15 September 1961, Volume 134, Number 3481 SCIENCE

CURRENT PROBLEMS IN RESEARCH

Reef Building

The growth of living breakwaters has kept pace with subsidence and wave erosion for fifty million years.

Harry S. Ladd

Whether one first sees a reef from the sea or from the air, one cannot but be impressed, not so much by the beauty of the curious structure as by its ability to withstand the force of the waves that ceaselessly break upon its seaward edge. It has been estimated that normal waves dissipate 500,000 horsepower—one-fourth the power generated at Boulder Dam—against the windward side of an open sea atoll (*1*). How can lowly plants and animals build a structure to withstand such forces? Actually, the forces of storm waves are many times as great, and though the reefs are damaged by storms, they do survive. Furthermore, as has been demonstrated, some of them have survived for as long as 50 million years. These structures are truly worthy of an engineer's respect.

Since the earliest days of navigation, mariners have known reefs at first hand and have feared their power to break up ships. The venturesome Lieutenant (later Captain) James Cook was wrecked on the Great Barrier Reef in 1770 and had to careen the *Endeavour* for extensive repairs before continuing his first globe-encircling voyage (*2*). Captain Henry Wilson, whose ship the *Antelope* was wrecked on a reef in Palau in 1783, was less fortunate. He and his crew had to build a new ship before proceeding homeward (*3*). Another famous explorer, La Pérouse, like his contemporary Captain Cook, was making a scientific expedition around the world when both of his frigates, the *Astrolabe* and the *Boussole*, were lost, in 1788, on the dangerous outer reefs of Vanikoro in the Santa Cruz Islands (*4*).

The Christian missionaries, who closely followed these early Pacific explorers, also had their difficulties in navigating under sail. The missionary ship *Duff*, in the midst of a lengthy voyage among the islands of the southwest Pacific, struck a reef in the little-known waters of eastern Fiji. She struck at night but managed to back off, leaving nothing to the reef but her name (*5*). The mission schooner *Harrier* was not so fortunate on the Great Barrier Reef (Fig. 1).

In 1890 there was a disastrous wreck on a reef in Torres Strait, near Thursday Island. The British India liner *Quetta*, of 3484 tons, bound from Brisbane to London with 293 persons aboard, was passing through Adolphus Channel, a reef area believed to have been adequately charted. Steaming through calm waters on a bright moonlight night she struck a flourishing coral pinnacle rising from 13 fathoms and sank within three minutes, with a loss of 133 lives. Sixteen years later divers blasted a porthole from the sunken ship's side, which had been thickly overgrown with coral. The charts available to the *Quetta* in 1890 were based on surveys made between 1802 and 1860, and it is possible, although not probable, that the pinnacle that ripped open two-thirds of the ship's bottom had grown sufficiently in the years that followed the surveys to become a menace to navigation after the charts were made (*6*). Atlantic reefs also have taken their toll (Fig. 2).

Storms, inadequate charting, poor night visibility, and faulty navigation have all played parts in driving ships onto reefs, but one large modern tanker lies rusting on a Pacific atoll for a different reason. During World War II she entered the deep narrow pass leading to a lagoon where much of the U.S. Fleet was stationed. The tanker was loaded with fuel for the fleet but had not been given proper identification signals, and those in charge of security were loath to clear her. She was ordered to turn back, even though this was obviously impossible in the narrow reef pass. To this day the reef organisms near the site of the wreck have not fully recovered from the oil bath that followed.

Reefs, however, are constructive as well as destructive. Some of the finest tropical harbors are protected by natural breakwaters in the form of reefs (Fig. 3). In Ceylon attempts are now being made to stimulate and control coral growth in binding artificial breakwaters (*7*).

Reef lagoons and atoll islands were used as stepping-stones and way stations by early Polynesian voyagers, who eventually sailed their outrigger canoes all the way from Indonesia to the high volcanic islands of Hawaii. Trading vessels of all sorts found safe anchorage in lagoons in the years that followed. During the Pacific campaign of World War II, protective reefs played a most important role in island defense.

Appearance of a Reef

What does a reef look like? At high tide nothing may be visible but a line of white breakers, possibly with a band of green water behind it. At low tide, in areas where tides have a range of several feet, the broad reef flat may be awash or actually out of water, revealed as a brown band. Part of the surface

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may be a smooth sand flat on which one could ride a bicycle, and I have seen planed rock pavements so smooth that one could—though I have never tried!—go about on roller skates. More often, tide pools, microatolls, and areas of short-branched or knobby coral heads make up parts of the surface. Water-filled pools help give a deceptive appearance of levelness.

The Builders

All wave-breaking reefs in the tropical seas are commonly called coral reefs, though both biologists and geologists have known for more than 50 years that on many reefs the calcareous algae are the essential, and in some places the most abundant, contributors. The corals exhibit greater variation in form and color than do the lime-secreting algae, and this diversity is doubtless responsible for the ease with which they won first place in the eyes of early observers (Fig. 4). The tips of many graceful staghorn corals are brilliant blue or violet; other palmate corals are bright pink or claret, yellow, green, or brown; most massive hemispherical colonies are more drab, but in some each corallite of the honeycomb surface contains a central "eye" of fluorescent green. When the colonies are intermingled in a pool or are cemented at various angles on the wall of a reef channel the effect is striking, to say the least.

Algae, on the other hand, are mostly shades of brown, yellow, or purple, and a single type of uniform shape and color will dominate a given area of a reef. Along the seaward edge the buttresses between channels may be covered almost entirely by pink or purplish globular colonies, and the result, though colorful, is unvaried; the encrusting type of algae may form a flattish pavement uniformly brown or yellowish-brown in color.

These two groups—the corals and the algae—are the important reef builders. The corals add bulk, the algae function as cementing agents. Among numerous minor contributors are the Foraminifera, both encrusting and benthonic types. The latter, though small individually, live in such abundance on reef flats that their shells, carried shoreward by the waves, form the bulk of the sands of the beaches that fringe reef-encircled islands.

Occurring widely, but in lesser abundance, are many other invertebrates—echinoids (sea urchins), mollusks, and tube-secreting worms. These minor groups may also function as agents of reef destruction. Locally, certain types of boring echinoids occur in tremendous numbers and may literally riddle a rock pavement solidly built by corals and algae. Several types of worms and clams bore into coral heads, both living and dead. When broken open, many corals are seen to be pierced by holes and to resemble a Swiss cheese. Other destructive borers include algae, sponges, and barnacles.

Wave-Resisting Features

The amounts of calcium carbonate taken from sea water to build a reef are impressive. At Eniwetok Atoll, for example, the limestone mass (reef complex) that caps the volcanic foundation contains more than 250 cubic miles of limestone; practically all the limestone was secreted by shallow-water organisms. The most noteworthy feature, however, is not the volume but the fact that parts of the mass of skeletal material are so constructed or so cemented that the reef can grow upward to low-

