

GEOLOGY AND BIOLOGICAL ZONATION OF  
THE REEF SLOPE, 50-360 m DEPTH AT  
ENEWETAK ATOLL, MARSHALL ISLANDS

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ABSTRACT

Twenty-two submersible dives were made on the outer reef slope of the southern half of Enewetak Atoll, Marshall Islands, to maximum depths of 365 m. No distinct thermocline was encountered. The outer slope of Enewetak is steep, averaging about 60° between depths of 90 m and 365 m on the windward side and slightly steeper on the leeward face. No terraces or shelves were noticed below 30 m. Vertical grooves were found on the windward face below 150 m. Talus accumulated below 250 m, and extensive sediments were encountered seaward of the wide (southern) channel at 200 m. Small-scale scalloping and pitting of the reef face occurred from 150-240 m. Rock surfaces below 250-300 m appeared heavily scoured. A solution unconformity at 360 m and another at 365 m were encountered separately at two locations on the windward side. Branched stony corals were found down to about 60 m, below which only plate-like forms occurred to a maximum depth of about 112 m. At 90 m, less than 1% of the substratum was covered with stony corals. *Halimeda* spp. algae were the most conspicuous macroalgae on the outer slope, being encountered to depths of 100 m or more. Algal films and small macroalgae were found on rocks at 140 m. Gorgonians and alcyonaceans appeared to dominate the substratum below 100 m. Indentations and caves at 120-160 m were populated with sponges, antipatharians, possible sclerosponges, and other sessile invertebrates. A sand slope below the wide channel had abundant seapens at 220 m. No populations of sclerosponges building reef framework were encountered. Talus blocks on sediment slopes provided attachment points for some sessile invertebrates. Below about 90-100 m, it appears that no significant reef framework is being constructed. In many areas, active erosion is evident. Significant quantities of sediment and talus are being transported downslope from the shallow reefs on the windward side, much of it apparently coming to rest below 365 m depth. The leeward face seemed to have less sediment transport. Pitting on the windward reef face may represent features formed during shallower sea level.

During the summer of 1981, the research submersible, MAKALI'I, was used to investigate lagoon and outer slope environments of Enewetak Atoll in the northern Marshall Islands. Twenty-two dives by 10 scientists were made on the outer atoll slope. The locations of dives at Enewetak are indicated on Figure 1. Dives were limited to the southern half of the atoll due to towing distance from protected lagoon waters.

The geomorphology of the outer slope is poorly known. Emery et al. (1954) reported, based on echo sounding profiles, that between the reef edge (about 20 m) and 450 m depth, the indicated slope was between 18° and 49°, averaging 33°. They also felt that when slopes were determined by more accurate means, the outer reef slopes would be found to be somewhat steeper than they originally estimated. Their figure 44 shows 25 radial sounding profiles around Enewetak which have little difference between them to depths of several hundred meters.

Ladd (1973) reported that Enewetak and Bikini had an average slope of about 38° from the terrace (reef) edge to 360 m. The reported sediments on the outer slope were mostly "coarse coral fragments and segments of *Halimeda*" in the upper reaches.

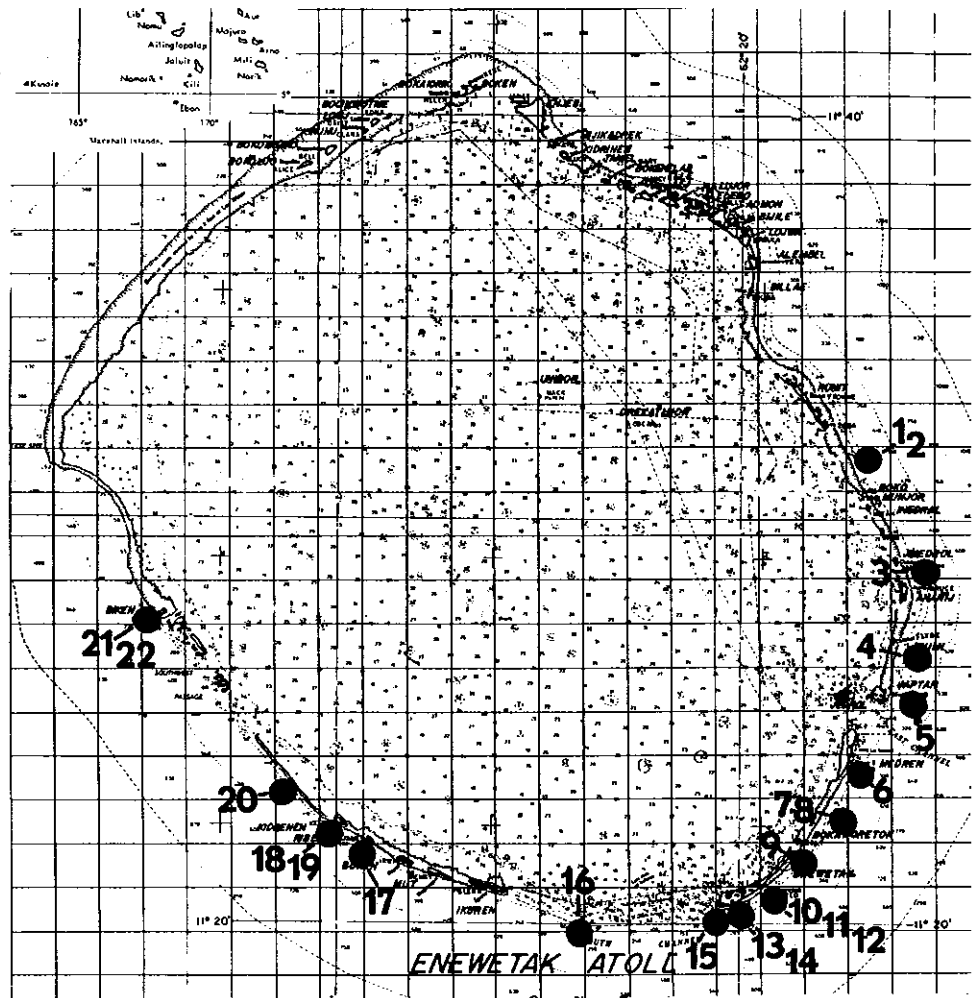


Figure 1. Chart of Enewetak Atoll, Marshall Islands, showing locations of dives by DSRV MAKALI'i on outer reef face during the summer of 1981. Actual dive numbers, scientist, depth, and date are included for each dive in Table 1.

Biological collections on the outer slope have been confined to SCUBA diving depths, and extensive diving has been limited by the sharks present at the atoll.

#### MATERIALS AND METHODS

The MAKALI'i has a maximum working depth of 365 m and carries one observer and a pilot. Still photographs were taken using an external 35-mm camera and strobe. An external television camera provided both immediate display on a monitor inside the submersible and a black and white video recording for replay.

An external instrument package, built by Neil Brown Instruments, Inc., provided depth, temperature, salinity, and light data on some dives. Problems with implementation of this equipment limited the amount of environmental data obtained.

On an outer reef dive, the submersible was typically deployed from the Launch-Recovery-Transport vehicle (LRT) over 30-40-m depths near the steep slope. It then descended to near the bottom and

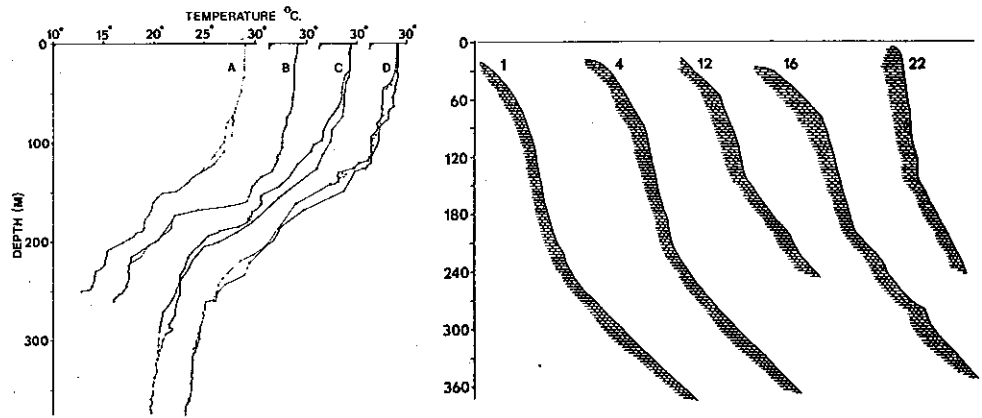


Figure 2. (Left) Temperature/depth profiles from four dives by DSRV MAKALI'I at Enewetak Atoll, Marshall Islands. Dual track profiles represent ascent and descent. Locations of dives of Figure 1 are indicated: a) Biken, western side of atoll (Dive 81-13, location 22); b) east side of wide channel (Dive 81-25, location 15); c) Bokandretok (Dive 81-49, location 7); d) Runit (Dive 81-46, location 1).

