Geology of Bikini and Nearby Atolls

Bikini and Nearby Atolls: Part 1, Geology

GEOLOGICAL SURVEY PROFESSIONAL PAPER 260-A

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By KENNETH O. EMERY, J. I. TRACEY, Jr., *and* H. S. LADD

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FOREWORD

BY ROGER REVELLE

Of all earth's phenomena, coral reefs seem best calculated to excite a sense of wonder. And of all the forms of coral reefs, the atolls have appeared to men of science to be richest in mystery and most strange. Rising alone from the empty sea, these ancient structures, growing now slowly, now fast, toppling when the sea retreats and flung up in haste when sea level rises, are like a Gothic cathedral, ever building yet never finished, infinite in detail yet simple and massive in plan. Tiny plants and animals are their builders. Their architects are the giant ocean and the restless wind.

Reef corals and calcareous algae can grow only within a few hundred feet of the sea surface, yet most atolls rise as isolated structures many thousands of feet above the ocean floor. Is the coral and other calcareous skeletal material simply a thin veneer over the surface of a flat platform of other rocks, or has there been a large relative rise in sea level which allowed the reef-building organisms to grow slowly upward on a pile of their own skeletal remains? This question has been debated for a hundred years.

In attempts to answer it, much was learned about atolls prior to 1946. But their geographic remoteness and the inadequacy of the available tools of investigation combined to limit this knowledge in most places to easily seen surface features.

In 1946, few American or European scientists had heard the name of Bikini Atoll. From 1946 to 1952, Bikini Atoll was studied intensively, from many different points of view and with modern tools of exploration, so that it has become perhaps the most thoroughly known atoll on earth. The papers included in this volume summarize and interpret this knowledge.

Planning for the scientific work on which this report is based began in the fall of 1945, shortly after it was decided to conduct tests of nuclear-fission weapons at Bikini Atoll. This decision had been made from rather little information, for Bikini, unlike neighboring Eniwetok and Kwajalein Atolls, had not been the scene of any major military activities in World War II. An accurate hydrographic chart of the lagoon and surrounding waters was needed for the safety of the many ships to be employed in the operation. Channels and anchorage areas had to be located and shore facilities established. Moreover, in order to gain a maximum of technical value from the weapons tests, a thorough understanding of the physical and biological environment of the proving ground was desirable. This was true particularly because the nuclear-fission explosions involved energy releases more comparable to those of large-scale geophysical phenomena than any previous man-made event. Likewise, the intensity of the nuclear radiation to be released was enormous, far greater than living organisms had ever experienced prior to 1945.

An advance task unit of survey and supply ships was sent to the atoll early in the spring of 1946. As one of its missions, this unit was to furnish living quarters, ships, small boats, aircraft, and other necessary support for a team of biologists, geologists, and oceanographers whose purpose was to carry out an integrated investigation of all aspects of the natural environment within and around the atoll: the currents and other properties of the ocean and lagoon waters, the surface geology, the identity, distribution, and abundance of living creatures, and the equilibrium relationships among all these. It was believed that these relationships might be disturbed by the nuclear-fission explosions and also by the introduction of large numbers of human beings and the mechanical equipment necessary for carrying out the tests. One of the problems posed was to separate these two kinds of disturbances. Accordingly, neighboring atolls were also to be investigated; these included Eniwetok Atoll where the preexisting environment had been altered by military activities, and Rongerik and Rongelap, which had scarcely been touched by the outside world.

The general responsibility for these studies of the environment was assigned to the Bureau of Ships of the Navy Department under the supervision of the writer and his associates in the Underwater Studies Group. Later, when Joint Task Force I was organized, this became the Oceanographic Section of the Task Force. The cooperation of universities, private research institutions, and several federal agencies was enlisted, including the Geological Survey, the Military Intelli-

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gence Division of the Office of the Chief of Engineers, the Smithsonian Institution, the Fish and Wildlife Service, the Woods Hole Oceanographic Institution, the University of California's Scripps Institution of Oceanography and Division of War Research, and the University of Michigan. Field work in biology, geology, and physical oceanography began early in March 1946 and continued until the end of August. Scientists responsible for different phases of the work were: H. S. Ladd and J. I. Tracey, Jr., surface geology of coral reefs and islands; K. O. Emery, submarine geology and sediments; C. C. Bates, beach studies; Gordon Riley, W. H. Munk, W. S. von Arx, and W. L. Ford, currents and diffusion in the lagoon, and water exchange between the lagoon and the open sea; E. C. La Fond, water temperatures and currents outside the atoll; M. C. Sargent and T. S. Austin, organic productivity; W. R. Taylor, land and marine plants; Leonard Schultz, lagoon and reef fishes; J. C. Marr and Vernon Brock, pelagic migratory fishes; J. P. E. Morrison, mollusks, birds, and land animals; M. W. Johnson, plankton. Project officers for the oceanographic section were Lt. Comdr. C. A. Barnes, USCGR, and Lt. Comdr. M. C. Sargent, USNR. The hydrographic survey ship, U. S. S. *Bowditch* (AGS–4), was headquarters for the scientific party. Other ships employed in the field work were U. S. S. *Sylvania* (KA *44*), U. S. *Blish* (AGS *10*), U. S. *Gilliss* (AGS *13*), YMS *463*, YMS *354*, YMS *358*, and ARS *8*.

Upon the arrival of Joint Task Force I in the test area two new phases of these investigations were undertaken: a seismic refraction survey of the atoll structure under the lagoon, carried out cooperatively by geophysicists of the Oceanographic Section and the Naval Ordnance Laboratory, and a reconnaissance study of the currents, temperatures, and salinities of the waters in the entire Marshall Islands area from latitude 20° N. to latitude 3° S. over a band of 20° in longitude. These observations were designed to extend and confirm both the large numbers of bathythermograph observations taken in the area during the war years and the very considerable pre-war hydrographic data collected (but not analyzed or published) by the Japanese. Comdr. B. Perkins, Jr., USNR, was the principal representative of the Oceanographic Section in the seismic studies; J. V. Atanasoff, M. B. Dobrin, and B. Snavely led the team of Naval Ordnance Laboratory geophysicists. The physical oceanographic reconnaissance of the Marshall Islands area was organized as part of the work of the Oceanographic Section by D. L. Bumpus, assisted by E. C. La Fond, G. C. Ewing, and H. Mann. Lt. Comdr. John Lyman, USNR, was project officer. Four destroyers of the patrol group were employed.

The primary responsibility of the late Vice Admiral W. H. P. Blandy, Commander of the Joint Task Force, and his deputy for technical direction, the late Rear Admiral W. S. Parsons, was to carry out the tests of nuclear weapons against naval vessels and other military equipment, but both leaders recognized the opportunity presented by Operation Crossroads to obtain basic scientific information. They and the technical director, Dr. R. A. Sawyer, wholeheartedly supported this aspect of the work of the Oceanographic Section.

In the spring of 1947, the writer was directed by the Joint Operation Crossroads Committee of the Department of Defense to organize a scientific resurvey of Bikini Atoll. This had as its primary purpose an investigation of any possible delayed or long-term effects of the radioactivity produced by the underwater nuclear explosion. Another objective was to undertake certain special geologic and biologic investigations needed to gain further understanding of the geologic history of the atoll. The most ambitious of these projects was the drilling of several deep holes on Bikini island (one of these was carried down to 2,556 feet) in order to gain further knowledge of the subsurface structure. This drilling was carried out by the George Failing Co., whose field superintendents were V. C. Mickle and E. Alexander. H. S. Ladd of the U. S. Geological Survey was scientific director of the drilling project. He was assisted by J. I. Tracey, Jr., of the Geological Survey, and Gordon Lill, of the Office of Naval Research. J. W. Wells conducted field investigations of the distribution and ecology of the corals of the atoll, and J. Harlan Johnson of the Geological Survey undertook similar studies of the calcareous algae. Dredging on the outer slopes of the atoll was carried out by R. D. Russell of the U. S. Navy Electronics Laboratory, assisted by E. H. Schuler of that laboratory. Preliminary work on the problem of solution of calcium carbonate in tide pools was undertaken by T. S. Austin, of the U. S. Navy Hydrographic Office, and T. Goro. Leaders of other scientific phases of the resurvey included Lawrence Blinks, Douglas Whitaker, G. M. Smith, and George Myers, all of Stanford University; Lauren Donaldson, of the University of Washington; and Lawrence E. Glendenin, of the Massachusetts Institute of Technology. Capt. C. L. Engelman, USN, was project officer for all technical phases of the resurvey; Dr. E. S. Gilfillan was technical director; and Capt. T. Hederman, USN, was commander of the task unit of three ships which carried out the expedition. The principal ship was the U. S. S. *Chilton*. Invaluable assistance in the drilling operations was given by a Construction Battalion detachment under Comdr. J. R. Denny, USN.

Study and analysis of the field results during the years following the resurvey emphasized the need for a twentieth of that on the reef, about the same as in the ocean waters outside the atoll. Occasionally, however, as found by M. W. Johnson, a phytoplankton "bloom" occurs in the lagoon, no doubt facilitated by the slow rate of dispersion of the floating plants. That the over-all level of organic activity is higher in the lagoon than in the ocean waters outside the atoll is shown by Johnson's finding of a relatively large zooplankton population in the lagoon waters. Certain zooplankton organisms are endemic to the lagoon, but characteristic open-ocean plankton are also abundant there. These tiny animals maintain themselves within the lagoon by taking advantage of the rotary circulation of the water. Many of them apparently remain in the deep eastward-flowing water long enough to avoid being flushed out through the southwestern passes.

Despite the fact that organic activity within the lagoon is higher than in the open sea, the lagoon-dwelling organisms have evidently been incapable of depositing sufficient calcium carbonate to keep up with the post-Pleistocene rise of sea level. This is shown by the distribution of organic remains found on the lagoon floor by Emery, Tracey, and Ladd. In the deepest parts of the lagoon the green algae, *Halimeda*, are not now able to grow profusely, apparently because the intensity of light penetrating to these depths is insufficient. The shallowest parts of the lagoon floor lie in an outer zone next to the reef and are made up of fine debris which seems to have orginated largely from the skeletons of reef organisms. Elsewhere in the lagoon *Halimeda* remains are the most abundant constituent of the bottom sediments, except in some of the deepest areas where Foraminifera may be the chief constituent.

Many of the features of modern reefs evidently reflect the relatively rapid and large changes of sea level during and since the Pleistocene. The 8- to 10-fathom terrace around Bikini and neighboring atolls is one example; others may be the coral knolls in the lagoon, the deep channels, and the slightly higher level of reef rock under the islands.

Bikini Atoll appears, on the whole, to be a healthy, flourishing structure. Many of the varied assemblages of animals and plants that live on its reefs, in its lagoon, and on its outer slopes take calcium carbonate from sea water to build their shells or internal skeletons. When these organisms die some of them are buried in place but the hard parts of many others are broken up by wave action or riddled by boring organisms and the sediment thus produced is deposited in the lagoon or on the outer slopes of the atoll. The most important groups thus contributing to the atoll are the corals, the Foraminifera, and the algae. Samples obtained by drilling into the atoll show that these same groups have been building up the massive foundations of the present reefs at least since mid-Tertiary times.

A series of special reports on these organisms and the ecologic factors controlling their distribution has been prepared by John Wells, the late J. A. Cushman, Ruth Todd, Rita Post, Storrs Cole, and J. H. Johnson. At Bikini Atoll today the algae are the dominant organisms, particularly on the reef margins and over large parts of the lagoon. The corals are dominant over large areas of the reef and on the hundreds of knolls that rise from the lagoon floor. Indeed, more species of corals are now known from Bikini atoll than from any other area in the world. Since Bikini atoll lies far from the assumed centers of dispersal in the East Indies, this probably merely reflects the intensity of the collecting done at Bikini during the two seasons of Operation Crossroads. The Foraminifera thrive on the reefs today and their shells in many places make up the bulk of the beach sands. Other types occur in the deeper parts of the lagoon and on the outer slopes. The study of the ecology of the living forms was of great value in interpreting the conditions under which the older sediments were laid down.

The seismic-refraction studies of Bikini, Eniwetok, and Kwajalein Atolls, by Raitt, Dobrin, and Perkins, have confirmed and extended the results obtained by drilling, which show that several thousand feet of relatively unconsolidated calcareous materials overlie a volcanic core in these atolls. The irregularity of the old volcanic surfaces suggests that these cones may have been islands and that they were not truncated by wave erosion during the early stages of growth of the atolls. Seismic velocities show that a considerable thickness of unconsolidated material also lies inside the rim of Sylvania Guyot, and the question remains as to why this structure failed to participate in atoll growth. Lateral and vertical variations in seismic velocities reflect the complex construction of the old volcanoes. There is some evidence for downward bending of the crust beneath them, but the extent of the bending is relatively small.

Results of magnetic surveys by Alldredge and his associates are consistent with the picture obtained both by drilling and by seismic studies. Magnetometer surveys of other atolls may therefore be used with some confidence as a means of establishing the thickness of calcareous material. The loose and porous character of this material, which allows almost a free flow of sea water, is well illustrated by Swartz's comparison of the vertical-temperature gradient in the drill holes with that in the surrounding sea.

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BIKINI AND NEARBY ATOLLS, MARSHALL ISLANDS

PART 1—GEOLOGY

By K. O. EMERY, J. I. TRACEY, Jr., and H. S. LADD

ABSTRACT

During Operation Crossroads in 1946 an opportunity was provided for studying the geology of Bikini and nearby atolls in the northern Marshall Islands. Numerous soundings and bottom samples were collected from the lagoons and outer slopes and detailed studies of the reefs and of the organisms growing on them were made. These geological studies were paralleled by investigations in physical and biological oceanography. In 1947, a resurvey was carried out. The reefs and islands were reexamined, additional dredging was done in the lagoon and on the outer slopes and 5 test wells were drilled, 1 to a depth of 2,556 feet. In 1950, the Mid-Pacific Expedition, working chiefly on problems of the deep sea floor, collected additional cores and deep dredgings from the lower slopes of Bikini Atoll and from the top of Sylvania Guyot that adjoins it on the west. During each of the expeditions some seismic studies were made and in 1947 an airborne magnetometer survey added to the subsurface information. As a result of these studies, Bikini is probably the best known atoll of the world.

Even casual inspection shows that the exposed parts of the atolls are closely related to the prevailing wind, waves, and currents, all of which come from the east-northeast. The reef edge is highest and is cut by numerous surge channels on the windward side. Reef debris carried by waves and currents have built up islands that are more numerous and larger on the windward side, with the largest islands located on seaward projections of the reef, where waves from several directions can attack the reef. Although the reef is continuously eroded on the windward side, the erosion there is more than balanced by rapid organic growth. On the leeward side, growth of the reef is less rapid and gaps are present in the reef; these are the passes to the lagoon.

The lagoons are circular to rectangular and except for numerous coral knolls, their basins have flat floors. The maximum depth is proportional to the size of the lagoon: Rongelap and Eniwetok, 35 fathoms; Bikini, 32; and Rongerik, 26. Around parts of the rim of the lagoons of all except Rongelap is a terrace that is as much as 2 miles wide; at Bikini and Eniwetok it is 10 fathoms deep and at Rongerik 4 fathoms. The terrace is widest within reef projections. Rising above the basin, the terrace, and slopes of the lagoons are thousands of coral knolls. The depth of their tops is independent of the depth of their bases. Some knolls are more than a mile in diameter, but most are less than a hundred feet. Those that reach near the water surface have steep or vertical side slopes that grade downward into more gentle talus slopes.

The seaward edge of the reef, particularly in indentations on the windward side, is bordered by a terrace whose outer edge is at a depth of about 8 fathoms at Bikini, Eniwetok, and Rongelap Atolls and probably less at Rongerik. Thus, the seaward terrace is slightly shallower than the lagoon terrace. On the leeward side the reefs are bordered by steep, locally vertical, slopes that extend to a depth of 20 fathoms or more. Other parts of the leeward reefs have been made irregular by slumping and land-sliding probably during severe storms from the south. The slopes around the atolls between the reef edge and 200 fathoms average about 45° and are somewhat steeper on the submarine buttresses that underlie reef projections. At greater depths the slopes become gradually gentler, until between 2,000 and 2,500 fathoms they merge with the floor of the deep sea. In the area are several guyots (flat-topped seamounts) that have an average depth of 700 fathoms. Eniwetok Atoll appears to have been built atop one or more guyots, and both Bikini and Rongelap Atolls adjoin other guyots.

On the basis of composition and structure the reef surface may be subdivided into several zones. The reef edge is bordered by a belt dominantly of calcareous red algae, the *Lithothamnion* ridge. It is followed by a coral-algal zone and perhaps by other zones of organic growth. The main reef flat is a broad rather barren expanse of relatively smooth rock covered in many areas by a mat of Foraminifera held in place by fibrous algae. All of the zones except the *Lithothamnion* ridge are covered by several feet of water except at low tide.

The islands which rise only 10 or 15 feet above the reef flat consist mostly of sand in the form of a wide sand flat and as marginal dunes. Locally, there are areas of reef and beachrock in the interior as well as on the margins of the islands. Sediments of both seaward and lagoonward beaches range from gravel composed of coral heads and broken reef and beach rock to sand composed of Foraminifera and broken coral, *Lithothamnion*, and other organic debris. The gravel and sand have locally become cemented by calcium carbonate to form layered beach rock that in turn is destroyed by abrasion and solution. Wave action carries the sands of the beaches lagoonward where it forms a ring 2 to 5 miles wide within the ring of the reef and beaches. Beyond the depth of 15 to 20 fathoms reached by the fine sand *Halimeda* debris is abundant. At depths greater than 30 fathoms the light reaching the lagoon floor is insufficient to permit a thick growth of *Halimeda* and at such depths Foraminifera are again dominant, but these Foraminifera are different from those of the beach. Thus, the lagoonal Foraminifera in water shallower than 30 fathoms are masked by faster-growing *Halimeda*, which in turn are masked nearer shore by the more rapidly deposited fine sand carried by waves and currents from the beaches. The fine sand is evidently the cause of relatively smooth lagoon floors

near the lagoon margin, and appears to be the chief cause of shallowing of small lagoons.

Sediments of the outer slopes consist mostly of coarse coral fragments and *Halimeda* debris near the surface. At greater depth the sediment gradually changes to fine sand and even to silt. Imbedded in these sediments are blocks of reef rock possibly weighing as much as a ton. At even greater depth, beyond the easy reach of abundant fine debris from the coral reef, the sediment is somewhat coarser, composed almost exclusively of the tests of pelagic Foraminifera, chiefly *Globigerina.* This *Globigerina* sand occurs low on the flanks of the atolls and on the tops of the guyots. At depths of about 2,400 fathoms the *Globigerina* sediments grade into red clay.

The areas of slow deposition of sediments on the lower slopes of the atoll and the edge of the guyot contain outcrops of basalt covered by manganese oxide. Samples of the basalt constitute the first physical proof that volcanoes are the bases of the atolls of the central Pacific. The basalt is scoriaceous and associated with it are tuff and volcanic glass. These facts are interpreted as indicating that basaltic eruptions took place near the water surface in post-Paleozoic time. Later truncation by wave action is indicated by the flat surface of the guyots and by the presence of rounded pebbles of basalt. On similar guyots east of the Marshall Islands, reef corals and other fossils of Cretaceous age were discovered. The existing atolls apparently were formed atop some of the guyots or atop incompletely truncated volcanoes in post-Cretaceous time.

Drilling on Bikini island to a depth of 2,556 feet, encountered no rocks older than Oligocene (?) although such may well exist at greater depth. The section consisted entirely of coarse to fine detrital organic limestone of almost pure calcium carbonate, moderately consolidated at irregular intervals in the top several hundred feet, but completely unconsolidated below 725 feet except for a 24-foot unit at 1,127 to 1,151 feet. The stratigraphic section is 0 to 850 feet, Recent and Plio-Pleistocene; 850 to 2-070 feet, Miocene; 2,070 to 2,556 feet, Oligocene(?). The tentative reference of the beds below 2,349 feet to the Oligocene was based entirely on the occurrence of one species of *Halkyardia.* This species has since been found by W. Storrs Cole in rocks of unquestioned late Eocene age on Saipan in the Mariana Islands. It is possible, therefore, that the portion of the "Oligocene(?)" referred to "Tertiary *c*" of the Bikini section may eventually be assigned to the late Eocene.

The limestone from top to bottom of the 2,556-foot section is believed to have accumulated in a lagoonal environment in water mostly less than 30 fathoms in depth. Much of it accumulated in shallower water, and some probably originated on the lagoonal margin of a reef in intertidal areas. Accumulation of the shallow-water organisms seems to have been essentially continuous throughout most of the atoll's history, indicating a continuing or periodic submergence.

Recrystallization of aragonitic shells and skeletons to calcite is limited to the irregularly consolidated intervals, and is believed to be due to emergence of the rocks above sea level. Accumulation of the limestone was interrupted by one early period of emergence. A 24-foot zone of recrystallized rock at 1,127 feet, of early Miocene age, is overlain by unconsolidated lower Miocene rock containing unaltered shells and skeletons. One or more possible Pleistocene emergences may have resulted in the moderate to complete recrystallization of rocks at 294 to 450 feet. Three rock units above 294 feet, characterized by distinctive Foraminifera seem to be related to present physiographic features of the atoll, and are believed to represent 3 late stages of growth, probably separated by two emergences due to late Pleistocene shifts in sea level. The first stage resulted in the formation of the present lagoon bottom; the second in the broad terraces at depths of 8 to 12 fathoms; and the last in the formation of the present reefs at the surface.

The islands appear to be fairly stable under existing conditions; some have undergone a loss of area, in rare instances there has been growth and the islands of the windward side appear to be migrating across the reef toward the lagoon. The islands may have been formed originally during a recent negative shift in sea level that permitted the erosion of reefs that had grown up close to the low tide level.

INTRODUCTION

LOCATION

The Marshall Islands is a group of atolls lying north of the Gilbert Islands and east of the Caroline Islands. All are enclosed in an area bounded by the parallels of latitude 4°30′ N. and 15° N. and the meridians of longitude 161° E. and 174° E. They are about 2,500 statute miles west-southwest of Honolulu, T. H., and 4,700 miles from San Francisco. Most of the atolls are distributed along two chains which are nearly parallel and trend northwestward. The eastern is named the Ratak (Sunrise) Chain and the western the Ralik (Sunset) Chain. Besides the two main chains there are several isolated outlying atolls. Altogether, the group contains 29 atolls, 5 islands having no interior lagoon, and 3 known submerged banks shallower than 10 fathoms. The highest land elevation within the group is 28 feet.

During the present survey several atolls were studied (fig. 1). Four of these, Bikini, Rongelap, Rongerik, and Ailinginae Atolls are members of the Ralik Chain. A fifth, Eniwetok, is an isolated atoll lying west of the chain. All these atolls lie within a rectangle bounded by latitudes 11° N. and 12° N. and longitudes 162° E. and 168° E. Except for two atolls of the Ratak Chain, they are the northermost of all the Marshall Islands.

PURPOSE OF STUDY

Several considerations were involved in the selection of Bikini Atoll for the atomic-bomb experiments. Presumably ranking high among these conditions which Bikini satisfied were remoteness from densely populated land, presence of predictable winds and currents, absence of nearby installations or islands likely to be contaminated by radioactive products, an adequate anchorage, and nearness to a major naval base—Kwajalein Atoll.

In addition to determining the effect of the atomic bombs on ships and material, it was desirable to estimate the damage to the animals and plants inhabiting the area. Accordingly, as explained by Roger Revelle in the foreword to this volume, specialists in various organic groups were taken to Bikini Atoll aboard the U. S. S. *Bowditch,* the base ship, to make population

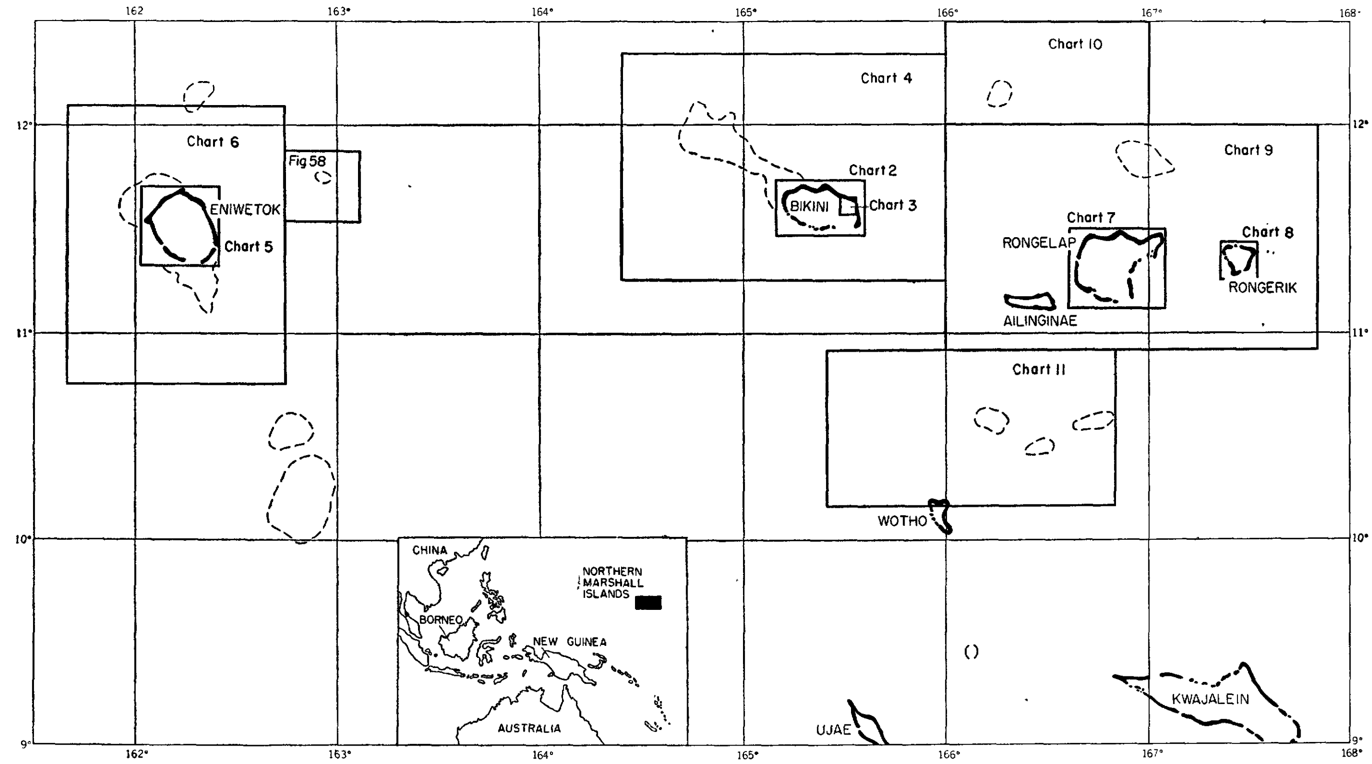

FIGURE 1.—Location of Bikini and nearby atolls.

and other studies before and after each bomb test. To avoid being misled by the effect of seasonal climatic changes, similar studies of additional atolls likely to be free from radioactive products were necessary to provide control in estimating the bomb damage to organisms. Thus, Rongelap, Rongerik, and Ailinginae Atolls were included. Brief studies were also made at Eniwetok Atoll prior to the tests to aid in determining possible effects of radioactive contamination downwind and down-current.

In addition to measurements of the biological damage produced by the bombs, it was necessary to estimate the effects on the physical environment. Accordingly, oceanographers were on hand to study the water characteristics, and geologists to study the subaerial and submarine topography and materials. Ladd and Tracey were primarily responsible for the geology of the reefs and islands. Emery investigated the submarine geology of the lagoons and the outer atoll slopes. As a result of the work, it appears that all five atolls are generally similar as regards their major features.

PREVIOUS WORK

The first European to see the Marshall Islands appears to have been the Spanish explorer Alvaro de Saavedra in the year 1529. As noted by James Burney (1803, p. 154–157), he first discovered a small group at latitude 7° N. which he called Los Pintados because of the tattooed bodies of the inhabitants. To the northeast in latitude 10° to 12° N. he landed at a second group of low islands which he named Los Buenos Jardines. Burney reckoned the longitude of the two groups to be 174° to 176° E. (The Marshalls lie between 162° and 173° E.) Allen (1920) and Krieger (1943) identify Los Pintados as a part of the Marshall group. S. E. Morison (1944) states that Miguel Lopez de Legaspi is reported to have passed through the Marshalls and named four of them in the year 1545.

Twenty-three years later Alvaro de Mendaña de Neyra sailed through the group on his way back to Peru after discovering the Marquesas and the Solomons. The Marshall Islands that he saw cannot be identified from his narrative but, as Morison (1944, p. 88) pointed out, the Spanish and Portuguese charts for more than 2 centuries afterwards showed a scattering of islands at the approximate position of the northern Marshalls (between latitudes 11° and 12° N.) called the Pescadores (fishermen) or merely Recifes (reefs).

The next European visitor seems to have been Sir Francis Drake aboard the *Golden Hind*, who made a landfall on islands of the Ratak Chain on October 13, 1579 (Riesenberg, 1940). He described the islands as thickly inhabited and mentioned the abundant coconuts and fruits.

After Drake for a period of nearly 2 centuries no Europeans seem to have visited the Marshalls. In 1767 Samuel Wallis in HMS *Dolphin* identified the Pescadores of the old Spanish charts. Morison notes (1944, p. 92) that from the positions given by Wallis (lat. 11° N., long. 167°30′ E. and lat. 11°20′ N., long. 167°02′ E.) he must have passed Rongerik and Rongelap Atolls. So far as known, the next visitor was Captain Marshall for whom the islands were later renamed. According to Morison (1944, p. 93) there is some doubt as to Captain Marshall's first name; most writers call him William but on at least one chart he is called John. He visited a number of the islands in 1788, but it is not known that he sighted any of the northern atolls with which this report is primarily concerned. Hager (1889, p. 52) states that Eniwetok Atoll was discovered by Butler in 1794.

Undoubtedly, other explorers stopped in the years that followed, but the earliest expedition which made an attempt to describe the geology of the islands was nearly 300 years after their discovery. This expedition, commanded by Otto von Kotzebue, a German who became a Russian subject, was a cruise of general exploration of the western and northern Pacific Ocean. Fortunately, included in the company was an able naturalist, Adalbert Chamisso. During the visits to the Marshalls in 1816 and 1817, Chamisso made many notes regarding the character of the reefs, islands, and lagoons of atolls in the Ratak Chain (Chamisso, 1821). For example, he was one of the first to note that the reef is best developed on the windward side and often contains passes or ship channels on the leeward side. He also mentioned that within prominent seaward projections of the reef, loose sand was commonly piled up as islands; and that other islands or rock banks often occur just within some of the ship channels. He noted that the lagoons are mostly 25 to 32 fathoms deep, are floored by fine or coarse sand and coral, and contain many scattered banks, or small reefs. These and many other observations have been confirmed by later investigators. Another of his contributions was a chart of some of the Marshall Islands. This was based in part on his own observations aboard Kotzebue's ship, the *Rurick*, but apparently he had to rely on data supplied by natives for the position and shape of the atolls in the Ralik Chain. A section of his chart is reproduced in plate 65, together with a similar section of the recent U. S. Navy Hydrographic Office Chart No. 5413 at the same scale. The positions of most of his atolls were fairly accurate and most of their names are similar to the presently accepted ones, although the spelling differs. It is noteworthy that he missed Bikini Atoll and a few others just south of Bikini; however, he used a similar name, Bigini, for what was probably the atoll now called Rongerik.

During a later cruise through the Marshall Islands in October 1825, Kotzebue investigated Rongelap, Rongerik, and Ailinginae Atolls which he named the Rimsky-Korsakov Islands and he discovered Bikini Atoll, which he titled Eschscholtz (Berg, 1926, p. 22). In this second voyage Kotzebue took O. Lenz, a physicist, who carried out physical oceanographical researches (Baker, 1931). Captain Hagemeister in 1829 discovered the group of Menshikov (Kwajalein) Islands, and Captain Schantz in 1835 found the Schantz (Wotho) Islands (Berg, 1926).

The United States Exploring Expedition under the command of Lt. Charles Wilkes carried out extensive investigations in the Pacific starting in 1838. In the *Peacock* and the *Flying-fish* he visited the northern Marshall Islands in May 1841. Rongerik was charted under the name Bigini and the old Spanish name Pescadores (U. S. Expl. Exped., 1858, p. 60). The island was recorded as being of coral formation with several islets and sand-spits on its reef. Low bushes were present but no coconut or pandanus and no human inhabitants (Wilkes, 1845, p. 113–114). The atolls of Rongelap and Ailinginae appear on the Wilkes chart under the names Radogala and Korsakoff respectively. The islands were in sight for 2 days and a few inhabitants were seen but a landing was not possible because of rough weather.

As noted by Taylor (1950, p. 2), Erwin Steinback published a general account of the Marshall Islands and their inhabitants in 1895. Many of the striking features of the islands, reefs, and lagoons were briefly described.

Some interesting charts of the Marshall Islands were made and used by the natives for sailing until the end of the nineteenth century. These consisted of a frame of split palm stems to which shells, usually cowries, or bits of coral were tied to indicate atolls. On some, the larger atolls were represented by triangular arrangements of some of the sticks. Refraction of swells near atolls was indicated by long curved sticks or by a series of short ones tied at angles to the frame. Cross-swell in the lee of atolls is also shown on some charts. Because the charts and their use were jealously guarded secrets of the chiefs, there is little uniformity in their style of construction. The most thorough study of these stick charts was that made by Capt. Winkler, of the German Navy, (1901), largely by close interrogation of the few remaining chiefs who understood their use. He found that the charts can be classified into three types: Meggado—a simple, idealized form used only for instructional purposes; Medo—a fairly detailed chart that includes several neighboring atolls; and Rebbelib—a chart of an entire chain of atolls. In his report are photographs of several stick charts and drawings of others. Amongst the drawings are two that include Bikini Atoll. Other stick charts have been described by Schück (1902), Joyce (1908), Lyons (1928), and Bryan (1938). That the charts contain fairly accurate information on swells was recently reiterated by de Laubenfels (1950). A copy of Lyon's chart with its interpretation is presented in figure 2. It encompasses an area of about 500 miles on a side. Photographs of two other charts that are on exhibit at the Bishop Museum in Honolulu are shown in plate 1. These are of the Medo type, one depicting the north end and the other the south end of the Marshall Island group. Both are constructed in the same style and adjoin each other, so they evidently were made as a set by one man.

During 1872–73 the U. S. S. *Tuscarora* in a general surveying expedition obtained a line of bottom samples several hundred miles north of Bikini Atoll. In the early part of 1899 the U. S. S. *Nero* was despatched from San Francisco to survey a route for a telegraph cable between the United States, the Philippine Islands, and Japan. Concurrent with meteorological and oceanographic observations, closely spaced samples of bottom material were brought up in the sounding cup (Flint, 1905). Like the *Tuscarora*, the *Nero* passed 400 miles or more to the north of the Marshall Islands but bottom samples in that part of the Pacific are so few that the ones obtained by these ships are of real importance.

The next scientific party to visit the Marshall Islands was on board the U. S. Fish Commission Steamer *Albatross*, making her third voyage. Alexander Agassiz was in charge and during January 1900 a number of very deep bottom samples were obtained throughout the entire Marshall Island group in trawls and sounding cups (Townsend, 1901). Some of the samples were from the slopes south of Rongelap Atoll (Agassiz, 1903). So far as known, this expedition was the only one prior to Operation Crossroads that collected deep bottom samples in the immediate area.

Many Japanese scientific parties visited the Marshalls during the period of the Japanese mandate from 1918 to 1944. Among the geologists who have written about the atolls are Tayama (1934) and Hanzawa (1942). In developing their new territory, the Japanese charted each of the atolls, mapping the island and reef outlines, and taking lead-line soundings in the lagoons and, less frequently, on the outer slopes. During the mandate, the only data collected from the region by non-Japanese were oceanographic observations in 1929 of the *Carnegie* at several stations about 500 miles to the northeast (Fleming, Ennis, Sverdrup, Seaton, Hendrix, 1945).