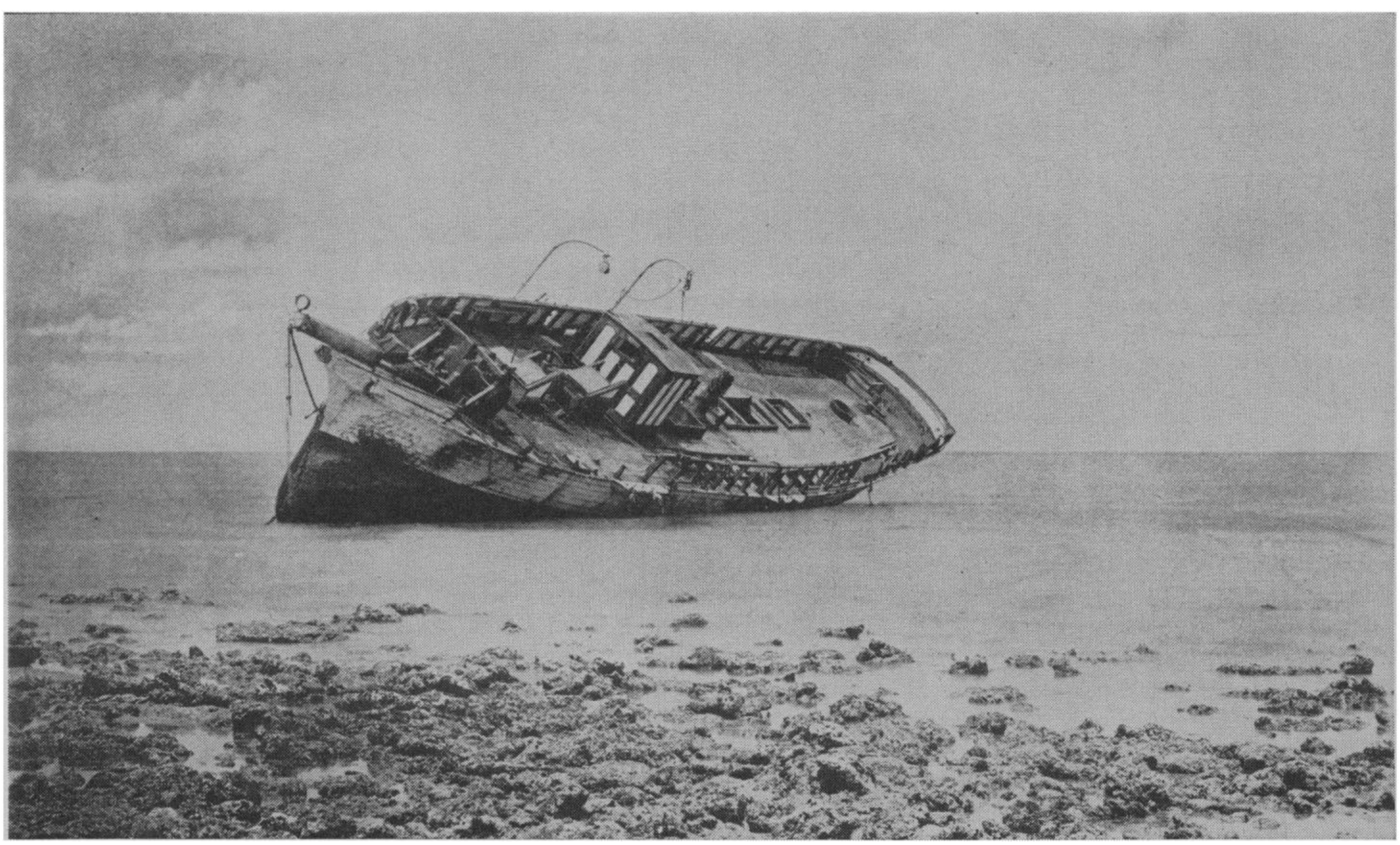

Fig. 1. Wreck of the New Guinea mission schooner *Harrier* on the Great Barrier Reef of Australia. [Courtesy W. H. Allen and Co., Ltd.]

tide level and maintain itself against wave attack. How is this accomplished?

Three distinct elements or processes are involved: (i) the growth forms of the builders, which enable them to construct an efficient baffle that, in addition to bringing a constant supply of refreshing sea water to all parts of the organisms, robs the incoming waves of much of their force by spreading the water in all directions; (ii) cementation by the organisms to the foundation on which they grow and to each other; (iii) lithification of sediments, probably an inorganic process, which takes place beneath reef flats and at intertidal levels on shore. The first two processes are well understood, the third is not.

Growth forms. The algae and corals that flourish along the margin of a reef exhibit two dominant growth forms. Some grow as thin veneers that do not break the force of the waves but do function efficiently as cementing agents. Others build spongelike structures that are so porous or intricately branched that the force of the oncoming wave is diverted and spread widely in many directions. The surface densely covered by such colonies acts like blotting paper.

The baffle effect, efficiently performed by the individual colonies along the margin, is repeated on a larger scale by major reef structures developed in the same area. The grooves and buttresses of the "toothed edge" (Fig. 5) concentrate the power of the oncoming waves into trenches, some of which lead through the marginal zone as surge channels below the reef surface (*8*). The lower part of each wave attempts to enter caverns below the reef surface. The resistance encountered in these already filled chambers absorbs some of the waves' power; another part is absorbed by spouting, geyserlike blow holes and by thousands of tiny holes in the pavement behind the marginal ridge. With each incoming wave water oozes upward through this sievelike pavement. The caverns beneath the reef margin have not been studied in detail, but enough is known to justify comparison with the well-known "room-and-pillar" caverns of mining operations.

Organic cementation. Encrusting calcareous algae (*Porolithon* and other lithothamnia) function effectively as enveloping lamellar growths that bind loose fragments to the growing reef edge, and they may even smother colonies of living coral. These organisms flourish in a constant supply of moving water, and they form a fairly solid pavement on the back slope of the marginal ridge, where weakened surges pass landward and where other water wells upward through the porous reef structure. Many of the corals along the reef edge also adopt the veneering habit, forming a living calcareous blanket that, when opportunity permits, may extend itself over areas of living algae. I have measured single colonies of veneering coral that extend for 30 feet along the reef margin.

Lithification. From the standpoint of reef stability and the development of wave-resisting qualities the reef margin is the crucial area. In this area organic binding seems to be the important process, but in other parts of the reef—on the wide flats behind the margin and even on the beaches—other processes of cementation occur. These bind the sediments of the flat and the sands of the beaches into fairly hard rock. The processes are probably chemical, in large part.

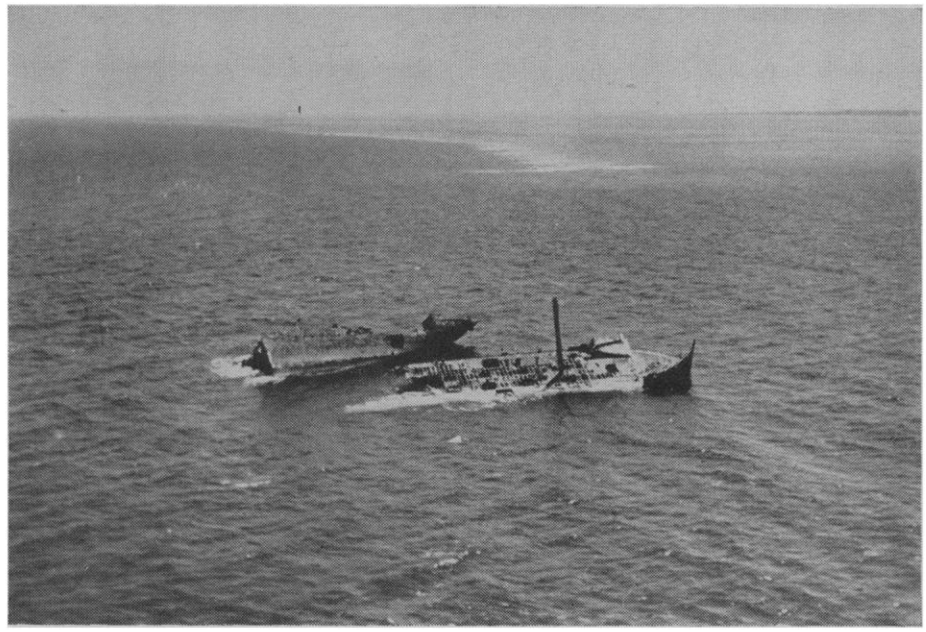

Fig. 2. Wreck on Andros Island reef, in the Bahamas. [Fritz Goro, *Life*]

Current Problems

Much of the present-day interest in reefs began shortly after Pearl Harbor, when we lost Guam, Wake, and the Philippines. We planned to recapture these reef-encircled islands and to occupy many others captured or long held by the Japanese. This planning, and our early attacks such as that at Tarawa, revealed how little we knew about reefs and the waters surging over them. Special reports summarizing all available information, hastily prepared for the Armed Services, were of some assistance, but it was not until after the war that intensive field investigations of reefs and reef islands were undertaken as part of military terrain studies. These studies, supported by the Army and carried out by U.S. Geological Survey personnel, coupled with the intensive reef studies made at Bikini and nearby atolls in the Marshall Islands, supported by the Armed Forces and the U.S. Atomic Energy Commission, have given us the sort of reef information that we lacked during the Pacific campaign of World War II.

Somewhat earlier—in the late 'twenties and 'thirties—oil was discovered in large quantities in certain ancient reefs. These discoveries continued after the war (*9*) and greatly stimulated reef work in general. A third factor that dates from the war years is the increase in activity in the fields of oceanography and marine geology.

Seaward Margin of the Reef

The most vital part of a reef is the marginal zone along the windward side. This is the zone where living organisms are concentrated, and it is the site of the most persistent wave attack. The remainder of the reef is largely dependent upon this zone, which is the place where building must take place if the reef is to flourish and expand. An understanding of growth processes in the windward marginal zone is an essential part

Fig. 3. The reef-protected harbor of Suva, Fiji. The entrance is through Levu passage, which breaks the barrier on the left. [Rob Wright, Fiji official photograph]

of the story of reef building. Ironically, this is the zone least accessible to direct observation. Problems and questions still remain to be solved and answered.

The zone of marginal growth, as here defined, consists of three distinct parts. The first is a ridge of living algae that rises above the reef flat and may be widely exposed at times of low tide. It is cut at fairly regular intervals by surge channels (Fig. 5). The next is a zone below low tide on the seaward slope, which consists of deep grooves separated by wide buttresses. This is the "toothed edge" so clearly visible from the air (Fig. 6). The lower part, at least, is a zone of rich coral growth, possibly the richest of all, that extends downward to the ends of the longest grooves at about 50 feet below sea level. This zone is so inaccessible that it has been dubbed the *"mare incognitum."* A third zone, in the moderately illuminated waters below normal wave base, at depths of 50 to 150 feet, is a zone where corals of a somewhat different type grow in abundance, but it has been only superficially explored by dredging (*10*).

