These transitional sections display a reef flat on average 500 m (1,650 ft) wide and a less steeply sloping fore reef that lacks the abrupt increase in slope between the 20 m and 30 m isobaths seen in profiles 13 through 27.

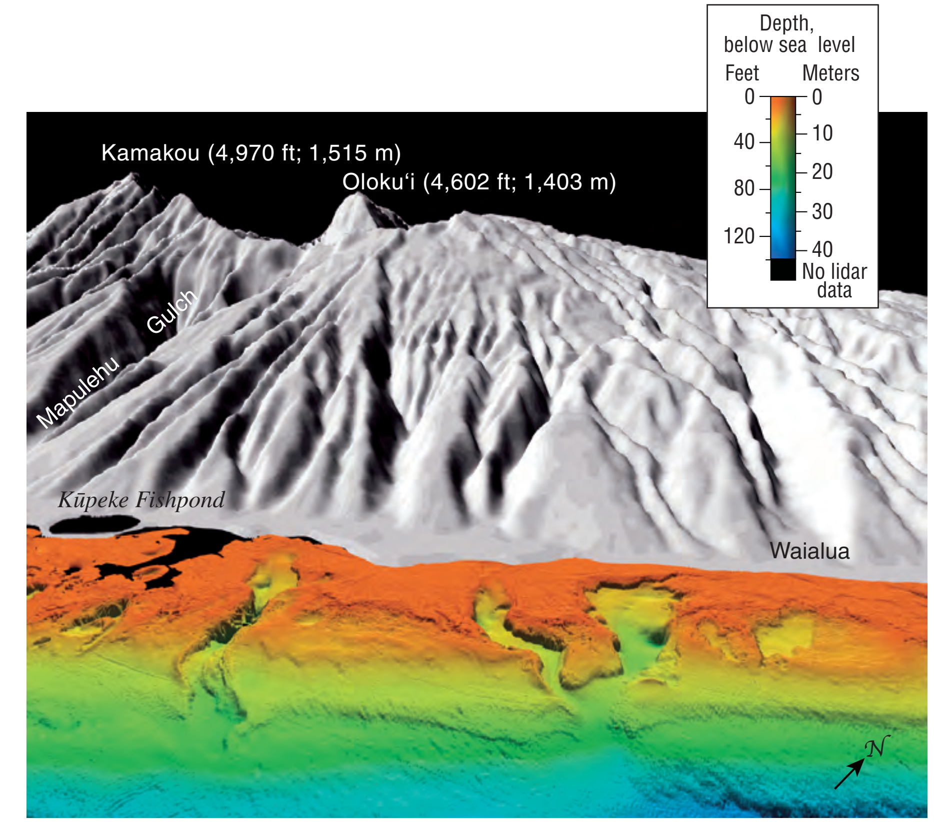

Figure 4. Perspective image of the land (grey scale) and reef (color-coded bathymetry) near Waialua, showing the correlation between terrestrial stream drainages and paleostream channels incised in the fringing reef off south Moloka‘i. Depths from SHOALS data. Approximate distance across the bottom of the image is 2.8 km (1.75 mi).

Figure 5. Underwater photograph of a spur-and-groove (SAG) structure off ‘Umipa‘a. The height between the sand-floored groove and the top of the coral spurs in the photograph is about 1.5 m (4.9 ft); the width of the groove is about 2 m (6.6 ft). Three of the main reef-building corals can be identified in the photograph: (*a*) *Porites compressa* (vertical fingers); (*b*) *Montipora capitata* (horizontal plates); and (*c*) *Pocillopora meandrina* (cauliflower). Wave-generated symmetrical ripples cover the sand bed. View is seaward.