After the expulsion of the Japanese in 1944, the U. S. Navy recharted some of the atolls which were to be used for naval bases. Lagoons of Eniwetok, Kwajalein, and Majuro Atolls were thoroughly sounded by launches carrying recording fathometers, and the outer slopes were partly sounded by larger ships. More detailed and accurate reef and island outlines were also made

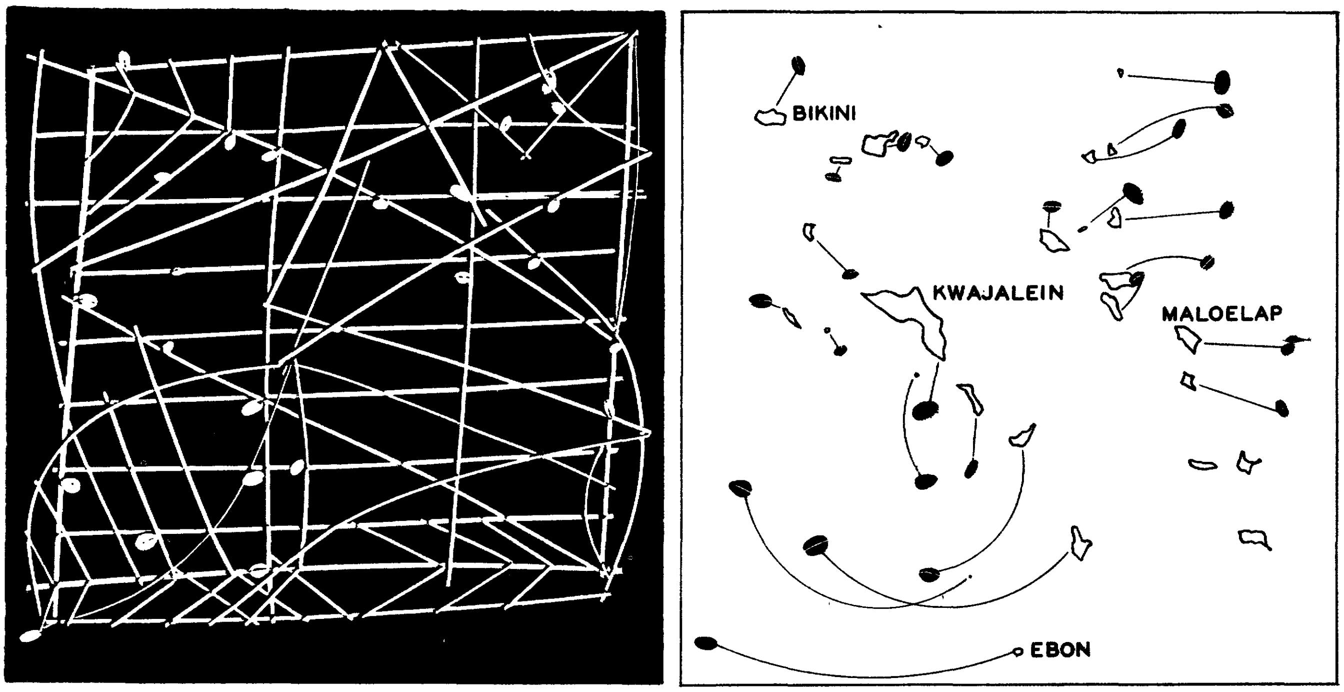

FIGURE 2.—Chart of Marshall Islander made from split palm stems and shells, with interpretation.

for these atolls from aerial photograph mosaics. Some of the other atolls, among which was Bikini, were swept for mines and parts of them were wire-dragged to provide safe anchorages. During the years immediately preceding Operation Crossroads a few scientific reports on the area were written as incidental results of the military activities. Among these reports is one by Stearns (1945), who described a small part of the reef at Eniwetok Atoll, another by Nugent (1946), who compiled various statistics of the general region mostly from charts; and one by Hess (1946), who described the flat-topped seamounts, or guyots, using extensive personal observations as well as data obtained from charts.

PRESENT SURVEY—MARINE PHASE

AIR PHOTOGRAPHS

Charts made by the Japanese during their occupation of the Marshall Islands were used as field sheets during the recent survey. These charts were soon recognized to be reliable in general though containing errors of several sorts. For example, the islands were consistently shown with a general rounded or bulbous outline, and the reef at some distance from the islands was usually displaced or of incorrect shape. Evidently, the Japanese based their charts entirely on fixes taken from shore or from aboard ship. The incorrect shapes of some of the islands as charted by the Japanese led to poor fixes during the recent marine surveying. Accordingly, before accurate final sounding charts could be prepared, it was necessary to revise the island and reef outlines as much as possible by a compilation of aerial photographs. Eniwetok Atoll had been recharted previously from aerial photographs by the Navy on Hydrographic Office Chart No. 6033, and needed no further modification.

Navy photographs for each of the four other atolls were assembled by matching points on overlapping pictures. This mosaic was traced and reduced by pantagraph to a scale of 1 : 40,000. The reduced tracing were adjusted so that the positions of islands or other known points matched the positions on the Japanese charts, which also were redrawn at 1 : 40,000 scale. Where necessary, the tracings were cut into narrow strips and reassembled with allowance for small discrepancies in positions. No particular difficulty was encountered in the work except for Ailinginae Atoll, the photographs of which were taken at a slight inclination from the vertical as though the airplane were flying out of trim, nose high.

During the field work at Bikini most of the survey beacons were plotted on the photographs with respect to vegetation. These plots served as good control for the aerial photograph compilation of that atoll. For most of the compilation, the islands were used as controls because they were the most accurately located parts of the Japanese charts, even though their general outlines were usually not good. Some islands, particularly those in the northwest corner of Rongelap Atoll, were shifted to accord with improved relative positions determined during the present survey. The Japanese charts showed little detail for these islands and for a few others found to be incorrectly placed, evidently because those parts of the Japanese survey were based only on reconnaissance. Similarly, from simultaneous sets of bearings on each atoll, Ailinginae was discovered to be charted by the Japanese about one-half mile too far northwest with respect to Rongelap Atoll. Because the Japanese chart of Rongelap was much more detailed and probably more accurate than their chart of Ailinginae, the position of Ailinginae was shifted on the new charts. Altogether, the recharting by aerial photograph compilation was done for Bikini, Rongelap, Rongerik, and Ailinginae Atolls. No claim is made for great accuracy, but the new charts certainly are much closer approximations of true conditions than are the old ones.

During the study of the aerial photographs, many miscellaneous observations were made regarding the distribution of surge channels, slump areas, old reef positions, beach rock, etc. Similar additional data were obtained on flights by the authors around Bikini and Eniwetok Atolls. These observations will be described in appropriate places in the text.

SOUNDINGS

SHIPS AND EQUIPMENT

During the course of the sounding work a large number of ships were used. Altogether, more than 6,000 miles of sounding lines (pl. 2–6) were run. (See table 1.) The sounding work in the lagoons was begun aboard the U. S. S. *Gilliss* (AGS *13*), which was equipped with a Bludworth recording echo sounder. Because of faulty installation or faulty parts this instrument failed after a few weeks, and the burden of lagoon sounding was transferred to a sister ship, the U. S. S. *Blish* (AGS *10*). which carried a Submarine Signal Co. echo sounder. The *Blish* collected more than half of all the lagoon soundings. These two ships were especially adapted to the work; in addition to an echo sounder, each had a gyrocompass pelorus, and space and power supply for taking simultaneous bottom samples. Additional sonic soundings were taken from the *Bowditch* No. 2 50-foot sound launch in shallow water fringing the inside margin of the reef at Bikini and Rongelap Atolls. Many sounding lines in Bikini Lagoon were also made available from earlier and concurrent surveys by sounding launches operated by naval personnel of both the *Bowditch* and the *Sumner*. Several lead-line sounding profiles extending from the beach to about 10-fathoms of water were obtained from aboard a DUKW. There was still one additional source of soundings in the Bikini Lagoon. During the course of experiments in the use of a new device, the "bottom scanner," several sonic profiles of coral knolls were made from an LCM. This instrument differs from an ordinary echo sounder in that the sound head, instead of being rigidly fastened to the ship's hull, is mounted in a trainable unit which sweeps back and forth at right angles to the ship's course. As a result, the soundings are taken on a zigzag course and those for each leg are momentarily visible on an oscilloscope. A photograph of the oscilloscope record is reproduced in plate 7 with profile of ship and scenic items added.

TABLE 1.—*Sounding and sampling data from northern Marshall Islands*

	Samples	Bottom photographs	Operation Crossroads soundings	Other[1] soundings	Total soundings
Outside areas:					
Bikini and Sylvania Guyots	69	18	6,300	870 CM	7,170
Eniwetok Atoll	4	0	1,270	4,320 N	5,590
Rongelap, Rongerik, and Ailinginae Atolls	37	24	9,690	130 C	9,820
Other guyots	0	0	2,870	300 CM	3,170
General area	1	0	610	3,190 CM	3,800
Total	111	42	20,740	8,810	29,550
Lagoon areas:					
Bikini island area	691	250	7,410	7,300 JN	14,710
Bikini Atoll (other)	892	175	13,340	9,800 JN	23,140
Eniwetok Atoll	365	93	----------	180,000 N	180,000
Rongelap Atoll	492	41	10,490	4,060 J	14,550
Rongerik Atoll	100	0	870	770 J	1,640
Total	2,540	559	32,110	201,930	234,040
Grand total	2,651	601	52,850	210,740	263,590

[1] C, Soundings from general navigational charts; N, Soundings from current or recent Navy survey; J, Japanese lead-line soundings; M, Mid-Pacific Expeaition, 1950.

The ships used for sounding in the lagoons were not generally useful for work in deep water outside the atolls because of the depth limitations of their echo sounders. Therefore, a larger ship, the U. S. S. *Sylvania* (KA *44*) was employed when available because she carried an echo sounder capable of recording to 2,000 fathoms and of being read visually to greater depths. Many radial and concentric lines were run on the outer slopes of the atolls during the daytime and surveys of nearby seamounts were carried out at night aboard the *Sylvania*. Some additional deep soundings were obtained by the *Bowditch* (AGS *4*) and the U. S. S. *Walke* (DD *723*) (pl. 5) while on scheduled runs between atolls. Some supplementary deep sounding lines were obtained during the mid-Pacific Expedition in 1950 aboard U. S. S. *Horizon*. These are of particular value because the echo-sounder recordings were far superior to the earlier ones.

Because of their large turning radius, these ships were not suitable for taking soundings near the reef edge in water shallower than about 250 fathoms. In order to fill this gap, radial lines at 1- or 2-mile intervals around Bikini and Rongelap Atolls were made by YMS *463*. These lines extended from about 350 fathoms into depths of only 2 to 50 fathoms. Additional soundings near the reef edge, but on lines generally parallel to the reef in 5 to 75 fathoms depth were obtained aboard YMS *354* and YMS *358*, while they were engaged in routine fishing operations. None of the minesweepers carried recording echo sounders, so all of their soundings were obtained by visual or audio-visual methods. Additional reef-edge soundings by lead-lines from a wherry extended some of the sonic profiles all of the way to the reef edge.

POSITIONS

During the running of a sounding line, the position of the survey ship must be determined at fairly short and regular time intervals. The length of time between fixes varied according to conditions but usually was between 2 and 5 minutes; for especially detailed parts of the survey fixes were taken at 1-minute intervals.

A number of different methods were employed in establishing the ship positions during the surveys. Most of the positions were obtained by gyrocompass pelorus equipped with a telescopic alidade. By use of this instrument the bearings of several known points were measured successively and were plotted on a chart with a drafting machine or parallel rules. Ordinarily, three or more points were used so that a triangle or polygon of error could be drawn. This pelorus method is especially useful where some of the fix points, such as island tangents, are of doubtful accuracy, or where only two fix points are available. Ship positions are subject to some error on very detailed plots because the bearings are not measured simultaneously; on turns they may be in error because of lag in the gyrocompass.

Another method, employing horizontal sextant angles was used exclusively aboard the launches and the *Gilliss*. By this method 2 men, each using a sextant, simultaneously measure the 2 angles between 3 fix points—usually beacons, prominent land objects, or marker buoys. The angles are set on a 3-arm protractor which is slid about on the plotting chart until a point is found from which the 3 fix points are subtended by the 2 angles (pl. 9, fig. 5). This point is the ship's position. The horizontal sextant angle method is useful on small ships, which carry no gyrocompass pelorus, and in areas where many accurately located beacons are available. Difficulties are involved if the fix points are of questionable position, are subtended by angles greater than 135°—the practical limit of the sextant—or if the beacons are frequently hidden behind ships, as was true in the target area at Bikini Atoll.

A sextant was also used to determine the distance to the reef from ships taking soundings near the reef edge outside the atolls. For this purpose, the vertical angle from the horizon to the outer reef edge was measured and corrected for earth curvature. That angle and the eye height above the water comprise two parts of a triangle from which the base, the distance, can be computed, ordinarily from a graph.

For surveys by the *Sylvania* in deep water entirely different methods of fixing the ship position were necessary. This very deep surveying was done at night, when close-in work was not safe. An attempt was made to schedule a departure from visual range at dusk and a return after dawn. The most accurate of the fix methods for the night surveying was radar (radio detection and ranging), which was found useful to about 20 miles from the closest islands. The available radar yielded ranges accurate to within a few hundred yards, but bearings were as much as 3° in error; therefore, where possible, ranges on two widely separated islands were obtained so that the ship's position could be established on a chart at the intersection of the two range arcs.

Far from land, fixes were restricted to star sights and loran (long range navigation) lines. The star sights were of only slight value because they were of sufficient accuracy only at dawn and dusk, at both of which times the ship was usually in or near visual range of land points. Loran, a method which depends on the measurement of the time interval between reception of radio signals sent simultaneously from pairs of widely separated transmitter stations, was also of limited usefulness, because it happens that the northern Marshalls are in a zone in which loran lines from several pairs of stations are nearly parallel. Since no point of intersection of these lines could be obtained, only "lines of position" were plotted. Thus, most of the deep water surveying had to be on a dead-reckoning basis. At dusk the ship started from a well-established fix position at the beginning of a set of projected courses. After dawn, when another accurate position was obtained, it was always found to be somewhat different from the position where the ship would have been if there had been no current or wind drift. The distance between the two positions was then apportioned throughout the lapsed time of dead reckoning, taking into account any nighttime positions which might have been obtained by any method. Considerable aid in the plotting was afforded by use of the DRT (dead reckoning tracer) by which a running plot of ship's position, ignoring drift, was kept.

Regardless of which method was used to determine the ship's position, a continuous plot, or boat sheet, of positions was kept. Later, when more time was available, the data were completely replotted on a final chart showing the more accurate island outlines yielded by air photo compilations. For this final chart, enough time could be taken to check the relative accuracy of each ship's position by seeing how closely it lay on a straight course and how nearly equal was the distance between successive fixes, taken at equal time intervals. By this careful checking, occasional erroneous fixes were discovered and discarded. The acceptable fixes were entered by time and a letter for the survey day. Time was used instead of the position number to facilitate the plotting of samples taken at intermediate times.

DEPTH CORRECTIONS

Although several different types of fathometers were used in the work, all operated on the same general principles and required the same kind of corrections. Many of the corrections are of minor nature such as variations in motor speed, variation in draft of the ship, and miscellaneous instrumental variations. Motor speed was usually checked each day and no correction for it was required. Other minor sources of error were checked separately but most of these were checked en masse by comparing sonic soundings with lead-line soundings at anchor once each day. The main cause of difference between the two kinds of soundings, however, was the fact that the acoustic units were not at the water surface. On most of the ships employed in the surveying the acoustic units were near keel depth and the echo-sounders were so adjusted that they indicated the depth of water below the keel rather than the depth below sea level. For the small survey ships and mine sweepers it was thus necessary to add a relatively constant correction of 12 to 15 feet to the sonic depth to duplicate the lead-line measurement of water depth.

Three other kinds of corrections were also necessary, all of a variable nature. The simplest of these, and one which usually could be ignored, depended on the position of the zero line of the recorded paper relative to the zero marking made by the recorder stylus. If the two were not exactly superimposed, a correction depending on their apparent depth difference was required. Another correction was much more variable, changing throughout the day as the tide height changed. In the northern Marshalls the tide height is considered to be the vertical distance of the water level above lowest low water (LLW). The mean range of tide at Bikini is 3.4 feet and the spring range is 4.9 feet with an extreme range of about 5.5 feet. Tide corrections to the soundings in the lagoon were based entirely on predicted tide curves for Bikini Atoll made especially for Operation Crossroads by the U. S. Coast and Geodetic Survey. Brief comparison of predicted tide with tide-gauge records for several days obtained by U. S. S. *Sumner* showed fairly close agreement. It is to be noted that the use of predicted tide levels for correcting soundings takes no account of abnormal water levels caused by storm waves and tsunamis but it serves as a close approximation. Because the tide range was small compared to the depths outside the atolls, tide corrections were not made for general sounding work in deep water, but were made for all lagoon soundings.

One last depth correction must be made. This correction has to do with the velocity of sound in the water, which is different at different depths. The velocity of sound in the ocean is directly proportional to each of three factors: temperature, salinity, and pressure. The last is, of course, proportional to depth. In order to determine sound velocity, then, it is necessary to know the temperature and salinity at several depths. As the official oceanographic observations were not available in final corrected form until after construction of the sounding charts had begun, and as these data did not extend below 800 fathoms, older data had to be used. The temperature and salinity curves of figure 3 are based largely on an unpublished average of Japanese stations between latitudes 11° and 12° N. and longitudes 160° and 180° E. Observations from 15 Japanese stations were averaged for values down to 547 fathoms, and from 6 stations to 821 fathoms (Barnes, C. A., personal communication). Below 821 fathoms the curves are a composite of *Carnegie* station 100 (to a depth of 1,368 fathoms), *Carnegie* station 154 (to 2,140 fathoms), and

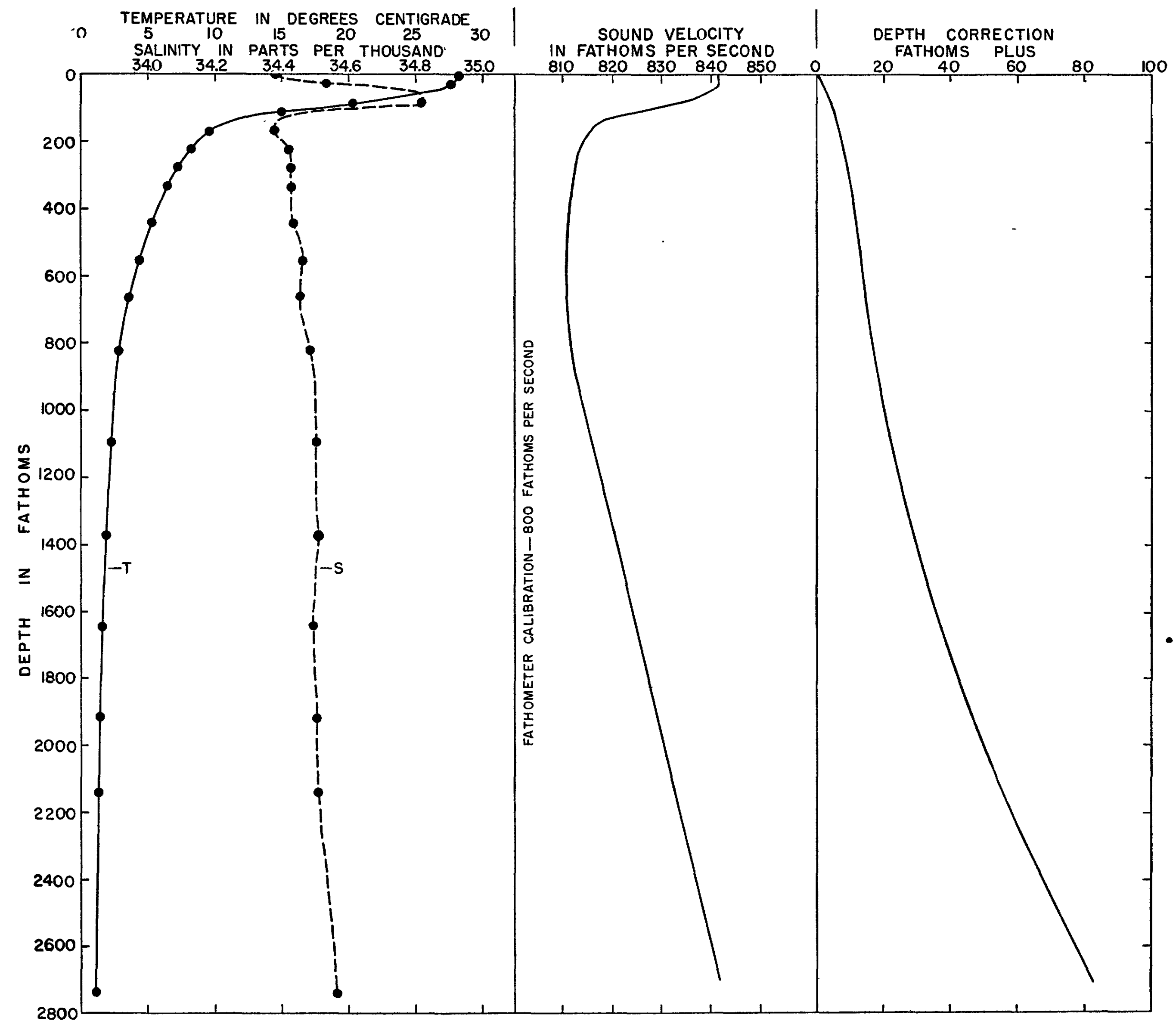

FIGURE 3.—Temperature-salinity, sound-velocity, and depth-correction curves for northern Marshall Islands.

Dana station 3628 (at 2,740 fathoms). The deep water at all these stations is essentially the same, and is believed to be like that in the northern Marshall Islands areas. The data show that the temperature is about 28° C. from the surface to about 30 fathoms, below which there is a sharp decrease in temperature to about 10° C. at 150 fathoms. Below that depth the temperature slowly decreases to 1.0° C. at 2,700 fathoms. The salinity curve is fairly constant at about 34.6 parts per thousand except between 20 and 120 fathoms, where it rises to a maximum of about 35.0 parts per thousand. From the temperature and salinity curves a third curve showing the variation of sound velocity with depth was constructed using the U. S. Coast and Geodetic Survey method and nomograph (Adams, 1942, p. 528–534, 872–881). This curve exhibits the highest velocity of 842 fathoms per second near the surface where the temperature is highest. Below about 50 fathoms there is a steady decrease of velocity in the thermocline. A minimum velocity of 806 fathoms per second occurs at about 700 fathoms, below which there is a gradual increase to nearly 840 fathoms per second at 2,700 fathoms. This increase of velocity at depth results from the increase of pressure at depth where the effect of temperature is not important. Although the actual velocity of sound in the ocean varied between 806 and 842 fathoms per second, all of the echo sounders were designed for a velocity of 800 fathoms per second. Since the echo sounders measure the elapsed time between transmission of a signal and reception of the echo, and multiply half of the time by the sound velocity to give depth, all of the indicated soundings are too shallow. They must be corrected by an additive factor proportional to the difference between 800 fathoms per second and the actual sound velocity of the water column through which the sounding is made. The effect is cumulative and the correction is greatest for the greatest depths. The right hand curve of figure 3 shows the amount of correction for various depths. It should be noted that the average correction is about 3 percent and that it is even higher at depths up to 200 fathoms and between 1,200 and 2,700 fathoms.

In general practice the U. S. Navy Hydrographic Office does not make velocity corrections on charts, in the belief that it is more important for general navigation to indicate the depth that another ship, using the same standard type of echo sounder, will find without having to make continuous depth corrections. For the convenience of the Hydrographic Office and in order to eliminate one source of error in drafting, the outside soundings were entered on the charts uncorrected for either the draft of the acoustic unit or for sound velocity of the water. However, since the purpose of the report is to present geological data, all contours on charts and graphs in this report are based on corrected depths. For the outside charts, this merely means the drawing of contours at the odd depth intervals shown in table 2.

TABLE 2.—*Depth correction for soundings in deep water*

Contour	Corresponding sounding[1]	Contour	Corresponding sounding[1]
0	0	1600	1561
100	92	1700	1658
200	190	1800	1755
300	288	1900	1852
400	386	2000	1948
500	484	2100	2046
600	583	2200	2139
700	682	2300	2235
800	780	2400	2330
900	878	2500	2425
1000	976	2600	2520
1100	1074	2700	2614
1200	1172	2800	2710
1300	1270	2900	2805
1400	1367	3000	2900
1500	1464		

[1] Uncorrected for draft of the acoustic unit (3 fathoms) or velocity of sound (variable)

For charts of the lagoon floors the velocity corrections are much smaller, partly because lead-line checks were mostly made at middepths of 15 fathoms. All corrections except that for velocity of sound were made prior to plotting of the lagoon soundings. As the error is small, depth corrections for sound velocity were not used for lagoon soundings.

SLOPE CORRECTION

In addition to the depth corrections to sonic soundings outlined above, still another type of correction is necessary for a full understanding of bottom profiles. Unlike a lead-line, the sound beam directed downward from the survey ship is not thin and pencillike, but it is a broad cone. In reality, sound is transmitted in all directions and moves outward in a hemispheric wave front; however, the sound moving laterally is of much lower intensity than that directed straight downward. For sound gear of the type used on survey echo sounders the beam pattern is such that the sound intensity drops 3 decibels (20 percent) between the beam axis and 15° from the axis. Ordinarily, this angle is considered the practical limit of the sound cone; however, reflections from nearby objects of high reflecting power may be obtained beyond the cone limits.

When the ship moves over a sloping bottom, the strongest echo is likely to be returned by that part of the bottom which is most nearly tangent to the wave front of the cone of sound. This may result in the strongest echo being returned from some point on a smooth slope shallower than the point directly underneath the ship. The exact position of the first recognizable echo depends on the steepness of the slope, its depth, and the character of the reflecting surface, as well as on the beam pattern. Because of these and possibly other factors, the complexity of the problem is such that slope corrections are very rarely made.

Shalowitz (1930) reported a method of making a simple trigonometric slope correction on assumption of a smooth plane bottom surface of known slope and a nondirectional sound gear. Neither of his assumptions are valid for the present surveys. Maurer (1933) attempted slope corrections for the soundings obtained by the *Meteor* expedition also by assuming that the sound gear was nondirectional. With such gear he showed that it is possible to sketch cross sections tangent to arcs drawn from the ship's position and having a radius equal to the measured echo sounding. Kuenen (1935) discovered that this method did not give good results in the interpretation of soundings taken by the *Snellius*. The method also fails for the soundings off the reef at Bikini because the uncorrected sounding profiles are far steeper than 45° at many points, and it is obvious that such steep profiles cannot be obtained in the first place by nondirectional sound gear. Because no satisfactory correction method has been developed, the sonic profiles accompanying this report are based on soundings corrected for all known depth errors except slope. In interpreting them one should remember that the true slope is steeper than that shown, perhaps by several degrees. In no case can the sonic profiles be steeper than the true ones. A different, but simpler problem, is presented for the soundings plotted in chart form. Shalowitz (1930) computed the lateral distance which soundings over sloping bottoms must be shifted so that the indicated depth corresponds to the actual depth. For the charts of the scale used in this report, this shifting, or slope correction, is so small that it can be neglected. Usually, it is far less than the length or height of the numbers that mark the soundings.

REFLECTIVITY OF BOTTOM

The strength of an echo is controlled partly by the ability of the bottom to reflect the incident sound. If the bottom materials are such that much of the sound is absorbed or is widely scattered, only a very small percentage of it will be returned to the ship's hydrophone. Examination of the fathograms made in the lagoons showed that a clear distinction can often be made between the traces recorded over *Halimeda* debris, sand, and coral. The *Halimeda* debris, because of its very high water content, is a poor reflector and much of the incident sound penetrates it. Part of this sound is reflected from beneath the surface of the debris; the rest is absorbed. Accordingly, the typical fathogram trace over *Halimeda* debris is wide but faint (pl. 3, fig. 1). In contrast, sand has a lower water content and is a good reflector; therefore, it reflects sound without much loss by absorption so that fathograms over sand are narrow and dense. Coral has a water content even lower than sand, but its surface is so rough that much sound is scattered. Fathograms over coral are similar to those over sand except that the indicated slopes are steeper than over sand (pls. 2–4). These characteristics allow the fathograms to serve as rough indicators of the nature of the bottom material.

"MOAT" EFFECT

During the survey a common peculiarity of the fathograms was ascribed to slope effect coupled with varying bottom reflectivity. Subsequent study of the phenomenon has yielded no better explanation. The fathograms show many coral knolls that rise gradually from the bottom, but some appear to be surrounded by a narrow moat. All graduations of size of the moat and of coral knolls can be found, so that at one extreme, the coral knoll appears only as a bump located entirely within a depression below the general level of the lagoon. Several actual examples are included on the sections of fathograms of plates 2 to 4 whereas figure 4 is a series of diagrammatic sketches. It is probable that the material of the coral knolls is a better sound reflector than is the *Halimeda* debris found between them; therefore, one might expect the coral knolls to produce echoes from the side lobes of the beam. The fathograms made when a ship passes near but not over a coral knoll would then indicate the diagonal distance from the ship to the coral knoll and not the true depth of the coral knoll below the water surface. If the coral knoll were farther away from the ship in a diagonal direction than the bottom directly below the ship, then the coral knoll should be indicated on the fathogram in a position beneath the regular bottom.

Experience with fathograms over other kinds of bottom would lead one to expect a double trace under such conditions with the echo from the coral knoll superimposed on that from the ordinary flat bottom. Instead, however, the ordinary bottom echo appears to stop and be replaced by a stronger side echo from the coral knoll. Where the coral knoll is farther from the ship than the bottom beneath, this exchange of echo source leaves an apparent moat. These are considered nonexistant in reality because they were not indicated by lead-line soundings made over some coral knolls, were not seen during diving operations on other knolls, and the depths of some are greater than any known depths in the lagoon. Currents, as indicated by current studies and by the grain-size of bottom sediments, are too slow to have scoured them; moreover, the moats have no preferred side as would be the expected result of current action. Conceivably, they

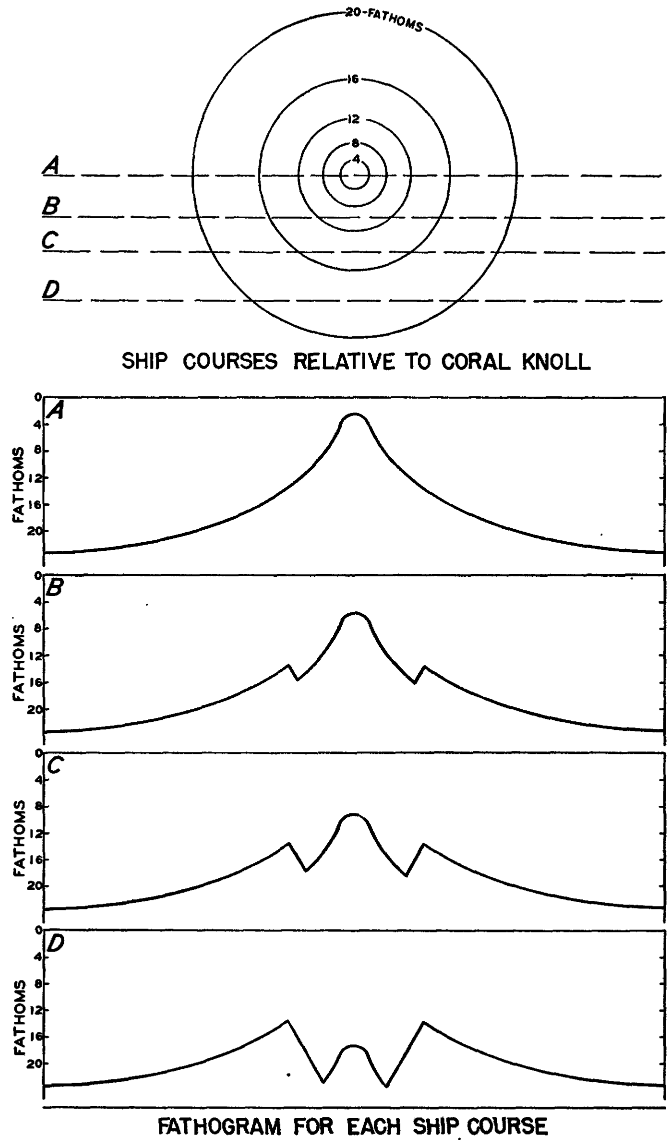

FIGURE 4.—Diagram of "moat" effect on fathograms near coral knolls.

might be produced by a settling of the coral knolls into a soft bottom, dragging along some of the adjacent bottom. The problem is interesting but unsolved. According to H. W. Murray (personal communication) the Coast and Geodetic Survey has found similar apparent moats near steep-sided objects such as sunken ships and submerged cliffs.

For lack of better information such depressions were ignored in the contouring of soundings and the bottom was considered to slope gradually away from the coral knoll. In addition, coral knolls having apparent moats were noted as reaching to shallower depths than were indicated by that fathogram. In several instances later fathograms made nearer the same coral knolls showed shallow depths on them, justifying this procedure.

ACCURACY OF SOUNDINGS AND CONTOURS

When lines of soundings are plotted some of them are more or less erroneous because of inadequate position control; others, like some of those on the outer slopes of the atolls were obtained in water too deep for use of the recorder tape. The latter may contain reading errors resulting from inexperience of the operator or mistakes resulting from faintness of the echo coupled with high interfering water noise. Often the discovery of such errors is difficult; however, where two sounding lines cross, discrepancies in depth at the point of crossing are readily apparent; usually, the erroneous line can be recognized by its relationship to other lines which cross it nearby. If the error is in position, as is usually true for dead reckoning lines, a judicious shift can be made so that the error of crossings is reduced or eliminated. If the error appears to be in depth alone, the line usually has to be deleted.

In order to determine the probable accuracy of the soundings the depth error at all crossings outside of the lagoons was plotted before any readjustments were made. Most of these lines are based on visual fixes and others on radar fixes or dead reckoning supplemented by some celestial observations. Of the 259 crossings, 50 percent differ by less than 32 fathoms and 75 percent by less than 68 fathoms (fig. 5). Figure 5 also shows that 10 percent of the crossing errors were in excess of 150 fathoms. All such extremely poor crossings were dead-reckoning lines in deep water distant from the atolls and thus had poor control or none at all. Some of these poor lines were readjusted in position whereas others having intermittent doubtful soundings were deleted. As a result, the final charts contain no known errors of more than 100 fathoms. Thus, the mean error of the final soundings is less than 32 fathoms and probably is closer to 28 fathoms. If a probable depth error of 28 fathoms were due to position alone it would involve an average position error of only about 75 yards near the atolls because of the steepness of their slopes. A check of this figure is provided by the fact that the visual position fixes taken at 5-minute intervals near the atolls were mostly within 75 yards of the best-fit course line through them. For comparison, the length of the U. S. S. *Sylvania* on which most of the soundings were taken is about 450 feet, or 150 yards; thus, the probable error in position of the soundings near the atolls and shallower than about 1,800 fathoms is about half a ship-length. Farther out, where control was much poorer and where the slopes were generally less, the positions are less accurate. The average position error there is probably between ¼ and ½ mile.

Within the lagoons the accuracy of the soundings again depends on both depth and position errors.