The submarine "toothed edges" of most windward reefs have been described from many areas. The patterns, so sharply marked on air photographs, have been observed somewhat more closely by swimmers. As yet, however, because of hazardous sea conditions, no one has succeeded in making a detailed examination at close range. Most workers, I among them, have regarded the groove-and-buttress system as primarily constructional, the buttresses being due to organic growth. Others believe that the grooves have been excavated by erosion and that growth is a relatively unimportant factor (*11*). The work being done by Thomas Goreau on the reefs of Jamaica supports the belief that the buttresses are constructional and is impressively documented (Fig. 7) (*12*). Newell *et al.* (*13*) described and illustrated closely spaced furrows or grooves from the Bahamas. As these are cut in oölitic country rock they certainly were *not* formed by growth. They may be due to erosion, as Newell and his associates suggest, but conceivably they could have been formed by solution when the sea stood lower. In any event, they do not closely resemble the typical grooves found off existing reefs in the Pacific. Cloud noted what appeared to be similar grooves in the face of a basalt-floored bench in Hawaii (*14*) but stated that he had not studied them. If the typical grooves are primarily erosional it is remarkable that they are well-nigh universal off windward reefs yet rare in other types of rock. It seems to me quite possible that improved diving techniques will eventually settle this most interesting problem.

SCUBA diving by reef students may also permit a closer examination of the growth zone immediately below the *"mare incognitum."*

Rate of Growth and Other Problems

Direct examination of exposed sections of elevated reefs and examination of samples obtained by drilling have shown that corals and other builders have persisted for long periods of time, long even when reckoned geologically. The calcareous skeletons left by one generation are superimposed on the skeletons of earlier generations, eventually accumulating thick deposits of limestone. The rate at which this rock-building takes place is of prime interest, and numerous attempts to measure it have been, and are being, made. The bulky skeletons of sessile corals lend themselves to measurement, though, as Vaughan pointed out, they are not ideal subjects (*15*). Vaughan made thousands of measurements of growth on 25 species, both naturally growing and artifically cemented to terra cotta or concrete disks fixed to iron stakes driven into the sea bottom. Mayor (*16*) measured the growth of corals in Samoa; Edmondson (*17*) did so in Hawaii. The late T. A. Stephenson and his wife Anne carried out well-organized and exceedingly valuable growth studies of several sorts on the Great Barrier Reef (*18*). One of the corals measured by the Stephensons is shown in Fig. 8. A number of fine studies of coral growth have also been made by the Japanese (*19*).

In 1960 J. Edward Hoffmeister began a long-term study of the Florida reef tract. His project includes growth experiments on reef corals similar to those mentioned above. Hoffmeister planted his first corals on the edge of the reef near Key Largo, an area lying between Dry Tortugas and the Bahamas where Vaughan made earlier studies. In addition to measuring growth rates on corals in their chosen environment Hoffmeister is transferring colonies from one environment to another to determine the effects of such changes.

The growth rate of individual colonies of coral is, of course, only an indirect measure of the growth rate of the reef surface. Estimates of the percentage of the reef surface covered by various species have to be made, and several types of losses have to be estimated and deducted. An over-all figure for reef growth, based on coral measurement, is probably less than 14 millimeters per year. This figure is comparable to estimates based on the measurements of organic productivity by Sargent and Austin (*20*) and by H. T. Odum and E. P. Odum (*21*).

The plant and animal communities that live on reef surfaces have long excited the interest of marine biologists, as attested by a voluminous literature. Several thousand organisms that live on reefs have been named and described, and much attention has been given to the life habits of the builders and of the organisms whose activities destroy reef rock. These studies have been carried on, and are being carried on, at biological laboratories established in reef areas and by special expeditions sent out to study reef problems. Examples are the comprehensive work done by (i) the British on the Great Barrier Reef of Australia, particularly the work of the expedition of 1928–29 under the leadership of C. M. Yonge (*22*); (ii) the laboratory maintained by the Japanese in Palau for 10 years; (iii) the laboratories of the University of Hawaii; and (iv) the Carnegie Laboratory that operated for many years at Dry Tortugas and in nearby areas (activities in these areas have now been taken over by the University of Miami in Florida and the Lerner Laboratory at Bimini in the Bahamas). Institutions such as the Bishop Museum of Honolulu have supported many expeditions studying reefs in various parts of the Pacific, and the Pacific Science Board has sponsored many special atoll studies.

Studies of organic productivity, mentioned in connection with reef growth, have led to interesting conclusions about reef builders. Sargent and Austin (*20*) found the rate of productivity to be higher on areas of the reef than in the surrounding waters of the open sea, and concluded that reefs are self-maintaining structures. The Odums discovered that the average coral colony contained three times as much plant as animal tissue, most of the plant material being filamentous green algae in the coral skeleton. They concluded that the reef they studied represented a true ecological climax or open steady-state system (*21*). Hedgpeth expressed skepticism, suggesting that the experiments be repeated several times at different seasons to test some of the assumptions on which measurements were made (*23*).

Among many other biological problems directly connected with reef builders are those involving the production of skeletal calcium carbonate by the corals with the aid of symbiotic algae (zooxanthellae) (*24*).

Reef Blocks

On the surface of many reef flats, blocks of reef rock occur near the seaward margin. They range in size from coral boulders a foot or more across to massive blocks 20 or 30 feet long. The largest block noted during the Marshall Islands investigations was estimated at 200 tons. The block shown in Fig. 9 was estimated at 150 tons. Some earlier workers interpreted large reef blocks as outliers or remnants of former reefs or islands. Indeed, it is difficult to determine the origin of some large blocks because the actual contact with the reef

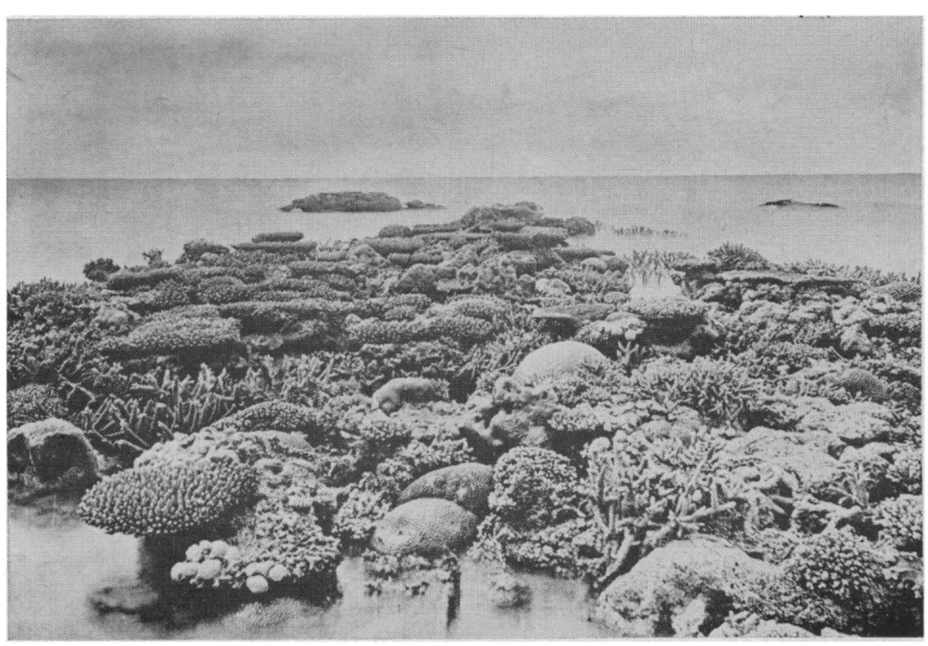

Fig. 4. Rich growth of corals exposed at low tide on Crescent Reef, Great Barrier, Australia. [W. Saville Kent, courtesy W. H. Allen and Co., Ltd.]

surface may be obscured by solution pits or overgrown by encrusting organisms. Some of the largest blocks may be remnants of an older reef, but there is now general agreement that most reef blocks are plucked from the reef edge or from the reef flat by storm waves.

The mechanics involved in moving the largest blocks are hard to understand, but the winds and waves that accompany hurricanes, typhoons, and tsunamis could move enormous masses if they were to strike an overhanging reef edge partially exposed at low tide (*25*). On 14 September 1953 there was a severe earthquake in Fiji. According to reports, the barrier reef on the eastern side of Suva harbor was raised about one foot, and large blocks of rock were thrown upon the reef by the tidal wave that followed the quake (*26*). In some areas reef blocks seem to follow a definite pattern, but the reasons for this are not clearly understood (*27*), and additional surveys would be welcome.

Landslides

In considering problems connected with the surfaces of reefs, the slopes below the sea, which control the outline of the reef at the surface, raise some interesting questions. Atolls tend to be circular, but many of the larger ones depart widely from this plan. They may show broad bights that are concave relative to the sea. Such indentations in the reef margin are well developed at Bikini Atoll, and submarine surveys there show that they continue to great depths. Fairbridge has suggested (*28*) that these are landslide scars, but those who charted the atoll (*27*) believe it more likely that the spurs and intervening bights reflect the original irregular shape of the flat-topped seamount on which the atoll was built. Drilling has shown that much of the reef complex of Bikini is unconsolidated, but there is believed to be a marginal wall of consolidated rock that would prevent large-scale slides. This question may eventually be resolved by additional drilling to more firmly establish the existence of the postulated marginal wall.

Fig. 5. Measuring depth in the surge channel through the algal ridge of the Bikini reef. [Fritz Goro, *Life*]

Passes

Most atoll and barrier reefs are broken by passes, some deep, others shallow. These have not received as much study as the more accessible reefs that border them, but enough has been done on passes through atolls to indicate that they probably record important steps in the Pleistocene history of reef building.