Figure 3. (Right) True slope profiles of outer reef face at Enewetak Atoll, Marshall Islands based on observations from the DSRV MAKALI'I. All distances and depths in meters. Numbers refer to dive locations indicated in Figure 1. Dive data are included in Table 1.

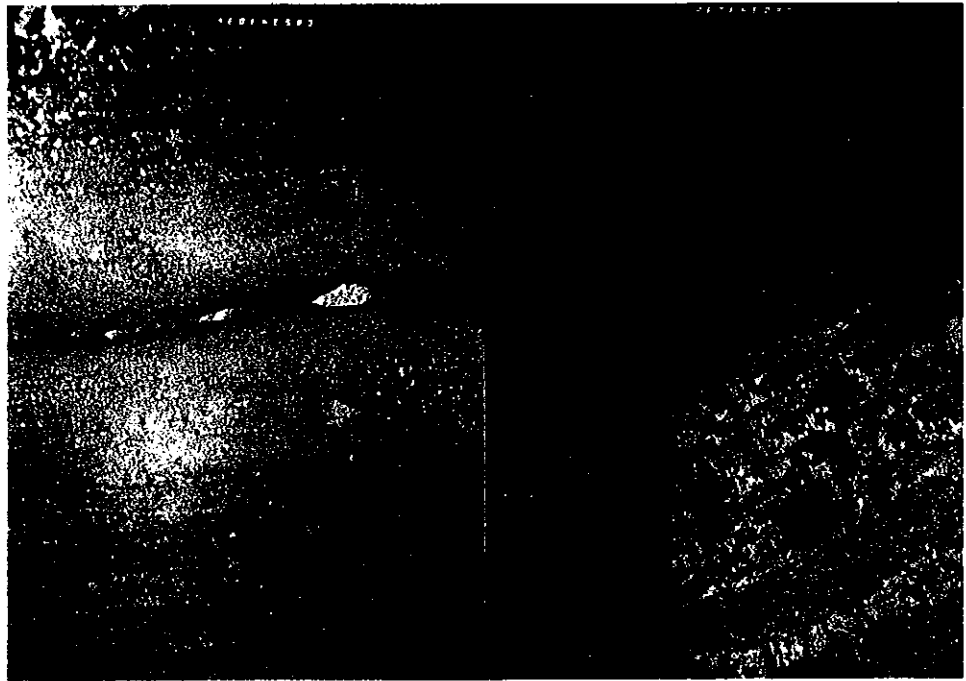


Figure 4.<sup>1</sup> (Left) Sediment chute at 225 m depth off Chinimi Island showing polished area a few meters across with central groove. Rock face on either side of the chute is heavily pocked (Dive 81-34, location 4, photo Suchanek). (Right) The same sediment chute as Figure 4 at 230 m in head-on view. The horizontal width of the photo is about 4-5 m with the central groove a few tens of cm wide (Dive 81-34, location 4, photo Suchanek).

<sup>1</sup> Photographs in Figures 4-18 are mounted sideways; the frame counter indicates the right side of the photographs.

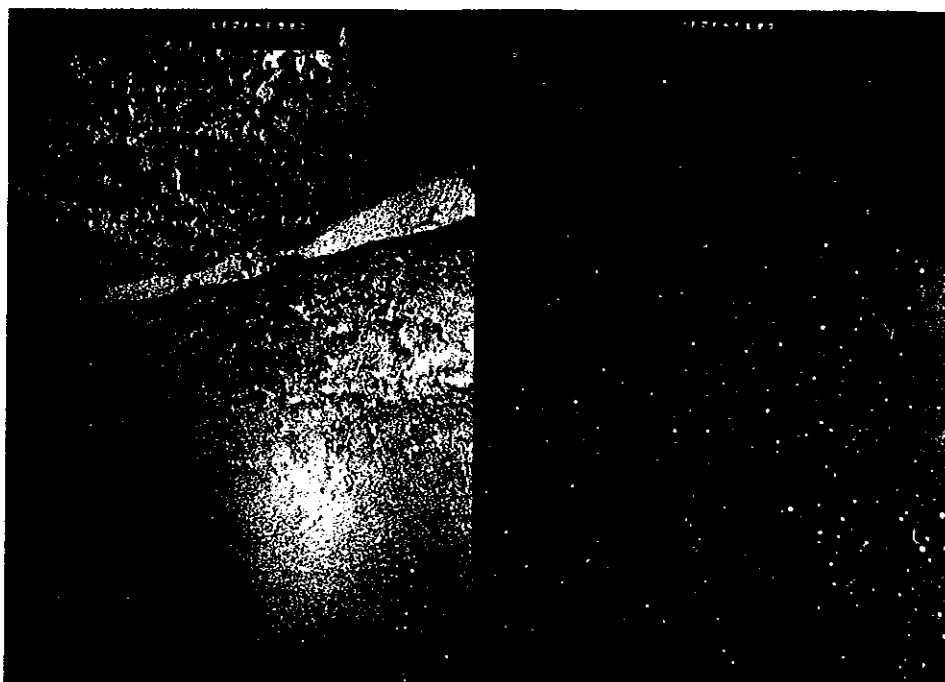


Figure 5. (Left) Sediment chute from Figure 4 at 235 m in an area where the slope decreases slightly from above with sediment present in the central groove. The groove also widens somewhat to about 1 meter (Dive 81-34, location 4, photo Suchanek). (Right) Lower terminus of sediment chute where it merges with a sediment slope at 240 m depth. This is the same chute as Figures 4 and 5. Another sediment chute merges from the left and the covering of sediment over rock on the slope is fairly thin (Dive 81-34, location 4, photo Suchanek).

followed the slope outward and down. In most cases, a transect was made down the reef face to the maximum depth of the dive, followed by specific work objectives during ascent to the surface. Initially, the submersible was oriented with the front directed outward from the slope to facilitate motoring out to the area where the slope dropped away steeply. Once an area of steep slope had been reached, usually at a depth of about 60 m, the orientation of the submersible was reversed to face the slope. The submersible was trimmed for slightly negative buoyancy and was motored away from the slope as necessary to remain clear of the bottom. This allowed the best view of the reef slope on descent and ascent. Generally, the submersible was maintained 2–5 m from the slope. The right lateral port allowed the observer an excellent view of the slope profile when the vehicle was facing the slope.

Collections were made using a mechanical arm with terminal claw. Individual specimens or rocks with sessile organisms were placed on a mesh basket attached to the front of the submersible.

Nearly 2,000 35-mm color slides were taken on the outer slope using the externally mounted camera. The original transparencies and original video tapes are archived at the University of Hawaii. Biological specimens are deposited with the Bernice P. Bishop Museum, Honolulu.