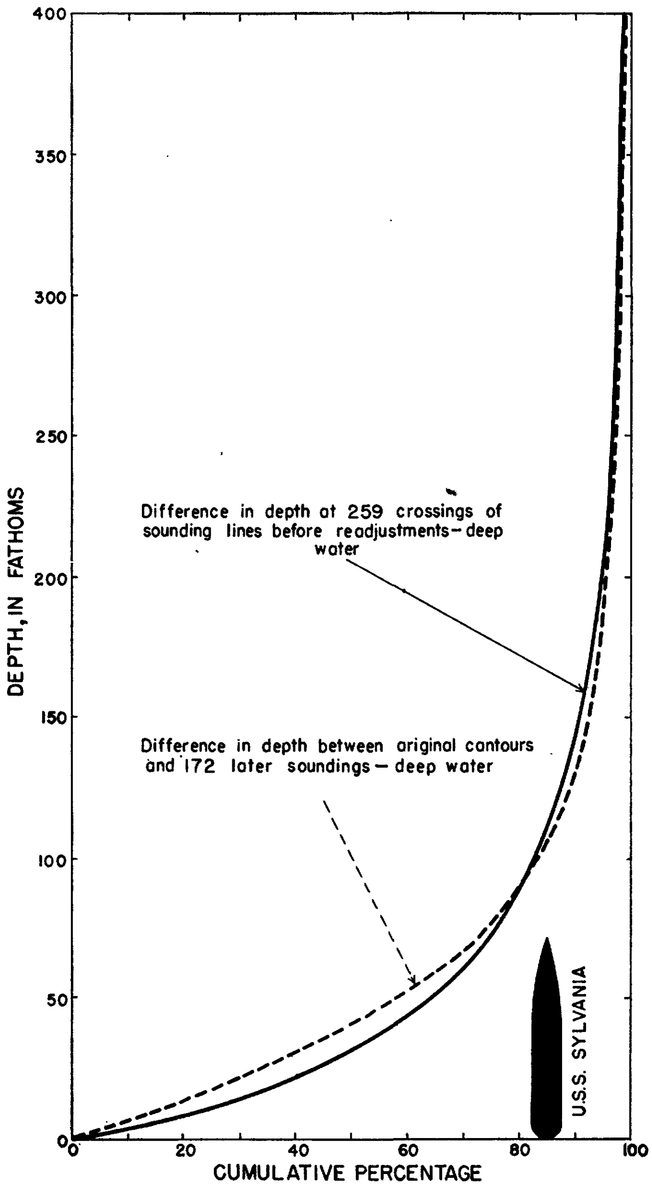

FIGURE 5.—Magnitude and frequency of sounding errors. For comparison the outline of the U. S. S. *Sylvania* on which most of soundings were taken is shown in lower right corner.

The average depth error is estimated at less than one-half fathom because occasional checks of the echo sounder were made by lead-line soundings, making possible the use of depth corrections for all soundings. Personnel errors are not present because depths were so shallow that all of the soundings were recorded on tapes. Comparison of sounding line depths at points of crossings is of little value in the lagoons because of the great steepness of the slopes around the coral knolls. The position error is best indicated by the distance between the plotted fix points and the best fit course line through them. The average distance of the points from that line is estimated at about 50 yards. Points which were erratic in position and spacing were deleted and were not used; therefore, the final positions of the soundings have an average error of much less than 50 yards, probably nearer 25 yards. This average error of 25 yards also is applicable to the bottom samples. It happens to be about half the length of the ships used in the survey, mostly the *Blish* and the *Gilliss*.

The accuracy in position of the contours is, of course, less than the accuracy of the soundings. Between sounding lines the shape of the contours is based only on an attempt to portray smooth slopes with adjacent contours following similar undulations. The drawing of contours is subjective in nature and depends largely on the experience of the cartographer and his understanding of bottom topography. The only true test of their accuracy is obtained by superimposing new sounding lines on the contour chart and checking the closeness of fit. After preliminary contours were drawn for the outer slopes of the atolls about 250 additional soundings became available. These soundings had been taken during Operation Crossroads by various ships which transmitted the records to the Hydrographic Office. After they were plotted on the contour charts, about 75 of the soundings were found to conflict with the previous sounding lines; a number of them were about 300 fathoms too shallow, suggesting that one echo sounder was out of adjustment. Others appeared to be offset because of navigational errors of the order of those to be expected in ordinary navigation, not surveys. The remaining 172 new soundings were corrected for depth error and compared with the depths obtained by interpolation of the prior contours. As shown by figure 4, the mean error is only 40 fathoms, less than half of the 100-fathom contour interval. This accuracy was better than that expected because most of the new soundings came from areas beyond visual range of the atolls. After completion of the statistics of contour error, the contours were shifted to agree with the new data.

BOTTOM SAMPLING

Samples were collected from the lagoons of Bikini, Eniwetok, Rongelap, and Rongerik Atolls and from the outer slopes of all except Rongerik. Altogether, about 2,650 bottom samples were obtained. Their distribution by area is shown by table 1.

For most of the samples an underway bottom sampler, the "scoopfish" was used (pl. 8, fig. 1). This device is a modification by Emery and A. R. Champion of a sampler originally designed by J. L. Worzel and others during World War II (Ewing, Woollard, Vine, Worzel, 1946, pp. 925–926). In operation, the sampler is lowered on a light wire cable from a high-speed winch while the ship is moving at speeds of as much as about 10 knots (pl. 8, fig. 4). The heavy nose and the fins cause the sampler to sink nearly vertically through the water. When the sampler strikes bottom, the wire slackens, and the winch is engaged to haul it back aboard ship. A small sample of bottom materials is collected in a cup which is driven back into a sleeve, thereby releasing a door which flaps shut over the cup opening and protects the sample from being washed. Only 20 to 50 grams of sediment are usually obtained but that quantity is sufficient for most general analyses. Fragments of coral were broken off and retrieved, sometimes looped around the wire cable. Once, even a coral block about 8 inches in diameter was caught between the cable and the instrument so tightly that it was recovered intact. Use of this sampler had two main advantages. First, samples could be collected at short intervals, less than 3 minutes apart, so that a line of samples at 800-yard intervals could be obtained from a ship moving at 8 knots. Secondly, the samples could easily be correlated with topography, which was recorded simultaneously by recording fathometer. An estimated 10 percent of misses occurred during the collection of about 2,300 samples. Most of the misses probably resulted from wear or occasional maladjustment rather than from hard bottom.

Many of the other samples were collected by snappers of which two types were used. One type (pl. 8, fig. 3) weighing 35 pounds was designed to trip when the lowering cable slackens as the device strikes bottom; when the cable is reeled in again the jaws automatically close. Jaws of the other type of snapper closed when a latch holding them open was disengaged by striking bottom. This snapper, built aboard ship, weighed 75 pounds. Samples collected by the snappers were much larger than those by the "scoopfish," often being as much as 2 pounds. More time per sample was required, however, because use of the snappers required the ship to be stopped or drifting. Accordingly, most of the snapper samples were taken alternately with bottom photographs which also required the ship to be stopped.

About 30 bottom samples were obtained by a coring device (pl. 8, figs. 4 and 5), which was a light-weight model of a gravity corer used extensively elsewhere (Emery and Dietz, 1941). About half of these cores were from the lagoon, where some difficulty caused by the presence of coral and hard-packed sand resulted in about 60 percent misses. Best results in the lagoon were obtained in *Halimeda* debris, in which several cores each about 24 inches length were recovered when enough lead slugs were attached to give the instrument a total weight of about 250 pounds. After experimentation with other samplers, the corer was found most reliable for collecting samples from the outer slopes and from Sylvania Guyot (a flat-topped seamount). Cores of *Globigerina* sand as much as about 14 inches long were collected from the latter at depths of 750 to 850 fathoms.

About 20 samples were collected by dredging, but more of that work would have been desirable. Some of these samples were cuts saved from dredgings made during biological trawlings. The dredge used was made of wire-link netting covered by canvas and supported by a steel framework and bail. The bail was constructed with a weak link on one side designed to break under moderate pressure and increase the chances of recovering the dredge when it became tightly caught on bottom. Because of the roughness and hardness of parts of the lagoon floor, no great success was met with when the dredge was operated from a ship, but excellent results were obtained when dredging was carried on from aboard a DUKW. Some additional dredging was done in deep water of the outer slopes, using a small dredge made of a pipe 4 inches in diameter, capped at the bottom and fitted with a bail at the top.

About a hundred other samples were collected by various miscellaneous methods. Most were beach samples scooped up by hand at about the high-tide level. Several samples were picked up from the bottom during diving operations. Large pieces of coral were sometimes recovered from the ships' anchors after they were hoisted (pl. 9, fig. 3).

All of the samplers except the "scoopfish" were ordinarily handled by a small gasoline winch carrying $\frac{1}{4}$-inch or $\frac{5}{32}$-inch steel wire cable. Unfortunately, only 1,100 fathoms of the smaller diameter cable were required to completely fill the winch drum, so that collection of samples in water deeper than about 1,000 fathoms was impossible. The "scoopfish" was operated by a small electric winch of the type designed for use with the bathythermograph. This winch carried 1,200 feet of $\frac{1}{16}$-inch wire cable.

Fairly good luck attended the collection of bottom samples. Misses were not particularly numerous in spite of the locally hard bottom, and only 4 instruments—2 snappers, 1 orange-peel bucket, and 1 core tube—were lost during Operation Crossroads in 1946. During the resurvey in 1947 one 600-pound corer, one core tube, and two dredges were lost. No losses occurred in the Bikini area during the Mid-Pacific Expedition of 1950.

BOTTOM PHOTOGRAPHY

In order to aid in the interpretation of the bottom samples and to furnish independent information on the environment of the lagoon floors, a large number of underwater photographs were made. The camera was one of those designed by Ewing, Vine, and Worzel (1946). It consisted of a water-tight brass housing with a glass port and contained a camera (pl. 9, fig. 2). Suitable leads through the housing were connected to a flashbulb in a reflector. Both housing and reflector were mounted on a vertical pole which was weighted at the bottom and attached to the hoisting cable at the top (pl. 9, fig. 1). A trip line and weight extended below the bottom of the pole so that when the assembly was lowered through the water the trip weight touched bottom first, releasing a spring which tripped the camera. A built-in synchronizer closed an electrical circuit, firing the flashbulb. In order to prevent spinning of the camera assembly as the cable paid out, a stabilizing fin was attached near the top of the pole.

The water in the atolls was so exceptionally clear that a Secchi disk could usually be seen deeper than 100 feet. Thus, in many places where sunlight penetrated the water flashbulbs were unnecessary; however, their use served as a check on the proper functioning of the camera. Ordinarily, the camera was not removed from its housing until after exposure of an entire roll of film. For some of the work the camera was set at 10 feet and for the rest at 5 feet above the bottom. Best results were obtained with a standard camera setting of 1/50 second at f.8. A few rolls of color film were also exposed.

In operation, the camera was lowered overside on the cable from the gasoline winch at 5-minute intervals while the ship drifted. This procedure resulted in several long series of photographs at intervals of a few hundred yards. About 350 of these remote-control bottom photographs were taken in depths ranging from 4 to 35 fathoms. Only a few exposures were made on the outer slopes because of the steepness of the bottom. About 200 additional underwater photographs were taken with the camera held by hand, either during diving operation, or from a small drifting boat, or while swimming in shallow water.

Usually the negatives were developed as soon as possible to check on the proper functioning of the camera. During the resurvey of 1947 about 30 additional photographs of the lagoon floor were made with the same type of camera. The Mid-Pacific Expedition of 1950, using a heavier deep-water camera designed and built by Carl Shipek, succeeded in making 2 photographs of the surface of Sylvania Guyot.

PRESENT SURVEY—LAND PHASE

AIR PHOTOGRAPHS

The excellent air photographs made by the Navy have already been mentioned in the section on the marine phase of the investigation. These photographs proved to be of great value, particularly in studies involving zonation and distribution of reef types; a number are reproduced in the present paper.

SWIMMING AND DIVING

Many of the reef traverses were supplemented by direct observation by swimming with a face mask. In view of the exceptional clarity of the water, and of the beauty and fascination of the underwater realm, it is surprising that few geologists seem to have used direct observation by swimming in their studies of coral reefs. The lagoon margin of the reef is usually accessible. Pools and surge channels near the seaward margin of a reef frequently are turbulent, but at low tide many can be explored by a careful siwmmer if the surf is not too high. Swimming off the seaward margin of the reef can be done on the calm leeward side at many times, but the rough windward margin of the reef is a treacherous place. Swimming was done at Bikini and Rongelap Atolls in several places off the windward reefs, but only in the summertime on days when the breeze was light and the surf low. If we had not had the advantage of an extensive stay in the islands, we should not have been able to accomplish this.

On several occasions the writers were able to explore coral knolls in the lagoon, in 25 to 50 feet of water, by using the regulation Navy shallow-water diving apparatus. The diving was done from a motor launch or landing craft (LCM) that carried the air compressors and other diving equipment. Face masks connected to the air hose were used rather than helmets, and a lead belt added the necessary weight.

One attempt to dive was made off the lee margin of Enirik island in one of the large erosional areas of the reef. The air compressors and equipment were carried by an amphibious truck (DUKW) driven to the edge of the reef. The attempt was cancelled by officials because the risk of fouled lines was felt to be too great.

Experience is necessary in estimating sizes and distances under water, because submerged objects appear to be larger and closer under water than they appear in air. The index of refraction in water is 1.33, whereas that in air is 1.00, and an object under water thus appears to be at three-quarters of its actual distance. The ratio of 1.33:1, or 4:3 is a convenient one to use, and it is a simple matter in underwater photography to set the camera focus at three-quarters of the actual distance; or if the distance be estimated by eye under water, the camera focus should be set at the apparent distance.

Underwater photographs taken while swimming or diving were made with the same equipment used for the bottom photographs in the lagoon studies taken from shipboard. Underwater photographs on the reef flat were taken with an open-topped metal box having a glass window on one side, and a swivel head on the bottom to hold the camera.

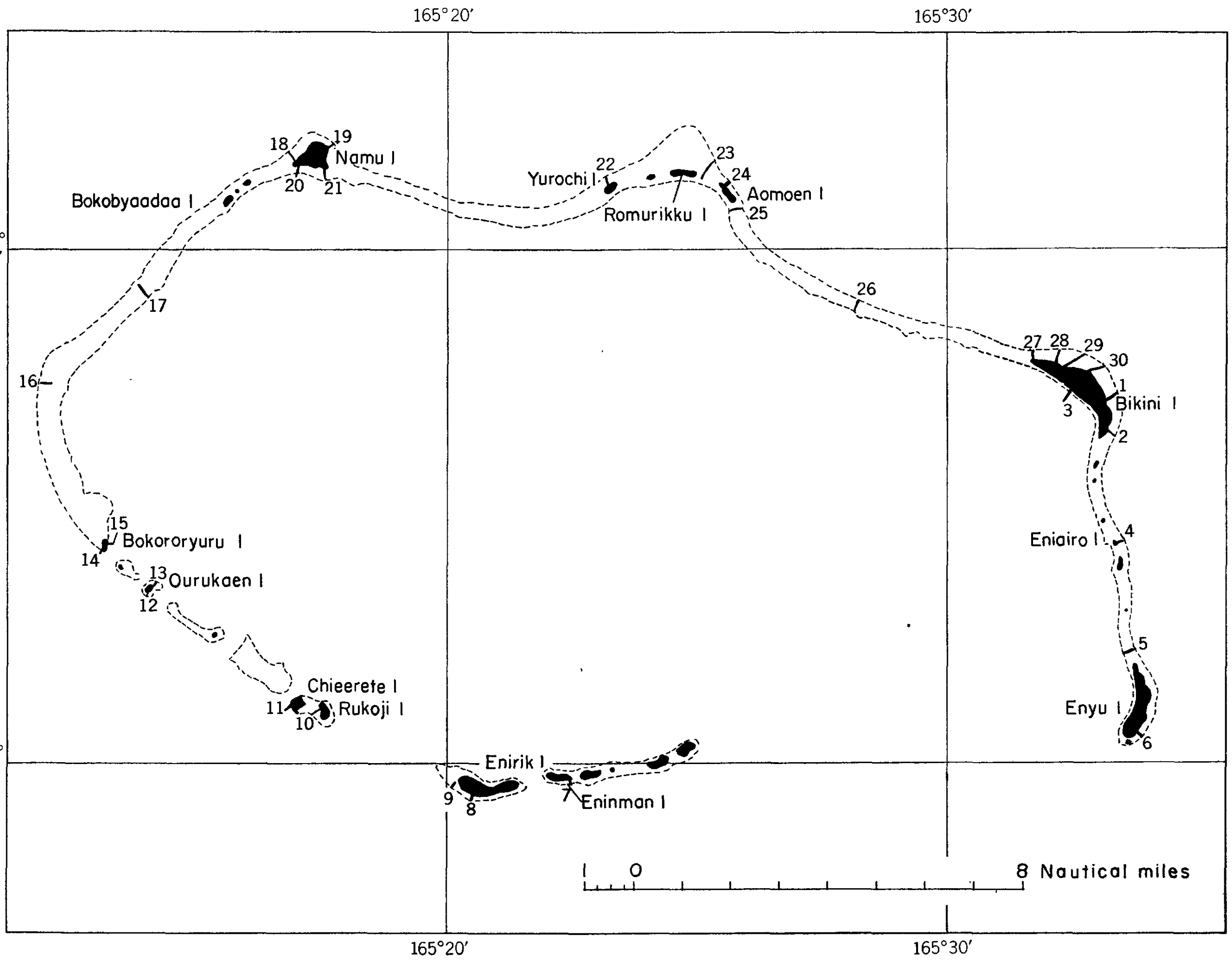

FIGURE 6.—Locations of measured reef traverses, Bikini Atoll.

TRAVERSES

At 30 localities widely spaced around Bikini (fig. 6), detailed traverses were measured across the reefs at right angles to the reef front. Measurements were by the compass-and-pace method and observations were recorded along a strip approximately 20 feet in width. The traverses show the relative abundance of corals and algae of the more important types and the distribution of channels, caverns, pools, and reef deposits. Generalizations drawn from the traverses and from scattered observations made in intervening areas including several trips made along the windward reef are given in the section dealing with the geology of Bikini; the traverses themselves are reproduced on pages 158 to 182.

PRESENT SURVEY—DRILLING PHASE

DRILLING METHODS

All drilling equipment and drilling crews were furnished by a commercial concern under contract with the Navy Department. The drill was the "1500 Holemaster" rotary type, mounted on a truck and complete with all necessary tools and equipment, including about 2,500 feet of drill stem. Rock bits were used for straight drilling and hard metal bits for coring. After setting 6-inch surface casing, the holes were continued with 5⅝-inch bits. In the deepest hole (no. 2B), 4-inch casing was set to a depth of 804 feet, the remainder of the hole being drilled with a 2⅞-inch rock bit. Salt water was used with salt-water mud at the beginning of the operation but proved unsatisfactory. During the drilling of the deep hole, fresh water and fresh-water mud were substituted.

V. C. Mickle, assisted by Emmett Alexander, was in charge of two drilling crews of three each, and the drill was operated continuously in 12-hour shifts. A geologist was on duty at all times, and in this work Tracey and Ladd and G. G. Lill, Office of Naval Research, were relieved from time to time by John W. Wells and J. Harlan Johnson (Ladd, Tracey, and Lill, 1948). Tanks of fresh water from the U. S. S. *Chilton* and other necessary supplies were furnished by Comdr. John R. Denny and his Construction Battalion detachment.

DRILLING OPERATIONS

As originally outlined, the drilling program called for a series of 5 holes, 3 to windward across Bikini Island and its reef, and 2 to leeward on opposite sides of one of the small southwestern islands. These holes were to be cored continuously to 300 feet and one of them carried by rock bit to 2,500 feet. When the first holes were put down, the core recovery was poor and the consumption of mud so great that changes seemed in order. The plan to drill on the cavernous reef flat was abandoned, and efforts were concentrated on completing the deep hole with as many core runs as time would permit.

A total of 812 feet was cored with a recovery of 135 feet (16.6 percent). The recovery was excellent in hard limestone and sometimes very good in the sand; it was poorest in loose or poorly consolidated material in which heads of hard coral were scattered in a matrix of softer sand. Cuttings were recovered at 5- to 10-foot intervals.

There was an appreciable loss of mud during all drilling, and, on occasion, cavities were encountered that stopped circulation completely. One such cavity was cemented and leakage at lower levels controlled by pouring a variety of absorbent materials, including rice hulls, sawdust, and corn meal, in the hole. Between 2,000 and 2,500 gallons of fresh water were used in each 24-hour period during the drilling of the deepest hole.

PRESENT SURVEY—GEOPHYSICAL PHASE

SEISMIC SURVEYS

In 1946 a seismic-refraction survey was made at Bikini Atoll by firing a series of depth charges on the lagoon bottom along four lines extending across the atoll, the resulting seismic waves being picked up by water-coupled microphones near shore (Dobrin, Perkins, and Snavely, 1949). The time-distance curves indicated the existence of three zones of different sound velocity. The first of these was about 2,500 feet thick, and the velocity of sound in it was 7,000 feet per second; the second was 5,000 to 10,000 feet thick, and the velocity of sound in it was 11,000 feet per second; the third, a zone of undetermined thickness presumed to be the igneous basement, the velocity of sound in this zone was 17,000 feet per second. In 1947 a vertical-velocity survey of the deep drill hole showed a more or less continuous transition in velocity from 7,000 feet per second at the surface to 11,000 feet per second at a depth of 1,800 feet. These data led to the conclusion that probably no essentially different rock materials appear in the atoll down to the foundation rock with the 17,000 feet per second velocity (Beers and Shugart, 1948; Perkins and Lill, 1948).

In 1950 as a part of Mid-Pacific Expedition (Revelle, 1951), Russell Raitt did supplementary seismic work in the Bikini area and other parts of the northern Marshall Islands. New data obtained during this survey necessitated some revision of earlier interpretations. A report on the early seismic surveys is given in chapter J and a report on the 1950 survey in chapter K. In chapter K, Beauregard Perkins compares and coordinates all available data.

MAGNETOMETER SURVEY

In 1947 as a part of a resurvey of Bikini the Naval Ordnance Laboratory and the Geological Survey collaborated in an airborne magnetometer survey over the atoll and over Sylvania Guyot adjoining it on the west. A broad negative anomaly was found over the atoll with several superimposed localized anomalies; the anomalies associated with Sylvania Guyot were larger than those of Bikini Atoll (Alldredge and Keller, 1949). Assuming uniform susceptibility and zero permanent magnetization Alldredge and Dichtel (1949) constructed a magnetic model of Bikini Atoll. Their study of this model indicated that the basement material may lie within 5,000 feet of sea level approximately 1 mile northeast of Bikini island. Alldredge, Keller, and Dichtel have reviewed the magnetic data and their findings and conclusions appear in chapter L of this report.

FIELD WORK

Ladd was in charge of geological work during the surveys of 1946 and 1947 and the drilling on Eniwetok Atoll in 1950–51, spending a total of 6 months in the field. During his absence in 1946 Emery acted as Chief of Party, and in 1947 under similar conditions Tracey took over this responsibility. After the bombing in 1946, J. E. Hoffmeister spent several weeks with the party in a reexamination of many of the reefs. During the resurvey in 1947 Gordon Lill of the Office of Naval Research, R. Dana Russell of the Navy Electronics Laboratory, and J. H. Johnson and J. W. Wells of the Geological Survey were members of the party. Russell was responsible for dredging in the lagoon and on the outer slopes of the atoll. Lill, Johnson, and Wells assisted with the drilling program and their special reports on other phases of the geological work form later chapters of the present report.

In 1946 Emery was directly responsible for phases of the investigation dealing with submarine geology and has prepared the sections of the report covering this work. Tracey and Ladd collaborated on studies of the reefs and islands and on the drilling. Tracey has prepared most of the text dealing with subsurface geology, including the detailed logs appearing on pages 214–259. Photographs not otherwise credited were taken by Emery in connection with his studies of submarine geology or by Tracey, who concentrated on the reefs and islands.

Work done by Tracey on the subsurface geology of Bikini was used by him in a dissertation presented in partial fulfillment of the requirements for the degree of Doctor of Philosophy at Yale University.

During the Mid-Pacific Expedition in 1950 the work was under the general leadership of Roger Revelle with Emery in charge of the submarine geology and Raitt in charge of the seismic studies.

ACKNOWLEDGMENTS

The geological work in the present report was supported by Military Intelligence Division, Office of the Chief of Engineers, and by the Bureau of Ships and formed part of the work of the Oceanographic Section of Joint Task Force One under the leadership of Roger Revelle, then Commander USNR. A brief explanation of the plan of Operation Crossroads and how it was organized and developed is given by Doctor Revelle in his foreword to the present series of reports. Dr. Revelle made many helpful suggestions and his understanding interest in all phases of the geological work is greatly appreciated. The Mid-Pacific Expedition of 1950 was led by Dr. Revelle.

Most of the soundings in deep water off the atoll slopes and the guyots were taken aboard U. S. S. *Sylvania* (KA *44*) with the interest and cooperation of Captain M. H. Simons, Jr. Most of the geological work in the lagoons was done aboard U. S. S. *Blish* (AGS *10*) commanded by Lt. F. A. Woodke, without whose interest and help little of the material would have been obtained. The sonic profiles of the top parts of the outer slopes were obtained by Ens. R. R. Zisette, Jr., commanding YMS *463*. Other ships aboard which soundings and other data were collected were U. S. S. *Gilliss* (AGS *13*), U. S. S. *Bowditch* (AGS *4*), U. S. S. *Walke* (DD *723*), YMS *354*, YMS *358*, and ARS *8*. During Mid-Pacific Expedition additional soundings were obtained aboard U. S. S. *Horizon* and UPCE (R) *857*. Equipment for submarine geological sampling was loaned by the Scripps Institution of Oceanography, the Woods Hole Oceanographic Institution, the U. S. Navy Electronics Laboratory, and the U. S. Navy Bureau of Ordnance.

Nearly all the chart making and sediment study was done at Allan Hancock Foundation of the University of Southern California. Laboratory and drafting equipment was supplied by Hancock Foundation, U. S. Navy Hydrographic Office, and the U. S. Geological Survey. The painstaking task of plotting the soundings obtained by the expedition was completed by W. W. Clarke, who worked on a full-time basis for a year and a half. Study and reduction of other field data and much of the drafting was done by geology department students working part-time over periods ranging from 3 to 18 months each. Large contributions were made by the following: W. Dell'Oro, Patricia Douglas, F. A. Fleming, J. F. Foster, J. G. Holwerda, K. H. Koford, J. F. Mann, and E. H. Shuler. J. F. Mann also assisted Emery in the field in addition to his regular duties as a naval officer. Similar field assistance was given by Ens. Barney Timmer. E. H. Shuler accompanied R. Dana Russell on the resurvey expedition in 1947 to obtain additional geological data. During Mid-Pacific Expedition R. S. Dietz obtained bottom samples and photographs aboard EPCE (R) *857*, R. F. Dill and R. Y. Morita made chemical analyses of waters from solution basins, and other staff members assisted in many ways. To all these individuals and organizations appreciation is expressed.

REGIONAL SETTING

WINDS AND OCEANIC CIRCULATION

In the northern Marshalls the wind blows chiefly from the east and northeast throughout the year. As shown by meteorological records from Ujelang, an atoll about 100 miles southwest of Eniwetok, these winds—the trade winds—are most constant in direction during the winter months, from December through March. Their velocity then is about 18 knots. During the rest of the year, when the belt of trade winds has shifted northward, the winds are generally lighter and more variable both in direction and velocity. Hurricanes and gales are infrequent but when they do occur they are most likely during the summer and autumn and usually come from the southeast. The rainfall is lowest during the time of trade winds, when it averages about 3 inches per month. The heaviest rains occur from September through November. At Ujelang the average annual rainfall is 83 inches and farther north at Bikini Atoll it is less. The mean average monthly temperature is uniform throughout the year, ranging between 81° and 83° F.

During most of the year the water current in the northern Marshalls comes from the east. This current, termed the North Equatorial Current, owes its origin to the action of the prevailing trade wind. In the summer and autumn the North Equatorial Current shifts northward with the trade wind belt and at this time the northern Marshall Islands region lies in a zone of variable currents, the North Equatorial Current and the Counter Equatorial Current. Similarly, throughout most of the year the waves and swell come from east-northeast and are caused by the trade wind. During the summer and autumn, however, a long swell from the southeast is often present. This is produced by storms in the South Pacific during the southern hemisphere's winter. A more complete discussion of some of the oceanographic characteristics of the region is presented by Robinson in chapter D of the present report.

DEEP-OCEAN FLOOR

PHYSIOGRAPHY

The two chains of the Marshall Islands in which most of the atolls are located end on the north at about the latitude of Bikini Atoll. Depths between the atolls in this general region range from 2,500 to 3,200 fathoms, or 15,000 to 19,200 feet (chart 1). Contours within the areas limited by dashed lines were taken from the larger-scale charts of the atolls and guyots surveyed during Operation Crossroads. Only one of these areas—Eniwetok Atoll—contained more than a score of soundings prior to Operation Crossroads. Altogether, nearly 26,000 soundings now available in those areas permitted accurate contouring. The rest of the chart was based on about 3,200 soundings that include those shown on Hydrographic Office Chart 5413 and overlay 11851, those on published charts of individual atolls, plus several lines obtained by ships en route to and from Bikini Atoll during Operation Crossroads and the Mid-Pacific Expedition. The positions of the soundings beyond the areas charted at a larger scale are indicated by dots on chart 1 of this report. If the 3,200 soundings were evenly distributed there would be 1 sounding for each 73 square statute miles. Because of the low density of soundings for most of the region a wide contour interval, 500 fathoms, was selected. This interval is sufficient to indicate the general shapes and characteristics of the atolls and guyots.

Inspection of chart 1 shows 21 atolls and at least 37 clearly defined guyots. In addition, there are a number of relatively shallow single soundings which may have been taken on the side slopes of other guyots. Other undiscovered guyots may exist in some of the several areas of more than 3,000 square miles in which there are no recorded soundings. The discovery of two new guyots by the U. S. S. *Sylvania* and U. S. S. *Bowditch* indicates the likelihood of additional ones.

The chart shows that some of the atolls and guyots occur as clusters. For example, Bikini, Rongelap, Rongerik, Ailinginae, and Wotho Atolls together with 6 guyots are all enclosed by the 2,500-fathom contour and they comprise a fairly compact group. This cluster and another one around Kwajalein Atoll are part of the Ralik (Sunset) Chain. Another group, consisting mostly of atolls, which surrounds Wotje Atoll is part of the Ratak (Sunrise) Chain. Eniwetok Atoll is located amongst a group of guyots whose arrangement indicates the presence of a third but almost completely submarine chain in the Marshall Group. Thus, in the northern Marshall Islands the middle chain, Ralik, contains about equal numbers of atolls and guyots, whereas the Ratak Chain to the east is nearly restricted to atolls, and the "Eniwetok chain" to the west is mainly composed of guyots. Apparently the difference in relative numbers of atolls and guyots of each chain is not related to differential submergence because the average depths of the guyots of each chain are about the same. Each of the 3 parallel chains has a width of between 75 and 150 miles; their overall length was not investigated because of the scarcity of soundings farther south. In addition to the guyots in the chains there are many others that appear to be isolated.

A hypsographic curve (insert of chart 1) was constructed for the region. As expected, the curve shows that much less than 1 percent (0.2 percent) of the area rises above sea level and only 2.2 percent of it is shallower than 700 fathoms, the approximate mean depth of the tops of the well-surveyed guyots. About 38 percent of the area is shallower than 2,500 fathoms. Examination of the curve and chart suggests that if the atolls and guyots were excluded the general depth of the region would be about 3,200 fathoms. Between this depth and 700 fathoms the atolls and guyots have a bulk volume of about 224,000 cubic statute miles. Above 700 fathoms the volume of rock is 3,000 cubic statute miles; this volume is almost entirely restricted to atolls. Thus, if one should assume that the guyots and the portion of atolls deeper than 700 fathoms are composed mostly of volcanic ejecta and the atolls above 700 fathoms are mostly of calcareous debris, he would find a ratio of volcanics to calcareous debris of about 75 to 1.

SEDIMENTS

DESCRIPTION

The most detailed and useful description of the deep-sea sediments of the area are those given by Murray and Lee (1909) for each of the *Albatross* samples. They described 8 samples of coral sand from the Marshall Islands but since each was small and appeared to have been washed in the sampler only qualitative data were given. All were fairly similar. They were gray colored, granular, and contained fragments of the following calcareous organisms: corals, pelagic and bottom-living Foraminifera, echinoid spines, gastropods, tunicate spicules, pteropods, heteropods, otoliths, ostracodes, and less frequently polyzoans, pelecypods, and alcyonarian spicules. Some siliceous remains of sponges, radiolarians, and diatoms are present. Most of the samples contained a small quantity of inorganic mineral grains including feldspar, magnetite, and glass.

There were 22 good unwashed samples of *Globigerina* ooze plus some smaller washed ones. Typically the *Globigerina* ooze was cream-colored, coherent, plastic, and contained an average of 75 percent calcium carbonate. The calcium carbonate is in the form of fragments of organisms: pelagic and bottom-living Foraminifera, echinoid spines, otoliths, coccoliths, rhabdoliths, ostracodes, and rarely of teeth, tunicate spines, and coral. Two samples contained crystals of dolomite. Usually, there was also about 3 percent of siliceous material mostly from radiolarians, sponge spicules, and less often of diatoms. From 1 to 2 percent of the ooze consisted of mineral grains—usually glass, feldspar, magnetite, and in some samples also pumice, augite, hornblende, olivine, chlorite, and palagonite. The median grain size of the mineral grains was about 0.08 millimeters, just slightly coarser than silt. Although not given by Murray and Lee, the median diameter of *Globigerina* oozes is highly variable, ranging, conservatively, between such extremes as 0.010 and 0.450 millimeters according to some analyses by Revelle (1944). About 20 percent of the ooze was listed as fine washings, mostly clays. Samples of *Globigerina* ooze taken from between Rongelap and Kwajalein Atolls were brownish, clayey, and contained only about 50 percent calcium carbonate but with 40 percent fine washings and 10 percent of mineral grains. This area, therefore, appears to be a transitional zone toward red clay, but still is properly classified as *Globigerina* ooze. Following the notations used in the original descriptions, these samples are shown on figure 7 as *GV*, *Globigerina* ooze with some volcanic sand.

Two samples of red clay from just beyond the borders of figure 7 were described by Murray and Lee. Like other typical red clays from the Pacific Ocean (Revelle, 1944) they are brown in color, plastic, and coherent. The median diameter of red clay samples is ordinarily about 0.001 millimeter. The two described samples have less than 9 percent calcium carbonate consisting of pelagic Foraminifera, echinoid spines, and teeth. Siliceous material was less than 2 percent and consisted of radiolarians, sponge spicules, and, in one sample, of arenaceous Foraminifera. The mineral grains in the red clay were between 5 and 10 percent and included pumice, feldspar, augite, olivine, magnetite, glass, palagonite, phillipsite, and manganese oxide. Most of the red clay, 84 percent, was classed as fine washings, mostly clays.

Some additional samples, mostly cores of *Globigerina* ooze and red clay were obtained near Bikini Atoll during Mid-Pacific Expedition in 1950. These will be discussed in detail in a later section of the report.

DISTRIBUTION

Prior to Operation Crossroads a large number of deep-sea sediments were collected during expeditions of the *Albatross* (Townsend, 1901), the *Nero* (Flint, J. M., 1905), and the *Tuscarora* (Hanzawa, 1928). The insert map of figure 7 shows the courses followed by these ships. All of the samples collected by the *Nero* and most of those by the *Tuscarora* are some distance from the Marshall Islands. The *Albatross*, however, obtained samples along both chains of the Marshall Islands.

All of the known deep samples from the vicinity are plotted on figure 7. Altogether, these comprise 211 samples obtained before 1946 plus 25 from Operation Crossroads and Mid-Pacific Expedition. They range to depths as great as 3,500 fathoms. Thirteen of the samples are of reef detritus called coral sand from the flanks of the atolls, 82 are of *Globigerina* ooze, and 141 are of red clay. If these samples were evenly distributed throughout the area of the chart there would be only one sample for each 9,000 square miles of the area, consequently, boundary lines between the three types of sediment cannot be drawn with much accuracy. The accuracy can be improved by making use of the better known topography of the area.