Each of the several large atolls studied in the northern Marshall Islands is cut by a single deep pass that is approximately as deep as the deeper parts of the lagoon behind it. Shallower passes through the reef are only as deep as the terrace that is well developed in the lagoon and on the seaward side of the reef. The deeper parts of the lagoon floor and the deep passes are thought to have been developed during the Pleistocene when, periodically, sea level stood several hundred feet lower than it does now. During the warmer interglacial stages of the Pleistocene, reefs developed on the prepared surface, growing upward more rapidly around the margins than elsewhere. This reef is thought to have flourished over the wide area now covered by the shallow terraces inside and outside the lagoon. The present reef is thought to have grown up during the postglacial rise of sea level, the shallow passes representing areas where for various reasons, possibly largely ecologic, the new reef did not flourish. This explanation, involving ideas suggested by Daly (*29*) and Kuenen (*30*), was given strong support by the detailed surveys of lagoons and passes made in the Marshall Islands (*27*). Its soundness should be tested by similar detailed surveys in other areas.

The lagoons of barrier reefs and the passes that connect them with the open sea are much less well known than comparable structures of atolls. The depths of some passes through barrier reefs exceed 100 fathoms. This is a promising field for future studies.

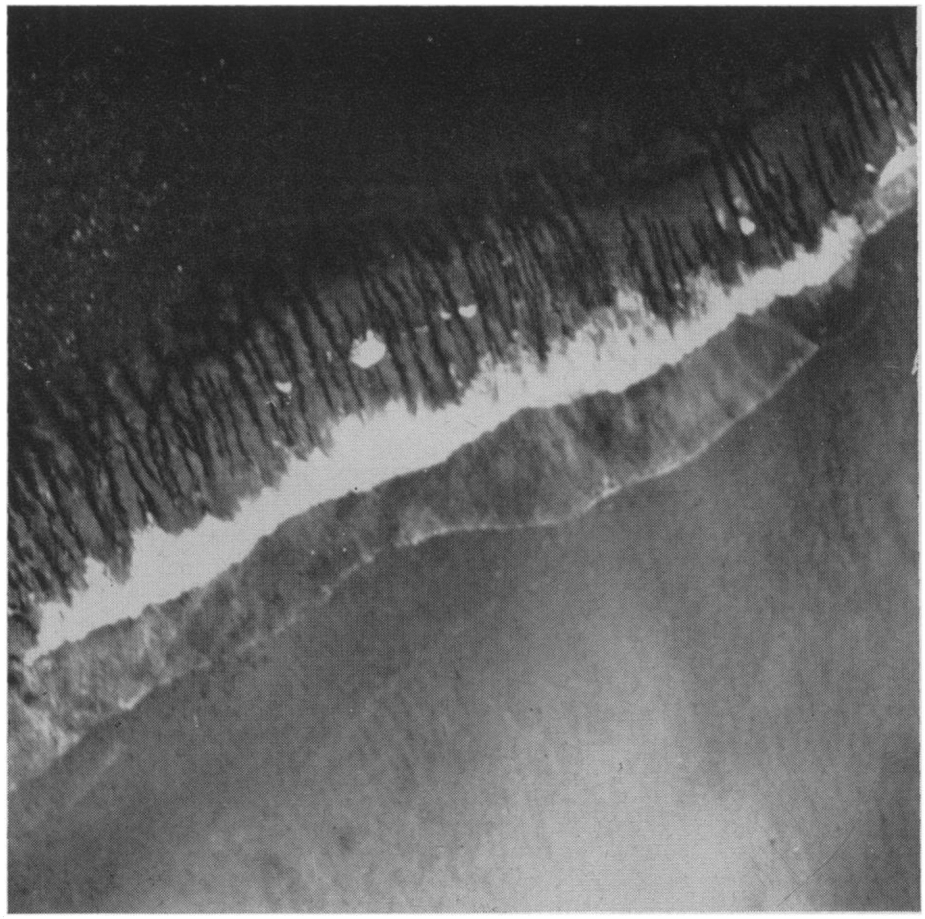

Fig. 6. Buttresses and grooves of the toothed edge of a windward reef, Bikini Atoll. The buttresses rise from a submarine terrace about 20 feet below the surface. [R. Dana Russell, air photograph from about 500 feet]

Beach Rock

Hard layers of calcareous sandstone and conglomerate occur on parts of many beaches behind fringing and offshore reefs. The layers, in most places, dip toward the sea or lagoon at angles of 8 to 10 degrees. The rock is especially well indurated on exposed surfaces, becoming more crumbly below. Beach rock is characteristically an intertidal deposit and, at best, the layers are but a few feet thick. Drilling on atoll islands shows that the layers are almost invariably present at intertidal levels (*31*). The beach-rock layers are wave-resistant and on many reef islands form the nearest approach to a persistent layer of hard rock.

The process of cementation, in many areas, seems definitely to be occurring at the present time. In the Marshall Islands, for example, a piece of a Japanese glass fishing float was discovered by J. I. Tracey firmly cemented in beach rock (*27*). Many explanations for the formation of beach rock have been suggested. They involve evaporation of interstitial water and cementation by certain types of algae, by bacteria, and so on, but none is satisfactory as a general explanation. Emery and Cox (*32*) thought that detailed mapping of the occurrences might show significant relationships to the abundance and composition of ground water or to other factors of shore environment. They mapped widely scattered occurrences in Hawaii but were unable to give a satisfactory explanation. Richard Russell and his associates have recently completed an extended investigation of occurrences in the Caribbean area, with results as inconclusive as those of Emery and Cox in Hawaii (*33*).

Intertidal Erosion

The layers of beach rock that occur on many of the beaches behind reefs are subject to chemical erosion. Contiguous pits and basins are developed on exposed bedding surfaces, being especially numerous in the seaward half of the beach-rock belt. They are highly irregular, being often separated from each other only by knife-edge ridges. These depressions obviously are formed by solution, as are the deep nips that are invariably present on all limestone shores in the tropics at about high-tide level. This type of solution is limited to intertidal levels where marked diurnal changes take place, yet the process is difficult to understand because normal surface sea water is known to be supersaturated with calcium carbonate. Revelle and Emery have suggested a hypothesis involving slow complexing or slow hydration and dehydration (*34*).

All reef investigators agree that some solution takes place at intertidal levels in reef areas, but since the process is not well understood, there is considerable disagreement as to its effectiveness. Revelle and Emery stated that the very existence of the broad and dead reef flat just below low-tide level indicated the efficacy of such solution, and they pointed out that it is as effective in sheltered lagoons as on exposed shores.

Much evidence indicating widespread reef planation—by solution, or waves, or a combination of the two—has been reported from the Pacific islands. For example; on the reef flats of Okinawa, MacNeil (*35*) found blocks of an older limestone (late Tertiary or early Pleistocene), weighing many tons, perched on pedestals of reef limestone 5 to 6 feet high at appreciable distances from the shore. The limestone blocks, broken from shore cliffs, appeared to have crept, slid, or rolled over underlying clays until they came to rest on a reef flat that stood 5 to 6 feet higher than it does now. Since that time they have been isolated by erosion that has planed 5 to 6 feet from the rest of the reef flat.