## RESULTS

*Physical Factors.* — **CURRENTS.** Currents were not evaluated beyond anecdotal observations based on motion of the submersible relative to the substratum. Enewetak is in the North Equatorial Current (NEC), which has a mean westward flow of 25–50 cm sec<sup>-1</sup> (Atkinson et al., 1981). However, the observed current direction did not always correspond with what had been anticipated based on a westward transport by the NEC. At the windward dive sites (southeastern quadrant of the atoll), the current was generally towards the south, but off south Enewetak Island,

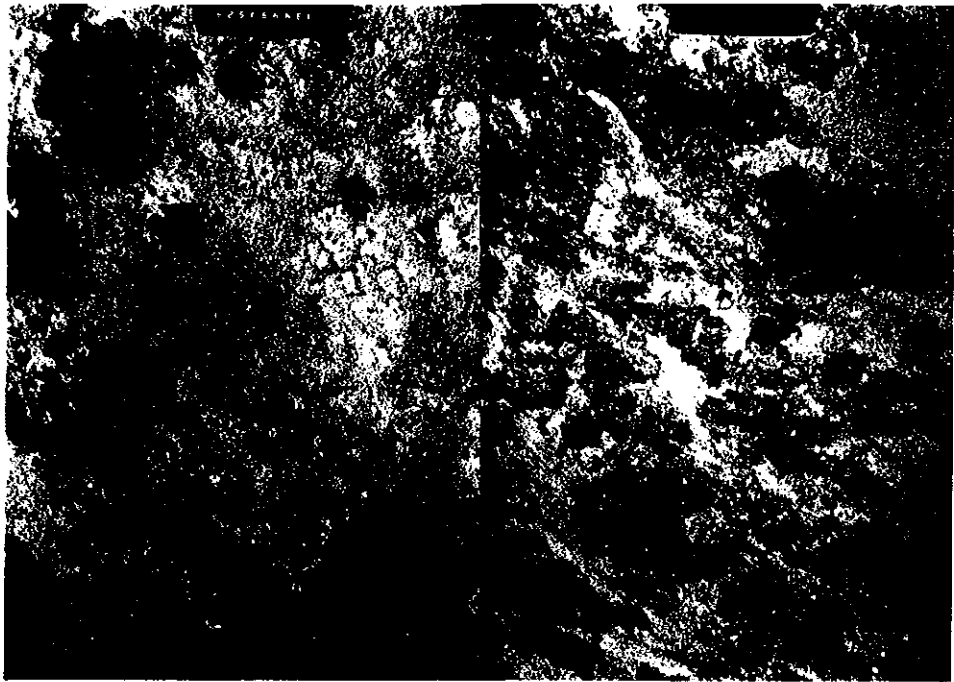


Figure 6. (Left) Reef slope at 70 m depth with patches of reef protruding from a *Halimeda*-dominated sediment slope. The sediment slopes at about 35–40° and has considerable evidence of bioturbation (mounds and mottled patches) on its surface. Width of photo is about 8–10 m (Dive 81-50, location 8, photo Highsmith). (Right) Steep reef slope of about 60° at 90 m depth. There is a thin coating of sediment where it can be retained on the slope. A sizeable, plate-like coral colony is present at the lower right (Dive 81-47, location 3, photo Wellington).

it reversed direction during two dives at 135 m depth. Off the wide passage between Enewetak and Iurigin Islands, the current also ran briefly to the east at 100 m depth. On the windward dive sites, the current extended to considerable depth but seemed to decrease below the thermocline at 150–180 m. However, significant currents were reported as deep as 230 m. On the leeward side of the atoll (southwestern quadrant) along the southwestern islands, the current sometimes ran towards the southeast at 105 m. Off Biken on the western side no perceptible current was reported at depth on two dives.

**TEMPERATURE AND SALINITY.** Plots of temperature against depth are shown for four dive sites in Figure 2. Sharp thermoclines were not encountered. A distinct surface layer of water with gradually decreasing temperature from about 29°C at the surface to about 25°C near 120 m was found. The rate of temperature decrease increased slightly at depths below 120 m. A slight thermocline was often measured near 150 m, with the temperature dropping 2–3°C over 10–15 m depth. Temperatures changed from 24–20°C at 150 m evenly to 14–11°C at 250 m. At 360 m the temperature was 8–9°C.

Slightly different temperature profiles were usually obtained on descent and ascent during a single dive of 1–2 h duration over a distance of several hundred meters.

Density schlieren (refractive index changes) were noted by most observers between depths of 70 to 175 m. Normally, one or two such areas were noted on

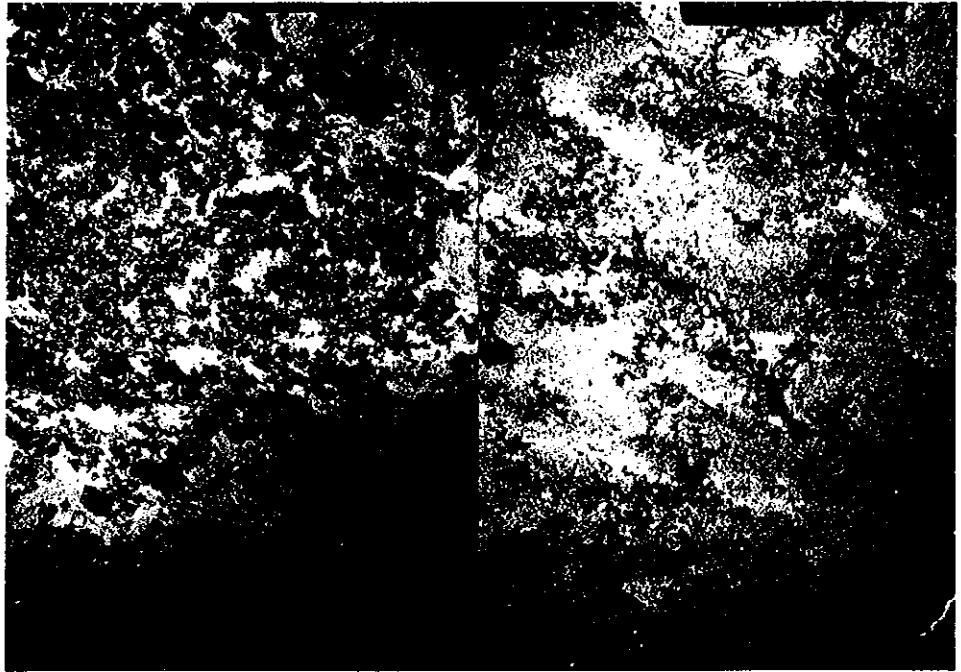


Figure 7. (Left) Steep reef face (about 70°) at 93 m with only a light dusting of sediment where it can be retained. Only small scale relief is present on a generally smooth face (Dive 81-33, location 5, photo Thresher). (Right) Reef face off Runit at 105 m depth with coarse *Halimeda* sediment pooled on small ledges and indentations of the rock face. The slope here is about 50–55° with some small, whip-like coelenterates growing where the rock surface is not inundated by the sediment (Dive 81-46, location 1, photo Hillis-Colinvaux).

descent or ascent, with three noted on one dive. All were associated with areas of rapid vertical temperature change, with at most only a very slight change (0.1–0.2‰) in salinity. Schlieren were evident with temperature changes between 1.1 and 3.5°C over a depth of 10–15 m.

No salinities below oceanic values were detected, and no ground water outflow beneath islands was observed on the seaward slope.

**LIGHT.** Light data were obtained on 12 outer slope dives, but due to lack of concurrent surface measurements, definitive extinction values cannot be calculated. However, corrected data from dives were used to construct a plot of their natural logarithms against depth. A linear, least squares regression yielded an extinction coefficient of 0.045 within a 90% confidence interval of +0.0025, with an  $r^2$  of 0.774. The variance unaccounted for by the regression is believed mostly a consequence of variable cloud cover. An average midday summer light value within the euphotic zone in the open ocean near Enewetak may be approximated by the formula:

$$\text{Light} = 506 \cdot e^{-0.045 \cdot \text{depth}}$$

Using this equation, the 1% level of surface illumination is reached at approximately 100 m depth, and about 0.1% surface illumination penetrates to 150 m.