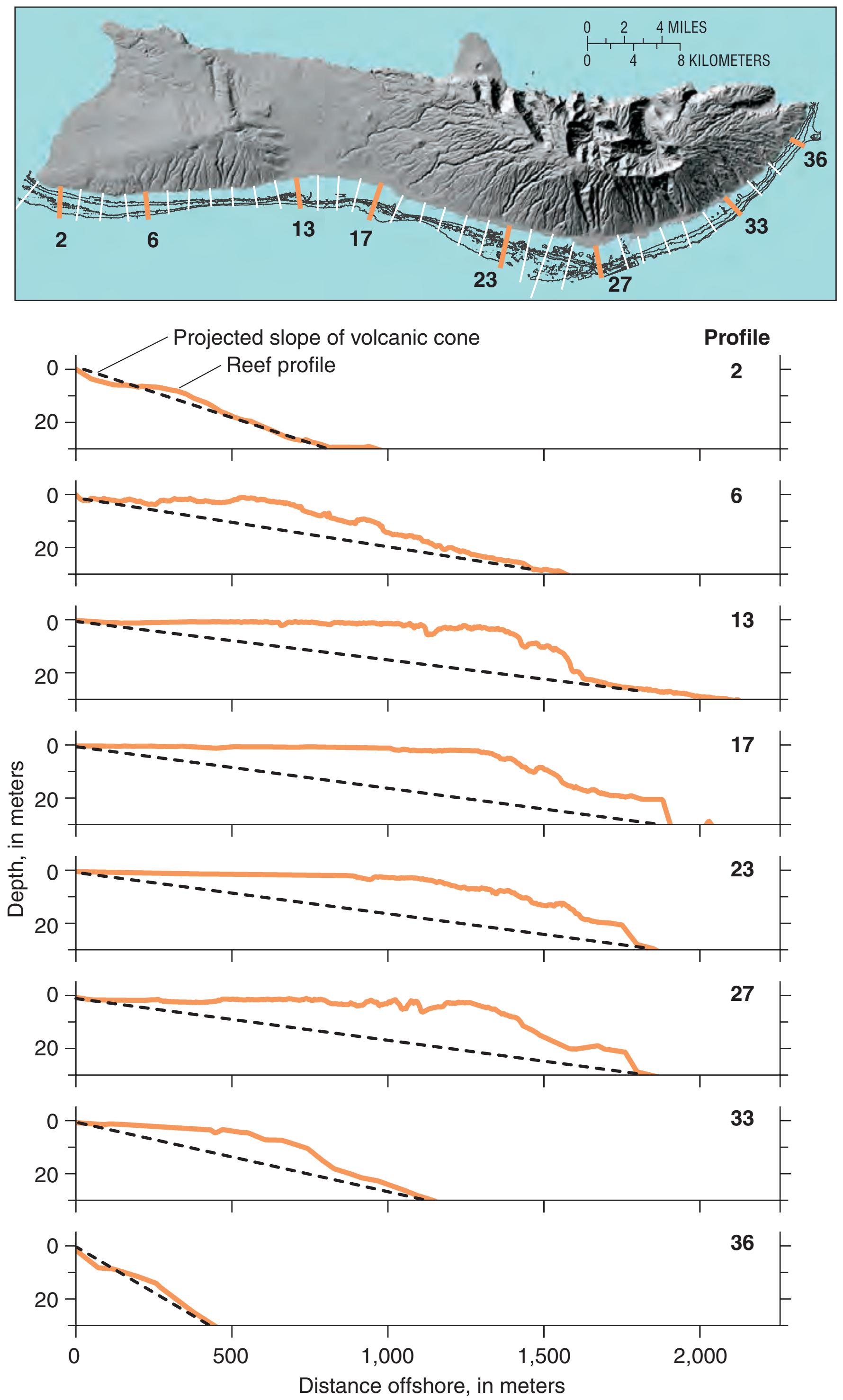

Figure 6. Depth profiles of the reef off south Molokaʻi, showing the variation in development of the reef complex alongshore. The dashed lines are projections of the slope of the volcanic cone through the reef profiles to provide some insight to the likely cross-sectional area of the reef complex. Note that the reef is almost nonexistent at the ends of the island (profiles 2 and 36) and extends more than 1,500 m (4,950 ft) offshore of the central portion of the island (profiles 13 though 27).

Small-Scale Morphology (10–100 m)

As part of an experiment to better understand small-scale reef morphology, almost 4,800 spur-and-groove (SAG) structures were mapped from the SHOALS bathymetric data along the 5-m (17 ft), 10-m (33 ft), 15-m (50 ft) and 20-m (66 ft) isobaths, with roughly 1,000 SAG structures measured per isobath. See Storlazzi and others (2003) for more information on how the calculations were made. Along the 5-m isobath (fig. 7), mean SAG heights were typically less than 1 m, with the lowest heights occurring off the middle of the island. Spurs at the 5-m isobath typically have much lower total coral cover than those along deeper portions of the reef. At this depth, the coral species that are most commonly observed are *Pocillopora meandrina* and the more robust *Porites lobata*. The alongshore trend at the 10-m isobath shows the lowest mean SAG heights at the east end of the island and a general increase in height from east to west. The trends in mean SAG height along the 15-m and 20-m isobaths displayed the greatest heights (>3 m) at the middle of the island. The spurs observed between the 10-m and 20-m isobaths typically have much higher percentages of live coral than those at 5 m. The deeper spurs tend to have slightly lower coral coverage at both the east and west ends of the island, where exposure to large waves is greater and they are covered by more robust species of coral (*P. lobata* and *P. meandrina*), than along the sheltered central portion of the reef where *Porites compressa* is dominant at similar depths.