A small insert on figure 7 shows the depth distribution of all of the known samples. Thus, of the 32 samples from between 200 and 2,200 fathoms only 1, or 3 percent, was red clay and the rest, or 97 percent, were *Globigerina* ooze or coral sand. This diagram then makes possible a rough estimate of the sediment most likely to be encountered at any given depth. For example, at depths shallower than 300 fathoms only coral sand should be expected, between 1,400 and 2,000 fathoms only *Globigerina* ooze, and below 3,000 fathoms only red clay is likely. In the transition zone between 300 and 1,400 fathoms either coral sand or *Globigerina* ooze is present, and between 2,000 and 3,000 fathoms either *Globigerina* ooze or red clay would be found. Arbitrary dividing depths were chosen at 1,000 fathoms and 2,400 fathoms between the three kinds of sediments. Through use of these arbitrary limits plus the available samples, regional boundaries were drawn on figure 7. Some departure from strict observance of the limits was deemed best. Coral sand

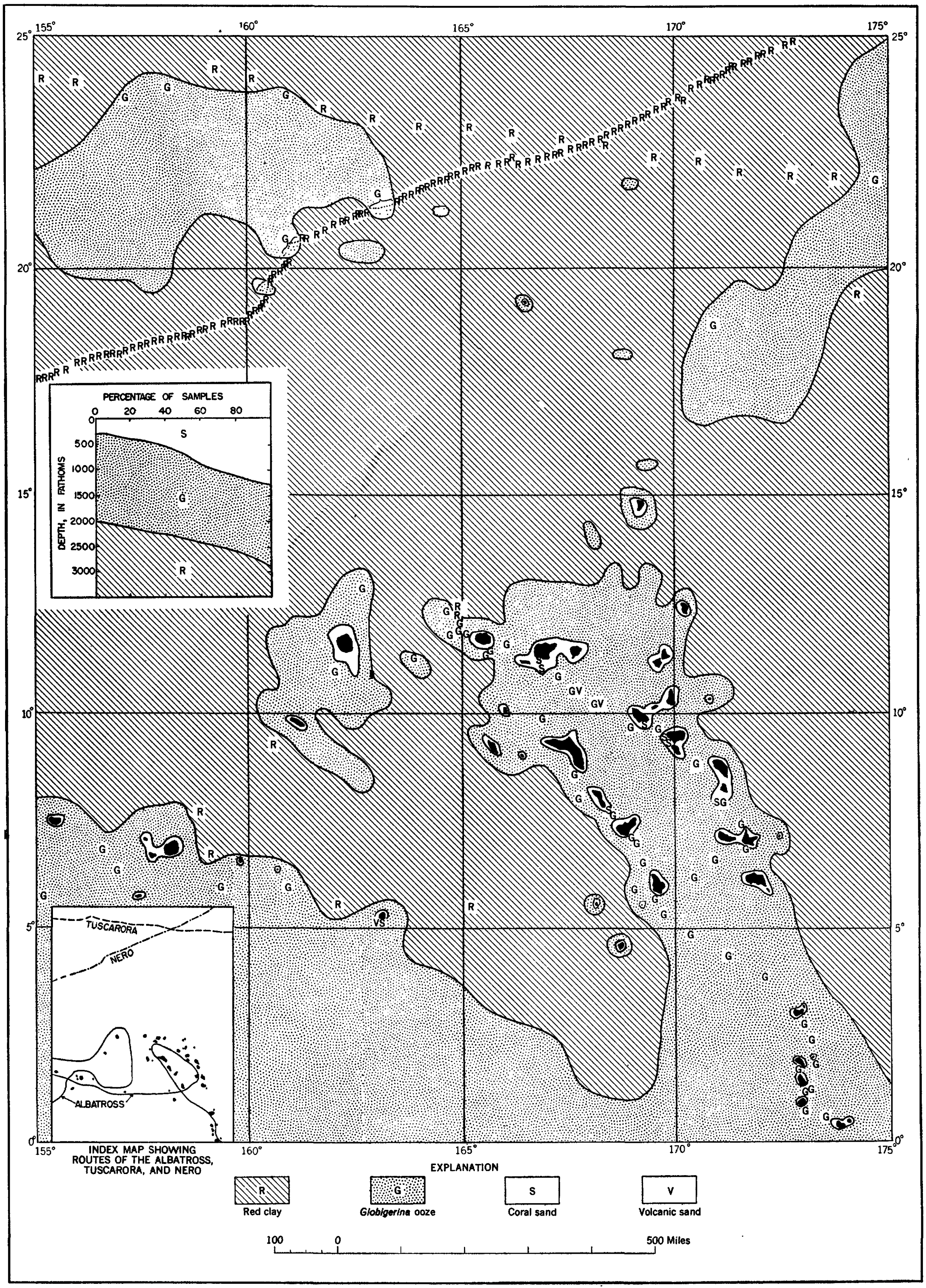

FIGURE 7.—Distribution of deep-sea sediments in Marshall Islands area.

was indicated only if slopes fringed an island or atoll which could serve as a supply area; but coral sand was not indicated for guyots even though their tops were shallower than 1,000 fathoms because samples from such guyots collected during Operation Crossroads and Mid-Pacific Expedition consisted almost entirely of the shells of *Globigerina* rather than of coral detritus. A departure from use of the 2,400-fathom lower limit for *Globigerina* ooze was made for elevations which rise from very great depths even though they do not reach the 2,400-fathom limit.

The steepness of the atoll slopes is such that no great difference in position of the boundary between coral sand and *Globigerina* ooze would result if the limits were chosen several hundred fathoms shallower or deeper than the 1,000-fathom contour used. The regional boundary between *Globigerina* ooze and red clay is subject to greater error. Some uncertainty is also present because of possible gradation between sediment types.

In general, figure 7 shows that the atolls are fringed by a peripheral zone of coral sand which must grade into *Globigerina* ooze covering the lower slopes and the area between atolls. The whole Marshall Island group is surrounded by a wide zone of *Globigerina* ooze which extends southward to enclose the Gilbert Islands. A branch of the area also trends northwestward enclosing the Caroline Islands. The resulting Y-shaped area of *Globigerina* ooze is completely surrounded by red clay as shown on a smaller scale more generalized chart by Murray and Lee (1909).

In 1938 Seiti published a general report and map covering the deep sea deposits of the southeastern part of the north Pacific Ocean.

GUYOTS

In areas of abundant soundings in deep water in the Marshall Islands, deeply submerged guyots (flat-topped seamounts) are indicated. Most of them range in depth between 500 and 900 fathoms, averaging about 700 fathoms. They are flat or nearly flat-topped and have diameters about the same as the atolls, mostly ranging between 10 and 30 miles, as shown by chart 1 (see also pls. 10 and 11). In 1946 sounding lines were obtained across five of the guyots and samples were collected from one of them. Many additional samples were obtained in 1950. Hess (1946) showed that similar guyots occur throughout much of the southwestern Pacific Ocean area.

ATOLLS

During Operation Crossroads five atolls, Bikini, Eniwetok, Rongelap, Rongerik, and Ailinginae, were investigated in some detail. The exposed part of each was mapped by compilation of aerial photographs and the lagoons of all except Ailinginae Atoll were sounded and sampled. The outer slopes of all were studied. A tabulation of some pertinent size and depth measurements (table 3) shows that these atolls range from 55 to 430 square statute miles in area. The range of maximum lagoon depths is 26 to 35 fathoms. Detailed descriptions of each atoll will be presented in later sections. The general form of the atolls (except Eniwetok) and their relations to some of the guyots are shown on plates 10 and 11. The outline and contours on these plates are from K. O. Emery; the airbrush shading is by Ossie Goodloe.

Data on the range and average of sizes and depths of atolls in the Marshall, the Gilbert, and the Ellice

TABLE 3.—*Statistics on the atolls*

[Numbers in parentheses are averages]

	Length (statute miles)	Width (statute miles)	Lagoon depth (fathoms)		Lagoon area (square statute miles)	Reef area (square statute miles)	Reef length (statute miles)	Maximum pass depth (fathoms)	Number of passes
			Maximum	Average					
Rongelap	33	20	35	27	396	34	93	33	9
Eniwetok	25	20	35	26	360	32	72	31	3
Bikini	26	15	32	25	243	30	66	30	8
Rongerik	11	11	26	19	57	12½	34	21½	2
Ailinginae	17	4	(?)	(?)	40	15	39	(?)	2
Marshall Islands:									
29 Atolls	5–58 (20)	1–50 (8)	8–48 (34)	7–31 (25)	2–880 (98)		9–189 (45)	1–35 (21)	0–12 (4)
5 Islands	1–4 (2)	¼–½ (⅓)							
Gilbert Islands:									
11 Atolls	5–32 (15)	3–17 (9)	5–20 (15)	5–15 (9)	8½?–178 (56)		14–65 (35)	7–20 (?)	0–5? (1)
5 Islands	2½–9 (6)	1½–2 (2)							
Ellice Islands:									
6 Atolls	3–14 (7)	1–8 (3)	6½–30 (?)	3–24 (?)	½–72 (20)		7–68 (22)	4–18 (?)	0–10 (2)
3 Islands	½–1½ (1⅓)	¼–1 (¾)							

Groups are presented in table 3 for comparison. Some of the data were taken from Nugent's (1946) compilation. These were checked and supplemented by additional measurements from the navigational charts. The three groups chosen are sometimes referred to as the "Low Islands," because all are atolls or surface banks. They are distributed in a northwest-trending string which is continuous except for the two interruptions which serve as the chief bases for distinguishing the three groups. Table 3 shows that the lagoons of the 29 atolls of the Marshall Group range in area from 2 to 880 square miles. The 5 atolls studied during Operation Crossroads differ from one another in some ways but appear to be fair samples of the whole group. The 11 atolls of the Gilbert Group, immediately southeast of the Marshalls, are generally smaller and shallower than the Marshalls, and the Ellice Group, still farther southeast, is composed of even smaller atolls. In general the atolls of smaller area have shallower lagoons. Each of the 3 island groups also includes several isolated islands which are smaller than any of the atolls and which, according to available charts do not have central lagoons. None of these islands were investigated in the field. All except the smallest atolls contain passes through the reef and at least one pass on most atolls was found to be nearly as deep as the adjoining lagoon. Unfortunately, few of the charts contain enough soundings to permit the determination of exact pass depths and of accurate topography on the lagoons.

GEOLOGY OF BIKINI ATOLL

Bikini Atoll is about 26 miles long from east to west, 15 miles wide from north to south, and is roughly oval in shape (fig. 6). Its marginal reefs are continuous except on the south side, and they range in width from less than a quarter of a mile to more than a mile, averaging about half a mile. The lagoon covers 243 square miles, with a maximum depth of 32 fathoms and an average depth of 25 fathoms.

The 26 islands, all located on the marginal reef, have a total area of about 3.4 square statute miles; omitting intertidal areas the islands cover about 2.4 square miles. The largest ones are Bikini, Enyu, Enirik, Namu, and Aomoen, and these contain most of the coconut trees, some of which rise to 85 feet above sea level. Most islands are only 8 to 12 feet above low-tide level, but parts of Bikini island are 16 to 19 feet high, and on Romurikku island the top of a dune lies 23 feet above the reef flat.

A number of passes penetrate the reef. The widest of these is Enyu Channel on the southeast which is 9 miles wide but only 4 to 10 fathoms deep. All the other passes are on the southwest side, and none of these is wider than about 1 mile. Enirik Pass is the deepest, reaching a depth of 30 fathoms between Enirik and Eninman islands. All the passes are navigable but except for Enyu and Enirik Passes they are crooked and fringed by shoals.

Mean high spring tides rise 5½ feet while mean high neap tides rise 3¼ feet according to "Sailing directions for Pacific Islands." This Hydrographic Office publication states that in 1930 there were 127 inhabitants, mostly on Bikini island. During the early part of the war the Japanese maintained a meteorological station at Bikini, but the atoll was bypassed and later taken over by United States forces in 1944 with no struggle. The only visible evidences of the war were the wrecks of two planes—one a U. S. Navy PBY, the other a Japanese bomber—and a monument to two Japanese airmen. Early in 1946 the 167 inhabitants were moved to Rongerik Atoll in preparation for the atomic bomb tests.

REEFS

ZONATION AND CLASSIFICATION

It is impossible in most places to traverse a reef without recognizing that the area is at least roughly zoned parallel to the reef front. Zonation of this sort has been recognized in many areas (Finckh, 1904, pp. 126–140, pl. 17). Mayer, 1924; Marshall 1931; Ladd, 1934, pp. 68–69; Ladd and Hoffmeister, 1945, pp. 109, 119–122; Teichert, 1947; Fairbridge, 1948). Some of the bands are growth zones wherein certain organisms outnumber all others; elsewhere the bands are sandy depositional flats or areas of solid-rock pavement. Differences in the composition of the reef surface and in organic growth are also observable laterally—along lines parallel to the reef front—but these differences are less striking than the banding that parallels the reef front. Zonation is clearly shown on air photographs (pl. 12).

In order to present a clear picture of the reefs of the atolls studied a classification of reef types was evolved which was found to correlate with the prevailing oceanographic conditions and to be applicable to other atolls in the same area. This classification is based primarily upon the characteristics of the marginal zone of the seaward side because this zone is the most vital part of the reef. Being in direct contact with the open sea, it receives a constant supply of water rich in food and nutrient salts. It supports the greatest concentration of living organisms and to a large extent it controls the environments of the reef zones that lie behind it. The character of the marginal zone and the nature of the assemblages of organisms that live on it are in turn dependent upon the characteristics of the submarine slope upon which it stands, its relation to the prevailing waves and currents, and other ecological factors. Accordingly, the different types of reefs occur in different sectors of the atoll (fig. 8).

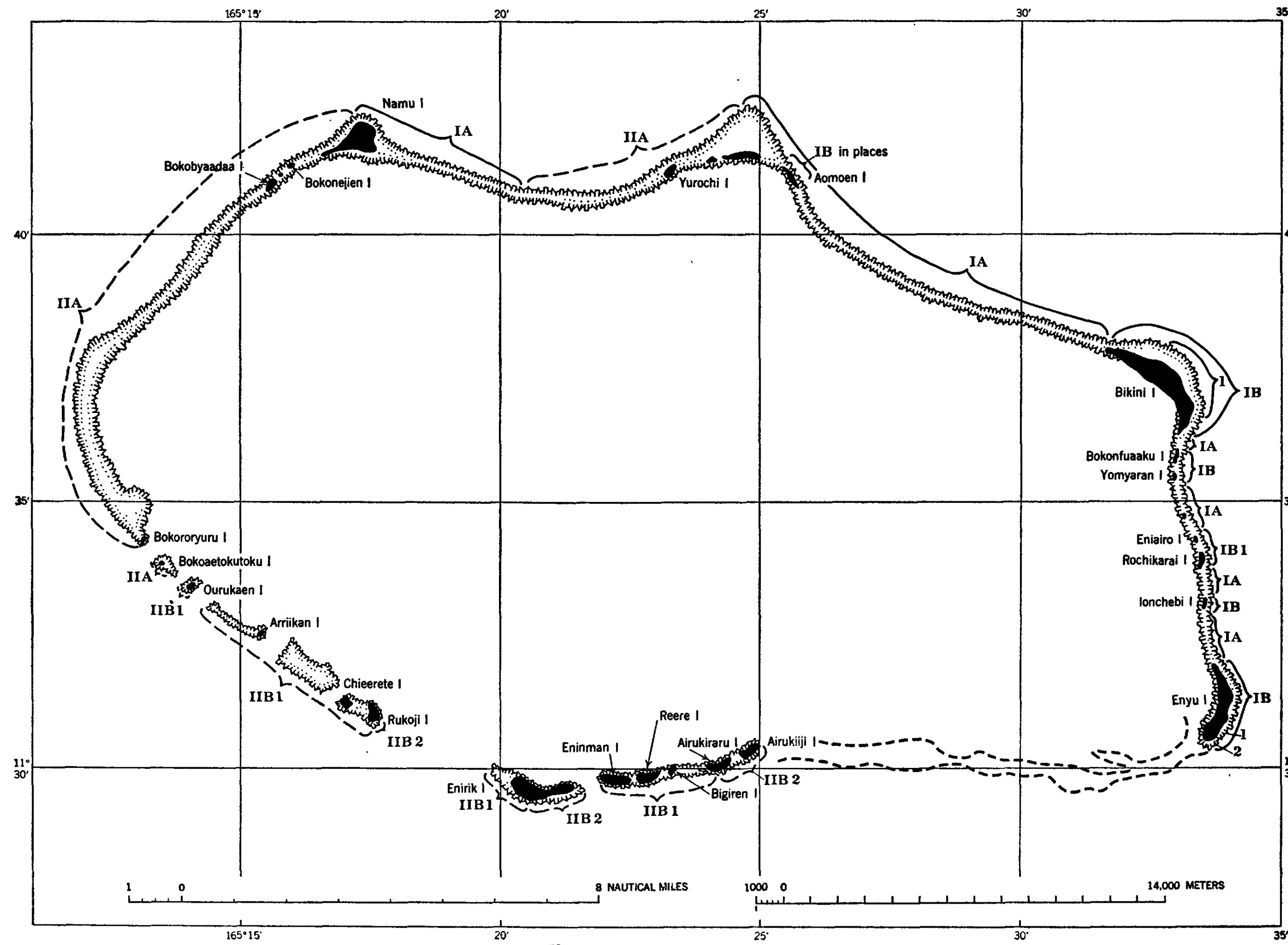

FIGURE 8.—Distribution of main reef types on Bikini Atoll. Refer to key in text.

Reef type [1]	*Occurrence*
1. Strongly grooved	Wave-windward side.
A. *Lithothamnion* ridge low, uncut by grooves	Areas between islands, concave seaward.
B. *Lithothamnion* ridge prominent, cut by grooves that form surge channels.	Areas, especially off islands, convex seaward.
1. Ridge formed by columnar bosses separated by intersecting surge channels, roofed over locally to form room-and-pillar structure.	Northeast reef off Bikini island.
2. Ridge formed of elongate buttresses separated by narrow surge channels roofed over to landward, and terminating in algal mounds and blowholes.	Southeast reef off Enyu island.
2. Grooves weak or absent	Leeward side.
A. Reef margin smoothly scalloped	Western reefs.
B. Reef margin made irregular by erosion	Southern reefs.
1. Reentrants large and irregular	South-southwest reefs.
2. Reentrants long, narrow, subequal in size	South-southeast reefs.

[1] The several reef types are illustrated on plates 13 to 15.

The distinctive features of the several reef types are as follows:

Type I, strongly grooved.—The seaward slopes of this type of reef are cut by well-developed grooves normal to the reef front 50 to 300 feet long, 3 to 10 feet wide, and 6 to 25 feet deep. The grooves are relatively straight but in some places are forked, usually downslope. The spurs separating the grooves are flattened algal ridges 25 to 50 feet or more in width. The tops of the ridges are covered by living algae, and the sides also appear to be algal, but there is no evidence that the algae are roofing over or otherwise filling the grooves.

Reefs of this type are best developed on the windward side of the atoll. They are characterized by well-developed algal growth that appears to be adjusted to strong steady surf. The waves remove much material from the reef in small pieces which are transported down the grooves and down the terrace. Eroded parts of the reef are healed by organic growth, and the reef appears to be near equilibrium. Since these parts are adjusted to strong surf, major storms have little additional effect.

Type I–A, Lithothamnion ridge low.—For the sake of convenience all the massive coralline algae of the marginal ridge are referred to the old collective genus, *Lithothamnion*, or, more simply, as lithothamnia. In this usage we are following Taylor who notes (1950, p. 6) that the commonest genus at Bikini Atoll is *Porolithon*, a segregate from *Lithothamnion*. The marginal ridge is a broad arch, sloping gently seaward and rising only 6 inches to 1 foot above the main reef flat. With rare exceptions the grooves, though well developed, are limited to the seaward slope beyond low-tide level. The reef flat behind the marginal ridge generally supports a rich growth of corals. This type of reef is characteristic of reef segments between islands; these areas are typically concave to the sea. There are no islands to impede circulation of water, and on the windward side new supplies from the sea cross the reef even during ebb tide. This circulation is probably mainly responsible for the rich growth of corals.

Type I–B, Lithothamnion ridge prominent.—The marginal ridge is a conspicuous feature rising 2 to 3½ feet above the main reef flat behind it (pl. 12). The well-developed grooves of the seaward slope cut across the ridge to form surge channels that extend 50 to 100 feet from the reef edge. Between waves much of the water that is piled on the reef drains seaward through these channels.

Reefs of this type are best developed on convex arcs of reef, especially where islands are present. The islands restrict circulation of water, and such flats support very few living corals. The reef flats in such areas are subject to erosion.

Type I–B–1, Lithothamnion ridge, formed in some areas of isolated columnar bosses.—The landward sides of such structures between surge channels are composed of calcareous algae that form a smooth pavement. These algae may grow laterally at low-tide level and eventually roof over the surge channels. This produces a type of "room-and-pillar structure" along the margin of the reef that is similar to the underground workings commonly developed in mining operations. When the roofing-over process is nearly or quite complete it may be recognized on aerial photographs by a honeycomb pattern (pl. 14, fig. 2).

This type of reef is well developed off Bikini island, an area given special attention in connection with the bomb tests. It seems to require rather special conditions and probably is rare, though it may have been present at one time or another over a large part of the Bikini reef.

Type I–B–2, Lithothamnion ridge, formed of elongate buttresses separated by narrow surge channels.—In areas where the surge channels are long and narrow—like miniature canyons—algae from the sides grow outward as a shelf at low-tide level eventually covering the channel to form a tunnel. The landward end of such a tunnel may remain open as a blowhole long after the rest of the channel is closed, and, in such cases, a crater-like algal mound is built around the opening (pl. 50, fig. 1). Reefs of this type are developed on the south and southeast sides of Bikini but are even better developed on the south-southeast side of Eniwetok where the terminal mounds rise 2½ to 3 feet above the reef flat.

Type II, grooves weak or absent.—On the seaward slopes of reefs grooves are rare or absent, and no true *Lithothamnion* ridge is developed. Reefs of this type are best developed on the leeward sides of atolls, and in most places there is no evidence of a terrace.

Type II–A. Reef margin smoothly scalloped.—The outline of the reef edge in some areas is straight or smoothly scalloped. The seaward slope ranges from very steep to vertical to depths of 30 or 40 fathoms. The marginal zone supports a fairly rich growth of corals and algae, but it rises only a few inches above the reef flat.

On the edge of reefs of this type growth apparently exceeds erosion; the reef is adapted to the weak surf present on the lee side. The broad reef on the western side of Bikini Atoll belongs in this category.

Type II–B. Reef margin irregular.—The margins of many reefs on the south sides of atolls are very irregular in outline. Two main types of irregularities exist, one of which, at least, appears definitely to be due to erosion. The southern coasts receive the most severe storms.

Type II–B–1. Reentrants large and irregular.—The sharply irregular reentrants in the reef margins in a few places are almost certainly due to erosion followed by collapse. These reentrants are 25 to 500 feet or more wide and extend into the reef for 25 to 200 feet. The floor at present is covered with debris—including large blocks, the irregular outlines of which match those of the reef edge. Debris of this sort occurs to depths of at least 100 feet.

Reefs with large irregular reentrants occur on the south-southwest sides of atolls in the northern Marshall Islands. They are adapted to the weak surf of such lee shores, but the severe storm waves from the south apparently cause major damage. Even in the reentrants, however, large blocks torn from the reef edge are veneered with living corals and algae.

Type II–B–2. Reentrants long, narrow, subequal.—The reentrants of this type are 100 feet or more in length, very narrow, and apparently shallow (10 to 15 feet at most). They are closely spaced, separated by narrow algal ridges (pl. 15, fig. 2). The reentrants and ridges together form a sort of comb structure that rises from a floor 15 to 25 feet in depth.

This type of structure occurs on the south-southeast reefs. It may be related to the blowhole type described under type I–B–2, but erosion rather than growth appears to be dominant at the present time. The lines of fissurelike reentrants form an erosion pattern that is hard to explain, and the present form may be determined by some earlier growth pattern.

WINDWARD REEFS

The windward reefs of the north and east differ markedly from the leeward reefs of the west; reefs on the south side that are subjected to heavy storm attack fall into still a third class. The sides of the atoll that are directly exposed either to the prevailing trades or to the southerly winds are bordered by a shallow terrace that slopes very gently seaward, from a depth of 15 to 25 feet at the reef edge to a depth of about 50 feet at the outer edge. Where well developed, the terrace is rather flat for a distance of several hundred yards from the reef edge; in other places its slope is 10° to 15°. The living reef rises from this terrace. The upward slope from the terrace to low-tide level is comparatively steep and forms a distinctive zone, as the remainder of the reef surface is comparatively flat (fig. 81).

REEFS ADJACENT TO ISLANDS

SEA SIDE

As described in the classifications given previously, windward reefs adjacent to islands (type I–B–1) have distinctive features, among which is the prominent cuesta-shaped *Lithothamnion* ridge. On the reef flat behind this ridge, other zones parallel the reef edge. A part of the reef off Bikini island shown in plate 12 is an excellent example of reef zonation. The marginal zone and reef flat may be divided into the following zones:

A. Seaward slope to terrace.
B. *Lithothamnion* ridge.
C. Coral-algal zone.
D. Outer *Heliopora* zone.
E. Main reef flat.
F. Inner *Heliopora* zone.
G. Beach.

Over large sections of the reef, living organisms occur in profusion and, considered as a whole, the reef appears to be flourishing. The marginal zones appear to be growing seaward, and some of the other zones are growing upward. However, very large sections of the reef flat appear to be static, with no appreciable changes due to growth, erosion, or deposition; one small area appears to be undergoing active erosion. Each of the zones is briefly described below, and an appraisal of the present trend is given.

Seaward slope to terrace.—In the area shown in plate 12 the submarine slope is approximately 150 feet wide and slopes at an angle averaging about 15° from low-tide level to the surface of the terrace. At fairly regular intervals along the slope there are nearly straight grooves at right angles to the reef front. These grooves are from 5 to 10 feet in width, as much as 25 feet deep at their inner ends, and their rock floors, conformable with the terrace, are covered in some places by a veneer of sand, gravel, or boulders. The grooves are separated by flattened spurs, 25 feet or more in width.

The spurs were not sampled, but the authors examined them by swimming with a face mask. They consist mainly of living algae, but there is no evidence to indicate that the algae are roofing over or otherwise encroaching significantly upon the grooves. The seaward ends of the spurs are bluntly rounded, and they are believed to be growing outward and upward, slowly extending themselves over the terrace.

Munk and Sargent (1948) have indicated that the reefs at Bikini Atoll are dynamically adjusted to prevailing ocean waves and have shown that the distribution of the marginal grooves can be correlated with the mean annual distribution of wave power around the atoll. The figures they give are impressive: against the windward side of Bikini Atoll alone the waves dissipate 500,000 horsepower, one-fourth the power generated at Hoover Dam. This force, however, is not very effective in eroding the reef. Under weather conditions prevailing at times of observation, such clastic material as is present on the floors of the grooves is not churned up and ground against the reef with each rhythmical wave advance, although on occasion the waters off the reef edge are slightly murky. Presumably, the clastic material passes seaward down the grooves and across the terrace. Probably there is mechanical abrasion during periods of exceptionally heavy weather, but this does not seem adequate to explain the grooves as erosional features. Kuenen (1933) and Hanzawa (1942) have discussed these grooves ("channels," "toothed edges"). They agreed that growth rather than erosion or solution is primarily responsible. Kuenen believed that the toothed edges of the East Indian reefs have been eroded since their formation, citing those described by David and Sweet (1904) from Funafuti as living examples in the open Pacific. The presence of grooves is apparently controlled by exposure to waves, and their length is influenced by the slope of the reef and by other factors. However, the most striking features of the zone where the grooves occur are the spurs, and these appear to be growth forms. The grooves, and the surge channels into which some of them lead, form a most effective baffle that dissipates the destructive energy of the waves and at the same time brings a constant supply of fresh water with oxygen, food, and nutrient salts to a maximum surface area.

Lithothamnion ridge.—At the seaward edge of the reef a rich growth of calcareous algae (lithothamnia) forms either a gently convex rim or a cuesta-shaped structure (pl. 14, fig. 1) whose steeper side faces the sea. The convex rim is formed chiefly along the stretches of reef that lie between islands, and the cuesta-shaped ridge is formed where the reef fringes islands, especially where the islands lie inside arcs of reef that are convex to the sea. The convex type rises only 6 inches to 1 foot above the main reef flat, but the cuesta-shaped type may rise as much as 3½ feet. The upper limit of each appears to be determined by the height to which the waves can wash regularly at low tide, because algae of the types growing on the reef edge cannot survive even partial desiccation—they require, in fact, considerable circulation of agitated water.

Some of the grooves of the seaward slope continue into or through the *Lithothamnion* ridge as surge channels for distances of 50 to as much as 300 feet. Pavement-forming algae cover the back slope of the ridge and form thickened rims along the edges of the channels to which each wave brings a fresh surge of water. The algae, by growing laterally at the surface, eventually roof over the landward parts of the surge channel, thus adding new reef surface and creating caverns beneath the reef. Before the roofing-over process is completed, blowholes may be developed, as described by Tracey, Ladd, and Hoffmeister (1948). From some of these the water issues from geyserlike algal craters, in other areas from a series of holes along an old fissure; in still other places hundreds of holes may form a honeycomb of openings. At low tide the geyserlike holes spout water violently and noisily with each incoming wave; from the others the water usually wells quietly, the mounds of water merging to form a thin sheet that washes landward over the flat.

The vigorous growths of algae along the sides of the surge channels and in areas of blowholes indicate clearly that the algae in those areas are making headway against the sea. The passages and caverns below the surface support a rich growth of corals which probably in time will fill much of the space there (pl. 16, fig. 2). The algal pavement that forms the gentle back slope appears to be fairly well stabilized in most places. Surge channels are being roofed over in many places, thus extending the area of the algal pavement. In other areas it is riddled by echinoid borings (pl. 18, fig. 1). The edges of the older borings are covered by new algal growth, however, and it is doubtful whether the echnoids can do permanent damage to the algal ridge. The buttresses that face the sea and receive a heavier pounding than any other part of the reef are completely covered by living calcareous algae; parts of them are covered by the smooth botryoidal crusts of pavement algae, and all channels and depressions are lined with globular masses of branching *Lithothamnion.* Among the numerous lithothamnia of the reefs there are three types that occur in great abundance: globular colonies (*Porolithon gardineri*) that flourish along the seaward edges of reef buttresses and along the upper parts of the surge channels; pavement-forming algae (*Porolithon onkodes*) that are best developed on the back slope of the ridge; and columnar colonies (*Porolithon craspedium*) that are most numerous on the reefs of the leeward side of the atoll where they are found near the edges of the seaward reefs and those facing passes. The thick branches of the globular clusters form porous masses capable of absorbing the force of heavy waves without breakage.

Coral-algal zone.—On the inner side of the marginal zone there is a belt of rich coral growth nearly 400 feet wide. True reef corals cover 50 percent or more of the area (pl. 18, fig. 2). Shallow pools contain many corals (pl. 18, figs. 3, 4). The remainder of the zone is mostly covered with pavement and nodular types of pink *Lithothamnion.* The pavement-forming algae surround beads of living coral and in some places seem to be encroaching upon them; in other places the corals appear to be encroaching upon the algae.

The coral-algal zone appears to be fairly well adjusted to existing conditions. The growth forms of the coral colonies—encrusting, low, and massive or with short, stubby branches—do not extend above the reach of waves at low-tide level. It is clear that they cannot rise higher without drying at times of low water.

Outer Heliopora *zone.*—In this area the general surface of the reef flat is distinctly lower than the zones to seaward and is covered by 1 to 4 feet of water at low tide. From the floor large subcircular masses, 3 to 25 feet or even more in diameter, consisting largely of the blue alcyonarian, *Heliopora,* rise close to low-tide level. In the outer part of this zone the microatolls are formed mainly by the scleractinian coral, *Acropora palifera.* This zone is a part of the belt of microatolls. In these structures, as in true atolls, there is a concentration of living forms around the periphery, although live colonies, particularly *Heliopora* and algae, may be growing sporadically all over the structure (pl. 19, fig. 2). The *Acropora,* which apparently is not quite so hardy a form as the *Heliopora,* is concentrated around the edge of the microatoll, and most of the colonies are at a somewhat lower level than the Helioporas; at low tide the tips of many *Heliopora* colonies break water.

The upward growth of the microatolls is definitely limited by low-tide level, but the growth around the rim of each structure is rich, and the masses appear to be expanding laterally in all directions. As they coalesce, they form a new reef surface—not so firm a surface as the pavement from which they grow but one that may become so eventually by continued organic growth and silting. Many of the dead Helioporas in the centers of the microatolls are covered by a film of sand very rich in Foraminifera.

Main reef flat.—Between the outer and inner *Heliopora* zones lies the main reef flat, a fairly level rock surface that is divided into two parts by what appears to be the margin of an older reef—one that may have flourished at a time before the part of the reef now lying to seaward had grown up to low-tide level and had thus effectively reduced circulation. At the present time this old reef line is a hummocky surface of limestone cut by wide transverse gaps and narrow longitudinal fissures. It is practically bare of organic growth, and parts of it that dry at low tide appear to be undergoing erosion by solution. The surface of the main flat on either side appears to be stabilized under present conditions. The main flat supports a variety of organisms, but there is no great development of reef-building corals or algae. Much of its surface is veneered with a mat of smaller Foraminifera held together by a fibrous alga, but the Foraminifera are not building up the reef surface. As they die, their shells are carried to the beach.

Inner Heliopora *zone.*—In the innermost zone of the reef flat the microatolls (pl. 19, fig. 1) are more widely scattered and in most places are smaller than in the outer zone. *Heliopora* is the dominant form, but, nearer shore, colonies of *Porites lutea* become increasingly numerous and in some structures almost completely replace the *Heliopora.* Nodules of living coralline algae 1-2 inches in diameter are abundant. If existing conditions continue, it seems likely that the microatolls will continue to spread and will eventually cover most if not all the intervening pool areas. Bordering this zone is the beach which will be described in a later section of the report.

LAGOON SIDE

In the lee of Bikini island is a discontinuous series of irregular reef patches that extends from near the edges of the beaches into the lagoon. The only waves that strike these reef patches are the long, slow ocean swells that enter the lagoon through the wide channel west of Enyu island. Some of these swells rise and fall with little turbulence but others become combers more than 6 feet high that break over the reef edge. The reef patches tend to be wider (into the lagoon) than long (parallel to shore), and they show concentric zoning rather than zoning parallel to the shore. Three fairly distinct zones may be recognized:

1. An outer zone with an irregular, lobate margin formed of discrete heads of coral and alcyonarians 4 to 20 feet in diameter. In the outer part below low-tide level large areas are covered by hydrocorals (yellow-green *Millepora,* the "stinging coral"), with a few small colonies of true corals. Inside this living margin are large subcircular areas that uncover a few inches at lowest tide. The rounded outlines of many of these masses have been determined by the alcyonarian, *Heliopora,* and the scleractinian, *Porites andrewsi* (ramose-growth form), but most of the colonies are now dead and veneered with a film of brownish algae. The bottom of the lagoon between the corals is covered by sand and broken coral on which there are widely scattered clumps of living *Halimeda.*

2. A middle zone, the floor of which lies 4 feet below low water. Colonies of *Heliopora* as much as 6 feet in diameter rise 2 feet above the sand-covered floor, but, like those in the adjoining outer zone, many are dead and partly encrusted with small, branching corals. The sands of the deeper areas are bound by living *Halimeda.*

3. An inner zone covered by 2 to 3 feet of water at low tide supports a considerable variety of living corals, but they cover only a small percentage of the bottom, the remainder being sand. The inner zone abuts against eroded beach rock where such is present, elsewhere against the sand of the beach.

REEFS BETWEEN ISLANDS

These reefs which comprise Type I–A of the classification have a low marginal ridge that slopes gently seaward and rises only 6 inches to 1 foot above the main reef flat. The flat behind the marginal zone is generally less distinctly zoned than the flat found off islands. In most places the flat supports a rich growth of corals for no islands impede cross-reef circulation even during times of low tide.

Lagoon reefs on the windward side in areas between protecting islands differ somewhat from those adjacent to islands. The absence of the island allows the waters of the open sea to wash entirely across the reef at times of high tide—indeed, there is some circulation even at low tide. Where ecological conditions are especially favorable, corals may be abundant all the way across the reef, from the sea to the lagoon. In other places extensive sand flats or deposits of gravel may line the lagoon side of the reef. Over large areas the sand flats are heavily populated with holothurians, whose sand-ingesting activities are in part responsible for reducing the grain size of the sediment. Beyond, in the shallow waters of the lagoon, there is a growth of corals—chiefly the hardy *Porites* (massive and ramose) and *Heliopora*, with some encrusting algae. The lagoon edge of this zone is deeply scalloped or serrate, with large irregularly shaped outlying patches. The lagoon reefs of the windward side are probably encroaching slowly on the lagoon—through organic growth and the deposition of sand and gravel.