**Geomorphology.**—Along the windward atoll rim, the first major change in shelf

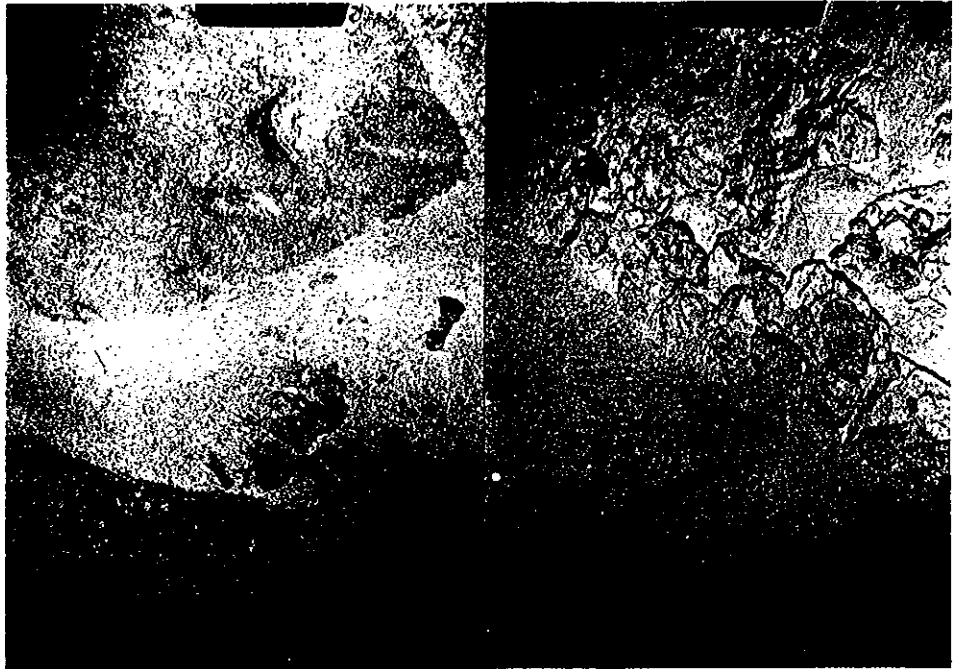


Figure 8. (Left) Terminus of sediment chute at 270 m, Runit, with large talus pieces mixed in with coarse, *Halimeda*-dominated sediment (Dive 81-46, location 1, photo Hillis-Colinvaux). (Right) Talus pile on rock slope at 330 m depth. The slope is covered with a thin dusting of sediment. Talus is of shallow-water origin as evidenced by visible coral colonies (Dive 81-49, location 7, photo Harrison).

slope occurs from 21 to 27 m, where the gentle slope increases to about  $30^\circ$  at near 60 m depth. Below 60 m, the slope increases to  $45^\circ$  or more, about  $60^\circ$  or more at 90 m, and greater than  $60^\circ$  from 90 to 150–200 m. Below about 200 m to 365 m the slope remains steep,  $45^\circ$  or more. Figure 3 presents slope profiles from several areas.

The leeward atoll rim has its first major change in slope closer to shore and much shallower, with a steeper profile than the windward side. Off the southwestern islands (Ikuren-Kidrenen), this change (shelf break) occurs at 12 m depth, sloping near  $45^\circ$  below that depth. On the southwestern face near Biken, the break occurs at only 3–6 m depth, with a slope of  $75\text{--}90^\circ$  below this. Overall, the slope on leeward faces is steeper than that of windward faces. Some areas are vertical for more than 100 m change in depth.

No terraces or shelves of any significance were observed between 20 and 360 m. Some indentations and caves occur on the face but not at consistent depth for any one dive area or between dive areas. It would have been advantageous to put the submersible down on somewhat level bottom for collections, but no outer slope area had any feature which approached the size and level needed for such maneuvers.

**SEDIMENT AND TALUS TRANSPORT.** Abundant downslope transport of sediment was evident everywhere. All surfaces capable of holding even small amounts of sediment had deposits on them. When viewing a series of small shelves from above, all surfaces appeared covered by calcareous sediment.

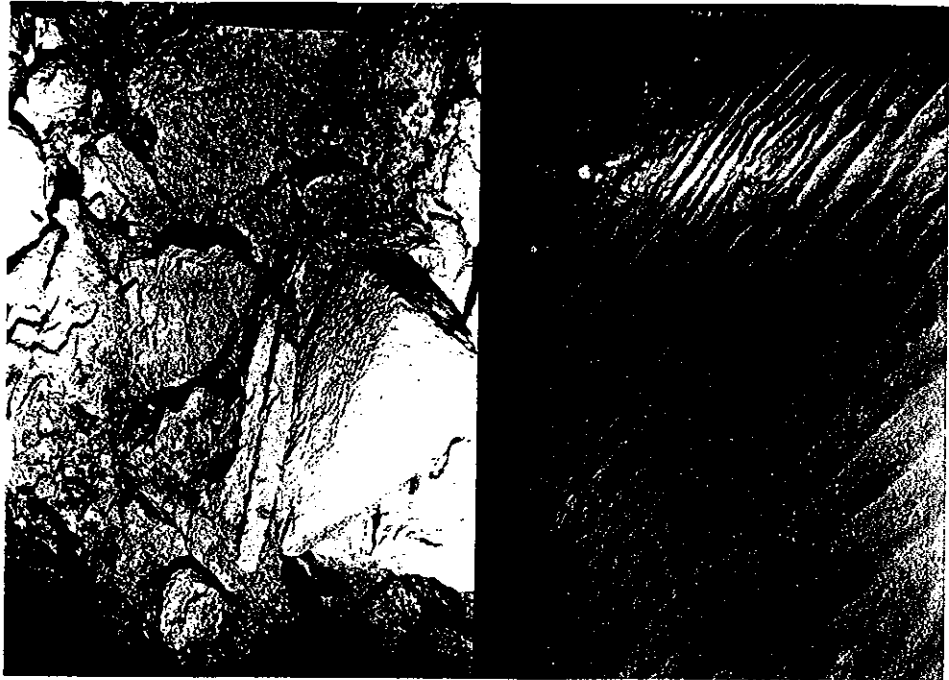


Figure 9. (Left) Large debris of shallow water origin on slope at 330 m depth. The photo is about 3–4 m in width (Dive 81-34, location 4, photo Suchanek). (Right) Current ripples on sediment slope of about 35° at 260 m depth, wide channel area. The current ripples are oriented up and down the slope. The rocks visible could represent talus brought down the slope (Dive 81-38, location 16, photo Colin).

Vertical grooves produced by sediment transport were common on the windward face below about 150 m. These consist of a polished, shallow depression in the rock face several meters wide with a deep groove up to ½ m wide at its center (Fig. 4). These sediment channels (chutes) continue for considerable distances vertically (Fig. 5). Eventually, they merge with sediment slopes as widening fans of sediment (Fig. 5). In some cases, sediment was present within the central groove, particularly at their deeper extremes where the slope decreased slightly or where depressions existed in the groove.

Significant sediment transport was evident both within the chutes and on intervening promontories. Rather than representing massive reentrants into the outer face, the chutes appear to be incised only as much as a few tens of meters. We did not attempt to connect a chute area with an upslope sediment downfall. A few chutes were followed downslope and eventually merged with a sediment slope at about 240 m depth (Fig. 5).