Two trends were observed in the calculated mean values of SAG width. Mean width along both the 5-m and 10-m isobaths increases towards the east end of the island, with the widths being slightly greater on average along the 10-m isobath than along the 5-m isobath (fig. 8). Mean SAG widths along the 15-m and 20-m isobaths exhibit a different trend from that observed along the two shallower isobaths, with the largest width values generally at the center of the island.

On average, the shallowest (0.7 m) and least variable mean SAG heights are along the 5-m isobath, whereas the largest (1.6 m) and most variable mean heights are along the 15-m isobath (fig. 8*A*). Similarly, the widest (104 m) and most variable mean SAG widths are observed along the 15-m isobath, whereas the 5-m isobath displays on average both the narrowest (71 m) and least variable widths (fig. 8*B*). The variation in the ratio of spur height to width with depth displays a pattern similar to spur height and width, increasing from the 5-m isobath to the 15-m isobath, then decreasing slightly from there to the 20-m isobath (fig. 8*C*). This trend suggests that spurs tend to become more peaked (greater height to width ratio) with increasing water depth. Overall, field observations showed that the grooves tend to be wider relative to the spur width in shallow water depths (especially in more exposed areas) than in deeper water, where the grooves tend to be narrower.

Numerous short, narrow SAG structures occur at shallow water depths (fig. 9), whereas in mid water depths fewer, wider, and taller spurs dominate, followed by a reversal back to more numerous, short and narrow spurs lower on the fore reef along the 20-m isobath. The numerous short, narrow SAG structures either truncate or merge together to form the fewer, taller SAG structures along the 15-m isobath. The tall, broad SAG structures deeper on the fore reef typically terminate and are replaced by numerous, low mounds or new spurs, often separated by areas of fine sand from the shallower, continuous SAG structures. This variation in SAG morphology causes a change in slope, with a relatively low slope between the 5-m and 15-m isobaths giving way to a steeper slope between the 15-m and 20-m isobaths, forming a morphology similar to the shelf-edge "buttresses" observed by Blanchon and Jones (1997) on the Caribbean Island of Grand Cayman.