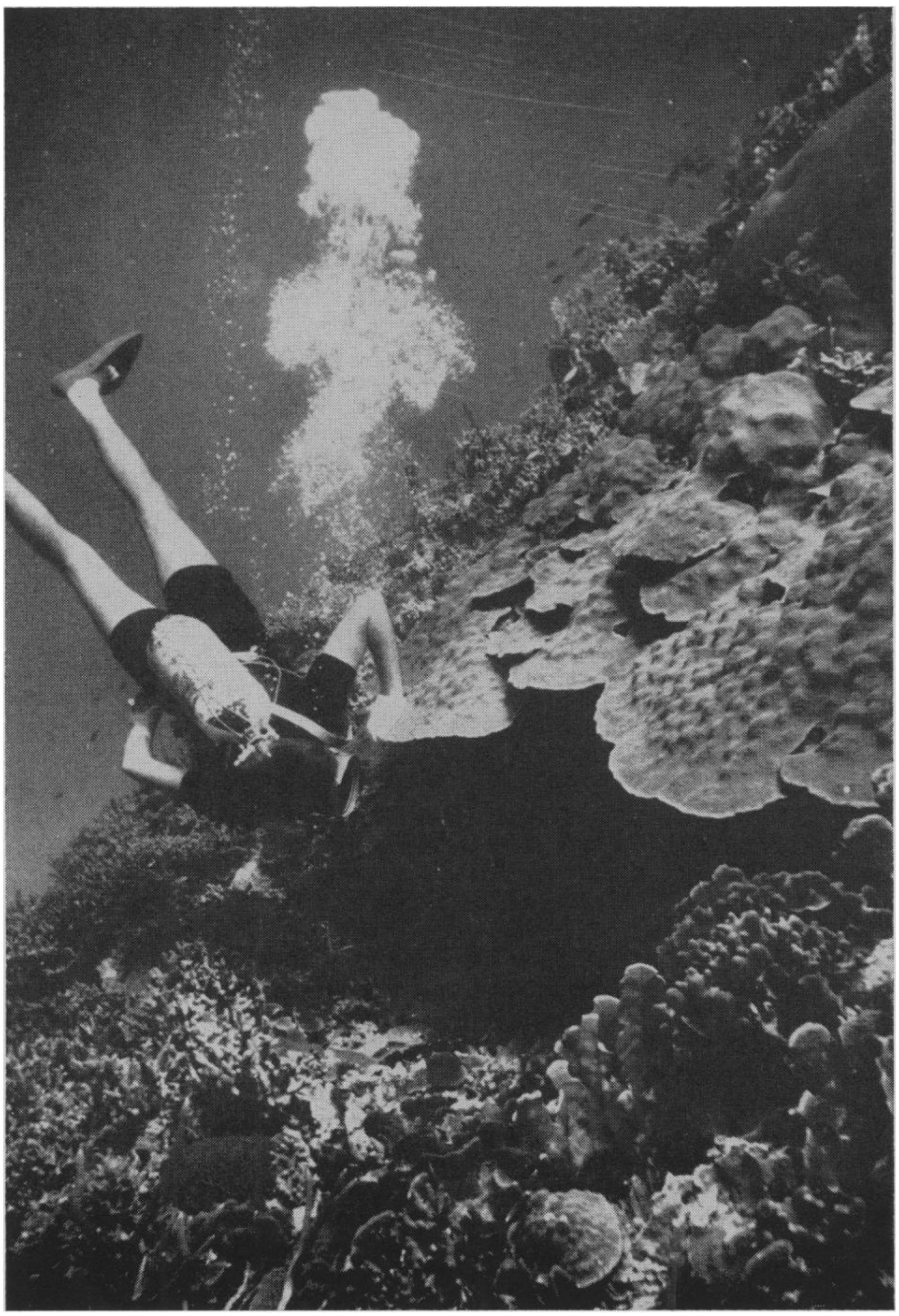

Fig. 7. Diver inspecting the under side of a flow-sheet of the coral *Monastrea annularis*, growing on the forward edge of the buttress on a reef near Boscobel, Jamaica. Depth, about 30 feet; the buttress terminates at 60 feet. [Thomas Goreau]

Recently, Norman Newell has questioned interpretations such as those given above. His investigations in the western Atlantic led him to believe that sea level is now at its highest position since the close of the Pleistocene and that intertidal erosion at this level has been negligible. He suggested that the elevated terraces in the Pacific may be of Pleistocene age (*36*). His conclusions involve a number of assumptions, and it can hardly be said that they invalidate the evidence for rapid intertidal erosion in the Pacific. Additional determinations of ages obtained from radiocarbon and other measurements from widely scattered areas may eventually resolve some of the differences of interpretation.

Origin of Reef Islands

The small low islands of sand and coarser debris that are found on many reefs, particularly on atolls, may be related to the postulated recent negative shift in the strand line of about 6 feet. Such a eustatic shift would stimulate erosion of any reefs that had grown to a higher level, resulting in masses of reef debris above the new (lower) sea level. Wave action is now shifting these masses slowly across the reef flat, and many are being reduced in size by wave activity. Evidence for this is seen in lines of truncated beach rock beyond the limits of the existing islands.

The Reef Complex

In 1950 Henson suggested the term *reef complex* for the aggregate of reef limestones and calcareous rocks associated with them (*37*). It is a useful term that includes the surface reefs, all outer reef structures, and the deposits that underlie the flat and the lagoon. The sediments making up the complex may be several thousand feet thick, with bulk ten times that of the controlling reef frame.

Charles Darwin was the first to think seriously about the thickness of reefs. His brilliant deductive theorizing on the nature of reef building was done before he had had an opportunity to see a true reef. He was, however, familiar with the effects of elevation of the land and with denudation and the deposition of sediment. Mentally substituting subsidence for elevation, and coral growth in shallow water for sediment deposition, he reasoned that the three main types of reef—the fringing reef along the shore, the barrier separated from the shore by a lagoon, and the atoll without a central island—might be genetically related and controlled by slow subsidence. Thus, with upward and outward growth on a sinking island, a fringing reef could become a barrier, and the barrier, in turn, an atoll. He recognized, however, that an atoll could be developed directly from a shallow-water bank without passing through the intermediate barrier stage (*38*).

It is difficult to generalize on the relative importance of vertical as compared with horizontal growth. In the Pacific, where atolls abound, it appears that many have grown upward on truncated platforms without ever being fringing reefs or barriers. Vertical growth in some areas amounts to several thousands of feet. If the submarine buttresses that fringe many atolls are growth forms, they are growing laterally as well as vertically, and in turn, the marginal zone of the surface reef is growing laterally over the buttress area.

Charles Darwin was the first of several students of coral formations to refer to them picturesquely as monuments or tombstones over subsiding land. W. M. Davis, who saw reefs only as physiographic features, referred to the low-lying atolls as "inscrutable." The core drill established the aptness of Darwin's simile and the ineptness of Davis's adjective. Along with its cores and cuttings, however, the drill brought up problems not envisaged by either Darwin or Davis. Some of these still await a satisfactory solution.

The drill holes put down by the British on Funafuti Atoll in the Ellice Islands penetrated 1114 feet of Quaternary reef limestone, and below about 750 feet the rock was heavily dolomitized (*39*). The hole drilled by the Japanese on Kita-daito-shima ended in Miocene ["Oligocene"] beds at 1416 feet, the upper levels being dolomitized (*40*). The deepest hole on Bikini (Fig. 10) went 2556 feet into Miocene, with no trace of dolomite. On Eniwetok the drills went beyond 4000 feet to a basaltic foundation below upper Eocene limestones. One hole showed a little dolomite in the Eocene rocks, the other showed much more, also in the Eocene; there was a trace of dolomite in the Miocene rocks but none in the younger beds (*31*). S. O. Schlanger, of the U.S. Geological Survey (*41*), concluded that the island dolomites were formed in several ways. Others who are studying the Pacific island dolomites include Donald Graf of the Illinois Geological Survey, Julian Goldsmith of the University of Chicago, R. G. C. Bathurst of Liverpool, England, and a group from the Shell Development Company of Houston, headed by F. J. Lucia. When all these workers have reported, we shall, no doubt, know much more about the origin of dolomite. At the present time the problem of atoll dolomites is far from complete solution. The situation has not been simplified by the discovery of dolomite in Miocene ooze below 11,700 feet of water off the coast of Mexico in the preliminary Mohole drilling project.

Drilling of the "inscrutable atolls" has brought forth other interesting complications. The over-all history, as postulated by Darwin, has been one of submergence. In parts of the Pacific the submergence started at least as far back as the Eocene, and during the intervening 50 million years there have been several subintervals of considerable length when the tops of the atolls stood hundreds of feet above the sea. Eniwetok Atoll was a high island and bore a high-island fauna and flora—not once but several times. Drill samples from Eniwetok Atoll have yielded land shells of a type that lives on high islands rather than on atolls. There also are rich concentrations of spores and pollens that record the existence on the emerged atoll of a tropical deciduous forest (*42*). This paleontological evidence is supported by petrologic evidence. J. I. Tracey of the U.S. Geological Survey, who made a detailed petrologic study of the Bikini cores and cuttings, recognized a recrystallized (calcite) zone in the Miocene at a depth of more than 1000 feet, overlain by beds containing unaltered (aragonitic) shells and skeletons (*27*). As the upper layers of ocean waters are saturated with calcium carbonate, Tracey concluded that the leaching and recrystallization took place during a period of emergence. Schlanger, who studied the petrology of Eniwetok samples, found zones of leaching and recrystallization similar to those of Bikini. He has called them "solution unconformities" (*41*).

Reef Foundations

With the drilling of one reef (Eniwetok) to its volcanic foundation (Fig. 11) we have obtained a fairly good picture of how that particular reef was started, and we know the length of its life. Its base was laid in late Eocene time on the tops of truncated volcanoes two miles above the floor of the deep ocean. We are probably justified in extending the Eniwetok findings to other atolls in the Marshall Islands and, perhaps, to other atolls in the Pacific Basin proper. When, however, we consider atolls outside the basin we are less sure of our ground. When, for example, we cross the andesite line that separates the Pacific Basin from Melanesia, we enter a province where uplift, rather than subsidence, appears to have been the dominant geologic process in post-Tertiary times.