From 30 to 75 m, small outcrops of rock were observed to protrude from the sediment-covered slope on windward dive areas (Fig. 6). Rock substratum does not predominate over sediment until the slope increases above 30–40°. Once this slope angle is reached, there appears too little opportunity for large amounts of sediment to accumulate (Fig. 6). From about 60 to perhaps 250 m or more, sediment accumulations are little more than a thin dusting on the rock surface with build-ups on small shelves a few cm wide. There may be occasional pieces



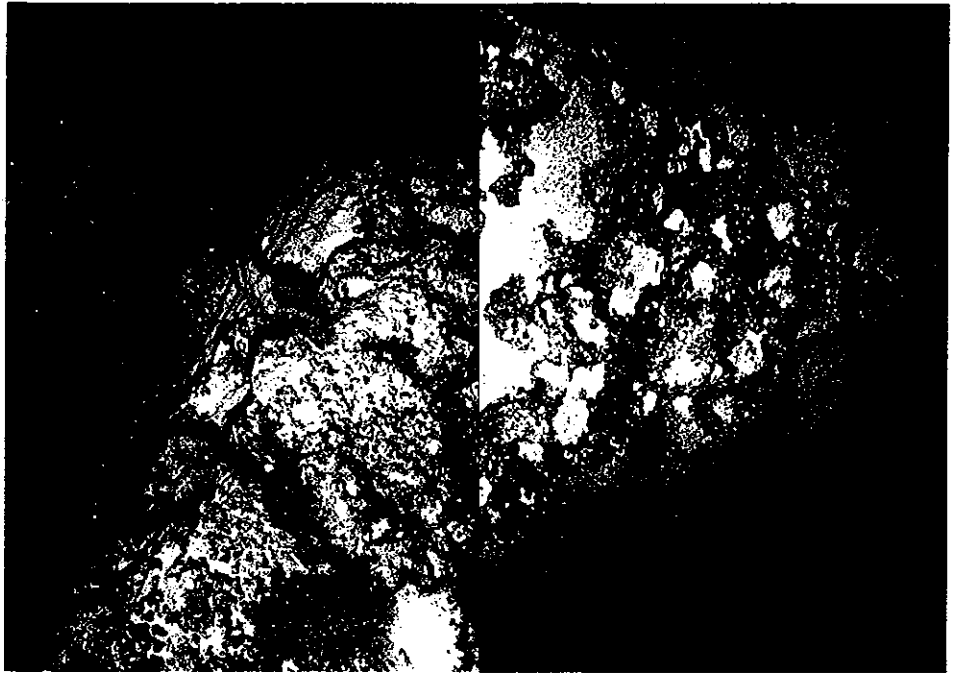


Figure 10. (Left) An indentation in the reef face at 120 m depth with thick sediment collected on a small ledge. Vertical and overhanging areas free of sediment have abundant sessile organisms. The feature seen here was not consistent at any depth (Dive 81-26, location 12, photo Suchanek). (Right) Area of scalloped rock face at 225 m with sediment collected in shallow depressions a few tens of cm across (Dive 81-34, location 4, photo Suchanek).

of talus perched on the slope at points, but no significant talus accumulation was evident until 250 m or deeper (Fig. 7).

In places near the maximum depth reached with the submersible, the slope decreased to about  $45^\circ$  and sediment and talus piles began. These features seemed related to local changes in slope or geomorphology. Often, a sediment slope at this lower angle of repose would be encountered for some tens of meters in depth, then continuing as a rock slope with the thinnest of sediment layers due to a slight increase in slope.

Talus at 250–360-m depths was often deposited in areas sharply delineated from adjacent sediment slopes (Fig. 8). This talus is almost all of shallow water origin, with dead coral colonies being readily identifiable among the blocks. Talus ranged in size from fist-sized and smaller pieces to large blocks several meters across (Fig. 9).

There seemed to be larger accumulations of sediment on the slope below the wide-channel area. Two dives were made in this area, one (Dive 81-25) near the eastern side and the second (Dive 81-38) near the center. On the eastern side, a large *Halimeda* sediment slope was encountered at 200 m depth on a horizontal traverse of the face. This sediment slope was several hundred meters wide. In the center of the wide channel, a similar slope was found somewhat deeper (over 250 m) and had current ripples oriented up and down slope in response to swift currents which must occasionally flow perpendicular to the slope (Fig. 9).

The rock surfaces of the outer slope have considerable small-scale relief. From

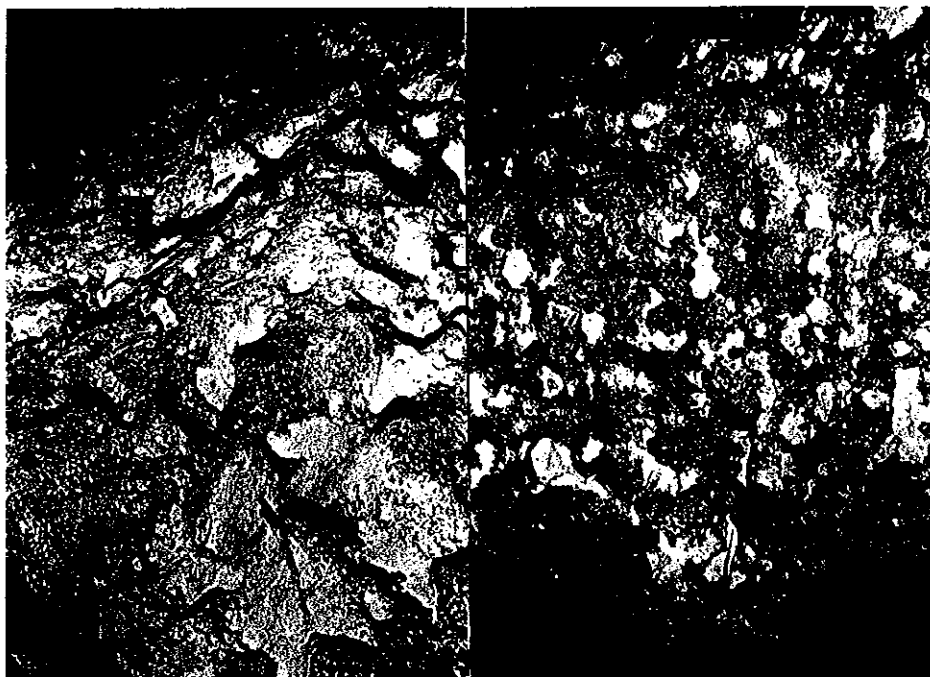


Figure 11. View along rock face at 210 m with extensive sculpturing. Small volumes of sediment are trapped in depressions. Vertical dimension of photograph about 3 m (Dive 81-46, location 1, photo Hollis-Colinvaux).

about 100–140 m, small caves and overhangs occur in the rock face. These cavities are incised a few meters at most into the face with accumulated sediment on lower surfaces (Fig. 10a). They may be relatively broad, tens of meters wide, or smaller. The upper, overhanging surfaces are free of sediment, offering the only areas where hard substratum is largely unaffected by sediment deposition and transport. Individual features might represent wave-cut notches, but the lack of these features at any consistent level argues against such an origin.

Small-scale scalloping and pitting of rock surfaces occurred over large areas from depths of about 150 m to as much as 240 m. The depressions are a few tens of cm across, are often nearly hemispherical, and are interspersed among areas of near-planar rock (Fig. 10). More extensive rugged surface features were noted as shallow pits, depressions, and pocks (Fig. 11). Small quantities of sediment were often retained in these.

Sediment scouring is also apparent on much of the outer face, particularly below 250–300 m where the rock face is smooth and exposed to downslope transport of sediment (Fig. 12). However, many rock surfaces at 300 m and below appear polished (Fig. 12), but this may not be the result of downslope sediment transport since these are areas that project up 1 m or more above the sediment surface. A similar condition was noted on carbonate blocks at similar depths off the north coast of Jamaica by Land and Moore (1975). It is possible that this surface texture is due to bioerosion.