LEEWARD REEFS

WESTERN SIDE

Much of the broad leeward reef on the west of Bikini Atoll, specifically the segment that extends from Bokororyuru on the southwest to Namu and nearby islands on the northwest (pl. 15, fig. 1), was not closely examined in many places because none of this 9-mile stretch of reef dries at low tide and there are no islands on which to land. "Landings" on the lagoon side are difficult because of lagoon waves and coral patches; but on the sea side deep water extends close to the reef edge. Ships may come in close, and "landings" on the submerged reef can be made with a skiff between the weak surges. The edge of the reef rises a few inches above adjacent parts of the main flat, and the growth of corals and algae that covers it is awash at extreme low tide.

The most striking feature of the western reef is the steepness of its seaward slope. This slope was first examined off the westernmost point of the reef by the authors, swimming with face masks; later the profile was measured accurately with a sounding lead from a skiff anchored to the edge of the reef. The visible part of the seaward slope is indeed a steep submarine cliff, as noted by Emery (1948). From a depth of 100 feet to an undetermined depth, greater than 180 feet, the cliff was vertical. The slope appears solid, with a rough, lumpy surface; some of the rounded masses on its surface may be old coral heads now overgrown with algae. Globular colonies of *Lithothamnion* were seen to depths of 20 to 25 feet; and green algae, including *Halimeda*, are present. Corals on the steep slopes cover somewhat less than 10 percent of the surface. There are light-colored patches on small ledges that probably are sand derived from the reef. Leeward cliffs such as those seen on the west side of Bikini Atoll appear to be very stable slopes. They are protected from the prevailing winds and from the heaviest storms by their location.

On the western side of the atoll the reef flat is wider than to windward, and it is covered by a greater depth of water. The marginal zone is characterized by a prolific growth of corals and algae, roughly in equal proportions. It rises closer to low-tide level than does the flat behind it; but there is no marginal structure comparable to the *Lithothamnion* ridge of the windward side, and in only a few places are areas of the reef actually exposed at low tide.

The main flat, which exceeds half a mile in width in many places, consists of a hard rock surface, 4 to 5 feet below low-tide level. The general surface is rougher than on the windward side, as tabular masses of coral 6 feet or more in diameter rise 2 to 3 feet above the rock flat. Open pools between the coral masses are veneered with coarse coral sand.

The organisms in the marginal zone appear to be well adjusted to existing conditions, and, because of the absence of strong surf, it is doubtful whether the rim can grow appreciably higher. Over the surface of the main flat the growth of corals and other organisms may result in a small net gain, in that the coral areas may be growing upward and slowly extending laterally, thus reducing the pool areas. This process may be aided in some degree by sedimentation, but, as the sand cover is everywhere very thin, this seems unlikely. The fact that on one measured traverse the sand cover on the reef flat thickened slightly toward the marginal rim suggests migration of sediments toward the edge of the leeward reef with little or no progressive upbuilding of the reef.

On the leeward side of the atoll the lagoon reefs are well developed because they receive fairly strong waves engendered by the prevailing trade winds in their passage across the lagoon—a distance of 10 miles or more. In favorably situated areas—for example, along the northwest margin of the lagoon—the reefs have some of the characteristics of the reefs that fringe the atoll to windward. In many places a distinct algal ridge borders the lagoonal reef, though it nowhere becomes the prominent cuesta-shaped structure that occurs off islands that face the sea to windward. The lagoon reefs to leeward are comparatively narrow and do not exhibit the distinct zonation that characterizes reefs facing the open sea on the windward side. The coral associations of these reefs lack many of the species characteristic of the windward seaward reefs but include some species found on the leeward seaward reefs. The margins of such reefs in general are irregular with many isolated offshore patches that, like the main reef, are awash at low tide.

SOUTHERN SIDE

Marginal zone.—The reefs of the southern side of Bikini are narrow in most places, and their seaward margins are made irregular by channels and sunken areas. Sharp reentrants in the reef margin appear definitely to be due to erosion. The reef edge is cavernous, and, owing to organic growth, the parts near the surface may overhang those below. The edge is composed of living organisms that are adjusted to the small waves and swells that normally strike this coast. Severe storms that at long intervals arrive from the south do great damage to the southern reefs (Emery, Tracey, and Ladd, 1949).

Parts of the edge are thrown upon the reef flat to form the reef blocks (negroheads) that are found in that area, and even larger sections may be loosened from the remainder of the reef and may sink to resting places on the shallow terrace that borders parts of the southern reef. The outlines of some of the blocks match those of the reentrants. The reentrants thus formed may be 25 to 500 feet or more wide and may extend into the reef for 25 to 200 feet. The terrace on which the collapsed sections of the reef edge rest is probably erosional, but it may represent a surface that antedates the present reef. The marginal zone appears to be flourishing and probably is slowly advancing seaward, at least during periods of normal weather. It rises about a foot above low tide and is covered by corals and algae. In most places the algae cover the buttresses between channels, the corals and their allies, particularly *Millepora*, occurring in channels and over slopes below low-tide level. The columnar type of *Lithothamnion* is very abundant on the buttresses (pl. 46, fig. 1), and the globular type occurs in the channels; but a *Lithothamnion* ridge comparable to that of the windward reefs is not present.

Reef flat.—The narrow rock flats of the southern reefs are covered in most places by 1 to 3 feet of water at low tide. This depth of water, the narrowness of the reef, and the absence of a marginal ridge that might interfere with circulation permit corals to grow sporadically all over the flat, and to cover one-half to three-fourths of the surface. Most of the colonies are less than a foot in diameter, and the patches on the flat yield the boulders that form the boulder rampart. The flats themselves appear to be in a state of equilibrium, except in those areas where storm waves have eaten deeply into the reef.

On the lagoon reefs near the southwest passes algae of the columnar type (*Porolithon craspedium*) tend to replace the globular colonies (*P. gardineri*), and the hydrozoan, *Millepora* becomes more important than the true corals. Likewise, near passes an algal-coral flat may form inside the marginal zone, merging into a rock flat which in many places is strewn with coral-head boulders; some lagoonal shores of the southern leeward islands are bordered with a boulder rampart.

REEF ROCK

Reef rock may be divided into two groups, algal or coral-algal reef limestone, formed of large organisms mostly in positions of growth, and detrital reef limestone composed of fine to coarse detrital grains and small whole organisms, some of them probably in or near their place of growth but most of them, including the fragmental matter, transported by currents and deposited across the reef flat. No sharp line of demarcation can be drawn between rocks of these two types.

ALGAL LIMESTONE

Algal reef limestone from the *Lithothamnion* ridge is composed principally of *Lithothamnion* in position of growth. Cavities in the *Lithothamnion*, and spaces between branches or knobs, are filled or partly filled by finely granular detritus consisting in part of tests of foraminifers. Open cavities are in places coated with encrusting forms such as *Miniacina* or *Homotrema*.

Rock from the coral-algal zone behind the reef margin consists of coral colonies, some of them in position of growth, cemented and encrusted by *Lithothamnion*. Granular detritus fills cavities between corals, and in general forms a larger proportion of the rock than in the algal limestone.

In thin sections of the rock the detritus is seen to consist of unsorted tests, many of them thin-walled pelagic species of Foraminifera, fine angular grains of coral or mollusk shells and small echinoid spines, all in a brown pasty matrix that even under high magnification appears to be finely granular.

Small spherulites of carbonate are scattered through the paste (pl. 42, fig. 4). They are mostly 0.03 to 0.05 millimeters in diameter, stellate, and are characterized by a radial structure that shows an interference cross under polarized light. Similar spherulitic structures have been found in crevices, coating the fresh surface of living *Lithothamnion*, closely packed but only one unit thick. In a few of the sections they form an appreciable percentage of the brown paste. These spherulites are probably spicules of tunicates, and have been reported by Hinde (1903) from many of the cores obtained at Funafuti.

DETRITAL LIMESTONE

From the marginal zone of the reef to the lagoon, rock forming the surface or consolidated platform of the flat consists of progressively greater amounts of unsorted organic remains and angular detrital material compared with the amount of coral and algae. Tests of *Calcarina spengleri* and less abundant *Amphistegina* and *Marginopora* form 10 to 30 percent of the rock. Delicate pelagic tests are present although not in quantity. Detrital grains—broken down from organic skeletons—consist of *Lithothamnion*, coral, echinoid spines, and mollusks, some little worn and others broken down to fine fragments. Most of the fragments are angular to subangular, but some are well rounded. The fragments are in a matrix of white porcelaneous to chalky carbonate that fills most of the intergranular spaces throughout the entire thickness of the specimens. Specimens were collected only from the hard surface of the reef, and therefore the variation with depth could not be determined.

In thin section the detrital fragments show little or no evidence of alteration although some open cavities in corals or foraminiferal tests are coated with minute crystals of carbonate. The white matrix in thin section consists of fine detrital grains in a gray to brown microgranular paste. In most specimens the paste appears to form the lithifying cement, although in some specimens, grains are coated with a thin rind of clear microgranular carbonate. In general the clear carbonate rind permeates the brown intergranular filling in minute veinlets and apophyses, and small patches of clear microgranular carbonate are spotted through the field of the brown paste. It seems evident that the paste was deposited at the same time or shortly after deposition of the detrital grains, and that the material was subsequently altered in places to clear carbonate. The clear carbonate appears to form first in small points scattered through the paste, and along the interface between detrital grains and the paste matrix, giving the appearance of a rind of carbonate that surrounds and cements detrital grains. The degree of alteration of brown paste to clear carbonate appears to be greater in specimens from rock flats that dry at low tide than in specimens from flats that are covered at low tide.

Overlying the present reef or the slightly elevated older reef rock is a flat-lying lithified boulder conglomerate that seems to form a platform-like foundation for many of the islands. Formations similar to this have been called shingle conglomerate by Stephenson (1931, pp. 25–96) who considers them to be recently lithified platforms of coral debris. Teichert (1946, p. 152) emphasized the sharp break between such rock and the overlying unconsolidated shingle by calling it shingle limestone. There is, he believed, a distinct age difference that should be stressed. At Bikini Atoll the rock is composed of small to large closely packed, well-rounded coral boulders set in a sandy or gravelly matrix. It is cemented throughout, but the surficial hardening is such that the rock appears more lithified than it actually is. The sandy matrix is less resistant to erosion than the solid coral boulders, which generally stand out on the surface of the platform, cemented only at the bottom to the rock below. Rounded and well-worn heads of *Favia*, *Porites*, *Astreopora*, and similar corals in random orientation are most common.

The conglomerate ranges in height from 1 to 4 feet above the reef flat, and generally stands 2 to 3 feet above it. The surface is much eroded, showing pronounced solution effect, and dips gently seaward. In some places where erosion has been progressive the surface of the conglomerate merges almost imperceptibly with the reef floor. More commonly, the transition from reef to the boulder conglomerate platform is abrupt and the edge of the platform is a rock ledge 1 or 2 feet high.

At Bikini the boulder conglomerate is best developed on the east and south sides of the atoll. A conglomerate is present at the south end of Bikini island, where several groins or rock bars of this material extend into the reef. These are covered by sand of the present beach where they join the island, however, and it is impossible to say how great is their extent beneath the island. The area of exposed conglomerate is very small compared to the area of the island as a whole. Enyu island is similar. A coral conglomerate is well developed at the north end of Enyu, and in a narrow belt around the south end several groins extend from the seaward coast of the island onto the reef. On the smaller islands between Bikini and Enyu the conglomerate appears to be a major feature of the island structure, for although it is normally exposed only in a narrow band, it is more or less continuous about each island except along the sandy lagoon beach. The string of islands along the south side of the atoll shows even larger exposures of coral conglomerate. Much of the area between islands from Airukiiji to Eninman is a conglomerate platform, still recognizable though it may be partly covered with loose boulders or sand near the islands, or much eroded on the reefs.

The oval, isolated southwestern islands have a narrow conglomerate rim on the south and southwest sides, although on Ourukaen and Bokoaetokutoku islands the rim is largely covered by sand.

In most places the boulder conglomerate is similar in grain size and physical appearance to detrital limestone. In some places it is similar to beach conglomerate or even to beach sandstone. Thin sections of the rock show cavities and pores mostly filled with brown finely detrital to microgranular paste, altered here and there to clear finely granular calcite. Some grains are firmly cemented by acicular carbonate, and some open cavities are lined with minute crystals.

The low platforms or groins on the reef lie 1 to 3 feet above the reef level, and they are covered by water during half of the tidal cycle. The brown paste probably represents fine material washed over the rock and filtered down through pore spaces and cavities both during and after deposition of the rock mass. The acicular carbonate lining cavities is confined to parts of the rock above low-tide level, and is probably similar to the cementation seen in beach rock in the intertidal zone. Fine borings are not abundant in the rock, but larger tubes 2 to 3 millimeters in diameter are abundant, and the tubes of boring mollusks are common.

SEDIMENTS ON REEFS

REEF BLOCKS

The seaward margin of the reef is composed dominantly of organisms growing in place and is the source of most of the sediments found on other parts of the reef. Normal waves break off small fragments of living or recently dead organisms, and storm waves break off larger pieces. The storm waves furnish the reef blocks (negroheads) that are present in large numbers near the reef margin on certain sections of the reef. If the edge of the reef is cavernous and overhanging so that storm waves can exert a lifting pressure, large sections of the reef may be broken free to slip down the seaward side or they may be cast upward and come to rest on the surface of the reef flat. At Bikini Atoll, slumped sections of the reef as much as 40 feet long lie on the shallow terrace that fringes the seaward edge and on the reef surface the largest block, 33 by 24 by 12 feet, is 75 feet from the edge of the reef.

Reef blocks are generally 100 to 300 feet back of the reef edge, and where abundant they occur in a narrow irregular band parallel to the reef edge (pl. 20, fig. 1). At Bikini Atoll the reef blocks are most abundant along the northwest stretches of the reef, west of Yurochi island (area 2, fig. 9), and from Namu island southwestward to the extreme west end of the atoll where the trend of the reef swings from southwest to southeast (area 3, fig. 9). Along these reefs the blocks are so abundant that from a distance their silhouette resembles that of a picket fence.

The reef blocks range in size from small coral boulders a few feet across to massive blocks of reef limestone 20 or 30 feet long. The largest ones seen on any of the atolls visited lie east of Bikini island (area 1, fig. 9). A block southwest of Enirik island measured about 25 by 25 by 12 feet. Normal range in size is 5 to 10 feet in maximum diameter and 3 to 6 feet in height. Shapes are very irregular. Most are blocklike, but some are massive coral colonies, particularly of *Heliopora* or *Porites*. Typically the blocks are cemented to the reef flat by calcareous algae; in many cases the cementation is so firm that the blocks seem to be in place as erosional remnants of a once higher reef mass. The relations of the corals within the blocks generally disproves this possibility and where there is a good alignment of corals in the block, the orientation is usually at some angle to the vertical, or even upside down.

The bases of the blocks are normally corroded by solution, and in some places mushroomlike shapes have been formed. These erosional forms are widely developed on coral reefs, particularly on reefs fringing shores of elevated limestone, and have been described and figured by many investigators. Erosion is greatest at high-tide level. Above high-tide level the rock is extremely rough and pitted. Small pits enlarge and coalesce leaving jagged limestone spines from a fraction of an inch to several inches long. The limestone is usually blackened and corroded on the surface, and white and porous internally. Corals and shells apparently are less affected than the matrix of the rock, and generally stand in bold relief on the limestone surface.

Below high-tide level the extremely jagged rock surface grades, in less than a foot, to a lumpy surface with smoothly rounded pits on which embedded corals and mollusks are not prominent. The rock, though porous, is a little more compact on the surface as if case hardened by the deposition of $CaCO_3$. This zone of erosion grades in about a foot into the lowest smoothly eroded zone. This zone is noteworthy in that the rock is harder than the rock above, at least on the surface. Internally it is riddled by boring organisms that may be partly responsible for the greater erosion at the base.

The jagged points formed above high-tide level are probably due to slow percolation and solution by rain water. This can only dissolve or leach the limestone, for it is never supersaturated; consequently even the internal structure of the rock may be affected down to and somewhat below high-tide level.

Some of the reef blocks are of a well-cemented heterogeneous coral conglomerate, with worn corals at all angles, and algal and shell fragments in a sand matrix. Many of those examined, however, consisted of oriented corals cemented by algal material, although with much sand and detrital filling between the corals. These doubtless are blocks from the growing reef.

The huge reef block off Bikini island is particularly interesting. The top of the block is formed of large *Heliopora* plates or colonies, more or less parallel and oriented at an angle of about 45° to the reef flat. The zone of *Heliopora* is 3 to 5 feet thick, and it rests on a conglomerate containing rounded pebbles and cobbles

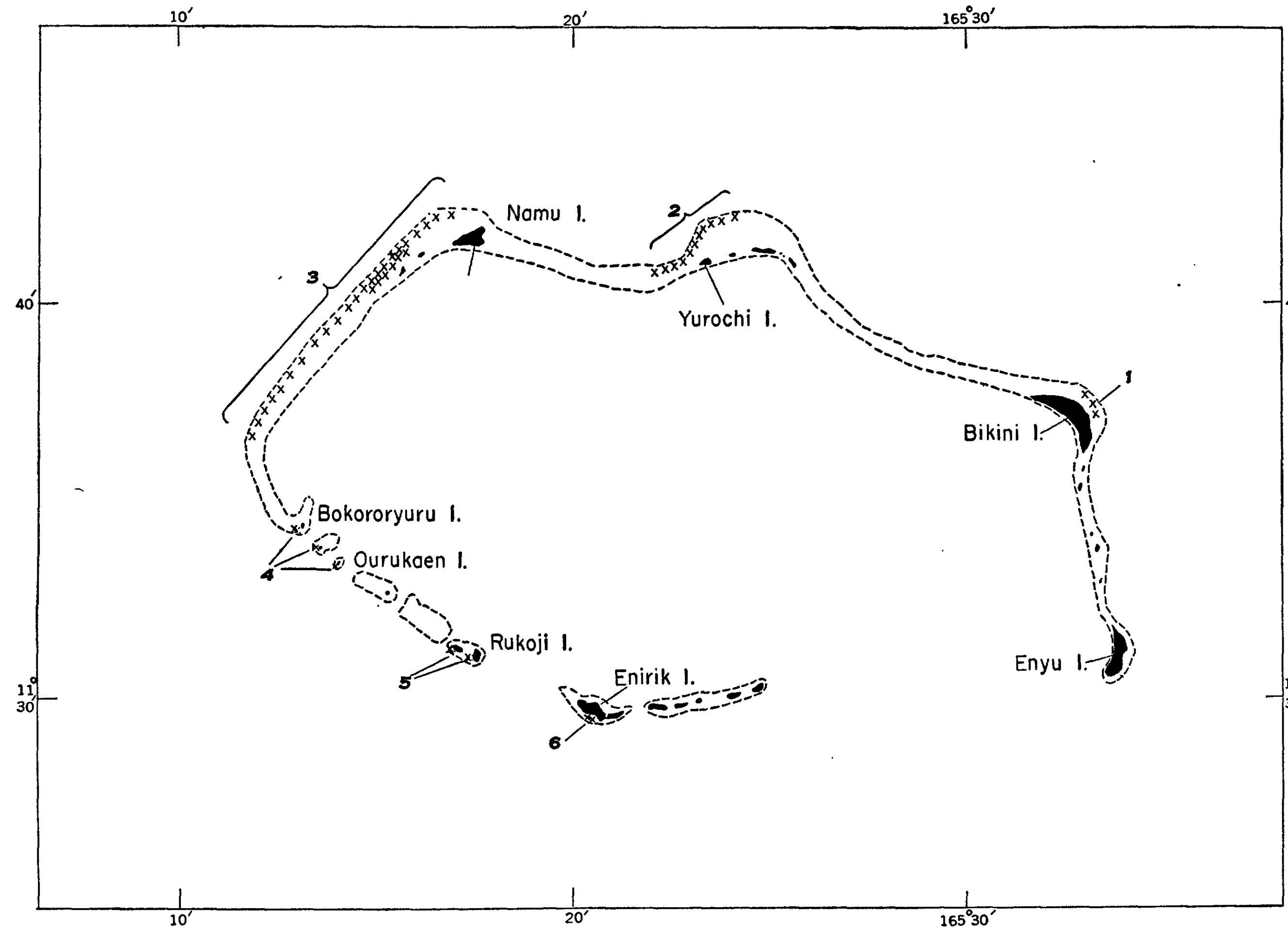

FIGURE 9.—Distribution of reef blocks on Bikini Atoll. Blocks torn from the seaward margin of the reef prevail along northwestward-facing reefs (areas 2 and 3). They are also present close to erosional reentrants on the southwest (areas 4, 5, 6) and along the large reef bend at Bikini island (area 1).

of coral. This is a significant relationship, for large colonies of *Heliopora* have not been observed growing on the outer slopes of the reef, but they occur in abundance on some sections of the reef flat where they often grow from a sand and cobble bottom. The conglomerate at the base of the *Heliopora* is not normally found on the outer slopes on the windward side, moreover where patches of gravel or boulders are present, coral growth is minor. The edge of the reef itself is largely *Lithothamnion*, and the only *Heliopora* present are a few very small colonies in the pools and larger channels. It is not certain, therefore that this block was torn from the reef edge. It seems equally unlikely that the block could be a remnant of a former reef level. If such a reef existed, at least 12 feet higher than the present one, it seems almost inconceivable that a large remnant could exist on the windward side near the reef edge, with no trace of such a higher level remaining in more protected parts of the reef or on any of the islands. The hypothesis remains that the block was a *Heliopora* colony torn from the *Heliopora* zone of the reef flat. This assumption leads to several difficulties. First, there is no cavity on the reef surface of size comparable to these blocks at any reasonably close distance. Unless the cavities have been healed leaving no apparent scar, the blocks must have been carried for a long distance over the reef flat. Large *Heliopora* colonies 20 to 50 feet or more across grow in 4 or 5 feet of water several hundred yards to the north, but it is not reasonable that storm waves from that direction, having traversed a long stretch of reef, would be strong enough to carry a block weighing 200 tons for a distance of nearly a quarter of a mile. The second difficulty is in the dynamics of wave erosion. It does not seem possible for a large wave travelling across a reef flat approximately at sea level to break out and lift a large block from the reef.

Distribution of the reef blocks.—At Bikini there is a fairly regular distribution of reef blocks (fig. 9) that may have some significance in regard to their origin. Blocks are most abundant along the northwest quadrant of the atoll—the northwest-facing reefs that stretch from Namu island to the western bend. The blocks do not occur beyond the western bend where the reef swings to the southeast, and they are rare east of Namu island where the reef trend changes from northeast to east. Farther east, where the reef swings northeast toward Yurochi island and becomes a northwest-facing reef, the blocks are again abundant. These are the only extensive areas of abundant reef blocks, but there are local areas of concentration on many parts of the windward and leeward reefs. The reef east of the middle of Bikini Atoll is one such example; blocks are not abundant there but the two massive blocks mentioned above are in this section. Another area of concentration is the reef south of Enirik island (area 6, fig. 9) and they also are common at several localities on the reefs along the southern string of islands (areas 4, 5, fig. 9). These areas of reef blocks coincide with areas of reef having the large erosional reentrants and it appears that the waves that broke up the reef margin lifted some of the broken blocks onto the reef flat.

Along the northwest reef the blocks occur on a reef flat that is studded with tabular coral colonies several feet in diameter growing in 1 to 2 feet of water. Many of the blocks resemble overturned colonies and may have been torn from the reef flat rather than from the marginal zone.

North of the west end of Namu island, where reef blocks are quite abundant, those examined were largely *Lithothamnion* algal limestone, and were probably derived from the seaward edge of the marginal zone. Evidence for this was seen in a large block of living, pink *Lithothamnion* algae, 10 by 10 by 4 feet in size, that rested on the seaward slope of the marginal zone only a few feet from the cavity from which it had been torn. It was awash, but projected about 2 feet above the crest of the reef. Apparently it had been broken off recently, but was not carried onto the reef.

The rare local patches of reef blocks that occur on parts of the windward reef seem to be confined to areas on the convex arcs of seaward projections of the reef, fringing islands. Blocks are rare or absent altogether, on the long reaches of the reef between islands, except for the two segments of reef facing northwest hitherto noted. Why they should be abundant on this section of the leeward reef, and absent on the southwest section, is not known.

MANTLE ON FLATS

Coarse detritus in the form of coral fragments and pieces of algae broken from the reef margin by wave action is present on the reef flat behind the *Lithothamnion* ridge. Many of the fragments are wedged between colonies of coral and some are solidly cemented there by living *Lithothamnion.* The volume of coarse material decreases lagoonward in most areas. Shallow pools on the flat are floored with gravel, sand and shell and contain some living corals. In places sand and fine gravel may accumulate near the lagoon margins of a reef. At low tide the tops of such deposits are exposed as bars.

The surface of the reef flat is covered by a veneer 2 to 5 millimeters thick of living tests of Foraminifera, principally *Calcarina spengleri, Amphistegina,* and *Marginopora,* along with much finely fragmental detritus bound by a thin mat of filamentous green or brown soft algae. In thin section the surface of some specimens of reef rock is seen to be a layer 1 to 2 millimeters thick of fine angular detrital grains and foraminiferal tests poorly cemented by a brown pastelike matrix. The surficial layer, and the coarser rock below, are riddled by borings of small organisms to a depth of 5 to 10 millimeters. Below this depth borings are uncommon. The borings and open cavities are partly filled by an unconsolidated mass of fine angular detritus that has apparently sifted down from the surficial veneer of living Foraminifera and green algae.

Surficial features appear to be definitely related to location on the reef with respect to water level. Specimens from shallow pools, depressions, or from flat areas not exposed at low tide show the greatest accumulation of organic remains and fine detritus, and the least surficial consolidation of this material. Specimens from flat areas that are exposed for a short time at low tide have a thin veneer of tests and detritus, bound by filamentous algae and partly consolidated by intergranular paste. The upper centimeter, approximately, of the rock is riddled by boring organisms, and the rock is solidly cemented by a paste matrix that under the microscope is partly altered to clear microgranular carbonate.

Specimens from hummocks, knolls, buttresses of the *Lithothamnion* ridges, and rock groins that are exposed over a considerable part of the tidal period show smaller amounts of surficial detritus. The rock surfaces show solution features and are partly coated by brown or green algae. The rock itself is firmly cemented not only by brown paste partly altered to clear microgranular carbonate, but also by the growth of finely acicular carbonate crystals that occur in the matrix and coat the surfaces of cavities. The riddled, spongy texture due to fine boring organisms is absent, but larger tubes 2 to 3 millimeters in diameter are comparatively abundant, and the tubes of boring mollusks may also be present.

ISLANDS

GENERAL FEATURES

There are 26 islands on Bikini Atoll, ranging in size from Arriikan on the southwest side, 600 feet by 250 feet with a dry land area of about 2 acres, to Bikini island, 2½ miles long by ½ mile wide with an area of about 450 acres. The shape of most of the islands is elongate along the trend of the reef, the lagoon beach roughly coinciding with the lagoon edge of the reef and concave lagoonward. The seaward beach is normally convex seaward. The maximum width of an island, on the average, is about half the total width of the reef at that point. This, of course, varies greatly for some islands.

The islands of Bikini Atoll follow a pattern. The largest islands lie on the major arcs or convex bends of the reef. Islands are absent on long-concave-seaward stretches of reef, and on the west side of the atoll. On the southwestern part of the atoll, cut by several passes, islands are small and oval in form.

Islands are formed on top of the reef platforms by the piling up of reef detritus by currents and waves and wind. Some of the materials have been consolidated to form conglomerates and sandstones. Unconsolidated reef detritus is made up of sand, gravel, and rubble from pebble to boulder size, most of the coarser material being of coral origin. Commonly the pebbles and larger pieces occur in a sandy matrix but, in places, especially in the centers of some islands, sand may be lacking entirely. A rubble of cobbles or boulders forms the beach shingle and the boulder ramparts of many islands. The boulders are angular to well rounded and the well-rounded ones in particular are almost always worn coral heads of such genera as *Porites*, *Favia*, and *Symphyllia*. Angular blocks are mostly of algal or coral origin; rarely they are composite fragments of reef or beach rock broken up by storm waves. The sands range widely in composition, grain size, degree of sorting, and structure. The most important components are foraminiferal tests, fragments of corals and mollusks, whole shells of smaller mollusks, fragments of algae (*Lithothamnion* and *Halimeda*) and fine angular grains formed by the breaking down of organic material. The sand is typically poorly sorted, containing pebbles and large angular fragments along with very fine detrital sand but rarely it may be so well sorted that it consists almost entirely of one type of foraminiferal test.

Any of the above materials may occur in consolidated form. Sand is lithified to form sandstone, generally associated with present beaches. The grains are entirely carbonates; constituents, size, and sorting vary in the same manner as in the sand. Stratification, if present, may be well developed or rude. The degree of lithification ranges from very friable, almost unconsolidated materials, to rocks so cemented and case-hardened that it is difficult to break off a specimen with a geologic pick.

Pebble to boulder conglomerate is generally well lithified. The spaces between pebbles or boulders are filled with finer material that, in many cases, is less well lithified, so that on exposed surfaces the boulders—generally rounded corals—weather out in bold relief. True reef rock is a mixture of corals and algae, larger fragments, and unsorted debris containing abundant foraminifers and fine angular detrital sand. Diagnostic characteristics are the presence of corals or large nodular masses of *Lithothamnion* in positions of growth, or the presence of abundant calcareous algae cementing detritus or corals. In some places reef rock resembles gravel or boulder conglomerate, in others it is distinctive enough to be recognized, and is included here as one of the lithologic types, although it is given a genetic name.

The above-mentioned groups of loose materials and lithified rocks form the islands of Bikini Atoll and of the other atolls studied. They occur in several well defined and generally distinctive deposits, the distribution of which is significant in the geological history of the islands.

STRANDLINES

The shores of islands are formed of unconsolidated sands, gravel, or boulders, or their consolidated counterparts—beach sandstone and beach conglomerate. As a general rule, beach conglomerate is associated with coarse gravel or boulder beaches, while beach sandstone is associated with sand beaches, but this is not by any means universal, for deposits shift in adjustment to new conditions of currents and waves, leaving lithified remnants behind. Although the conglomerate and sandstone are older than the present unconsolidated strand deposits, they are, of course, derived from loose deposits; therefore, the latter will be discussed first.

BEACHES

Sand beaches form a major part of the strandlines of most large islands, and of many small ones. These are best developed on the lagoon shores of islands but both Bikini and Enyu islands have wide sandy beaches on the seaward side, with a broad, gently sloping berm above the high-tide level. The seaward coasts of Enirik and Namu, and of most of the smaller islands, are generally rocky in the intertidal zone, with sand accumulations on the rocks above high-tide level at the edge of the zone of vegetation.

During most of the time spent at Bikini Atoll the waves on the beaches in the lagoon were lower than 4 feet with an average period of about 6 seconds. The breaking point was nearly always in water shallower than 3 feet. Part of the time the waves did not curl over and break but only ran a short distance up the beach and then retreated again. Waves on the seaward beaches were much smaller because of their travel over the wide shallow reef surface. They were never found larger than 1 foot in height. Under normal conditions these waves do not break but lap the beach gently. During storms, however, it is probable that very large waves strike the shore and during periods of high swell waves nearly 10 feet high have been seen breaking on the lagoon beaches. Except locally near points fortified by beach rock, the wave crests in the lagoon were nearly parallel to the beach and thus caused little long-shore transport of sand (Munk and Traylor, 1947; Grant and Shepard, 1939). When, however, large swells enter from Enyu Channel there is a considerable long-shore drift of sand to the north along Bikini island's lagoon beach. When the party returned to Bikini Atoll in 1947 it was noted that all the pontoon docks and wrecks on Bikini island had sand piled on the south side.

Currents from causes other than waves likewise appear to be negligible near the lagoon beaches. However, both the general oceanic currents and the breakers at the outer edge of the reef pile up water on the reef so that the sea level of the reef area near Bikini Atoll is usually about 2 feet higher than outside the atoll or within the lagoon. This hydrostatic head causes strong currents at right angles to the reef. The current across the reef at one point was estimated at 5 knots. Such currents are strong enough to shift the sand near the ends of islands and sand bars which block the flow of water. At these points curved spits are common. (See pl. 20, fig. 2.)

Aerial photographs (pl. 20, fig. 2) also show the presence of lagoonward bulges of the inner edge of the reef between islands and bars on the north, east, and south sides of the atoll. These bulges evidently are the result of lagoonward prograding of the reef edge by deposition of sand carried from the reef surface by currents. Where the transport of sand across the reef is blocked by islands and bars, much of it is added to the island beaches. On the westward side of the atoll the direction of the reef current is much less obvious from the appearance of sand bars. This is evidently due to the known reversal of current direction on the leeward reef at ebb and flood tides.

COMPOSITION

Aerial photographs and examination afoot reveals that each of the islands is almost completely fringed by beaches, and that other beaches in the form of bars are present on the reef between the islands. Most of the beaches consist chiefly of sand-sized particles, with subordinate amounts of gravel. However, seaward beaches of islands on the south side of the atoll contain a very large proportion of gravel and boulders. Repeated examination of sandy beaches at nearly 30 points close to Bikini island yielded over 1,700 records of beach material. Of these notations 66 percent were sand, mostly coarse, 19 percent were gravel, which usually formed local strips parallel to the beach, and 15 percent were of beach rock.

About 40 samples were collected from the lagoon and seaward beaches of most of the islands of Bikini Atoll. Most are from Bikini island and the adjacent islets. The composition of the beaches is highly variable, with materials ranging from fine sand to small cobbles, usually arranged in parallel belts along the beaches. An attempt was made to collect spot samples which were representative of most of the material lying between the high- and low-tide lines, excluding cobbles and large pebbles. (See pl. 26, fig. 4.) Although this method is not accurate, insufficient time was available for taking channel samples carefully, and it is doubtful whether such samples would have been more useful than the spot samples.

The beach sands consist almost entirely of organic debris present in varying proportions (pl. 21, figs. 1, 2). Foraminifera range between 10 and 60 percent of the total, and consist mostly of only three species. The most abundant species is *Calcarina spengleri;* a white to orange or brown lenticular form having numerous projecting spines. It was found concentrated on the 1- and ½-millimeter screens. Broken spines mostly were collected on the ⅛-millimeter screen. The species next in abundance is *Marginopora vertebralis*, a flat round disk mostly 2–5 millimeters in diameter. Its large size and white color render it especially conspicuous. A very good concentrate of *Marginopora* sp. was usually found on the 2-millimeter screen in the course of making mechanical analyses. Another tan foraminifer, *Amphistegina* sp., is somewhat similar to *Calcarina* in color and shape, but is spineless and has a smooth, polished test. Both together give the light-orange tint which is more or less characteristic of the seaward and some lagoon beaches.

Also abundant in the beach sands are many broken coral fragments (pl. 21, fig. 3). They are hard, polished, and slightly translucent. These properties, together with the presence of pores, permit their recognition. The grain-size varies from cobble to less than ⅛ mm. *Lithothamnion* is present but is less abundant than coral, from which it may be distinguished by its bleached porcelaneous appearance, chalky on large fragments, smooth and polished in smaller grains. The size range is similar to that of coral; frequently, grains consist of *Lithothamnion* encrusting coral.

Fragments of *Halimeda* are usually present, and in a few places they are abundant, but in most beach sands they are rare. They can be recognized by their characteristic segmented shape, their internal cellular structure, and their finely perforate surface texture. Many other organisms contribute small but generally-present quantities of more or less fragmentary material. Chief among these are the spines and plates of echinoids, shells of gastropods and pelecypods, and more rarely ostracodes, gorgonian spines, and colonies of bryozoans, listed in the order of decreasing abundance.

Most grains, whatever the origin, show some degree of abrasion. For many small grains the wear is so complete that the origin cannot be determined for certain. An effort was made to identify these grains and to speed the identification of larger grains by use of stains. The calcite and high magnesium content of *Lithothamnion* in contrast to aragonite and low magnesium of coral (Clarke and Wheeler, 1922) may serve as a basis for some selective staining, but efforts using some of the stains recommended by Twenhofel (1941, p. 128–131) proved unsuccessful. Chief among the stains tested were Lemberg solution, potassium ferricyanide, silver chromate, and copper nitrate.