There are many barrier reefs and some atolls in Melanesia, and along with them are elevated Tertiary and younger reefs as much as 1000 feet above sea level. The Mbukatatanoa (Argo) reefs in eastern Fiji, for example,

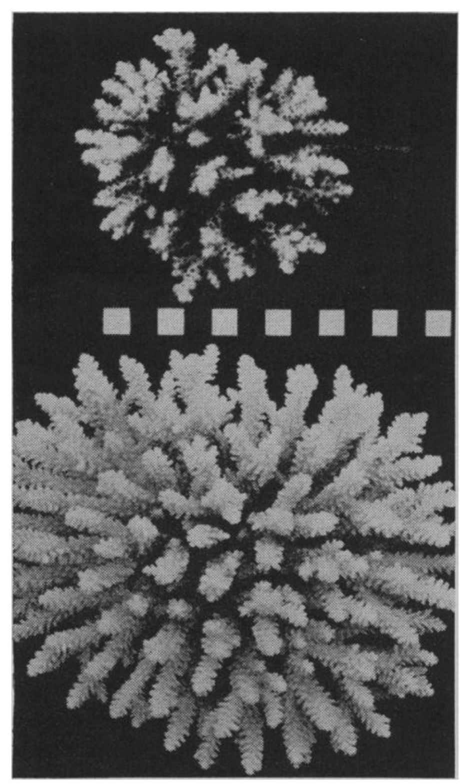

Fig. 8. Growth of coral planted on the Great Barrier Reef. This specimen (*Acropora quelchi*) increased 57 and 78 percent, respectively, on the greater and lesser diameters in a period of 187 days. White squares represent square centimeters. [T. A. Stephenson, courtesy Anne Stephenson and the British Museum (Natural History)]

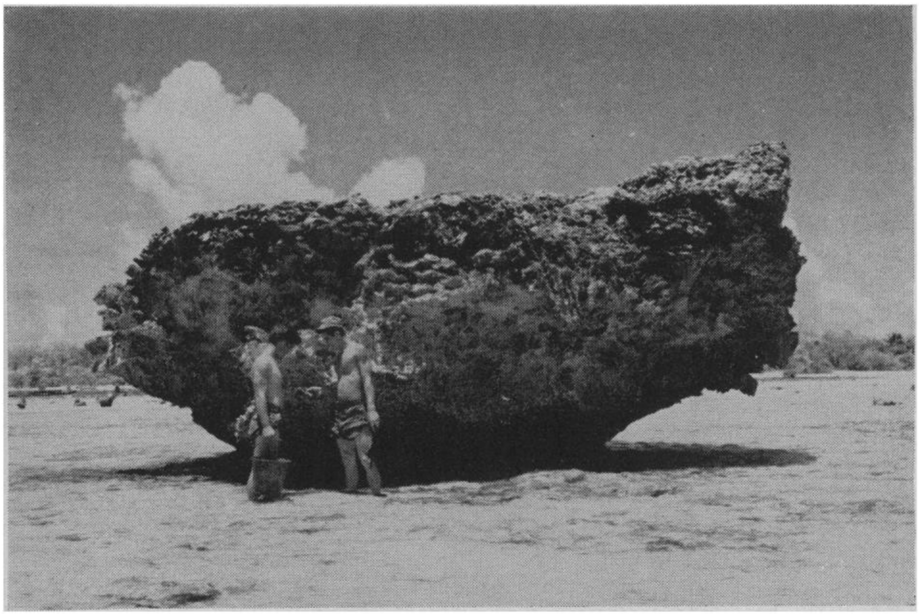

Fig. 9. Reef block on a reef off Enirik Island, Bikini Atoll. [J. I. Tracey, Jr., U.S. Geological Survey]

Fig. 10. Deep drilling on the lagoon shore of Bikini Island. [U.S. Navy]

form an atoll comparable in size to the larger atolls of the Pacific Basin, though somewhat more irregular in outline. The nature of the foundation upon which it grows and the thickness of the reef are not known, as neither drilling nor seismic investigations have ever been made there. The numerous barrier reefs in the same area have been examined in a few places. They lie off islands on which Tertiary and younger limestones are exposed above volcanics, but we have no definite idea of the nature of the foundation of the existing reefs or of the thickness of the structures.

Several submerged banks that may represent "drowned" reefs have been examined. One of these, Alexa Bank, in Fiji, measures 5 by 10 miles and has a raised rim and other features which suggest that it may once have been an atoll. A seismic survey indicated a depth of calcareous material of several thousand feet, comparable to that found at Bikini and Eniwetok atolls. The bank is assumed to have a volcanic foundation (*43*).

In the Indian Ocean, where atolls also occur, we know practically nothing about the nature of the reef foundations.

Links to Other Sciences

The building of reefs is primarily a biological process, but geological processes such as erosion and sedimentation enter as soon as the first reef organism is damaged by wave attack. Thereafter, reef building is a combination of organic and inorganic growth. Ultimately the effects spread to many other scientific fields.

Oceanography. Oceanography is concerned primarily with the chemistry of ocean waters and with their movements. In a broader sense it includes studies of bottom topography and many aspects of marine biology. On this latter basis, reef building is not only *linked* to oceanography—it is an integral part of it. I shall not attempt to discuss this broader relationship but shall cite a specific example in which the growth of reefs has, in an important way, directly affected strictly oceanographic processes.

The 50 atolls and small coral islands that form the Marshall and Gilbert island chain are spread across some 800 miles of ocean. The chain stands athwart the Equatorial Current system, and small and insignificant as the reefs are at the surface, they cause large-scale eddies in the North Equatorial Current, the Equatorial Countercurrent, and, possibly, the South Equatorial Current (*44*). Acting with surprising effectiveness as a topographic barrier, the scattered atolls affect the circulation, the temperature, and the salinity of an enormous area of deep ocean.

Geomorphology. Existing reefs and reefs of the past are specialized land forms and have always had a strong appeal for the physiographer or geomorphologist. Recently emerged reefs, whether fringing, barrier, or atoll, retain their characteristic form for appreciable lengths of time, and a close study of the limestones of which they are composed will, in many instances, support the reef interpretation. Limestone masses of other types that have been elevated for long periods of time may, through the vagaries of atmospheric solution, assume a reeflike shape that may lead to the erroneous interpretation that they are reefs. All elevated limestone masses in the tropics tend eventually to assume a basin shape that strongly suggests that of an atoll, yet the mass may be composed of bedded limestones that accumulated below wave base. It is not safe, therefore, to assume, as some physiographers have done, that all basin-shaped islands were once atolls. Submerged banks and terraces may also represent old reefs, but none of these have been examined with sufficient thoroughness to establish their origin beyond question.

In the tropics all limestone masses that rise above the sea bear a nip or notch, whose center lies at about high-tide level. On most limestone islands there are remnants of what appears to be an older nip, whose center lies about 6 feet above present high-tide level. The prevalence of such an older nip in widely separated parts of the Pacific has led many workers to conclude that it records a time when the sea stood 6 feet higher than it does now. Attempts to date the beginning of the 6-foot fall by radiocarbon analyses have been, and are being, made. Cloud, after reviewing all types of evidence, suggested that the shift began 3000 ($\pm$ 1500) years ago (*45*).

It should be pointed out that in the Pacific there is at least one area without an older 6-foot nip. Every one of the numerous limestone islands of Palau in the western Pacific shows a well-developed nip at existing high-tide level, but no trace of an older, elevated nip has been found. Wave erosion is known to be a factor in nip formation, but the controlling factor seems to be intertidal solution. In Palau, where rainfall is heavy and vegetation is dense—to yield necessary carbonic acid—it may be that solution proceeds faster than it does elsewhere. Conceivably, it may have proceeded so rapidly that all traces of an earlier nip have been destroyed.

Elevated and submerged reefs preserve evidence that points clearly to shifts in the strand line. In many instances this evidence seems to be tied to local elevation or submergence of the island or continental coast near which the features appear. Islands separated by several hundreds of miles may exhibit elevated strand-line features or buried zones of leached limestone that can be correlated, suggesting that the changes in land and sea were essentially uniform throughout an entire island group. Attempts have been made to extend correlations of this sort beyond single groups; indeed, such correlations have been stretched one-third of the way around the world—from the southwest Pacific through Hawaii to the eastern shores of North America (*46*). Those who support such interpretations postulate eustatic (world-wide) changes of sea level. The changes, however, imply a stability of the lands that is hard to accept because in many areas, including many island areas, there have been uplifts and submergences in fairly recent geologic time. In parts of the southwest Pacific, islands separated by only a few miles preserve old strand lines at different levels, and in other places the lines on opposite sides of a single island cannot be correlated, as the island has been tilted during elevation.

Attempts to correlate emerged and submerged strand lines over wide areas will doubtless continue, for they offer fascinating fields for speculation. As isotopic methods for dating limestones are improved it may be possible to establish some correlations more accurately and, perhaps, to come to some measure of agreement about eustatic shifts of sea level in late geologic time.