A solution unconformity on the windward side of the atoll was most evident

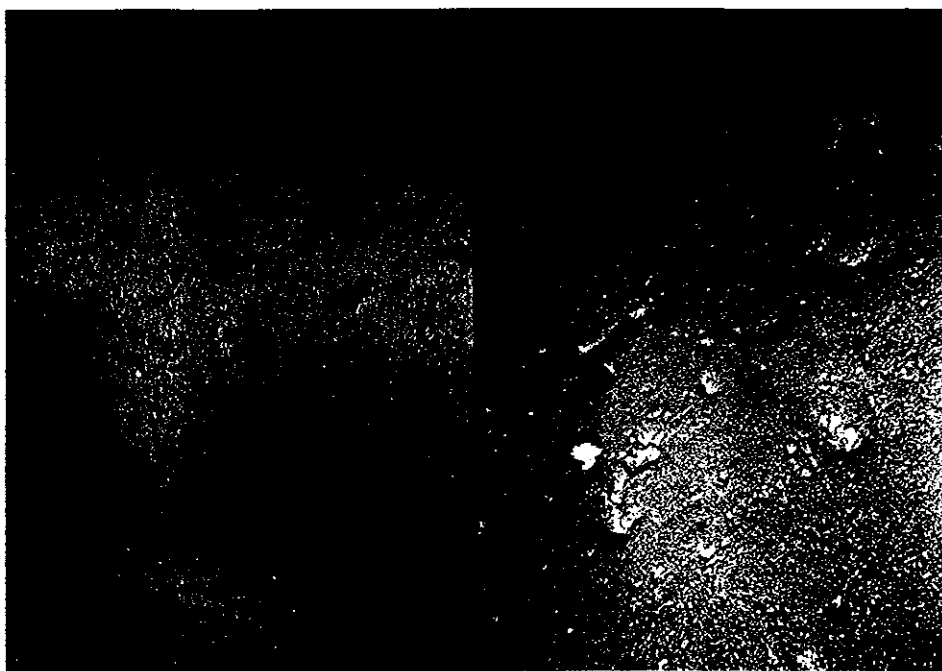


Figure 12. (Left) Rock face overlain with thin covering of sediment, wide channel area, at 280 m depth. The face has a slope near 45° and a sediment fall area abuts the left side of the photo. Vertical dimension of the photo about 5 m (Dive 81-38, location 16, photo Colin). (Right) Rock surface with small pits and pocks at 360 m, Runit. Small gorgonians or coral colonies, plus solitary corals are visible (Dive 81-46, location 1, photo Hillis-Colinvaux).

at 360 m depth on an area of steep-faced rock at Runit Island (Dive 81-46) (Fig. 1, area 1) but was also slightly exposed at 365 m off the southern part of the atoll (Fig. 1, area 8). The solution unconformity was evidenced by a series of horizontal layers several cm thick over less than 1 m of vertical face (Fig. 13). This almost certainly represents the top of the Tertiary *e* (Cole) unconformity reported by Ladd and Schlanger (1960) and Schlanger (1963) at slightly over 310-m depths in cores drilled on Medren, Engebi and Eugelab Islands. The slightly greater depth of the unconformity on the flanks of the atoll implies a slight down slope of this feature towards the atoll rim or a potential slight tilting of the atoll. Additionally, the exposure of the unconformity indicates that there is active erosion of the outer reef face at 360 m depth, a fact that is also apparent from the nature of the rock surfaces at this depth.

*Organisms and Biological Zonation of the Outer Face.*—Differences of dominant fauna and flora on the outer face were noted between windward and leeward slopes as were differences over distances of only a few meters in one location.

The reduction of light-dependent fauna and flora with depth has been well documented in Jamaica (Lang et al., 1975; Hartman, 1973). At Enewetak, stony coral colonies occur to depths in excess of 100 m but cover only very small percentages of the substratum at such depths. Branched forms, particularly *Pocillopora eydouxi*, occur to about 60 m. Beyond that depth, stony corals are limited to plate-like forms (*Leptoseris*, etc.). Near 90 m, less than 1% of the slope of the



Figure 13. (Left) Solution unconformity exposed on a near vertical rock face at 360 m, Runit. The horizontal dimension of the photograph is estimated as 4 m wide with several distinct layers visible in the unconformity. Small scale pitting of the rock surface, similar to that in Figure 12 left is evident (Dive 81-46, location 1, photo Hillis-Colinvaux). (Right) Exposure of solution unconformity at 365 m, Bokandretok, on sloping face thinly covered with sediment. The large plume-like antipatharian was collected and measured 1.35 m height. Sediment ripples here oriented up and down the slope (Dive 81-49, location 7, photo Harrison).

windward side is covered by stony corals. The colonies which do occur, though, are often relatively large (Fig. 14). The deepest observation of a stony coral colony was about 112 m.

*Halimeda* spp. algae are the most conspicuous macroalgae on the deep slope to depths of 100 m or more. The presence of this genus is further documented in this volume (Hillis-Colinvaux). Rocks collected as deep as 140 m had a surface film of green-colored microalgae and small, fan-like, green algal thalli. Calcareous algae, presumably corallines, were seen on rock surfaces to at least 150 m where rock surfaces were protected from downflowing sediment.

Below the zone where stony corals occur, gorgonians and alcyonaceans are the most visible benthic organisms. Fan-like gorgonian colonies extend vertically with their flat portion facing the current which moves along the reef face (Fig. 14). Nephtheid alcyonaceans are common in areas protected from sediment accumulations such as near-vertical and overhanging rock surfaces. Indentations and small caves at about 120–160 m have sponges, small (probable) sclerosponges, antipatharians, and other sessile invertebrates on overhanging portions that are protected from sediment (Figs. 11 and 15).

The sand slope on the eastern side of the wide channel provided an interesting contrast to hard substrata at similar depths. An unidentified sea pen (Penillidae)

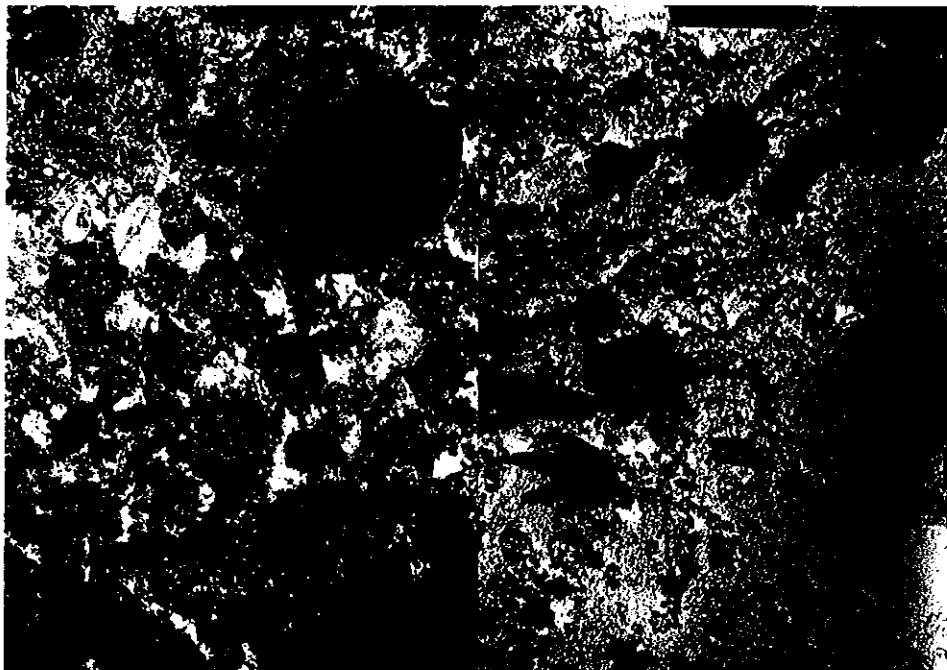


Figure 14. (Left) Stony coral colony at 112 m depth on steep rock face. Also visible are small macroalgae, distinct *Halimeda* sp. plants, and small sponges (Dive 81-50, location 8, photo Highsmith). (Right) Area at 142 m depth with abundant fan-shaped gorgonians on steep (about 45°) slope. There is one alcyonarian in the upper left corner (Dive 81-25, location 15, photo Colin).

was very abundant, reaching densities of several per m<sup>2</sup> over large areas of *Halimeda* sand slope (Fig. 16).

Commercially valuable anthozoans (precious corals) were not common on the Enewetak slope. A few isolated large colonies of antipatharians were found at depths near 90–100 m. Some colonies of gold coral (probably *Paragorgia* sp.) were encountered off Runit near the depth limit of the sub (Figs. 16 and 17) and more colonies could be seen deeper. A colony of bamboo coral, possibly of the genus *Lepidisis*, was also photographed at 360 m at the same location, but the photograph is not suitable for inclusion here. This area differed from most others in being steep and extremely rugged between 330 and 375 m depth, with little sediment.