Other interesting, though rare, components of the beach sand were found in insoluble residues remaining after treatment with dilute hydrochloric acid. Rare sponge spicules were the only organic constituents recognized. Less expectable in the residues were many shards of glass, probably of volcanic origin and for the most part containing small anisotropic acicular crystals. The index of refraction of the glass ranges from 1.52 to 1.58, and in some pieces it may be slightly beyond this range. The shards range in size from 10 microns or less, to one grain of about 1.5 millimeters length. They probably are not from broken bottles left on the Bikini beaches, because samples from similar bottles contain no incipient crystals. Probably the volcanic glass arrived at Bikini Atoll as floating pumice, because at least three specimens of pumice or cinder were picked up on the beaches of Bikini and nearby atolls. One piece, 3 inches in length, however, was found to consist of glass unlike that in the beach sand; it may possibly be a cinder from a ship's firebox. In none of about 15 beach-sand samples tested did the insoluble residue comprise more than a few one-hundredths of one percent of the total. No systematic variation in percentage was found, and the areal distribution of insoluble residue appears to be erratic. Two large beach-sand samples weighing 250 grams from each end of Bikini Island contained no insoluble residue.

LATERAL MOVEMENT

In order to present a concise picture of the sediment variations, vials of quartered beach-sand samples from Bikini and adjacent islands were placed on a chart over plotted sample positions. The samples showed a general decrease of grain size from the middle of the seaward beach toward the ends of Bikini island and from each end of the island to the middle of the lagoon beach. This trend is subject to variations, caused by local environmental conditions. In order to show this trend quantitatively, a number of samples were selected for mechanical analysis. These were quartered, placed in Tyler screens, and shaken by a Ro-tap machine for 10 minutes each. Only a negligible amount passed the 1/16-millimeter screen. Histograms of the size distribution are shown in figure 10. All samples are fairly well sorted, few having sorting coefficients (*So*) above 2.5. The sorting coefficient is the square root of the ratio of the quartiles ($So=\sqrt{Q_3/Q_1}$), where Q_3 is the coarse quartile and Q_1 is the fine quartile. Both the histograms and median diameters given in figure 10 illustrate the general decrease in grain size away from the middle of the seaward beach and toward the middle of the lagoon beach. This change in grain size is accompanied in a general way by a reduction in the percentage of fragile components such as foraminiferal tests, and an increase in percentage of the more resistant grains of coral debris. The ratio of Foraminifera to coral grains decreases from about 2:1 at the middle of the seaward beach to about 1:2½ near the middle of the lagoon beach.

The change in grain size and composition of the sand reveals something of its history. Apparently, most of the sand has its origin on the broad reef northeast of Bikini island. The Foraminifera that are an important constituent of the sands live on the reef flat. With soft algae and detrital sand they form a thin mat or veneer over large areas of otherwise barren reef rock. The sand of the flat is carried by waves and currents southwestward to the seaward beach. It is then moved westward or southward along the beach. Part of the sand travels past the spits at the ends of the island and is added to the sand bars or other islands beyond Bikini. The remainder is washed around the ends of Bikini and travels along the lagoon beach to its final destination—the middle of the beach where it stays until dissolved or comminuted. The net distance covered is about 3 miles, but the total distance must be many times 3 miles, because of repeated washing up and down the beach slope by wave action. During this long transportation the fragile, hollow foraminiferal tests are broken and comminuted so that they may be readily dissolved or carried in suspension outward from the beach. The more resistant grains travel farther but they too become continuously worn smaller.

LAGOONWARD MOVEMENT

In addition to long-shore transport, some sand is shifted outward—at right angles to the beach. An indication of the nature of this shifting is given by the changes in the beach profiles shown on plate 66. Additional information can be provided by examination of the bottom samples which were collected by snapper

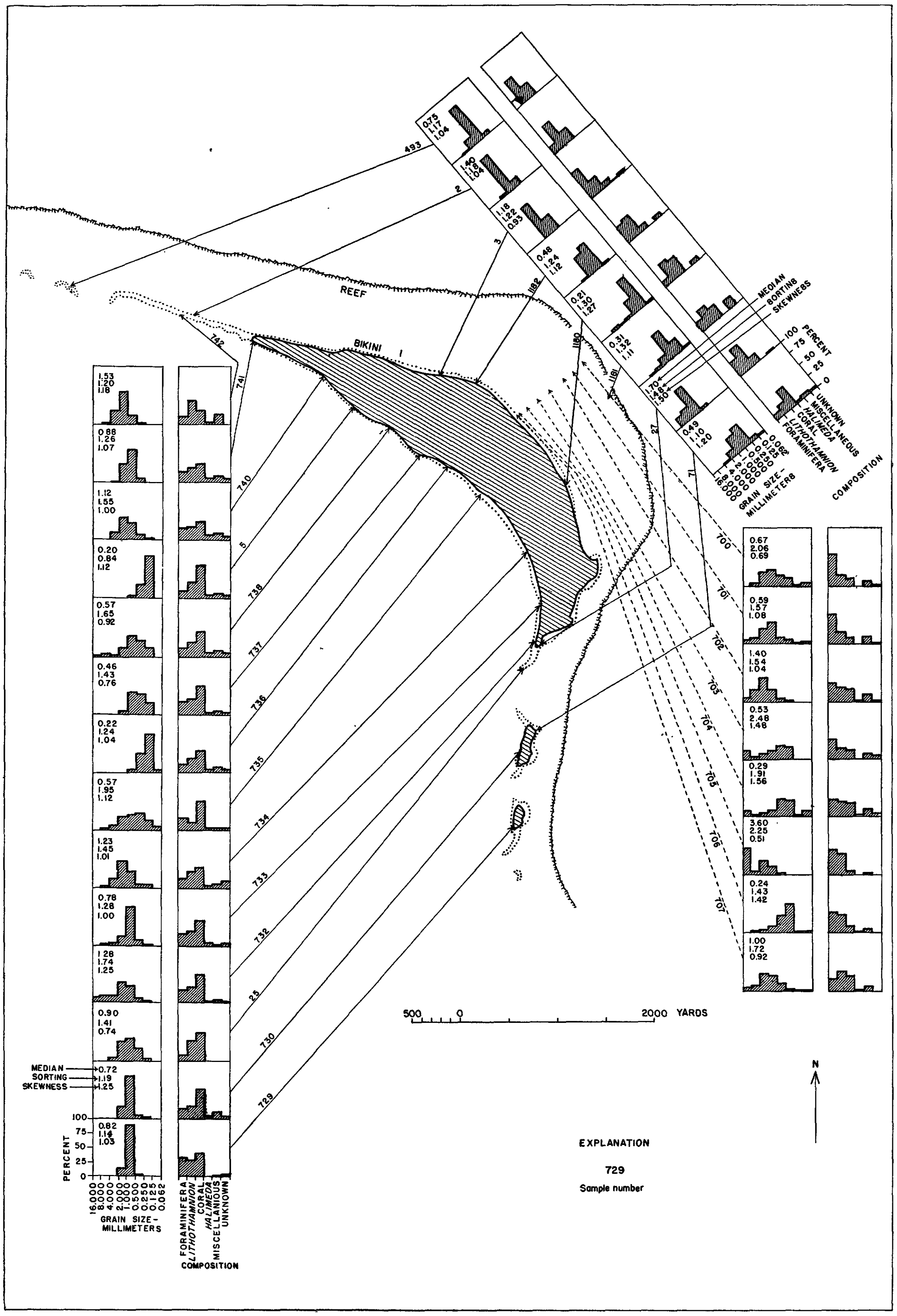

FIGURE 10.—Histograms of size distribution of beach and reef-flat sands around Bikini island.

or scoopfish in profiles normal to the beach. Nine such profiles were made. After the samples had been quartered and put into glass vials, the vials were placed atop the charted sampling positions. Casual examination showed that off the west half of the lagoon beach at Bikini island the grain size decreases continuously from shore out to at least 50-foot depths, 1,200 yards lagoonward. Off the south half of the island, however, the sand decreases in grain size only from shore to about 500 yards. At that point, in depths of 16 to 21 feet, the sand again becomes fairly coarse, followed by a zone of decreasing grain size. In all profiles the general organic composition of the sand is approximately uniform, except for a few samples that consist only of coral, broken from small coral knolls or even from individual coral heads on the bottom. Since such samples are of growth *in situ* and not of transported debris, they are not included in the profiles of sediment samples.

In order to present some of this information on sediment distribution, characteristic samples of sufficient size for mechanical analysis were selected from three profiles. The results of the mechanical analyses are shown in figure 11. For comparison, the bottom depth profiles are also presented. The diagram clearly shows the second coarsening which extends from the south end to a point off the middle of the lagoon beach. Its presence may be the result of transportation by very strong currents sweeping the debris west-northwestward from the surface of the reef just south of Bikini island. Large seasonal waves may also transport much of the coarse beach sand lagoonward into water too deep for the usual small waves effectively to move it back to the beach. In either event, after the coarse sand is deposited on the lagoon floor it may become mantled by finer sand carried from the beach by ordinary wave action and currents, and deposited in order of decreasing grain size. Since the sand of the beach is being comminuted continuously, the beach serves as an ever-present source for the distribution of the finer debris over the adjacent lagoon floor.

A sediment trap was set at a depth of 34 feet near one of the bottom sample profiles. Three other traps were set at other points in the lagoon but only the one near the beach was recovered. All were of the same design (fig. 12) and were made of 16 gauge galvanized sheet steel. They contained a top pan to catch any sediment which might drop downward through the water, and a lower pan to retain any sediment which might be carried by currents just above the bottom. A waffle-like grill was placed in the bottom of both pans to prevent any washing out of sediment by currents or spilling during recovery of the trap. The base of the trap was a broad disk intended to prevent the trap from settling into the bottom. A small brass chain was tied to a bail at the top of the trap, and a 15-pound weight was attached to the chain 6 feet from the trap. The other end of the chain was tied to a small aluminum buoy. In operation, the trap was lowered from a drifting DUKW in such a way that the trap touched bottom gently and the anchor weight dropped near it. Only enough chain was provided to that the buoy was submerged to a depth of several feet.

After an interval of 27 days (April 14 to May 11) the trap was recovered and found to contain many organisms not usually obtained in bottom samples. Among these were, in order of decreasing abundance, 10 snails about ¾ inch long, 9 fish about 1 inch long, many snail eggs, some Harpecticoid copepods, annelid worm larvae, crab larvae, ostracodes, hydroids, nematode worms, and worm tubes. Also present was 6.2 grams of sediment in the top of the trap and 51.7 grams in the bottom. As shown by figure 11, the material in the bottom compartment has just about the same grain-size as nearby bottom samples, whereas that in the top is finer than the finest bottom sample of any profile. The results are interpreted as indicating a lagoonward transport of the comminuted beach material plus some bottom materials stirred up by wave action. The effectiveness of the waves in moving the bottom sand is also shown by the frequent presence of ripple marks in bottom photographs.

MEASUREMENT OF SLOPE PROFILES

During the stay at Bikini Atoll a number of profile measurements of beach slopes were made. Profiles at 28 different sites were obtained, and at each site measurements were repeated at convenient time intervals in order to determine what natural changes occur in the beach. Profiles were measured on April 9, April 17, May 6, and June 14, 1946.

The only instruments needed for the work were two poles, 6 feet in length and marked lengthwise in inches. In operation, assistants held each pole in a vertical position 6 feet apart and in line at right angles to the shore line. The assistant holding the pole farthest from the water sighted across the top of his partner's pole to the horizon. He then read on his own pole the interval subtended by his line of sight. The distance to the top of the pole could be read to ⅒ inch, and it represents the difference in elevation of the two points on the beach. After it and the beach character were recorded, the two poles were shifted 6 feet farther up the beach and another measurement was made. Thereby, a series of elevations and distances were obtained from which the profile could be plotted. In order to make possible a comparison with later profiles, each one was extended to a wooden stake or some other

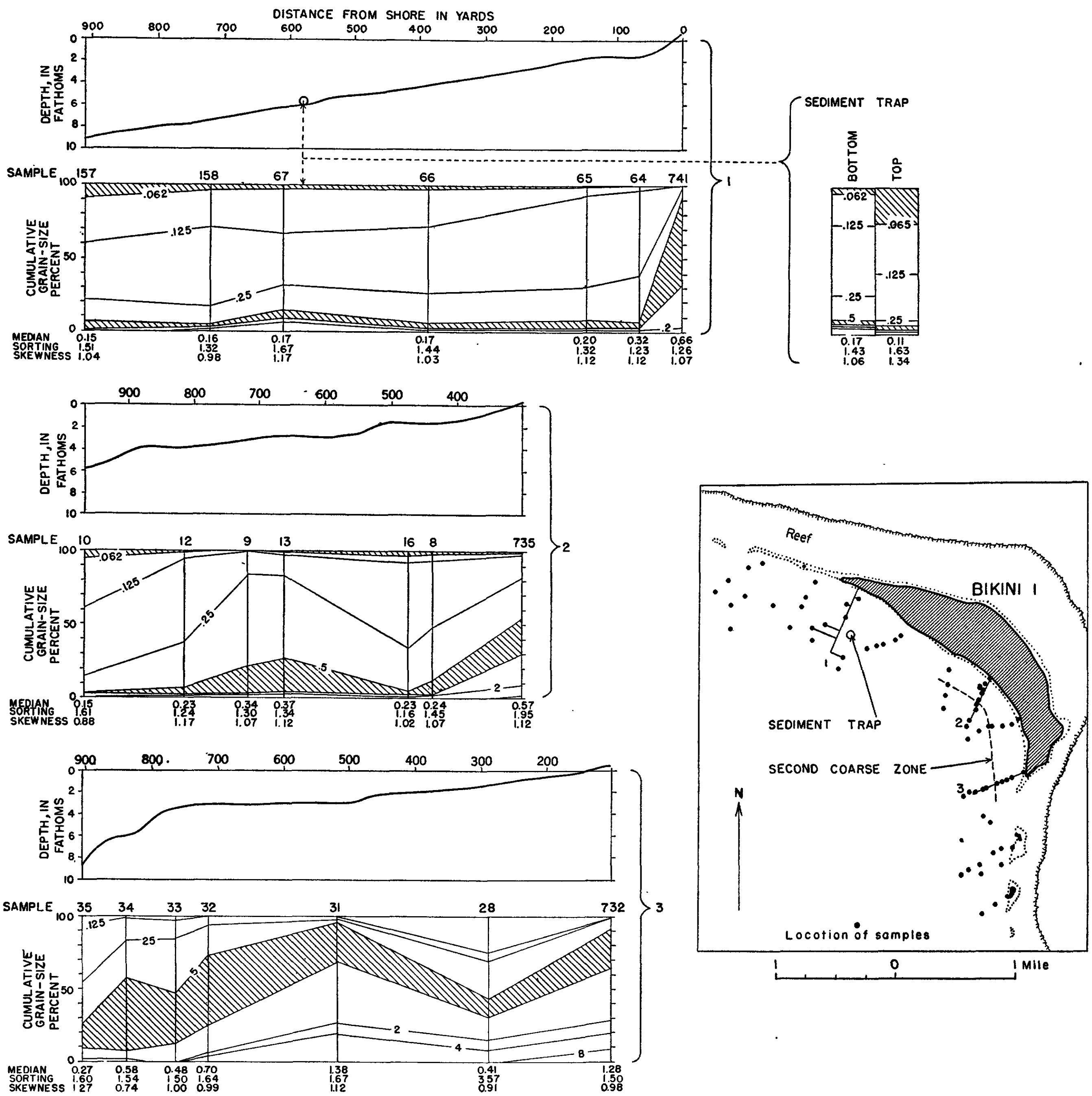

FIGURE 11.—Variation in size of sand grains with distance from lagoon shore off Bikini island.

object which served as a semipermanent bench-mark. This method is rapid and is believed to be accurate to the closest 2 inches. The largest source of error came from the accidental pushing of either pole into the soft sand surface.

SLOPE-PROFILE CHANGES

A total of 81 profiles were measured at 28 beach positions. Many of these profiles were later discarded chiefly because the spot was altered by the activity of man. For example: some of the control stakes were removed by road-building, some of the profiles were artificially changed when the top of the beach was quarried for sand, and a few profiles were inaccessible or valueless when landing craft or wrecks came ashore atop them or nearby. When any of these things happened, the earlier profiles were usually cast out and a new site was selected for later profiles. Moreover, none of the profiles made after the bomb tests are considered here. As a result, only 68, or about 80 percent, of the profiles are believed to be fairly free

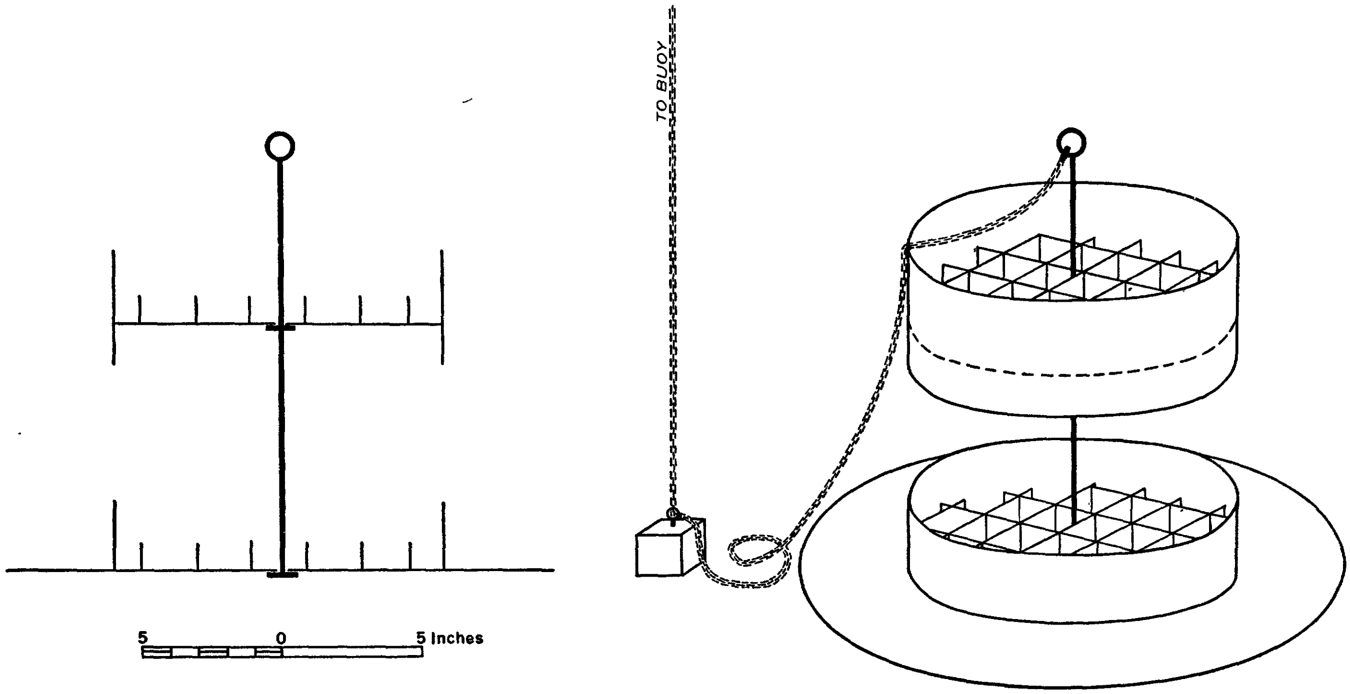

FIGURE 12.—Bottom-sediment trap used in Bikini Lagoon.

from man-made effects. These are shown on plate 66. In general, this compilation shows that the profiles are variable, are concave upward, and that the lower part of many of them is composed of beach rock.

Profiles were measured repeatedly at the same site to learn whether significant differences might be ascribed to natural cyclical changes. California beaches which have been more thoroughly studied than others, generally exhibit both seasonal and tidal cycle variations with sand height in the intertidal zone lowest during the winter and just after spring tides (LaFond, 1939). At Bikini the measurements were conducted over a period of only 3½ months, too short a time to indicate a seasonal cycle with any certainty. On one occasion, a 24-hour period of swells through Enyu Channel that produced surf 8–10 feet high resulted in a marked steepening of beach profile and the addition of several feet of sand to the beach. It is reasonable to expect that the storm season of late fall would result in marked beach recession. The 2-week tidal cycle variation of beach level is also uncertain partly because the time intervals between measurements were too long. Yet, some measurements were made at spring tides and others at neap tides, and for each date there are just about as many instances of cutting as filling of the beach profile. Profiles show an average variation of about 6 inches, 3 times the probable error of measurement. Therefore, the study suggests that tidal cycle variations, if present, are obscured by changes from other causes. It is possible that those changes which were found are largely the indirect result of activities of man too obscure to be evaluated.

During the 1950 expedition five of the beach profiles were repeated, nos. 7, 13, 14, 16, and 18. The repeats for nos. 7, 14, and 18 could not be accurately located because the wooden marker stakes had rotted away; however, no great change of the beach at those points was indicated. Profiles 13 and 16 were relocated, and the results are shown on plate 66. Comparison with previous results shows a cut at profile 13 that amounts to about 40 inches and includes some beachrock. This is in agreement with the general trend of cutting at that point during 1946. The repeated profile 16, on the other hand, indicates a fill in the upper part of the beach.

SEDIMENTARY FEATURES

Many minor sedimentary features are well represented on the sand beaches. Some of these are the result of the movement of grains by waves. Particularly common on the subaerial part of the beach are swash marks, the lines of debris marking the point of farthest advance of a wave. This debris is picked up and carried by flotation on the leading edge of a wave advancing over the beach and it is stranded when the water recedes or sinks into the sand (Evans, 1938). The tests of Foraminifera, particularly of *Calcarina*, are concentrated in swash marks because they have open cells and are of relatively low specific gravity. Locally, the beaches exhibit differential sorting of the constituents by the presence of wide thin parallel strips of different grain size and composition. The highest concentration of coral occurs in broad, coarse-grained strips and presumably develops from exceptionally strong waves. Between the coarse-grained strips are finer-grained ones which mark the work of smaller waves. The deposition of successive layers of these strips one above the other has developed a laminated beach structure like that described by Thompson (1937) for California beaches.

Beach cusps were present during several of the visits to the beach, and were also shown by aerial photographs. These cusps are triangular masses of sand which point toward the water and extend completely across the beach. The interval along the beach between points of the cusps was 10 to 25 feet in the lagoon and only 1 or 2 feet on the seaward beaches. It is known that the beach cusps are formed by waves striking beaches, but the exact mechanism of formation is still unsettled.

Another direct effect of wave movement is the formation of ripple marks in subaqueous parts of the beach. It was observed that the ripple marks were usually of large amplitude and wave length, averaging about 6 inches and 20 inches respectively. These large ripples were never found on subaerial parts of the beaches because of the ease with which they are destroyed as the water over them becomes shallower. Instead, as the tide ebbs, the ripples slowly shift away from shore, always remaining at about the same depth. The only ripple marks found on the subaerial parts of the beach were those obviously formed by wind, judging from the strike of their crests, their position, and their movement by the wind.

Waves have a direct effect on the beach by moving the sand grains, and they also indirectly produce some other characteristic sedimentary features. These features are formed by interstitial air attempting to escape from the sand when water soaks into the beach. Some of the air escapes directly, forming en route small vertical holes in the sand surface. Where the beach is closely laminated, layers near the surface may tend to trap the air and are therefore caused to arch upward to form air laccoliths, or sand domes. Elsewhere, in areas of fine- or medium-grained sand the air is forced into more or less spherical pockets, giving rise to a cakelike texture of extremely high overall porosity. These features: sandholes, sand domes, and high porosity are common on many beaches (Emery, 1945). They, together with the activity of boring crabs, and the lack of cohesion between the coarse sand grains, cause the beaches at Bikini to be soft or loose.

BOULDER RAMPARTS

Gravel and boulders form many of the seaward and lagoon beaches of Bikini Atoll, but great concentrations of these in the form of ramparts are present only on islands located along the south side of the atoll. There are 13 such islands. All 9 that were visited had well-developed boulder ramparts along much of their southern coasts; on 2 of the small westernmost islands the rampart extends along the windward sides of the islands facing passes through the reef; on Enyu island, which faces the widest pass of all, the rampart continues around the southwest end and faces the pass on the west; one small island is completely encircled by a boulder rampart except for a sand beach on the western side.

COMPOSITION

Some of the boulders are subangular to rounded blocks of reef rock, but most of them are coral heads (*Porites*, *Favia*, etc.) that have been only slightly modified in shape by wave action. The boulders vary considerably in size; the largest is 2 or 3 feet in maximum diameter. The gravel and boulders on the backslope appear to be coarser on the average than those on the seaward slope. Some of the boulders were originally coral colonies much larger than any now growing on the surface reefs, and some consist of forms (such as *Hydnophora*) that, according to John Wells' observations, are not now found living on surface reefs at Bikini. It seems probable that many boulders originate in what Wells calls the innominate zone of rich coral growth down the seaward slope, a zone that we found inaccessible to direct observation or dredging.

SLOPES

The ridge of boulders is typically steep (pl. 55, fig. 1), sloping seaward from 15° to 20° in the intertidal zone; above high-tide level the slope is steeper in most places and may be vertical if waves have undercut the rampart. In some places the ramparts extend 5 or 6 feet above high water, descending gently to landward from a narrow crest or rising still higher to landward beyond the break in slope at the top of the rampart.

Three sections across a boulder rampart are shown (fig. 13). The rampart on the southwest end of Enyu island (A, fig. 13) rises to a crest about 10 feet above low-tide level, or about 5 feet above high water. The crest is sharp, the backslope drops gently and abuts a second, earlier rampart that crests about 20 feet behind the first. On Rukoji island (B, fig. 13) a boulder bed rises to a maximum 10 feet behind the top of the rampart, whereas in another section (C, fig. 13) a short distance away, the high point of the boulder bed is

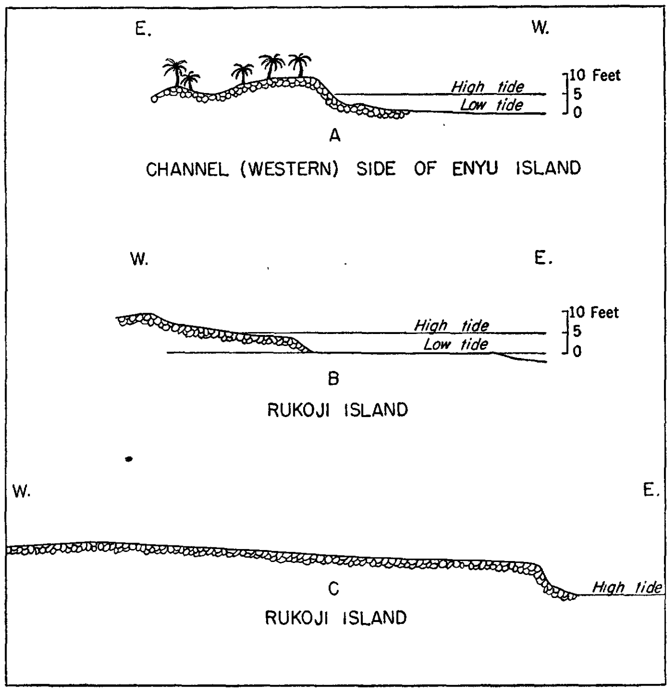

FIGURE 13.—Sections across boulder ramparts. A double rampart (A) on the west side of Enyu island is 10 feet above low-tide level. Maximum elevations are in some places at the crest of the rampart (B); in others well inland (C). Both (B) and (C) are sections from the same rampart on Rukoji Island.

100 feet behind and several feet higher than the rampart. In each of these sections the top of the rampart is about 5 to 6 feet above the high tide level, while the top of the rise behind the rampart is 2 to 5 feet higher. At Rukoji the boulder rampart along the east coast facing Rukoji Pass is 100 feet wide. Its crest rises 5 feet above high tide level, its upper part sloping at an angle of 40°. On the southeast side of Ourukaen the crest of the rampart dips 30° to the sea but the average slope is about 18°.

DISTRIBUTION

The boulder rampart on Enyu island at the eastern end of the south side of the atoll has already been mentioned. Similar structures were noted on the islands to the west. Boulders of coral in the rampart at Enirik were among the largest seen anywhere, measuring as much as 3 feet in diameter.

On the southeast side of Rukoji the rampart extends inland for 100 feet as a deposit of loose coral heads blackened by weather. Most of the heads are 6 inches or less in diameter but a few reach 3 feet. Some are so worn that the original surface of the colony has been removed and the growth form obscured or entirely lost. With the corals there are numerous worn shells of *Tridacna*. The surface of this deposit of boulders is nearly 10 feet above high tide. The rampart and its landward extension continue essentially unchanged around the southwest side of the island and are found also on the shore that faces the lagoon. Only at one place, an area near the middle of the western side, is the boulder rampart absent; at this place it is replaced by a sand beach.

On Chieerete island to the west no well defined rampart is present but a veneer of cobbles and boulders covers parts of the beach rock belt above high tide.

At Ourukaen, an island lying northwest of Ourukaen Pass, the rampart is similar to that on Rukoji. On the southeast where the pass meets the sea the rampart extends from the zone of beach rock blocks to the edge of the island's vegetation. In some places the deposit continues inland as a boulder flat, elsewhere it is replaced by sand. At the northeast corner of the island the sand banks rise 5 feet above the rampart and to the west the sand has been piled into dunes that rise 9 to 10 feet above highest tide.

ORIGIN AND MOVEMENT

As previously mentioned, the southern reefs are part of the leeward side of the atoll but are subject periodically to strong southern swells and on rare occasions to violent storms. Umbgrove (1947) has long recognized that in the East Indies ramparts are highest on the side where the wind exercises its greatest force most regularly. Fairbridge and Teichert (1948), who restudied the rampart system at Low Isles on the Great Barrier, also recognized a relation between rampart development and periodic wind systems. At Bikini Atoll the southern reef margins do not have such a rich growth of calcareous algae as does the *Lithothamnion* ridge of the windward coasts, but corals are proportionately more important. The reef flats off the southern islands are narrow—from 200 to 500 feet wide—and their margins are smooth except where broken in places by large erosional reentrants. Accordingly, at times of high tide, even ordinary waves cross the narrow flats with great force, audibly rolling loose coral boulders over the flat and the seaward slope of the rampart. In normal times waves that cross the reef tend to flatten the rampart slope, but the ramparts are probably built, moved, or destroyed only by waves of major storms. The ramparts locally form double or even triple ridges that are approximately parallel, each possibly the result of a single storm.

BEACH ROCK

About 15 percent of the area of beaches near Bikini is rock, and casual observations elsewhere in the northern Marshall Islands suggest that this ratio is common. This rock has been termed beach rock because of its relationship to the beach. It is calcareous, and usually composed of the same kind of materials as the loose sand and coarser debris lying on or adjacent to it. Cross-sectional breaks of the beach rock show it to have the same textural laminations as the loose beach sand. The laminations range from about 1/16 to 1 inch (pl. 22, fig. 1) and alternately consist of well-sorted coarse grains and well-sorted fine grains (Emery and Stevenson, 1950). In most areas the strike and dip of the beach rock is identical or nearly identical with those of the loose sand, commonly about 9°. In some places, such as at the ends of elongate islands, the beds do not conform to the present beach and it locally contains material that is much coarser than the loose sand associated with it, indicating that shore conditions have changed since that beach rock formed. In all except a few places, the beach rock is intertidal.

Where the beach rock consists dominantly of cemented coarse material it is referred to as beach conglomerate. Where it consists of cemented material of sand size it is called beach sandstone. Pettijohn (1949, p. 226) and others object to the use of the term sandstone for a clastic rock composed principally of carbonate fragments, as sandstone has come to mean to many geologists a rocl in which quartz dominates. We prefer to use the term sandstone rather than calcarenite, however, following the usage of most geologists who have studied modern reefs.

Thin sections of most samples of beach rock consist of fragments of *Lithothamnion*, coral, Foraminifera, and other calcareous organic debris. The proportions are variable and fall within the range of composition of the loose sand or loose gravel of beaches.

Most beach rock is especially well indurated on the exposed surface. Below the surface the degree of consolidation decreases, and some sandstones are crumbly and friable a few inches below the hard surface. The surficial nature of the consolidation may be seen on a fresh fracture across a specimen of beach sandstone as a whitened layer 1 to 5 millimeters thick. Intergranular pore spaces within this layer are filled or nearly filled with white porcelaneous to chalky carbonate. Below the crustal layer, pores are open. The white chalky material seen in thin section consists of a brown microgranular matrix containing minute angular detrital grains. The matrix is similar in appearance to that which occurs abundantly in reef rock but it is limited to the uppermost few millimeters of the rock. In some specimens this matrix seems to cement the grains, but in others it is separated from the sand grains by a rind of clear acicular or granular aragonite generally ranging in thickness from 0.05 to 0.5 millimeters. Generally the fringe is a solid band around the grains, in which the acicular structure at right angles to the grain surface can be discerned under crossed nicols. In a few places, however, the aragonite needles are discrete, or are joined only near their bases. Staining tests made with Meigen solution as well as optical index tests, indicate that the mineral normally is aragonite, although calcite needles are not rare. In some specimens the cementing rind consists of finely granular or microgranular calcite.

The cementing action probably is occurring at the present time. It certainly has operated during the very recent past because part of a Japanese fishing-net glass float was discovered embedded in an exposure of beach rock. On certain flats of Eniwetok Atoll that were the scenes of landing operations during World War II numerous pieces of shell fragments are now (1951) firmly cemented into the beach rock. On one flat a glass bottle and a brass cartridge case were found cemented in rock though not so tightly as were the pieces of steel. Daly (1924, p. 139) recorded another case of rapid cementation at the Tortugas Laboratory. In 1910 a hurricane piled calcareous sand on the site of the laboratory wharf. Less than 2 years later the sand between the tide marks had been lithified to a depth of about 75 centimeters, forming a lens of typical beach rock. Reclus (1873, p. 174) also cited several occurrences of Recent lithification that may fall into the same category. At Elsinore, north of Royan, France, for example, some ancient Danish coins were found cemented in coastal sediments and a cannon was found imbedded in a calcareous deposit near the principal mouth of the Rhone River.

Beach rock similar to that of the Marshall Islands occurs in South America and the West Indies (Branner, 1904); where Lyell (1850) reported the finding of human bones and artifacts within beach rock. Gardiner (1898, p. 443–444) also reported the active development of beach rock at Rotuma and Fiji; other Fijian occurrences were described by Ladd and Hoffmeister (1945, p. 106, 119, 141). Kuenen (1933, p. 86–88) described it from many places in the East Indies, and Evans (1900) from the Persian Gulf. The authors have also seen it on Kaui, T. H., and on beaches of Mono Lake and Pyramid Lake in the United States.

The cementation has been ascribed to deposition at the surface of salts carried upward by capillary movement of water (Kindle, 1918; Emery and Foster, 1947), to evaporation of water carrying calcium carbonate dissolved from the exposed island surface by humic acids (David and Sweet, 1904, p. 74) and to undetermined biochemical processes. Whatever the cause, it must be one which is largely restricted to the intertidal zone and which therefore probably is active at low tide on the wet sand exposed between previous high tides.

Rather strong evidence for solution of calcium carbonate at depth in the beaches and redeposition at the surface is presented in a separate section on intertidal waters of beaches at Bikini Atoll.

After the beach rock has formed, it is subject to abrasion and solution. A high polish is one form of abrasion that is apparently related to the fineness of grain size, as may be seen in a photograph of specimen B-42 (pl. 22, figs. 2, 3) in which thin beds of fine material are highly polished, whereas beds of coarse material are comparatively rough. The polish is caused at least in part by abrasion, for larger organic grains and tests are cleanly truncated flush with the surface. Also, polished beach sandstone in place seems to be confined to those beaches where the rock is barely exposed through the beach sand, and is covered by only a thin sand veneer that scrubs the rock with each wave. These grains have the same composition and hardness as the rock; if very hard grains such as quartz were present, the surface would probably be roughened. The glazed appearance of the surface, however, may also be due to an unknown chemical or biochemical effect, suggested by the fact that the polished surfaces of specimens fluoresce a bright reddish-orange under an ultra-violet lamp. In fact, they show the strongest fluorescence of any samples from Bikini Atoll.

Turbulent movement of water on the beach rock also results in the development of potholes like those described by Wentworth (1944) in which the abrasive tool is usually a loose fragment of beach rock. Most of these are located on the upper part of the belt of beach rock and some are modifications of earlier solution basins.