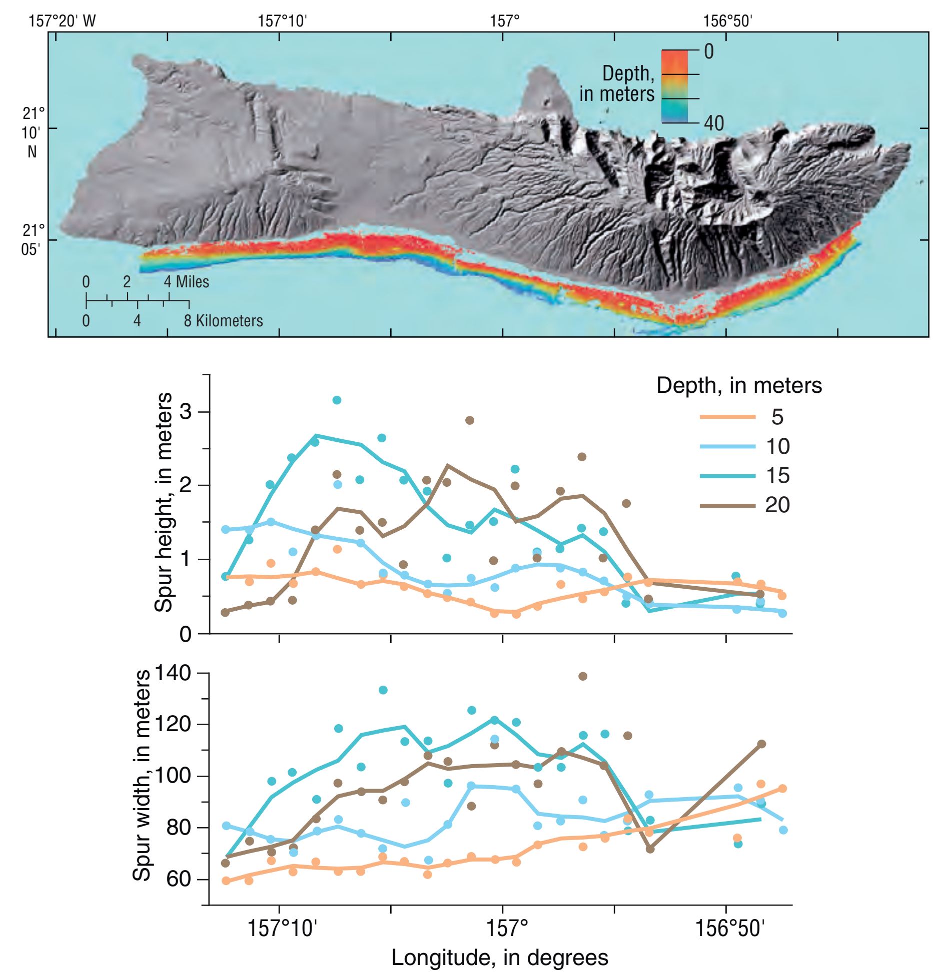

Figure 7. Plots showing the variation in spur-and-groove (SAG) morphology along the reef off south Molokaʻi. Each of the data points represents the mean spur height or width calculated over a 500-m (1,650 ft) segment of the line. Note that along the 5-m (16 ft) isobath mean spur height is higher near the ends of the island, while at greater depths (15–20 m, 50–66 ft) the heights are greater near the middle of the island. Along the 5-m isobath, and to a lesser extent along the 10-m (33 ft) isobath, mean spur width increases to the east end of the island. At greater water depths (15–20 m), spur width tends to be greatest near the middle of the island. The curves are running averages to display how spur height and width tend to vary alongshore.

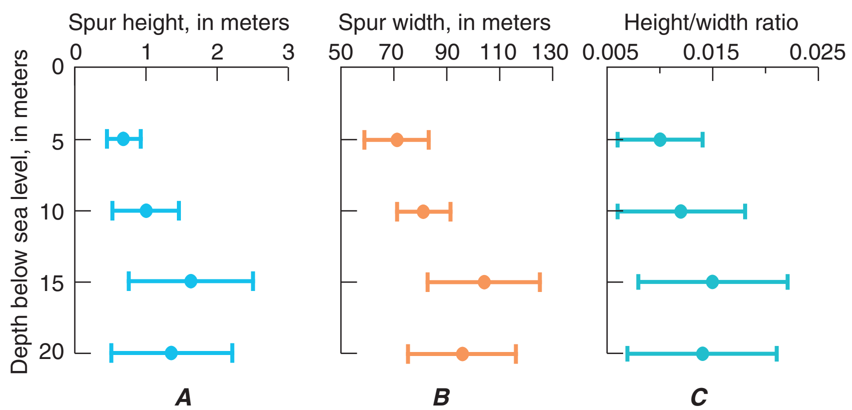

Figure 8. Variation in mean spur-and-groove (SAG) morphology with water depth. *A*, Mean ±1 standard deviation of spur height. *B*, Mean ±1 standard deviation of spur width. *C*, Mean ±1 standard deviation of the ratio of mean spur height to mean spur width. Note how all three parameters' means and their variability are smallest at the 5-m isobath, largest at the 15-m isobath, and then slightly less at the 20-m isobath than at the 15-m isobath. These variations are likely a tradeoff between light available for photosynthesis and wave energy.

Implications Of Observations To Understanding Recent Reef Development

The shape of the reef is a direct result of coral growth rates and patterns, and thus the shape of the reef conveys important information about the external factors that affect reef development. The primary physical constraints on rocky corals along a single exposed reef are food, light availability (Stoddart, 1969; Dustan, 1979), and the forces imposed by ocean waves. Light has been shown to decrease rapidly (logarithmically) with increasing water depth. Light is critical to coral growth because the symbiotic algae (zooxanthellae) housed in the corals require light for photosynthesis. Water motion induced by surface waves dominate the near-bed flow field on the inner portion (<35 m depth) of the south Moloka‘i shelf, where significant reef has developed. Wave-induced motions, and therefore wave-induced forces on corals and the sea floor, decrease rapidly (exponentially) with increasing depth. These wave-induced motions can, when very high, physically break corals, and at slightly lower levels they may inhibit settlement by juvenile coral polyps.