Petroleum geology. Structures having many of the characteristics of existing reefs have long been recognized in our older fossiliferous rocks, including those of the Paleozoic. Some geologists and biologists were loath to make direct comparisons between ancient and existing reefs because present-day reef builders did not exist in Paleozoic time. As early as 1911, however, Vaughan summarized available evidence and concluded that Paleozoic reefs were formed

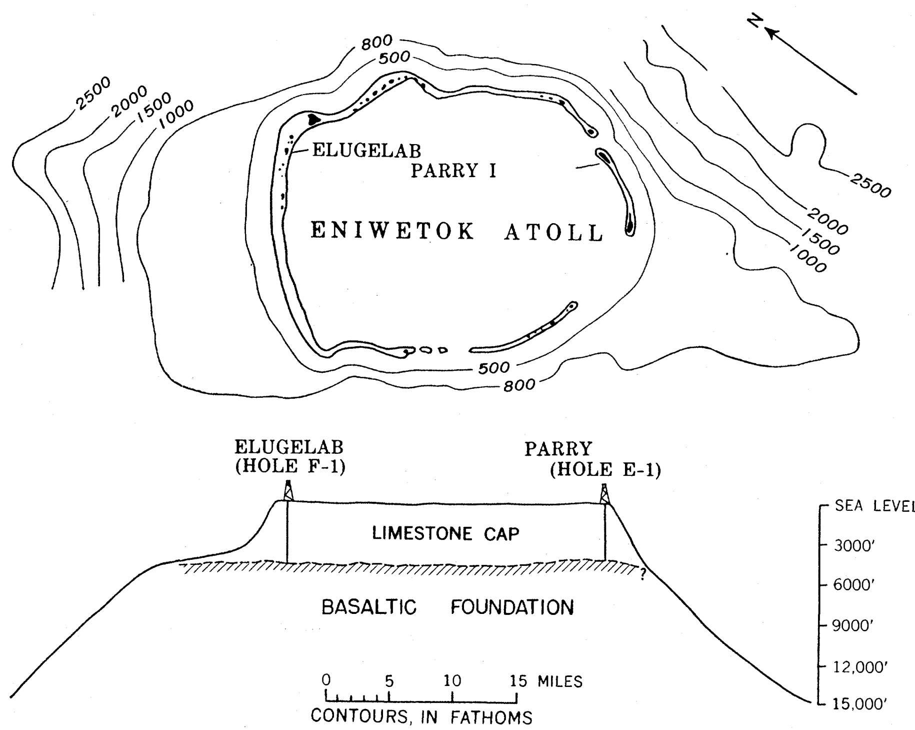

Fig. 11. Generalized chart and section of Eniwetok Atoll. [Contours from a chart prepared by K. O. Emery, 1954; after Ladd and Schlanger, 1960]

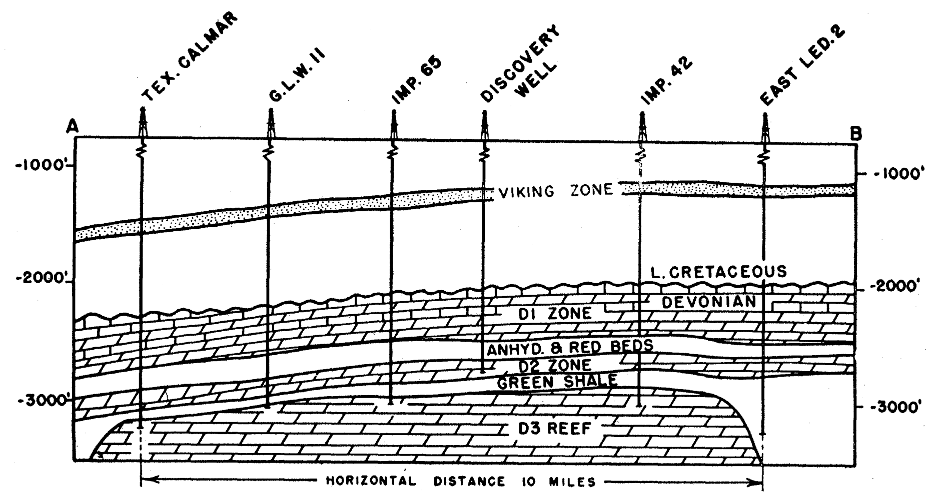

Fig. 12. Northeast-southwest section across the Leduc field. The vertical scale is exaggerated 20 times. [After Waring and Layer, 1950]

under conditions (depth, temperature, water circulation, type of bottom, composition, and specific gravity of oceanic waters) essentially similar to those of today (*47*). This interpretation took on great practical significance when rich deposits of oil were found by drilling ancient reefs.

As early as 1927 it was recognized that the Permian Capitan limestone of west Texas and southeast New Mexico had many of the characteristics of a reef (*48*), and in 1929 it was so described (*49*). This interpretation has since been documented by intensive studies (*50*). This ancient reef, which became a leading producer in the "Reef fields," compares favorably in size with the largest of existing reefs, as it is several miles wide, hundreds of miles long, and thousands of feet thick.

Similar discoveries in other widely scattered areas have demonstrated that ancient reefs form excellent reservoir rocks. In 1947, for example, the first wells were drilled into a Devonian dolomitized reef in Alberta, Canada. This became the highly productive Leduc field (Fig. 12) (*51*). With the help of the drill, geologists have learned more about ancient reef builders, about the regional relations of buried reef masses, and about the diagenetic changes (consolidation, cementation, dolomitization, and so on) that have taken place in the original reef rock. Needless to say, both geologists and geochemists have been aided in their investigations by studies of existing reefs.

Sedimentation. Reefs and their associated lagoons form nearly ideal sites for the study of many sedimentary processes. The lagoon of an atoll may be regarded as a large but fairly well controlled laboratory specializing in locally derived calcareous sediments. No foreign material enters the circuit except for minute pelagic organisms that come in over the windward reef, accompanied, on rare occasions, by pieces of pumice that have floated in from an up-wind volcano. The encircling reef effectively controls the waves and swells of the open sea, though a typhoon or hurricane may, on occasion, interrupt the established routine. Most reef lagoons lie in the trade-wind belt, and for nine months each year the winds blow fairly steadily from one direction. This may lead to the establishment of a primary circulation (overturning wind-driven circulation) and a secondary circulation (rotary circulation composed of two counter-rotating compartments) (*52*). Waters from the open sea feed this system over the windward reefs, and a comparable amount of water escapes through leeward passes and over the leeward reef.

The absence of terrigenous sediment on an atoll reduces the operation of many sedimentary processes to their simplest terms. There are no clay minerals, and much of the clay-size carbonate, apparently, is carried out of the lagoon. Most of the material accumulated in the lagoon is coarse clastic sediment. All deposition is in fairly shallow waters, and definite patterns can be recognized and mapped (see *27* and *53*).

Structural geology and geophysics. As mentioned in the section on geomorphology, both elevated and submerged reefs preserve evidence that points clearly to shifts in the strand line. In areas where the shift appears to have been regional, the reef evidence may give valuable support to theories involving major earth structures. In the western Pacific, for example, beyond the andesite line that separates the Pacific Basin proper from the continental area, many of the numerous islands are arranged in arcs that are convex with respect to the basin. Most of these arcs have deep trenches along their convex fronts, and there is much evidence from the study of seismology, volcanology, and earth gravity to indicate that these are active areas of orogenic deformation. There are considerable differences of opinion as to how the forces are acting and about the timing of major events, but there is agreement on certain aspects, and reef studies have contributed to the over-all study.

In the Pacific Basin there are scattered surface atolls and submerged flat-topped seamounts (guyots), both of which indicate submergence. The guyots now lie several thousand feet below the sea surface, yet dredging on them has yielded shallow-water organisms as old as Middle Cretaceous (*54*).

Biogeography. As already noted, existing reefs are the homes of many sorts of plant and animal communities. No other environment in the sea supports such a variety and abundance of life. Scattered as they are over an area of more than 50 million square miles, reefs offer unrivaled opportunities for the study of geographic distribution and the relations of organisms to each other. The faunas and floras of ancient reefs are as yet comparatively little known, but the field holds much promise, and studies of older reefs should add greatly to our understanding of present geographic patterns.

As an example, I should like to cite a proposal for which definite plans are now being considered. The plan calls for the drilling and sampling of a deep hole on Midway Island in the Hawaiian Islands—a hole that would penetrate the sediments beneath the existing reef and reach the basaltic foundation. The importance of Midway becomes clear if we briefly review the known and the assumed history of the Hawaiian Islands.

The surface geology of the Hawaiian Islands—located in the center of the world's largest ocean—has been worked out in considerable detail (*55*). The chain stretches for 1600 miles from northwest to southeast. The exposed rocks are almost entirely volcanic, the oldest probably being late Tertiary in age. Geologists have long favored the view that the northwest islands are the oldest and that volcanism progressed southeastward to the island of Hawaii, where such activity still persists. It is thought that the outpouring of lavas to build islands from the floor of the deep sea depressed the crust, causing slow submergence which, like the volcanism, progressed from northwest to southeast. Islands, such as Midway, on the northwest, are now coral reefs, and a considerable thickness of calcareous sediments probably lies beneath them. If several thousand feet of fossiliferous sediments underlie Midway, a drill hole might disclose a history dating back to the Cretaceous or even earlier. Before attempting the expensive process of drilling it would be well to check the thickness of the sedimentary cap with a seismic refraction survey. Plans for such a survey are being formulated, and it is hoped that drilling will follow.

If such a drill hole can demonstrate and document an appreciably longer geological history for Hawaii than is indicated by its youthful surface rocks, it would offer a reasonable solution for one long-standing biogeographical problem and might throw considerable light on another.

1) If it can be shown that the Hawaiian Islands date back as far as the Cretaceous, and if it is assumed that they were built up slowly—flow by flow —as they are being enlarged today, it will appear that there may have been some land in existence during all post-Cretaceous time. In that case, the land plants and the land invertebrates (land shells), which show a high percentage of endemism and have long been recognized as ancient stocks, would always have had a home of sorts. There would be no conflict between biological and geological evidence.