The lower parts of the belt of beach rock usually have extremely rough, pitted, and cuspate surfaces (pl. 24, fig. 1). The cusps are jagged and sharp, and they are remnants of rock left by the enlargement and coalescence of 3 or more adjacent pits. Some pits and cusps are minute, less than an inch across, and superimposed on larger ones that range up to 3 feet across and nearly as deep. The pitted rock surfaces are gray to dark brown. Under the binocular microscope most of the surface is seen to be thinly covered with a film of brown or blue-green algae. In thin sections of specimens of rock, the trace of the weathered surface shows no crust or coating. A narrow zone at the surface, less than a millimeter wide, shows slight evidence of deterioration and the presence of minute channels due possibly to microscopic boring organisms. As in the polished beach sandstone, the rock near the surface is more completely indurated and less porous than the rock below, because of the filling of pore spaces by finely granular to microgranular gray to brown paste. The solution in the basins and pits may take place in the same manner as off the California coast, where, as the result of biochemical action, the sea water in small pools on the rock becomes acid enough at night to dissolve calcium carbonate and alkaline enough at day to precipitate it (Emery, 1946). This process at Bikini will be discussed more fully in a report by Revelle and Emery.

INTERSTITIAL WATER

It is possible that the origin of beach rock may be determined by study of the changes in the chemical properties of interstitial water in the beaches. This water is influenced by temperature changes, by infiltration of sea water, ground water, and rain, and by various biological processes. Accordingly, a complete study of it will require a long series of measurements. During the short time available for this work at Bikini in 1950 only preliminary results could be obtained. The field work was done chiefly by R. F. Dill. At noon during low tide, the temperature was measured at several depths at the lower, middle, and upper parts of a lagoon beach. To samples of the moist sand a small amount of distilled water was added, forming a slurry on which pH and Eh [1] were determined with a Beckman pH meter. The results (fig. 14, table 4) show that isotherms through the sand tend to be parallel to the sand surface, an effect of diurnal heating. The lines of equal pH and Eh, however, are convex upward and they decrease with depth. The high positive Eh values show that the environment is an oxidizing one and that hydrogen sulfide is not present.

In addition, samples of water from the top of the water table (bottom of the section) and from the adjacent lagoon were collected at midnight, noon, and late afternoon and analysed for temperature, pH, Eh, chloride, and oxygen. These data showed that diurnal changes are not great in the lower part of this beach at least. Larger changes may be expected nearer the sand surface. Chlorides in late afternoon were low because of a heavy rain. Oxygen, supporting the Eh measurements, varied from just below to just above the saturation values.

Biological activity appears to be of only secondary importance at the water table, deep in the sand, because plants cannot photosynthesize owing to absence of light, and animals are not abundant nor active enough to convert much oxygen to carbon dioxide, judging from

[1] Eh, also known as redox potential or oxidation-reduction potential, is the measure of energy of oxidation or electron-escaping tendency of a chemical system. It is expressed in millivolts, relative to the hydrogen electrode. From it the concentrations of the oxidized and reduced forms of any pair, such as ferrous and ferric ion or sulfate and sulfide ion, could be computed if equilibrium were established and the solubility products are known. In complex solutions like sea water in which organisms live, equilibrium does not usually exist and use of Eh is limited. Experience has shown, however, that Eh is positive when dissolved oxygen is present in sea water, and negative when oxygen is deficient and hydrogen sulfide is present.

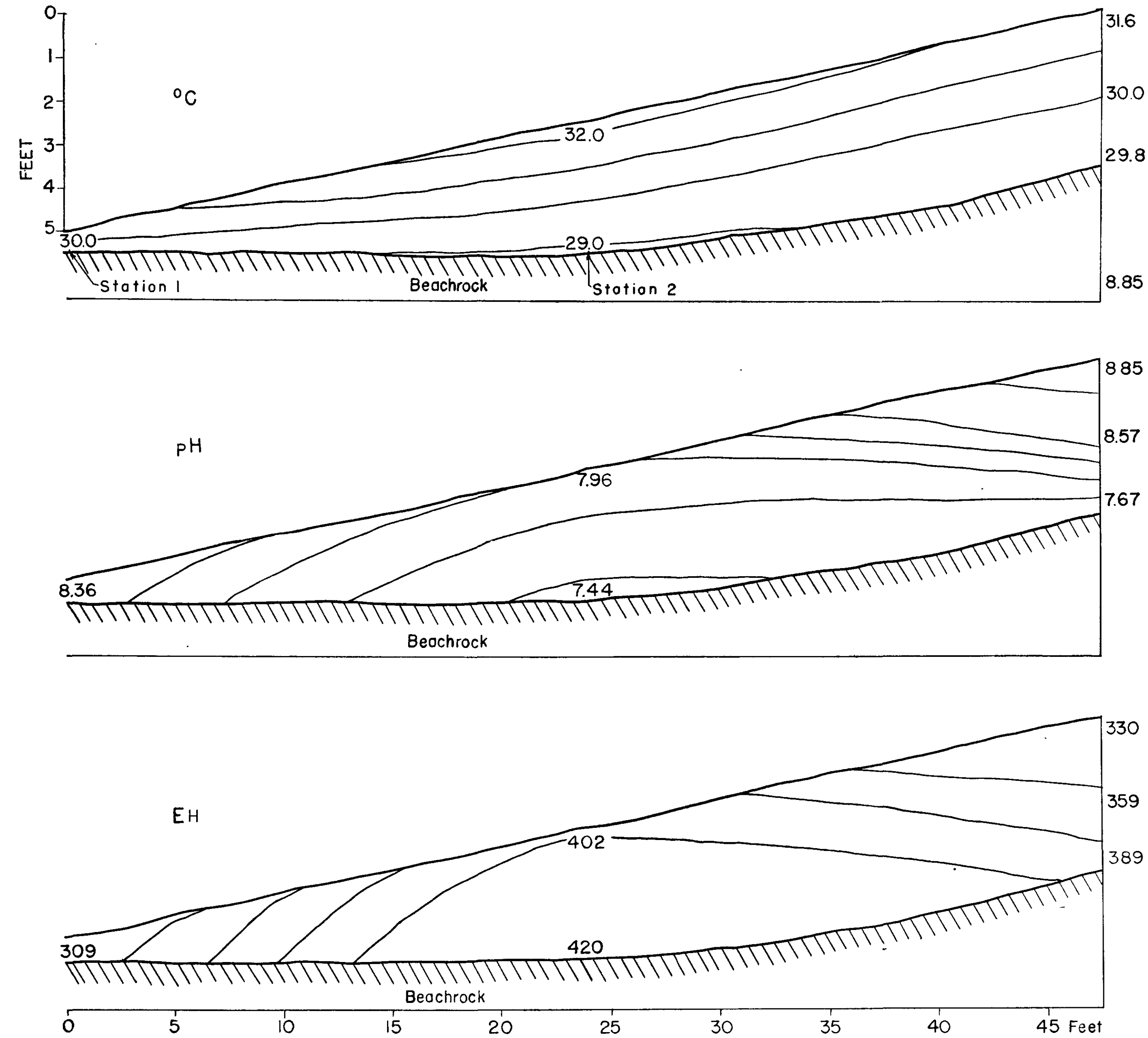

FIGURE 14.—Interstitial water in lagoon beach, Bikini island. Eh, also known as redox potential or oxidation-reduction potential, is the measure of energy of oxidation, expressed in millivolts, relative to the hydrogen electrode. The Eh and pH of the sand samples were determined with a Beckman pH meter.

the oxygen and Eh measurements. Outflow of ground water from the Ghyben-Herzberg lens also appears to be minor, because of the high salinity and Eh of the beach water, as compared with values obtained for samples of the ground water from borings located several hundred feet inland. Perhaps temperature increase during the day has been of greatest importance, for it could have caused the loss of both oxygen and carbon dioxide at the sand surface, thereby producing the observed Eh and pH cross-sections. Loss of carbon dioxide (high pH) would favor conversion of calcium

TABLE 4.—*Diurnal changes of interstitial water of lagoon beach at points 1 and 2 of figure 14*

	Time	Temperature (° C.)	pH	Eh	Cl⁻	O_2
Point 1	0000	27.8	8.00	321	18.59	3.86
	1200	30.0	8.36	309	-------	-------
	[1] 1700	-------	-------	-------	-------	-------
Point 2	0000	28.0	8.07	318	18.87	5.42
	1200	29.0	7.44	420	-------	-------
	1700	-------	8.28	3.5	18.03	3.82
Sea water	0000	27.5	8.06	104	18.75	3.60
	1200	31.1	8.36	64	18.75	6.21
	1700	28.0	7.88	3.9	16.80	4.72

[1] Location covered by water.

bicarbonate to calcium carbonate, followed by deposition of the latter. To this effect should be added the deposition at the surface of all salts on evaporation of water brought up by capillarity, as suggested for California beaches (Emery and Foster, 1948). Continued investigation of the relationship between beachrock and interstitial water is warranted along this promising course.

INLAND SURFACES

Inland from the beaches and the ramparts the surface is more or less completely covered by vegetation. Among the commonest plants is *Scaevola*, known in some parts of the Pacific as the fan flower that forms almost impenetrable thickets at the edge of the beach; in some areas *Suriana*, also known as bay cedar, likewise forms dense thickets. Other basic woody plants are *Guettarda* and *Tournefortia* (Taylor, 1950) growing as bushes or as separate trees. Concentrations of *Cordia* with curved and sprawling trunks make tangled woodlands that are as difficult to penetrate as a mangrove swamp. Among the taller trees are the coconut palm and the *Pandanus* or screw pine and the massive *Pisonia* (pl. 56); the last named was found most abundantly in open woodland on the small leeward islands. The plants grow on a variety of deposits, mostly unconsolidated.

BOULDER BEDS

Boulder beds form the interiors of many of the islands that are rimmed by boulder ramparts. The small southwest islands, such as Ourukaen, Bokoaetokutoku, and Bokororyuru, all have bouldery flats on their northeast sides. These are in general hummocky; shallow depressions several feet deep are present in some localities. Secondary ridges behind boulder ramparts are present on Rukoji and Enyu islands, but ridges are not apparent in the interiors of these islands. On Ourukaen, however, a single ridge crosses the center of the island. It is nearly 4 feet high, trending N. 12° W. East of this ridge the island surface is bouldery, whereas to the west it is sandy. The ridge is apparently a former boulder rampart, and all the island to the west has been added later as a sand-tongue accumulation.

GRAVEL FLATS

The flat interiors of many islands are of gravel. The material varies from completely unsorted sand and pebbles to well-sorted pebbles, cobbles or boulders. The coarser gravel flats preserve their original depositional structures that in many cases show the growth of the island. The southeast end of Namu island, for instance, is a sparsely vegetated expanse formed of sandy pebble gravel. On the broad gravel flat is a series of ridges more or less parallel to the present lagoon shoreline. These are 3 to 4 feet high and about 100 feet apart, with very gently sloping sides. The broad troughs between ridges have parallel streaks of light- and dark-gray gravel that show up clearly on airphotos. The light bands are 10 feet wide, the dark bands narrower.

The surface of the gravel flat is barely consolidated. A crust is present that is perfectly apparent to one walking over it, but the consolidation is so slight that it is impossible to obtain a sample that will hold together.

SAND FLATS

The larger islands of all the atolls are dominantly of sand, generally fine-grained. In the island interiors it forms extensive flats where it is horizontally bedded. In many places the sand surface shows gentle, rather irregular swells.

SAND DUNES

Dunes are found on the borders of islands inside sand beaches and normally nearly parallel to them. They are common on long reaches of windward beach, and they occur also on beaches that are nearly parallel to the prevailing easterly trades, but they are not found on sheltered shores. On Bikini island low dunes are common along the eastern or seaward coast. The highest dune noted on the atoll is on the north coast of Romurikku island, in the concave beach in the middle of the island. The coast faces north, and parallel to the beach is a dune 17.5 feet above the high water mark and about 23 feet higher than the reef flat. It is very steep on both sides, and the top is 17 feet higher than the adjacent interior island flat. The crest and inner slope of the dune are covered with beach shrubs (mainly *Scaevola*) and stunted palms, and the seaward slope is partly covered by vegetation, so that the dune is fairly stable.

BEDDED ROCKS

Exposures of consolidated rock are rare inside the marginal rim of the islands, but on a few of the low, barren islands there are wide flats of bedded rock.

Aomoen island, on the north side of the atoll, is formed of bedded rock largely covered by sand. The strata are more or less parallel to the present lagoon and seaward shores. In most places those near the lagoon dip lagoonward; the dip lessens gradually away from the shoreline, and the rocks are broadly arched over the center of the island. Continuing seaward, they dip more and more steeply in this direction, although not so regularly as on the lagoon side. Near both shores of the island the bedded rock is well indurated, the dip is 5° to 8° or more, and in all respects the rock resembles beach sandstone. The flat-lying rock in the center of the island, on the other hand, is poorly indurated and thin. During the course of construction work on the island, the Seabees drilled many jackhammer holes through the rock. They reported that rock in the center was never more than 1 foot and normally less than 6 inches thick, and was very friable (see fig. 15), whereas the dipping rock on the margins of the island was 4 to 6 feet thick and very hard.

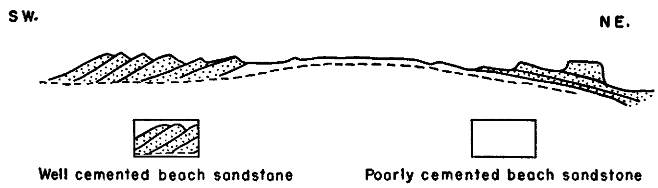

FIGURE 15.—Generalized section through Aomoen island. Peripherally dipping beach sand, and flat-lying inshore sand form an apparent arch. Dipping marginal beds are well lithified to a depth of 4 to 5 feet; interior sands are poorly indurated to a depth of 6 inches to 1 foot.

A somewhat different section is seen on the small islands of the east reef, between Bikini and Enyu islands. The parts of these inslands covered by vegetation are sandy, but the seaward sides, inside the rocky beach crest, are wide flats of bedded rock dipping lagoonward. Only a narrow margin on the seaward side is covered by rock dipping seaward (fig. 16).

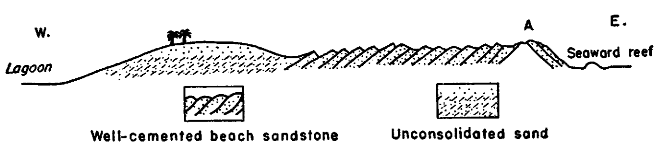

FIGURE 16.—Generalized section through small island south of Bikini island. Island apparently was originally a sand bar at A. Lagoonward transport of sand because of easterly winds has built successive westward-dipping beds of beach sand now lithified, and exposed by westward migration of the sand bar. All small eastern islands, between Bikini and Enyu, show this structure.

Apparently the island first started as a sand bar at *A* (fig. 16), parallel to the reef. The sand on both beaches of the bar was lithified to form beach sandstones dipping in opposite directions. The prevailing easterly winds carried sand lagoonward over the bar, exposing the lithified rocks at *A*. The bar, therefore, moved lagoonward, leaving behind a trail of bedded rocks that had been indurated while they were buried. The rocky flat between Rochikarai and Eniairo islands is more than 500 feet wide.

Many bars between islands on the north and east sides of the atoll have this structure to a lesser extent. With the exception of the wide flat on Aomoen island with its "arch" of bedded rocks, all other localities have their bedded rocks dipping uniformly lagoonward, covered by a dunelike sand bar and beach on the lagoon side. Bedded rocks are rarely exposed on the flats of islands on the south sides of atolls because these flats are generally covered by a veneer of sand, gravel, and boulders.

SOIL

By EARL L. STONE, JR.

Information about the soils of Bikini Atoll has been limited to the general remarks of Taylor (1950) and to some specialized microbiological studies (Johnstone, 1947). Taylor noted that in wooded parts of some islands a fine black humus accumulated and that in less densely covered areas there was a little humus that together with a litter of twigs and leaves, and crustose Myxophyceae (Cyanophyceae) more or less completely covered the calcareous sand. Several samples of such surface soils were collected by J. I. Tracey, Jr., and H. S. Ladd in the course of other work. Although only limited interpretations are possible from such samples, they have been analyzed chemically because of the absence of such data elsewhere. Characteristics of the 9 sample areas are given in table 5.

The air-dry samples were sieved and only the material finer than 2 millimeters was analyzed. The pH was determined potentiometrically, soluble salts by conductivity measurement in a 1:2 soil-water mixture, and organic matter by chromic acid titration according to the method of Peech (1945, pp. 25–38). Soluble nitrogen and the amounts of phosphorus, magnesium, and potassium soluble in Morgan's extractant (1 N sodium acetate, pH 4.8) were determined by the procedure of Peech and English (1944, p. 167–195). The results appear in table 6.

As might be expected, all samples are nearly neutral or alkaline, excepting the solid masses of organic matter segregated from sample B–121. The samples were taken during the dry season and although all contain relatively high levels of soluble salts these values must be regarded with caution because of the likelihood of concentration by evaporation from the soil surface. Three samples, B–13, B–14, B–27, have concentrations such that, if they were characteristic of the deeper layers as well, only the most salt-resistant plant species could endure. In these three a very considerable part of the conductivity can be accounted for by the amounts of potassium and nitrate and hence an influence of ground water or atmospheric salinity is not necessarily implied.

The organic matter values are generally high but this is scarcely surprising in such superficial samples. Although sample B–13 appears to contain more than 50 percent organic matter the fraction analyzed is only about one-fifth of the total sample mass, the remainder being coarse fragments.

The contents of nitrate nitrogen are variable. The larger values are exceedingly high and probably reflect concentration near the surface. Similarly, the highest potassium values suggest such concentration, as indicated by comparison of the successive one-half inch samples, B-27 and B-28. The very high values for soluble phosphorus in all samples, although no measure of the total content, indicate either the presence of phosphates in the parent materials or the influence of bird guano. The uniformly high magnesium values result from the considerable amounts of this element in some of the reef-building algae.

The charcoal observed in 5 of the 9 sample localities presumably results from the use of fire by natives in clearing groves.

TABLE 5.—*Description of soil-sample areas*

Sample No.	Location		Character of surface	Vegetation	Depth of sample (inches)	Character of sample	Remarks
	Island	Position					
B-13	Rukoji	360 feet from south shore.	Flat cobble-boulder floor.	Open *Pisonia* forest	0-1	Black organic crumbs mixed with well-weathered gravel.	
B-14	do	800 feet from south shore, island center.		*Pisonia* grove	0-1	Brown organic matter well distributed in fine gravelly sand.	
B-15	do	600 feet from north-west coast.	Brown foraminiferal sand.	Scrub, mostly *Guettarda*	0-1	Loamy sand with well-distributed organic matter. Sands uniform, well weathered, with many foraminifera.	Charcoal present.
B-27	Yurochi	South central part	Sandy		0-½	Organic crumbs mixed with slightly weathered fine gravel and coarse sand.	
B-28	do	do	do		½-1	Coarse foraminiferal sand with organic matter incompletely mixed.	
B-29	Uorikku	180 feet south of north beach.	Sand	Coconut, *Pandanus*, grass.	0-2	Coarse to fine sand mixed with finely divided organic matter.	
B-32	Bikini	450 feet east of lagoon beach, center of island.	(1)	Coconut grove and grass	0-4	Fine gravelly sand with much fine sand and finely divided organic matter. Gravel well weathered and coated with organic matter.	Charcoal present.
B-36	Namu	550 feet north of lagoon beach.		*Pisonia* forest	0-1	Brown, uniformly loamy fine sand	Charcoal present.
B-37	do	do		do	1-4	Loamy fine sand containing well-weathered organic-stained gravel.	
B-38	do	740 feet from lagoon beach.	Thin gravelly soil	Coconut grove with grass.	0-1	Loamy sand, less uniform than B-36.	
B-39	do	860 feet from lagoon beach.	do	Mixed coconut *Pandanus* and *Pisonia*.	0-1	Gravelly sand, high in organic matter, the mineral particles very well weathered and stained.	Charcoal present.
B-121	Ourukaen	Center of island	Sand	*Pisonia* forest	(2)	Well-weathered, brown-stained loamy coarse sand.	Charcoal present. Small lumps of phosphate-cemented sand.
B-121-0	do	do	do	do	(2)	Solid masses of well-decomposed organic matter (1-1¾" diam.) segregated from B-121.	

[1] Description of this profile:

Depth (inches)	
4	Grass roots and leaf mold.
7	Black to dark brown dusty sand.
12	Brown to tan dusty sand.
60	Bedded white sand and gravel.

[2] Surface sample.

TABLE 6.—*Chemical analyses of soil samples*

Sample No.	Sample depth (inches)	Percent of sample analyzed [1]	pH	Soluble salts K x 10 [5]	Organic matter (percent)	Pounds per acre [2] of indicated constituents [3]				
						Nitrogen as—		P	Mg	K
						NO_3	NH_3			
B-13	0-1	17	6.70	2,180	53.2	2,000	?70	4,200	7,000	4,250
B-14	0-1	45	7.30	950	33.1	400	?60	4,000	8,000	790
B-15	0-1	94	7.35	200	9.9	200	?60	500	5,500	200
B-27	0-½	81	7.80	900	37.8	500	?60	2,500	12,000	4,600
B-28	½-1	93	7.50	230	10.5	100	20	500	5,000	195
B-29	0-2	79	7.25	340	24.3	?40	40	500	4,500	225
B-32	0-4	71	7.30	300	17.9	5	40	400	5,000	200
B-36	0-1	89	7.50	318	18.7	5	?50	1,100	5,500	445
B-37	1-4	81	7.20	225	11.8	5	40	350	5,000	230
B-38	0-1	80	7.35	185	19.6	5	40	250	3,000	210
B-39	0-1	44	7.40	190	23.5	5	30	550	5,500	500
B-121	(4)	92	6.55	210	15.2	550	?45	700	1,750	285
B-121-0	(4)	94	4.60			2,500	1,200	1,500	1,250	1,600

[1] Percentage passing 2-millimeter sieve.
[2] Sample areas were calculated as 2,000,000 pouuds of soil per acre.
[3] Constituents readily soluble in Morgan's extractant.
[4] Surface sample.

GROUND WATER

During the 1946 expedition the water in a shallow pool used by the natives as a water source was found by Tracey to be brackish and high in hydrogen sulfide. Whether this was produced by sulfate-reducing bacteria that live below the ground surface or only in the pool could not then be determined. An accumulation of leaves and other debris in the pool furnished abundant food for bacteria.

Further investigation of ground water was carried out during the 1950 trip. Samples of ground water were obtained from a 4½-foot soil auger boring in the bottom of a sand and gravel borrow pit 515 feet from the lagoon shore near the middle of the island and from a 2½-foot boring in the bottom of a silted-up well at the Japanese radio station 450 feet from the seaward shore near the south end of the island. The water-table at both places was about 10 feet below the general ground surface. Rough levelling showed the water table to be about 1 foot above low-tide level. The water level in the native well measured in 1946 was about the same elevation. There is no question but that the water level at all three places was well below high tide, and it probably was between middle and low tide, though it is possible that the water levels were measured near the bottom of their tidal fluctuation. The fresh-water lens must, therefore, be only a few feet thick. The very low chlorinity at the borrow pit probably results from the sampling of only the topmost layer of ground water. The positive Eh and absence of hydrogen sulfide odor indicates that the water is in an oxidizing environment.

Samples of water were also obtained from two of the open test holes drilled in 1947. The high-water level and low chlorinity probably results from the accumulation of rain water above plugs in the hole formed by the setting of drilling mud. This is supported by the fact that a soil auger hole a few feet from well 2B failed to encounter the water table, though it was drilled to a depth of 3 feet below the water level in the well. All findings are summarized in table 7.

TABLE 7.—*Ground-water measurements*

Place	Date	Feet above low tide level for—		Feet from shore	Cl^- (‰)	pH	Eh (mv)
		Water-table	Ground surface				
	1946						
Native well	Aug. 18	1	1	1,200	--------	------	------
	1950						
Hole in borrow pit	Sept. 24	1	12	515	0.093	8.0	+278
Japanese well	Oct. 8	0–1	11	450	1.10	------	------
Test well 2A	Sept. 24	3	16	100	.032	9.1	+298
Test well 2B	Sept. 24	14	19	275	.086	8.5	+252

LAGOON

PHYSIOGRAPHY

Altogether, about 37,800 soundings from Bikini Lagoon are available (table 1). These are not evenly distributed but are concentrated in the northeast corner near Bikini island surrounding the bomb site. Thus, 60 percent of the total number of soundings are located in only 8 percent of the area, so that in part of the area the sounding density is 17 times as great as throughout the rest of the lagoon. The small area has a density of 1,300 soundings per square statute mile, a density not exceeded by any chart of which the writers are aware. Because of this fact soundings in the corner were mapped on a larger scale base chart and contoured at a 2-fathom interval, in contrast to the 4-fathom contour interval for the general lagoon (charts 2 and 3).

TERRACE

A shallow terrace borders part of the reef at Bikini Atoll (fig. 17), separating it from the lagoon basin. The terrace is best known inside the reef projections at Bikini island, where it has a maximum width of about 2,000 yards. The terrace is also present about half way between Bikini and Aomoen islands and again in the reef projection at the Uorikku-Romurikku-Aomoen island group. At no other place within the reef is the terrace known for certain to be present, owing to insufficient sounding density elsewhere. However, the floor of Enyu Channel between Enyu and Airukiiji islands is probably a related feature. At the extreme west end of the lagoon is a broad area shown by the contours to be shallower than 4 fathoms. A similar area borders Enyu island. Depths in both areas are uncertain, being based only on a few Japanese soundings. It is notable that a shallow area comparable to that in the western part of Bikini Lagoon occurs in the western projection of Eniwetok Lagoon.

Most of the terrace off Bikini island is between 10 and 11 fathoms. The two smaller sections of the terrace to the northwest lie at similar depths. Much of the floor of Enyu Channel is also flat between 10 and 11 fathoms, but nearly half of it, though fairly flat, lies at 6 or 8 fathoms. The channel floor may have been irregular from the start or the shallower portion may have been built up by reef growth from an original 10-fathom level.

One of the most interesting characteristics of the well-sounded part of the terrace is the series of closed depressions in it. Two of them, one south of the west end of Bikini island and one west of Yomyaran island, have floors 18 to 19 fathoms below sea level, or 8 fathoms below the surrounding terrace surface. The latter depression is elongate parallel to the reef and

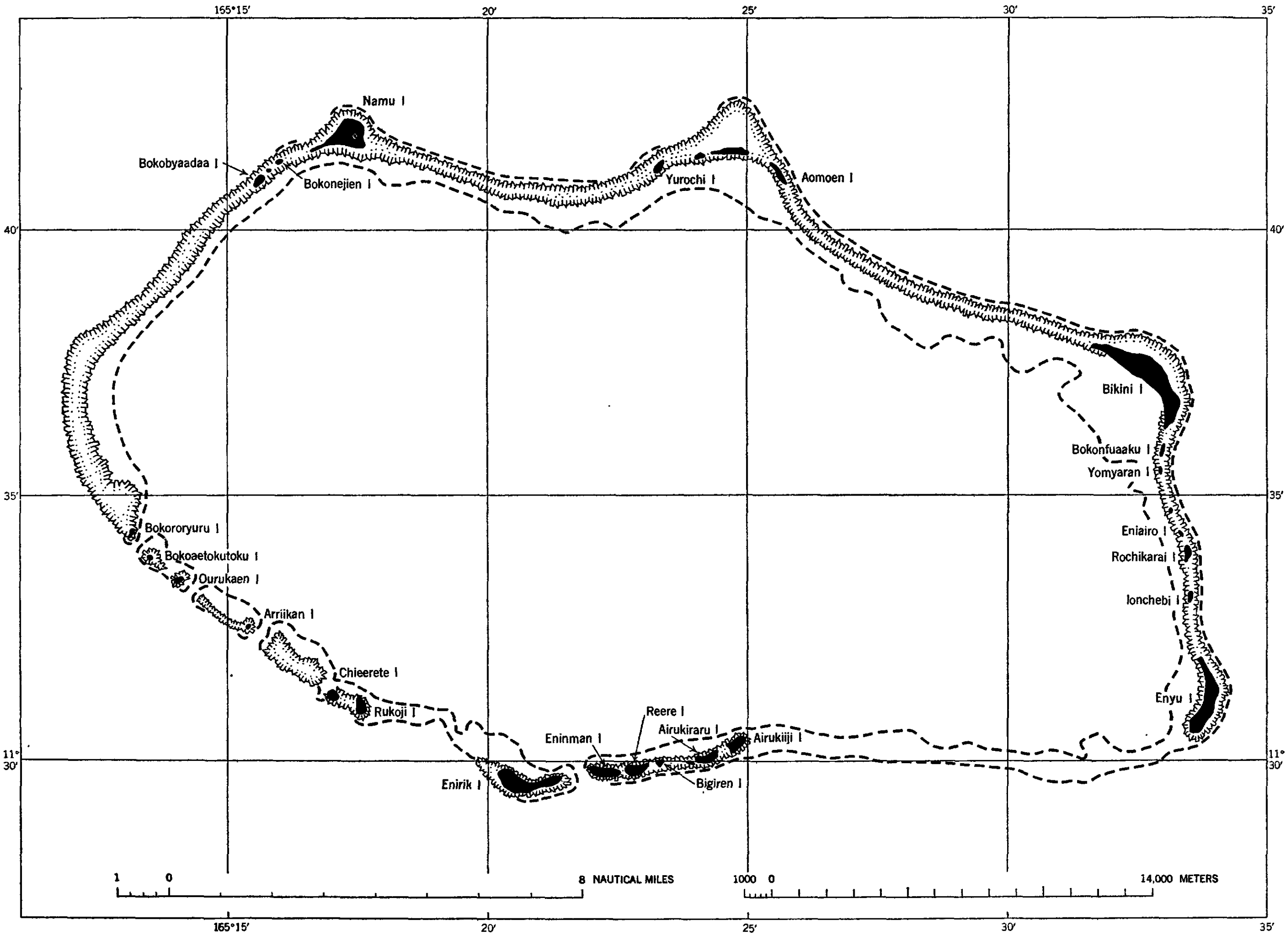

FIGURE 17.—Sketch map showing distribution of terrace on the seaward side of the reef and inside the lagoon, Bikini Atoll. Terrace outline shown by heavy dashed line. The seaward terrace averages about 8 fathoms, and is generalized to include all areas with a gentle offshore slope. Lagoon terrace averages about 10 fathoms.

thus may indicate a now-submerged growth stage of the reef but the irregular shapes of the depressions suggest that they may be sinks formed by groundwater when sea level was lowered during glacial times.

At the edge of the terrace a relatively steep slope leads down to the main basin of the lagoon. The slope averages 2.3° between the 12- and the 24-fathom contours but locally it appears to be 19° or more. This average slope is steeper than the one extending from the reef to the terrace level, which averages only 1.9° between the reefs and the 10-fathom contour.

BASIN

The main basin below 20 fathoms has a more nearly elliptical shape than does the reef edge. The long axis of the ellipse trends N. 80° W. About half of the area is deeper than 28 fathoms and the maximum depth encountered in the sonic surveys was 32.1 fathoms, or 193 feet. Only one or two other soundings were 32 fathoms or more; accordingly the maximum depth is taken as 32 fathoms near the middle of the lagoon. Seventeen Japanese lead-line soundings exceeded this value, only two of which were 34 fathoms and one, 35 fathoms. These figures are thought to be too high, due probably to the drift of the sounding boat under the influence of wind or current.

The basin floor is flat except where it is interrupted by coral knolls. The average slope between the 24- and the 28-fathom contours, neglecting the coral knolls, is only 0°14′, and between the 24-fathom contour and the center of the lagoon at 31 fathoms it is only 0°05′. Chart 2 shows an apparent greater flatness of the floor in the west half of the lagoon but this is due to a much lower density of soundings in that area. In the northeast corner where soundings are densest, the floor is roughened by many coral knolls and small depressions. Additional soundings would probably reveal similar topography in other parts of the lagoon.

CORAL KNOLLS

A feature common to all coral lagoons—barrier as well as atoll—is the growth of isolated mounds of coral on the bottom. These coral knolls may be small—less than 10 to 50 feet across and 3 to 20 feet high—but very large ones are numerous, and these may be from several hundred feet to more than a mile in width at the base, rising nearly to the surface of the water from even the deepest part of the lagoon.

Related features have been described by many early writers in different parts of the world. Dana (1851, p. 363) reported the presence in quiet waters of patches of coral that rise nearly to the surface and sometimes seem to grow from a narrow base like a mushroom, so that they may be toppled if struck by a ship. In a later volume, Dana (1872, pp. 139, 140) quoted the journal of J. A. Whipple, who, in 1857, examined the reefs about Turks Island, south of the Bahamas. Whipple figured and described a "coral head" standing in water 50 feet deep. Its trunk, which made up two-thirds of its height, was only 15 feet in diameter in the upper part, but it supported a tabular mass one hundred feet in diameter whose top was bare at low tide. Hartt (1870) in his "Geology and Physical Geography of Brazil" described similar structures from the reefs of the Abrolhos, which he said are called chapeirões, signifying "big hats."

The term "coral head," used by Dana and still commonly used by sailors and others, is not satisfactory as it is loosely used in several senses—for instance, to denote a flourishing colony, or several associated colonies, or a coral, living or dead, of the massive, rounded type such as *Porites*. "Coral pinnacle" has been used by some writers; however, because many of these structures in the Marshall Islands are no more than broad, low mounds, we prefer Darwin's term, "coral knoll" (1889, p. 41, 91–95), as being sufficiently descriptive and inclusive.

The distribution of coral knolls, like the character of the lagoon floor, appears to be controlled by the sounding density. Thus, the coral knolls appear to be densest near Bikini island, next densest in the rest of the eastern half of the lagoon, and scarcest in the western half (chart 2). Many of the larger coral knolls are outlined in some detail by a score or more of soundings. Others, however, appeared so small that they could be indicated only by one or two soundings. Most of these are closely bordered by deeper water, indeed their side slopes are so steep that contours are impractical. They are therefore indicated on the chart by a hachure symbol accompanied by a number showing the depth in fathoms to the top of the knoll.

Four coral knolls in Bikini Lagoon were surveyed with considerable accuracy by lead-line soundings from a DUKW which was allowed to drift slowly past a buoy marking the coral knoll. At the time that each sounding was taken both the range and bearing to the buoy was estimated, permitting the depths to be plotted on a radial graph on which contours at intervals of 1 fathom were drawn (fig. 18). Each of the four coral knolls surveyed was of somewhat different shape. The contoured side slopes range up to 45°, but some other coral knolls which were investigated using diving gear were found to have vertical slopes for as much as 10 fathoms of their depth. Underwater photographs taken on some of the coral knolls are presented in plate 23.

The range of depths to the top of coral knolls was determined from the original sounding charts. The tops of more than a third of the known coral knolls are between 4 and 12 fathoms deep, and there is a secondary maximum depth frequency between 20 and 24 fathoms. This depth distribution may not be very accurate, however, because of relative scarcity of soundings over half of the lagoon, also because many of the small coral knolls were not mapped or counted.

CORAL KNOLL OFF ENINMAN ISLAND

An excellent example of a typical knoll was examined by diving from an LCM that was equipped with air compressors and shallow-water diving gear. The knoll lies about 1⅓ miles north of Enirik Pass in about 20 fathoms of water. The top is roughly 150 feet in diameter, flattened but with a maximum relief of about 15 feet. The highest point is about 6 fathoms below the surface. The upper surface is rough and irregular; some ledges are 5 feet or more in height. Coral is dominant and seems to cover 75 percent or more of the top, although much of the surface beneath the spreading corals is covered with *Halimeda*, *Lithothamnion*, and calcareous sand, especially in pockets. A great variety of corals is present including massive heads of *Porites* several feet in diameter. Great fragile bracketlike growths, as much as 10 feet long, of several species of *Acropora*, and large thickets of staghorn *Acropora* occur in hollows. Although not so prominent as the corals, *Lithothamnion* everywhere encrusts and cements the bases of the corals to form a hard crust or cap over the entire top of the knoll. In hollows, living *Halimeda* is abundant and white segments of the alga form much of the sandy debris scattered over the knoll. It is inferred that the sand is a veneer on the limestone crust of the knoll even though some patches were more than 6 inches thick. Mollusks are common though not abundant. *Tridacna* (pl. 24, fig. 1) up to 8 inches or more are numerous; a number of larger ones from 1 foot to 2 feet in length were found, and one very large specimen was 3 feet in length. Schools of large fish cruise over the knoll; schools of smaller species hover over single coral heads.