The width of the reef and the relative heights and widths of SAG structures provide an indication of where reef development may be greatest through the combination of high light availability for photosynthesis but relatively low wave-induced forces for the species that compose the reef community off south Moloka‘i. Maximum calculated mean spur height and width, and thus of SAG development, were measured along the 15-m isobath. In shallower depths (5–10 m), the high light availability appears to be offset by the high wave-induced forces, keeping SAG structures small, whereas along the 20-m isobath and deeper, decreased light availability inhibits high relative growth despite the low wave-induced forces (Dollar, 1982).

The reef flat is widest along the central portion of the south Moloka‘i shore and narrowest at the east and west ends of the island, even though light penetration at these shallow depths is relatively uniform. This further suggests that wave-induced forces, which vary spatially (see Storlazzi and others, this vol., chap. 11), might be a primary control on large-scale reef morphology along south Moloka‘i.

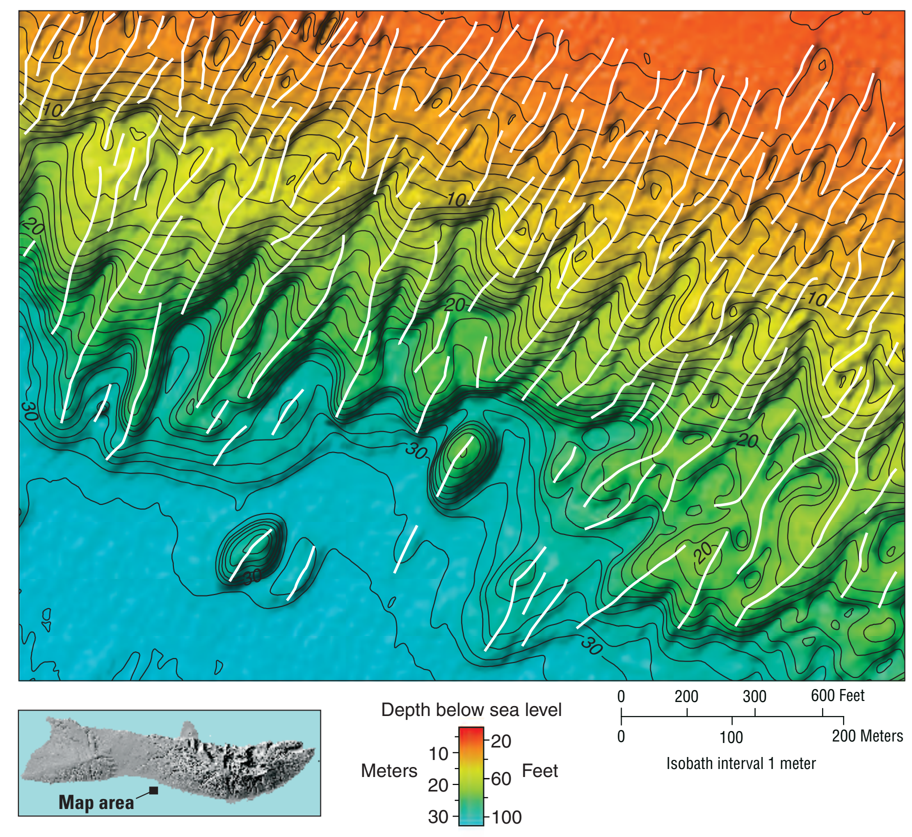

Figure 9. Color-coded image of the SHOALS bathymetry offshore of Kaunakakai overlaid with 1-m (3 ft) contours to highlight spur-and-groove (SAG) morphology. The white lines denote interpreted spur traces. Note that most of the short, narrow spurs at shallow water depths merge to form taller, broader spurs around the 15-m (50 ft) isobath. Most of the spurs at the 15-m isobath bifurcate with depth or simply truncate and are replaced by smaller, more closely spaced SAG structures. Some of the structures around the 30-m (99 ft) isobath are coral-covered mounds isolated by sand from the SAG structures at shallower depths. Also note the transition from the broad reef flat at the top of the image at a depth of 2–3 m (7–10 ft) to the steeper sloping fore reef between 10 m (33 ft) and 30 m (99 ft), below which is the more gently sloping insular shelf.

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