Some probable sclerosponges were found on overhanging areas protected from sediment (Fig. 15) at around 150 m, but nowhere were they abundant. There are three species known from Enewetak, but the organisms observed and photographed (but not collected) could not be assigned to species. It is almost certain that sclerosponges are not making a major contribution to atoll framework above 360 m at Enewetak as has been shown for Jamaican reefs (Lang et al., 1975).

Talus blocks on sediment slopes provide a point of attachment for some sessile invertebrates. One large brown tunicate (Fig. 18) was often seen attached to small coral blocks at depths of 300 m and more. Anemones were also found under similar conditions. This implies that under normal conditions, downslope movement of sedimentary material must be relatively slow.

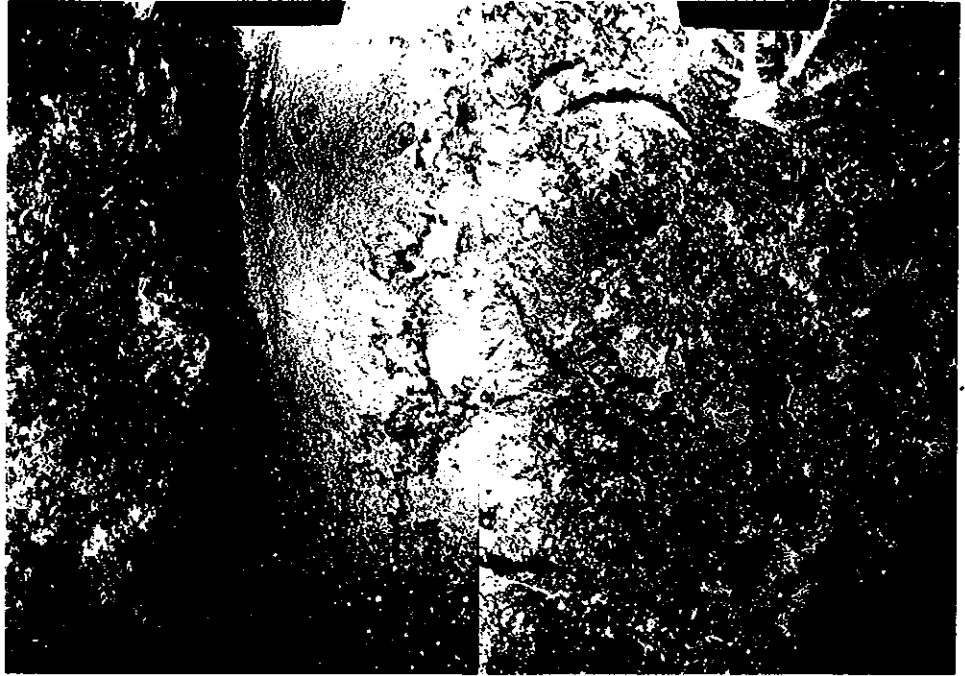


Figure 15. (Left) Sediment-floored indentation in reef face at 135 m depth. Overhanging portion of the face has a rich encrusting fauna. There are possible small sclerosponges in this area. Virtually no sessile macroorganisms occur on the area immediately below this shelf (Dive 81-47, location 3, photo Wellington). (Right) Rich biological community on overhanging face at 138 m with neptheid alcyonarians, possible stylasterines (not collected), encrusting coralline algae, sponges, and possible sclerosponges (Dive 81-50, location 8, photo Highsmith).

Steeply sloping rock surfaces, often overlain with a thin coating of sediment, seem to be particularly poor sites for benthic invertebrates. Few sessile invertebrates were found in such areas, the scouring action of the sediment perhaps being the limiting factor. The heavily scoured areas of the chutes seem devoid of macroscopic benthic animals.

#### DISCUSSION

The dives around the southern perimeter of Enewetak provided basic information on physical factors, geomorphology, and biological communities of a coral atoll at depths beyond those normally examined in situ. Unfortunately, our observations were hampered by their cursory nature and our inability to effectively collect either biological or geological samples. The cooperation of 10 scientific observers on outer slope dives (Table 1) in making general observations in addition to gathering data on their specific interests allowed formation of the present overview of the slope environment of Enewetak.

The steepness of the slope at Enewetak is somewhat greater than determined previously (Emery et al., 1954). This is not surprising, considering the limitations of echo sounding on steep slopes and had been predicted (Emery et al., 1954). Except for the area below the wide passage, there are few sizeable areas of sediment accumulation between 300 and 360 m. In most areas, the slope is too steep for

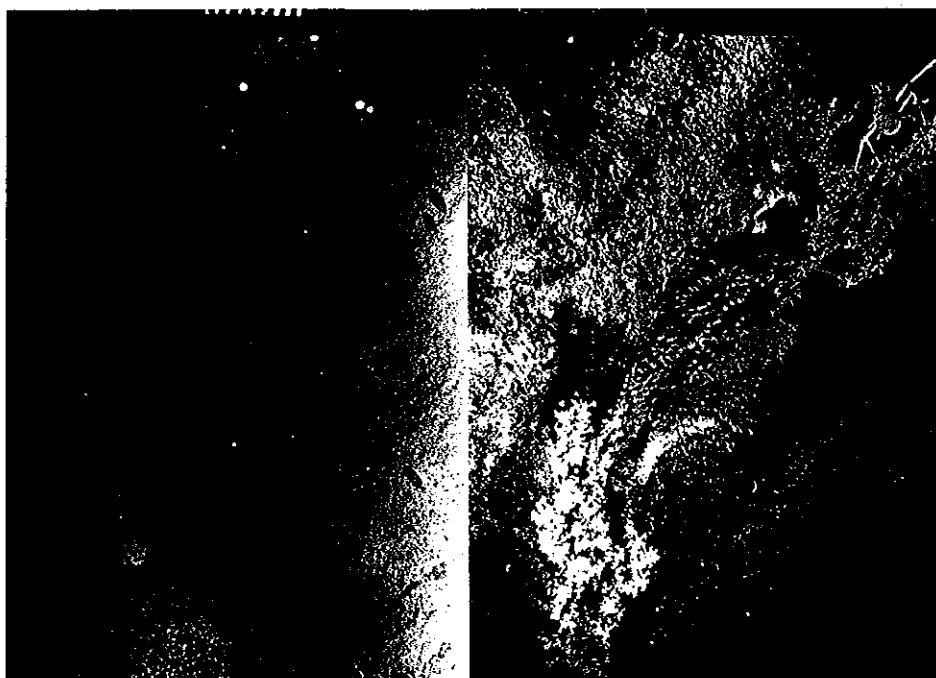


Figure 16. (Left) Large numbers of unidentified sea pens on a *Halimeda* sediment slope at 220 m depth. The slope was about 30° with the area of abundant sea pens extending over 100 m or more of bottom (Dive 81-25, location 15, photo Colin). (Right) Colony of gold coral, possibly *Paragorgia* sp., at 363 m depth. There is a galatheid crustacean on the corallum, in the lower right of the photo. The central part of the photograph is occupied by another corallum, probably a gorgonian, while the gold coral polyps are to the right and left of that. This was photographed on a vertical to slightly overhanging rock with microrelief on its surface (Dive 81-46, location 1, photo Hillis-Colinvaux).

significant retention of sediment. Where there are some accumulations, as at the base of reentrants in the face, they are localized and probably thinly cover rock substrata. In one area on the windward shore off Runit Island (Fig. 1, location 1) the face between 330 and 360 m was quite steep and rugged, something which was not seen elsewhere on the windward slope. There was ample evidence at any depth along the windward face of the atoll of local variation in slope and other geomorphological features.

Most of the sediment downwelling on the windward reef face originates in shallow water. The rapidly increasing slope below 15–20 m depth on the windward side of the atoll necessitates that sediment can only be transported seaward down-slope. The large amounts of sediment in shallower areas near the angle of repose (Fig. 6) at about 30–80 m may be transported to depth gradually or moved in large quantity by a single catastrophic event (typhoon, seismic event). The lack of significant areas where sediment could accumulate implies that most must end up at some depth below 360 m.