2) If the marine invertebrates obtained from such a drill hole are comparable in diversity and abundance with the faunas obtained from similar drill holes in the Marshall Islands, this would lend support to the suggestion that many elements of the Indo-Pacific fauna (now widely thought to have migrated *from* Indonesia) actually originated in the mid-Pacific and migrated, with the help of favorable winds and currents, *toward* Indonesia (*56, 57*).

References and Notes

1. W. Munk and M. Sargent, *U.S. Geol. Survey Profess. Papers No. 260-C* (1954).
2. J. Gwyther, *Captain Cook and the South Pacific* (Houghton Mifflin, Boston, 1954).
3. G. Keats, *An Account of the Pelew Islands* (Luke White, Dublin, 1793).
4. R. Discombe and P. Anthonioz, *Pacific Discovery* **3**, No. 1 (1960).
5. J. Wilson, *A Missionary Voyage . . . in the Ship Duff* (Chapman, London, 1799).
6. W. Saville Kent, *Proc. Roy. Soc. Queensland* **42** (1891); *The Great Barrier Reef of Australia* (Allen, London, 1893).
7. J. W. Wells, written communication (1961).
8. Munk and Sargent (*1*) estimated that 95 percent of the incoming wave was dissipated by friction, largely within the surge channels; the other 5 percent was converted to potential energy to maintain a water level at the outer edge of the reef.

T. Link, *Bull. Geol. Soc. Am.* **60**, 381 (1949).

10. J. Wells, *Geol. Soc. Am. Mem. No. 67* (1957), vol. 1.
11. P. E. Cloud, Jr., after studying the reef off Saipan and in other parts of the Pacific, favored erosion as the more important factor but admitted that in some areas growth might be a controlling factor [*U.S. Geol. Survey Profess. Papers No. 280-K* (1959)].
12. T. Goreau, *Ecology* **50**, No. 1 (1959).
13. N. D. Newell, J. K. Rigby, A. J. Whiteman, J. S. Bradley, *Bull. Am. Museum Nat. Hist.* **97** (1951).
14. P. E. Cloud, Jr., *Atoll Research Bull. No. 12* (1952), p. 43.
15. "The proportion of living tissues to the stony skeleton is relatively small, and as the skeleton after very young stages usually is not entirely covered by the living soft parts, other organisms may attach themselves to the previously formed skeleton, and increase its weight, or boring organisms may enter the skeleton, begin its destruction, and decrease its weight. As many boring organisms have calcareous tests, they destroy a part of the original skeleton and add the weight of their own. Minute algae . . . bore into the skeleton and ramify through it almost or quite to the boundary of the living soft parts" [T. W. Vaughan, *Carnegie Inst. Wash. Yearbook, 1915* (1916)].
16. A. G. Mayor, *Carnegie Inst. Wash. Publ., Dept. Marine Biol. No. 19* (1924), pp. 51–72.
17. C. H. Edmondson, *Bishop Museum Bull. No. 58* (1929).
18. T. A. Stephenson and A. Stephenson, *Sci. Repts. Great Barrier Reef Expedition* (1933), vol. 3, No. 7.
19. T. Tamura and Y. Hada, *Sci. Rept. Tôhoku Imperial Univ.* (1932), vol. 7, No. 4, pp. 433–455; S. Motada, *Palao Trop. Biol. Studies* **2**, 1 (1940); S. Kawaguti, *ibid.* **2**, 309 (1941).
20. M. Sargent and T. Austin, *U.S. Geol. Survey Profess. Papers No. 260-E* (1954).

H. T. Odum and E. P. Odum, *Ecol. Monographs* **25**, 291 (1955).

22. C. M. Yonge, *A Year on the Great Barrier Reef* (Putnam, London, 1930).
23. J. Hedgpeth, *Geol. Soc. Am. Mem. No. 67* (1957), pp. 39–40.
24. T. Goreau summarized some of the problems of growth and calcium carbonate deposition in reef corals in an article beautifully illustrated in color. Goreau described an isotope-tracer technique in which radioactive calcium-45 is used. He found that corals are unable to distinguish between stable and radioactive varieties of calcium. His method proved so sensitive that growth could be measured in specimens exposed to calcium-45 for only a few hou [*Endeavour* **20**, 32 (1961)].
25. Examples of the ability of storm waves to damage the reef edge were observed along the southern side of Bikini atoll. In this area, in addition to reef blocks on the surface, there are sharp re-entrants in the overhanging reef margin. The largest of these is more than 500 feet wide and extends into the reef as much as 200 feet. The collapsed sections now rest on a shallow terrace, and their outlines match the re-entrants above.
26. *Pacific Islands Monthly* **24**, No. 3, 31 (1953). John W. Wells examined these blocks when he visited the site in 1954.
27. K. O. Emery, J. I. Tracey, Jr., H. S. Ladd, *U.S. Geol. Survey Profess. Papers No. 260-A* (1954).

R. W. Fairbridge, *Geograph. J.* **115**, 84 (1950).

29. R. A. Daly, *Am. J. Sci.* **30**, 297 (1910).
30. P. H. Kuenen, *Marine Geology* (Wiley, New York, 1950).
31. H. Ladd and S. Schlanger, *U.S. Geol. Survey Profess. Papers No. 260-Y* (1960).
32. K. O. Emery and D. C. Cox, *Pacific Sci.* **10**, 382 (1956).
33. R. Russell, "Prelim. notes on Caribbean beach rock," *Louisiana State Univ. Coastal Studies Institute Publ.* (1958).
34. R. Revelle and K. O. Emery, *U.S. Geol. Survey Profess. Papers No. 260-T* (1957).

F. S. MacNeil, *Bull. Geol. Soc. Am.* **61**, 1307 (1950).

36. N. D. Newell, *Science* **132**, 144 (1960).
37. F. Henson, *Bull. Am. Assoc. Petrol. Geologists* **34**, No. 2, 215 (1950).
38. C. Darwin, *On the Structure and Distribution of Coral Reefs* (Scott, London), p. 185.
39. G. Hinde *et al.*, "The Atoll of Funafuti," *Proc. Roy. Soc. (London)* (1904).
40. S. Hanzawa, *Jubilee Publ., Prof. H. Yabe's 60th Birthday* (1940), vol. 2, p. 755.
41. S. O. Schlanger, written communication.
42. E. B. Leopold, written communication.
43. "Shipboard Report of Capricorn Expedition," *Scripps Inst. Oceanog. Rept. No. 53–15* (1953), p. 4. The bank is more fully described by R. W. Fairbridge and H. B. Stewart, Jr., *Deep-Sea Research* **7** (1959), 100 (1960). The seismic survey was conducted by Russell Raitt.
44. M. Robinson, *U.S. Geol. Survey Profess. Papers No. 260-D* (1954).
45. P. E. Cloud, Jr., *Sci. Monthly* **79**, 195 (1954).

H. T. Stearns, *Bull. Geol. Soc. Am.* **46**, 1071 (1945).

47. T. W. Vaughan, *ibid.* **22**, 238 (1911).
48. P. B. King and R. E. King, *Univ. Texas Bull. No. 2801* (1928), pp. 109–145.
49. E. R. Lloyd, *Bull. Am. Assoc. Petroleum Geologists* **13**, 645 (1929).
50. P. B. King *U.S. Geol. Survey Profess. Papers No. 215* (1948); N. D. Newell, J. K. Rigby, A. G. Fischer, A. J. Whiteman, J. E. Hickox, J. S. Bradley, *The Permian Reef Complex of the Guadalupe Mountains Region, Texas and New Mexico* (Freeman, San Francisco, 1953).
51. W. Waring and D. Layer, *Bull. Am. Assoc. Petroleum Geologists* **34**, 295 (1950).
52. W. von Arx, *U.S. Geol. Survey Profess. Papers No. 260-B* (1954).
53. E. McKee, J. Chronic, E. Leopold, *Bull. Am. Assoc. Petroleum Geologists* **43**, 501 (1959); J. I. Tracey, Jr., D. Abbott, T. Arnow, *Bishop Museum Bull. No. 222* (1961).
54. In a comprehensive report on the sunken islands of the mid-Pacific Mountains [*Geol. Soc. Am. Mem. No. 64* (1956)], Edwin Hamilton reported that shallow-water fossils of Middle Cretaceous age had been dredged from flat-topped seamounts lying less than 800 miles from Hawaii.
55. The general geology of the larger islands of Hawaii has been described and mapped under a long-term cooperative project between the Division of Hydrography in Hawaii and the U.S. Geological Survey. The work was done under the leadership of Harold T. Stearns and Gordon A. Macdonald. The last volume in the impressive series of reports, one dealing with Kauai, appeared in 1960 (G. Macdonald, D. Davis, D. Cox).
56. H. S. Ladd, *Am. J. Sci.* **258**, 137 (1960).

57. Publication of this article was authorized by the director of the U.S. Geological Survey. I am indebted to Joshua I. Tracey, Jr., and F. C. Whitmore, Jr., of the Geological Survey, and to John W. Wells of Cornell University, who read the manuscript critically and offered valuable suggestions.