Relatively little sediment seems to move down the extremely steep leeward reef face. Except in the area of the southwest channel, which is a series of sediment passages less than 10 m deep between shallow reefs, there are few regions on the leeward side of the atoll where distinct sediment sources (grooves, channels, reentrants, etc.) are found on the reef slope above 30 m depth. The expanse

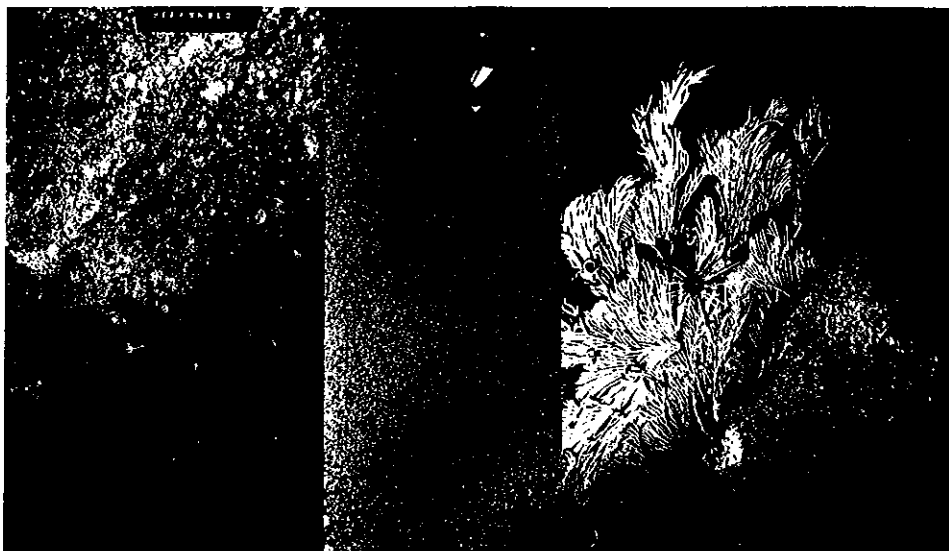


Figure 17. (Left) Vertical to overhanging rock face at 363 m, Runit, with gorgonians and bamboo coral (far left). Virtually no sediment is present in such areas due to the steep slope and lack of ledges or indentations (Dive 81-46, location 1, photo Hillis-Colinvaux).

Figure 18. (Center) Tunicate on an isolated piece of talus on a *Halimeda* sediment slope at 285 m depth. The mechanical hand of the MAKAL'I is visible on the right. The block to which the tunicate was attached was loose on the slope and easily picked up. The tunicate was not collected (Dive 81-34, location 4, photo Suchanek).

Figure 18. (Right) Large gorgonian at 363 m with echinoids, ophiuroids, and crustaceans on it. A large sea anemone also occurs on the rock surface at the lower center of the photo (Dive 81-46, location 1, photo Hillis-Colinvaux).

between the reef crest and extremely steep reef face is very narrow, from a few tens of meters to a maximum of perhaps 100 m. The reef crest on the leeward side serves to retain lagoon sediment and prevent its movement seaward. Only in the southwest channel can sediment be easily transported seaward. This is the only area of leeward reefs where significant reentrants are developed on the upper portion (to 30 m depth) of the reef face.

It seems unlikely that there is any significant construction of reef framework below about 60 m depth. The scattered stony corals below 60 m probably do not contribute any substantial amount of calcium carbonate. The general lack of major calcifying fauna on the slope argues against any framework construction at depth, and there is ample evidence of an erosional environment from 150 to 365 m depth. No significant populations of sclerosponges, which potentially could produce reef framework at depths below the lower limit of stony corals (Lang et al., 1975) were found at Enewetak. The exposure of the solution unconformity at two locations (360 and 365 m), almost certainly through erosion, is indicative of present day conditions.

The pitting and pocking of the reef face from 150 m to as deep as 240 m deserves further consideration (Figs. 10 and 11). No obvious organisms (sea urchins, bivalves, gastropods, etc.) known to heavily erode reef substratum in shallow water were seen in or near these features. Indeed, many of the pocks were partially filled with sediment, implying they are not actively being produced. Where downwelling sediment has eroded vertical reentrants in the reef face, the pocks are



Table 1. Summary of dives on outer slope by submersible MAKALI'I at Enewetak Atoll, 1981

Dive No.	Scientist	m max. depth	Fig. 1 location	Date
81-10	J. Randall	190	17	18 July
81-11	D. Devaney	180	18	18 July
81-12	J. Randall	240	21	19 July
81-13	D. Devaney	240	22	19 July
81-14	J. Randall	138	10	20 July
81-15	D. Devaney	200	11	20 July
81-25	P. Colin	280	15	3 Aug.
81-26	T. Suchanek	250	12	22 Aug.
81-33	R. Thresher	365	5	30 Aug.
81-34	T. Suchanek	340	4	31 Aug.
81-38	D. Self	365	16	3 Sept.
81-39	G. Wellington	170	9	4 Sept.
81-40	R. Highsmith	120	6	5 Sept.
81-42	L. Hillis-Colinvaux	365	19	7 Sept.
81-43	G. Wellington	365	20	8 Sept.
81-44	P. Colin	135	13	9 Sept.
81-45	R. Highsmith	120	14	9 Sept.
81-46	L. Hillis-Colinvaux	365	1	11 Sept.
81-47	G. Wellington	135	3	12 Sept.
81-48	R. Highsmith	90	2	12 Sept.
81-49	J. Harrison	365	7	15 Sept.
81-50	R. Highsmith	150	8	15 Sept.

being erased (Figs. 4 and 5). The zone of pocked face is almost certainly too deep to have been exposed to the atmosphere during the lowest sea level of the last glaciation (about 130 m, 15,000 y.b.p., Milliman and Emery, 1968). However, it would have been in relatively shallow water where bioerosion is more pronounced. The greatest development of pocks seems to be in the 200–23-m depth range, which would have been 70–100 m depth using Milliman and Emery's (1968) figures.

Based on the amount of talus encountered in areas below 250- to 365-m depths where slopes are still steep, there must be considerable accumulations of talus below 365 m. There is very little information concerning the nature of the slope where large talus accumulations might exist (500–1,000 m and deeper), but the decrease in slope of the outer face (Emery et al., 1954) might well be due to talus accumulation. Moore et al. (1976) found in Jamaica that talus accumulations made up much of the island slope to as much as 800 m depth where sill reefs did not block downslope transport.

Some comparisons can be made with Jamaican deep-reef communities (Lang, 1974). The depth limits for stony coral colonies were similar (max. depth of 98 m in Jamaica, rare below 75 m), but scleractinian colonies probably penetrated slightly deeper at Enewetak. Species of *Halimeda* were common to about 70 m in Jamaica, but only one species, *H. cryptica*, was found to a maximum of 98 m (Lang, 1974). *Halimeda* was perhaps more abundant at Enewetak below 70 m with plants occurring to 100 m or more (Hillis-Colinvaux, this volume). The slightly greater depth penetration of stony corals and macroalgae at Enewetak may be due to a slight increase in light penetration, but it could also be attributed to the lesser slope at depths of 70–100 m at Enewetak (although still around 60°) compared to the essentially vertical deep forereef below 70 m at Discovery Bay, Jamaica (Lang, 1974). This non-vertical slope would effectively make the weak light at depth more accessible to organisms.

The variation in biological communities at a given depth in different areas has not been adequately examined. Organisms on hard substratum are profoundly influenced by slope angles and downwelling sediment, but more subtle determinants of distribution are poorly known.

Associations of numerous different organisms were observed and photographed. At deeper depths (below 300 m), soft corals were often found to have a variety of crustaceans and echinoderms (Fig. 18) on them. Such associations may be simply facultative, providing a means of feeding higher in the water column or protection from predators.

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