A sample of sand collected by J. W. Wells consisted of unsorted organic fragments (pl. 26, fig. 2). About half of the material is coarser than 2 mm. Of this coarse fraction, 80 percent or more consists of *Halimeda* segments or fragments as much as 8 mm in length. Coral fragments, mollusk shells and fragments, especially small shells 2 to 5 mm long and several species of discoid Foraminifera as much as 3 mm in diameter are common, but all these form only a small proportion of the material. The finer fraction consists of grains from 2 mm to less than 0.01 mm in diameter. Larger grains

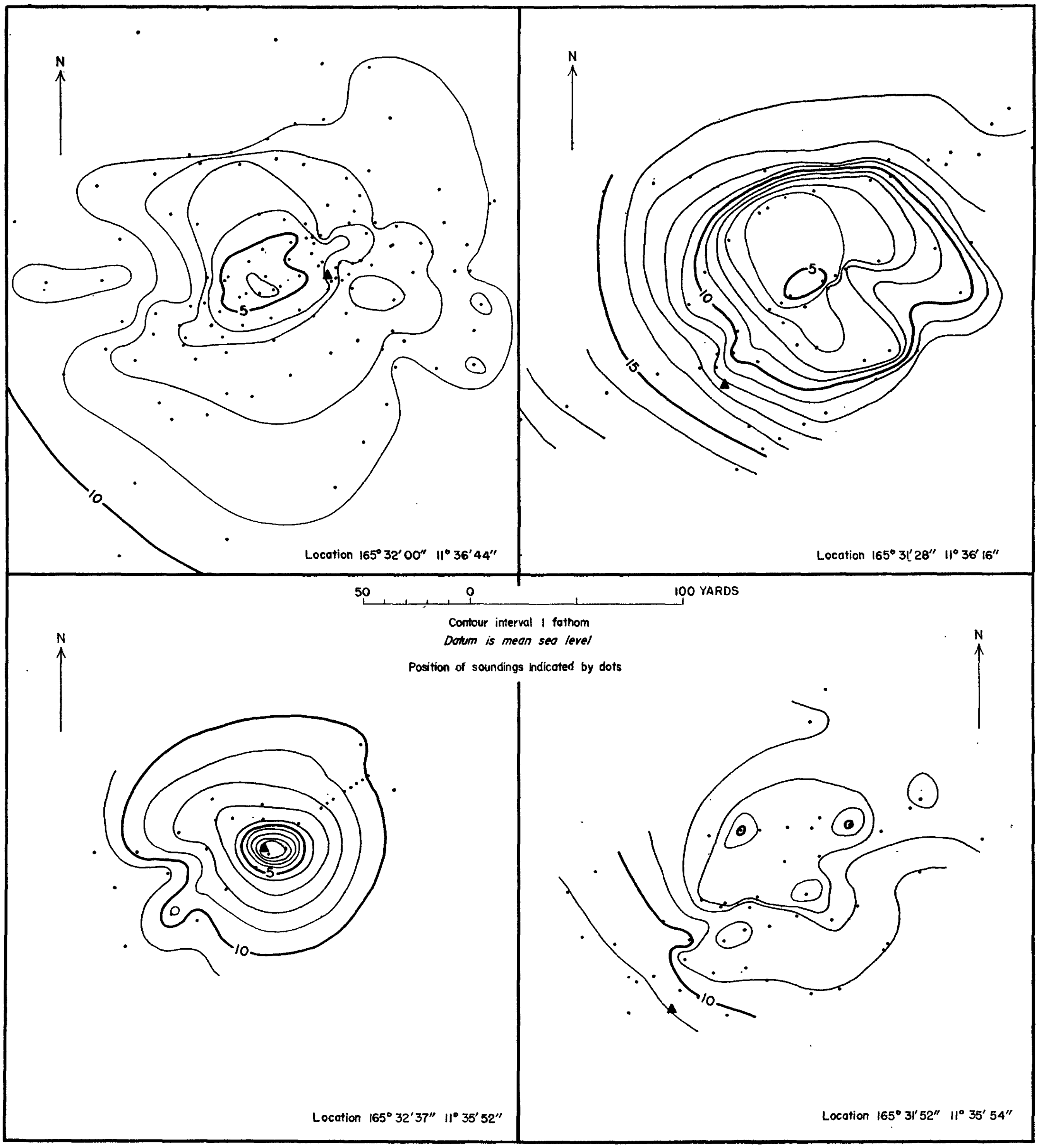

FIGURE 18.—Lead-line surveys of coral knolls, Bikini Lagoon. The positions of the soundings are indicated by dots. Solid triangles mark the location of buoys, the range and bearing of which was estimated each time a sounding was taken

of this fraction are recognizable organic remains, especially fragments of Foraminifera and mollusks. Smaller grains are in general unrecognizable fragments, most of which are very angular although some seemed somewhat rounded. Particles finer than 0.01 mm may have been present, but if so were lost in scooping up the material.

The sides of the knoll and the edge of the flat top were not examined. When seen through a face mask while swimming on the surface 50 feet above them, the slopes appeared to dip off steeply on all sides. The angle of slope was difficult to judge but appeared to be between 45° and 60°. The nature of the sides could not be determined except that they were white. Living coral at depth looks dark, and since the sides appeared much lighter than the top of the knoll, they probably are formed of debris and sand. Coral growth probably is not very active and any colonies present are small.

OTHER CORAL KNOLLS

A knoll lying on the terrace fringing the eastern shore of the lagoon was also examined by diving. Its flattish crest rises to within 30 feet of the surface and shows a relief of about 10 feet. It was estimated that living corals in considerable variety (mostly branching forms but with some massive heads) cover half of its surface and that about 20 percent of the total area was covered by dead coral. There were, likewise, many small algal nodules.

A coral knoll in the western half of Enyu Channel was somewhat different in shape. It is a low rounded ridge that rises 15 to 20 feet above the flat 10 fathom floor of the channel and extends roughly north and south. The width of the ridge is about 150 feet, the length unknown but more than 200 feet. The entire top is a jagged mass of living and dead coral, largely *Acropora*. Some cementation by *Lithothamnion* is present and coarse *Halimeda* and foraminiferal sands occur in the hollows. The base of the west side is a wall 5 feet high and steep (60°). Beyond the base the floor of the channel is flat and composed of coarse white debris.

In the northeast quarter of the lagoon other observations were made by diving in 20 feet of water off the mid-point of Aomoen Island. In this area many corals (*Acropora*, *Astreopora*, *Stylophora*) were found growing, the larger colonies rising 3 to 4 feet above the sandy lagoon floor. As noted by Hoffmeister, all of the species appeared to be identical with those growing on the surface reefs.

Parts of the northern side of the lagoon were also examined by swimming with face masks and by diving. Much of the shallow area is sandy but there are areas of rich coral growth. One such patch in 30 feet of water was closely examined. It is several hundred feet in diameter and rises 8 to 10 feet above the lagoon floor and shows a variety of corals including *Millepora*.

From the coral knolls examined in Bikini Lagoon, from fathogram surveys of all the lagoons studied, and from profiles drawn through the four knolls shown in figure 18, we may generalize on the shape and constitution of typical coral knolls. On well-developed knolls that rise from depths greater than about 10 fathoms the lower slopes are generally less than 15°, whereas the upper slopes range from 20° to more than 45°. Smaller knolls that rise from shallower bases are usually 10 to 30 feet or more in diameter and grow 10 or 20 feet to the surface with near-vertical and sometimes overhanging sides. They grow from a flat sand or gravel bottom with little or no apron of debris at the base. Still smaller knolls, no more than low mounds of coral a few feet high but 10 to 50 feet across, are common in protected areas on flat bottoms in about 30 or 40 feet of water. Such mounds cover about 20 percent of the bottom area of the bay formed by Tufa island on Rongelap Atoll. They are plainly visible as dark patches in airphotos, and can be seen easily from a boat. They occur over the entire lagoon, but may be more abundant in protected shoaler waters.

REEF OPENINGS AND DEEP CHANNEL

The main reef at Bikini Atoll is broken by eight openings, all in the south side of the atoll. Six of them are less than a half mile wide and all except one are less than 19 fathoms deep. Enyu Channel is the widest, being 10.2 statute miles, so that it serves as the main entrance for shipping and is one of the main sites of inward and outward transport of water. It forms a sill that is about 10 fathoms deep for half its length. The other half ranges from 8 to 6 fathoms in depth. It is probable that the sill is related to the 8- to 10-fathom seaward terrace. The shallower parts may be the result of coral growth on a submerged reef.

The deepest entrance is Enirik Pass near the middle of the south side of Bikini Lagoon. Depths of about 30 fathoms occur there just within the reef. A channel extends almost directly north from the entrance into the lagoon. Its width is only one-quarter mile but its axis is everywhere deeper than 26.6 fathoms. This minimum depth occurs at a point about 2 miles lagoonward of the reef. Deeper sections of it reach 29 fathoms. This channel would be the point of surface drainage for the lagoon if sea level were to be lowered sufficiently.

DISTRIBUTION OF DEPTHS

The percentage frequency of the various depth zones throughout the lagoon is given in figure 19.

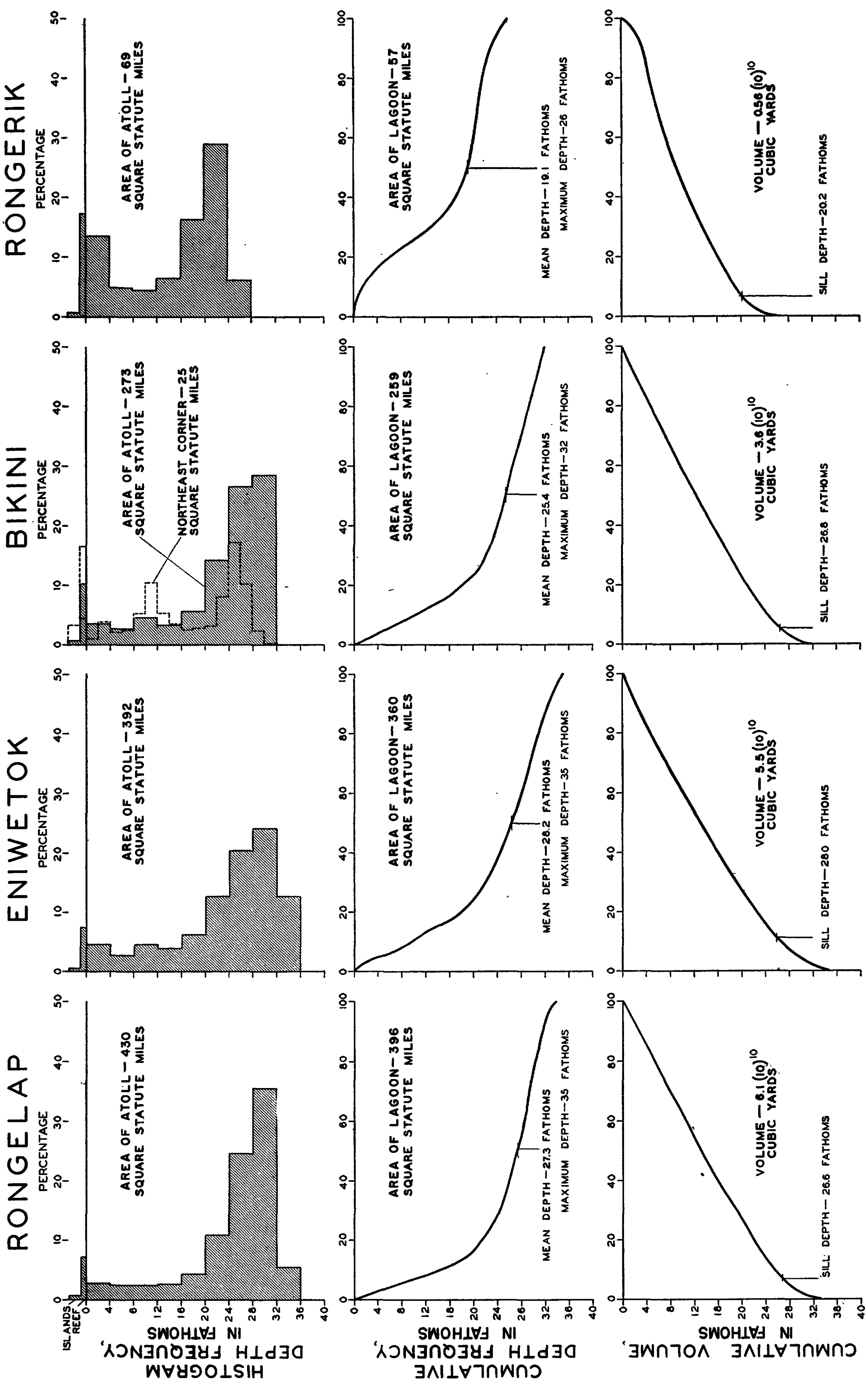

FIGURE 19.—Percentage frequency of various depth zones in four atolls.

The area of each depth interval between contours—the coral knolls being taken into account—was obtained by cutting roughly along each contour of an ozalid print of the contour charts, and by weighing the paper for each contour interval. The weight of paper representing a square statute mile was first determined and the weight of each contour interval was then converted to area. It is believed that figure 19 is correct to within 2 percent. The histogram shows that depths of 20 to 28 fathoms are widespread, with the mean depth being 25.4 fathoms. The bulge of the histogram and cumulative curve between 0 and 4 fathoms is due chiefly to the flat shallow area at the west limit of the lagoon. The 10–12 fathom terrace shows best as a prominant bulge for the histogram made for the detailed northeast corner of the lagoon. Typically, the islands comprise only about 1 percent of the atoll area. The volume of the lagoon below low tide is $3.6\ (10)^{10}$ cubic yards, of which only 5.5 percent lies below the sill depth of the deep channel, 26.6 fathoms.

SMOOTHNESS COEFFICIENT

Because of the difference in spacing of sounding lines throughout the lagoon, as well as the presence of numerous coral knolls too small to be shown by contours, a misleading impression of flatness of the lagoon floor may be gained by casually viewing charts 2 and 3. In order to avoid this, a new parameter, the smoothness coefficient, was devised. This is simply the percentage of flat floor covered by a section of fathogram made during 15-minute, or 1½- to 2½-mile intervals. A flat floor was defined as one having less than 1 fathom variation other than gradual slope in that distance. The percentage of flat floor is expressed in terms of units between 1 and 10, each unit representing 10 percent. For example, the smoothness coefficient for the fathogram of plate 2, figure 1 is 6, of plate 2, figure 2 it is 4, of plate 3, figure 1 it is 2 and of plate 3, figure 2 it is 3. The smoothness coefficient was estimated for a large number of fathogram sections in Bikini Lagoon. Most of the irregularities are considered to be small coral knolls as they are too steep and sharp to be hillocks of *Halimeda* debris and too large to be the result of lifting and dropping of the ship by waves.

The results (fig. 20) show that the flattest areas correspond to the areas of most abundant fine debris, probably reflecting the mantling or smoothing effect of this deposit. The sill of Enyu Channel is also flat. At the greatest depths in the lagoon little of the floor is flat, suggesting that loose sediments are not able to mantle the bottom effectively because of the growth of coral knolls; this is in contrast to conditions in the peripheral areas. The average smoothness coefficient for the entire lagoon is 4.6, meaning that only 46 percent of the area is flat within 1 fathom.

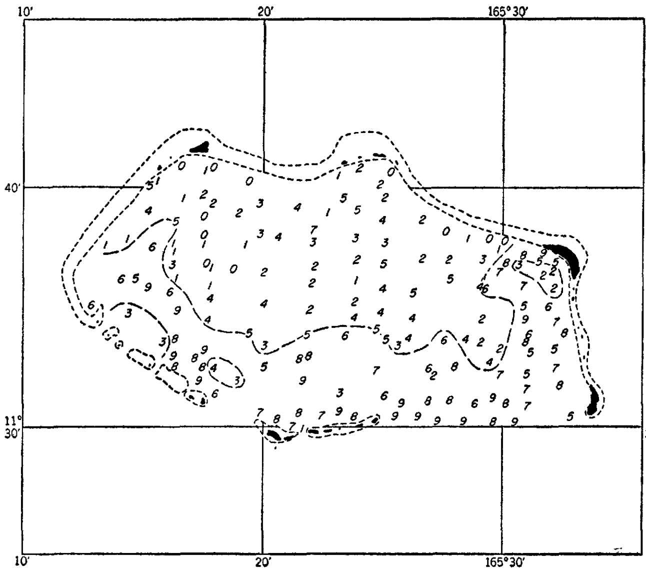

FIGURE 20.—Map showing percentage of flat area (smoothness coefficient) in Bikini lagoon. The smoothness coefficient shows the percentage of flat floor covered by a fathogram made during a 1½- to 2½-mile interval. The percentages are expressed in units between 1 and 10, each unit representing 10 percent. Dashed lines in lagoon separate the more level areas from those that are rougher.

SEDIMENTS

At Bikini Atoll about 50 days aboard ship were devoted to the collection of samples and underwater photographs, usually in conjunction with sounding operations. A total of about 1,150 samples were collected from the lagoon during the 1946 expedition and these were supplemented by about 325 more in 1947. About 450 of those taken after the bomb tests were from the bomb area or so close to it that they were subject to modification by bomb effects: they are neither reported nor made use of in this report. Thus, there remain about 950 samples suitable for study of the lagoon floor. Of these, about 60 are snapper samples, 40 were picked up on beaches, 20 are dredgings, and 12 are cores. As shown by figure 21 the samples are well distributed through the various depth zones, although they are concentrated in the area near Bikini island.

In the laboratory the samples were transferred to small glass vials. These vials were placed atop the corresponding sample positions as plotted on the lagoon chart, thus giving a general impression of the sediment types and their distribution. Each sample in turn was examined with a binocular microscope and the bulk percentage of the various components was estimated visually. The chief components include Foraminifera, coral, *Halimeda*, and shells of mollusks (pl. 25). Material finer than about one-half millimeter required an unwarranted amount of time to identify as to source organism so it was grouped together as fine debris. This group was checked occasionally by sieving and weighing, but it should be considered only a grouping that includes some medium sand and some coarse silt. Some components larger than one-half millimeter were too rare to justify percentage estimates so they also were grouped as miscellaneous. This group includes *Lithothamnion* and other coralline algae, echinoid spines, sponge spicules, and bryozoans.

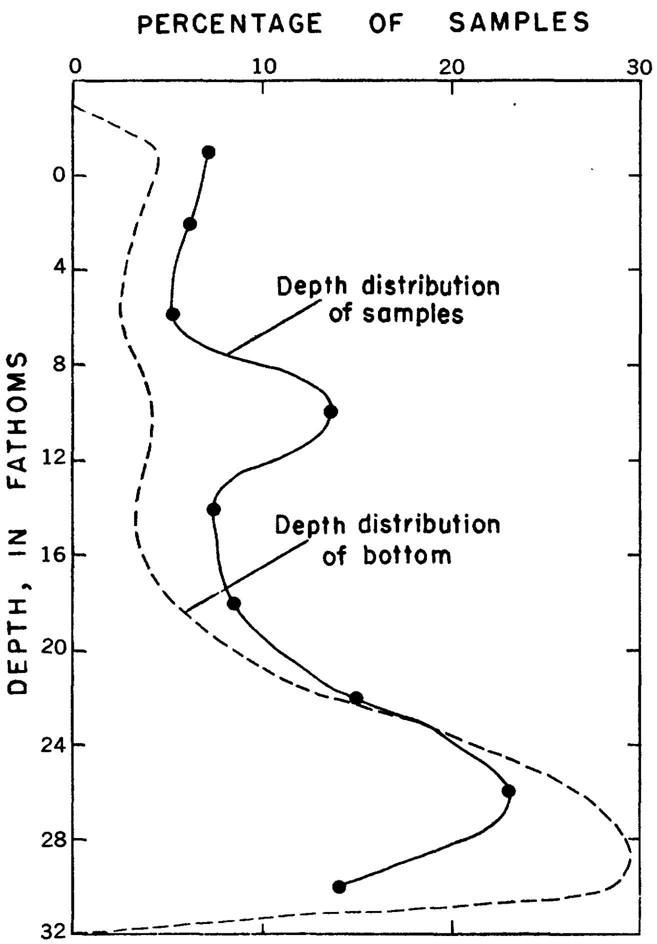

FIGURE 21.—Depth distribution of samples collected in lagoon relative to depth of lagoon floor, Bikini Atoll.

In examining the samples it soon became obvious that most of them consisted of granular debris taken from relatively flat areas between coral knolls, others chiefly of one or two pieces of coral with only a few grains of fine sediment. On comparison with the sounding record it was found that at least some of the latter samples were broken from the top or sides of coral knolls. Because coral knolls are topographic highs, little detrital sediment from the main reef or pelagic sediment from the overlying water can accumulate on them; therefore, the coral knolls in a sense are similar to rock outcrops on land that are barren of Recent sediment but which may supply debris to surrounding areas. The lagoons can then be considered as made up chiefly of two distinct but superposed environments: (1) the topographic highs characterized by active growth chiefly of coral with relatively little accumulation of granular material, and (2) the gentle slopes or flat areas between coral knolls where granular debris from the reefs and knolls, from the water above, and from *Halimeda* and Foraminifera growing on the bottom are deposited. Minor amounts of coral are found in the flat area, as talus debris near the base of the coral knolls and as growth in situ on the bottom.

Many of the samples contain abundant dark gray grains of the same shape and organic origin as the white or cream-colored ones. A few of them appear in the *Halimeda* debris of plate 26. In many instances mixtures of the two kinds of grains give a salt and pepper appearance to the samples. On treatment with dilute hydrochloric acid, the black grains left a residue of organic material identified by Dr. Francis Drout (personal communication) as follows:

"* * * two or three small masses (no more than a few hundred microns across) of *Gomontia polyrhiza* (Lagerh.) Born. and Flah. in good growth and a few not very healthy (but smaller) masses of *Plectonema terebrans* Gom. There were occasional shrunken filaments which I suppose are *Mastigocoleus testarum* Born. and Flah. I found nothing that could be interpreted as *Hyella caespitosa* Born. and Flah."

Similar boring algae have been discovered in ancient rocks such as the Ordovician of Sweden (Hessland, 1949) and may be taken as evidence of deposition in shallow-water environment.

Shells of mollusks are found at all depths but are rare in most sediments. In samples collected along the south side of the lagoon near passes, however, the volume of mollusk shells exceeded 12½ percent.

About 12 cores were taken in *Halimeda* debris outside the bomb area. The available coring gear was so light that the longest core was only 19 inches. When the cores were collected they were examined and noted to be white or cream colored at the top but grayish at depth. Mechanical analyses of them, however, indicated no significant change of grain size with depth (fig. 23); that is, no comminution with depth by crushing or solution is apparent.

Examination of the sediments in the laboratory revealed the frequent presence of grains stuck or fused together in a solid mass (pl. 27, fig. 2). Usually the pieces are less than 2 centimeters long. This fusion is common in *Halimeda* debris but is not restricted to it.

The cementing material not only fills interstices between *Halimeda* segments, bryozoans, mollusk shells, coral, and other debris but it also forms a thin coating on the surface of these fragments.

An encrusting foraminifer, *Homotrema*, is illustrated in the report by Cushman, Todd, and Post (1954). Another encrusting type, *Carpenteria*, has been found in some of the lagoonal sediments. The encrusting Foraminifera are common from all depths of the lagoon. Encrusting Foraminifera have been reported from the lagoon at Funafuti by Chapman (1900–1903). Brady (1884) cited the occurrence of *Carpenteria* at depths as great as 1000 fathoms, but it is not stated that the specimens were alive when collected. Similar appearing crusts of *Lithothamnion*, distinguishable only under high magnification, are found on many coral fragments and shells from the shoaler parts of the lagoon, and they occur at least to depths of 22 fathoms at Bikini. *Lithothamnion* encrustations have been reported by Foslie (1929), who noted it in collections from the East Indies, the Mediterranean Sea, and elsewhere.

PERCENTAGE OF COMPONENTS

AREAL DISTRIBUTION

The percentage abundance of the various components of each sample were plotted in chart form and lines of equal abundance were drawn through the 25-, 50-, and 75-percent values. The completed maps of Foraminifera, *Halimeda* debris, fine debris, and shells for the general lagoon are presented in figure 22. Miscellaneous components were not plotted in map form because of their low values. No map for coral was made because of its extreme variability and bacause the sampling methods were inadequate for such coarse material as coral heads and fragments. If coral could have been accurately plotted it would have presented a complex picture showing abundance on each coral knoll and paucity in intervening areas.

The figure shows that the large heavy-walled forms *Calcarina spengleri* and *Marginopora* make up more than 25 percent and locally more than 50 percent of the beach sand (pl. 21). Off the beach Foraminifera decrease in abundance to less than 10 percent, but in the deepest parts of the lagoon Foraminifera are again abundant, comprising as much as 50 percent of many samples. The assemblage of Foraminifera from the deeper parts of the lagoon is, however, entirely different from that found on the beach, and includes the delicate tests of more than 150 different species.

Just off the beaches fine debris is present in appreciable quantities. This debris increases lagoonward to a point several miles from shore where values of 50 to 75 percent are common. On the downwind side of the lagoon the area of most abundant fine debris is wide, irregular, and located farther from shore than on the upwind side. In fact, the zone appears to be almost entirely absent along most of the upwind periphery from Aomoen island to Enyu island, except along Bikini island. Fine debris is less abundant near the middle of the lagoon where it constitutes less than 10 percent of the total components present in each sample. The sand, therefore, has a ringlike distribution, open at the east end like a horseshoe.

Covering most of the middle and deeper part of the lagoon is an area of abundant *Halimeda* debris (pl. 26). In most of this area *Halimeda* segments make up between 75 and 100 percent of each sample. The richest ones are in the eastern half of the lagoon. Spots of relatively low abundance of *Halimeda* segments generally coincide with the areas of abundant deeper-water Foraminifera.

VERTICAL DISTRIBUTION

The same large set of about 1,000 samples used for determining the areal distribution of the sediment components were replotted according to depth of water. All samples for each 4-fathom depth increment were grouped together and the percentages of each component in them averaged. The result is shown in figure 24. It appears, that on the average Foraminifera are most abundant in the shallow samples while *Halimeda* debris is most abundant at depth. Fine debris averages more than 20 percent at all depths but values greater than 50 percent occur between 0 and 8 fathoms. Shells are about equally abundant at all depths. Coral is rather erratic.

Some care must be used in interpreting figure 24 as it shows only the average composition of samples at given depths. For example, Foraminifera constitute two or three times as great a percentage in the beach samples as in those below 20 fathoms. The total volume of weight of Foraminifera on the beaches may be greater than that of Foraminifera produced at depth, but it is not two or three times greater, for the larger area of the lagoon floor must be taken into consideration.

The sediment data for Bikini Lagoon presented in figure 24 was replotted in figure 25 with proper weight given to the actual area covered by each depth zone. Because the lagoon floor covers a much larger area than the beaches, it is apparent that there is more than twice the bulk of Foraminifera at depth as in the beaches, even though the individual deep samples contain a smaller percentage of them. Figure 25 also illustrates the enormously greater abundance of *Halimeda* debris in the deeper waters.

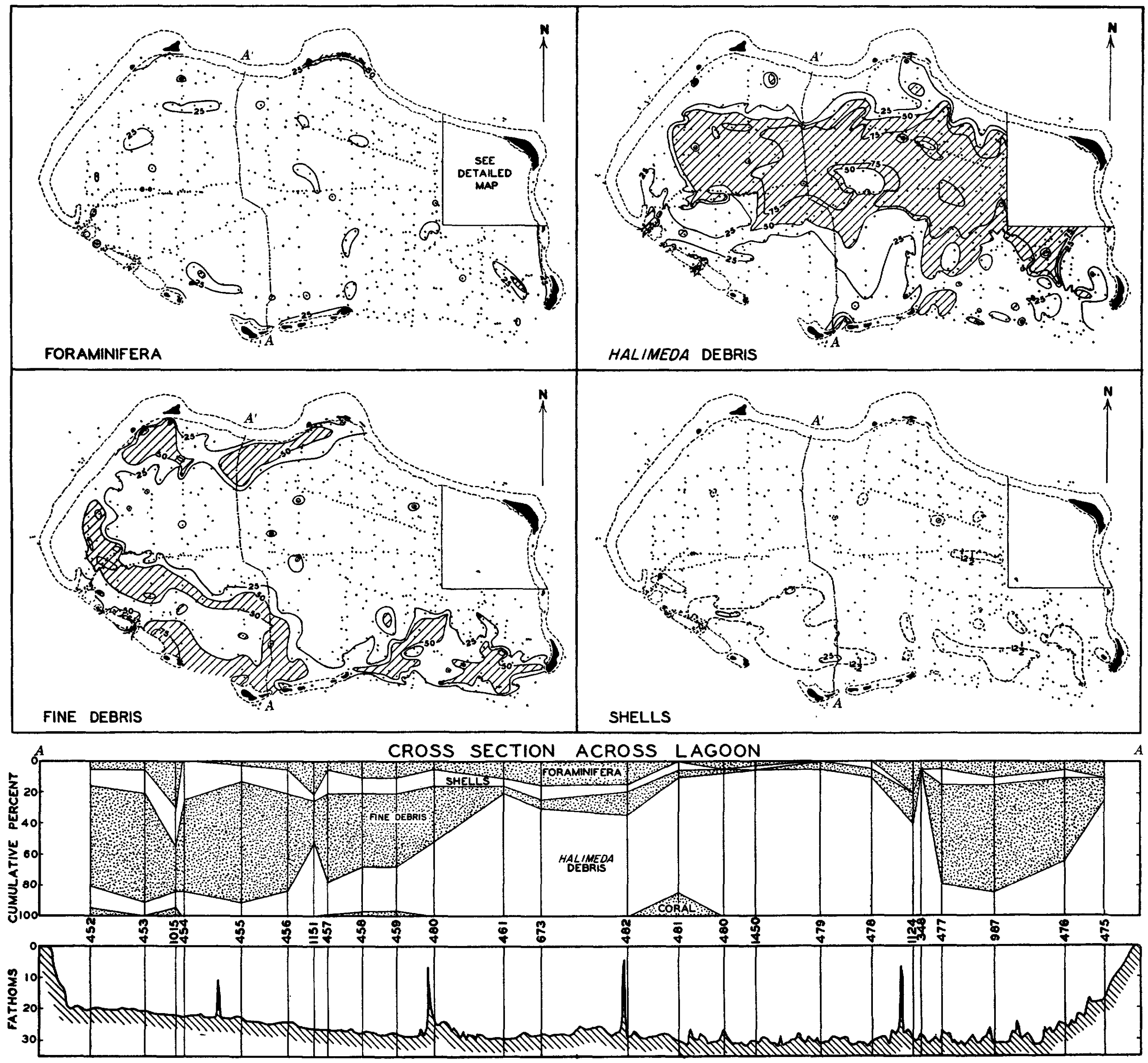

FIGURE 22.—Maps showing the percentage abundance of the important constituents in the sediments of Bikini Lagoon. Lines of equal abundance are drawn through the 25-, 50-, and 75-percent values. Reef boundaries are shown by dash line. Dots mark sample localities. Locality numbers of the samples used in constructing the cross section are shown above the profile. Detailed map on plate 67.

In summary, then, figure 24 indicates the probable composition to be expected of a given individual sample taken from any depth, while figure 25 shows the composition of the lagoon as a whole.

OVER-ALL DISTRIBUTION

In order to make a general chart of the bottom materials it was necessary to simplify the sample descriptions. This was done by assigning to each sample a sediment name that is controlled by its most abundant component. No uncertainty existed if one component amounted to more than 50 percent, but if each of two were, for example, 35 percent, the sample was assumed to be transitional and located on a boundary between areas of different composition. The classes named were foraminiferal sand, coral, *Halimeda* debris, and fine debris. Neither mollusk shells nor coralline algae were abundant enough to characterize any large samples.

Underwater photographs also proved to be extremely helpful in identifying bottom materials. The photographs of plate 24 show some of the forms that characterize sand bottoms. Coral exists not only as the coral

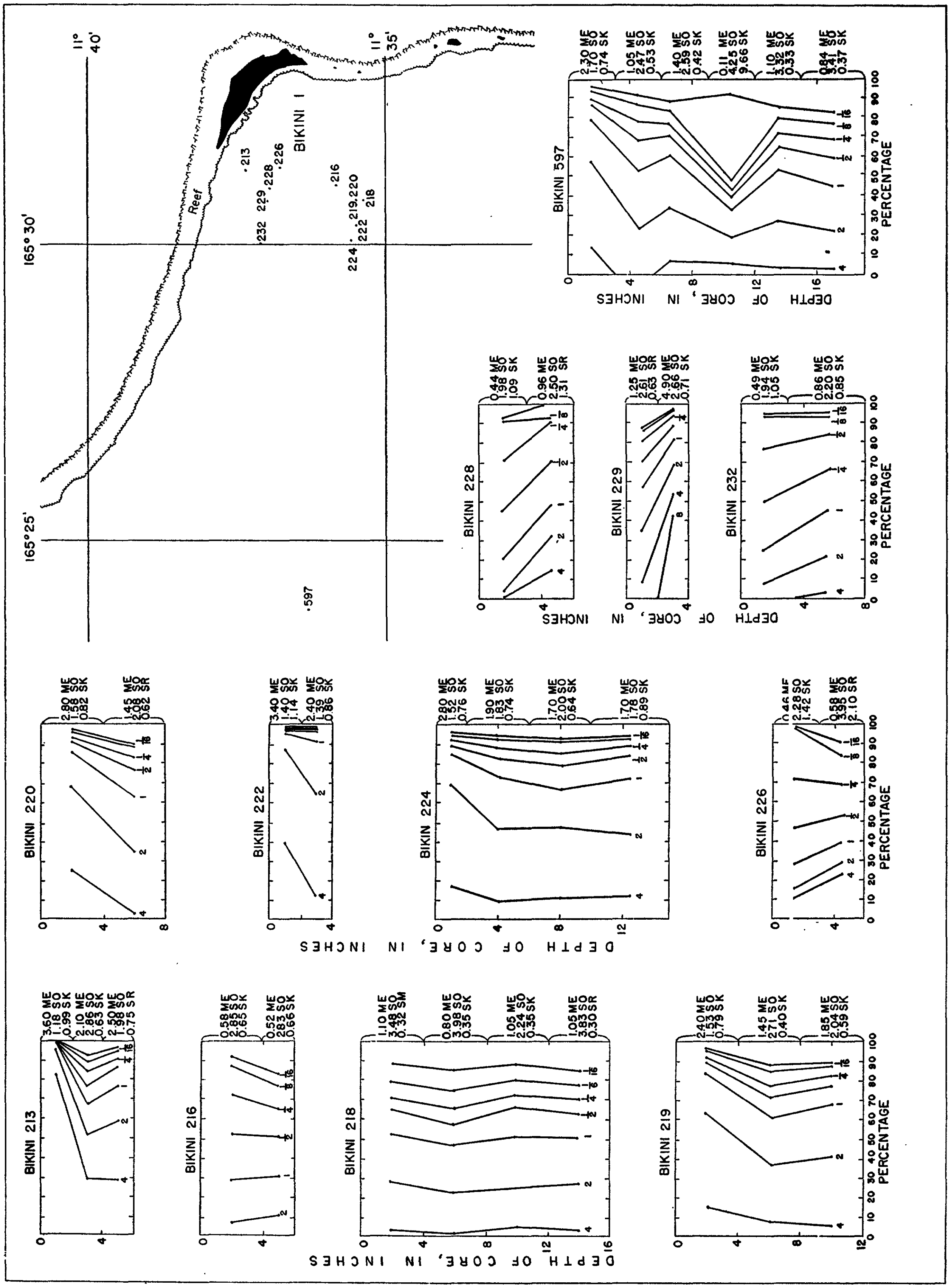

FIGURE 23.—Grain-size distribution of *Halimeda* debris in cores from Bikini Lagoon.

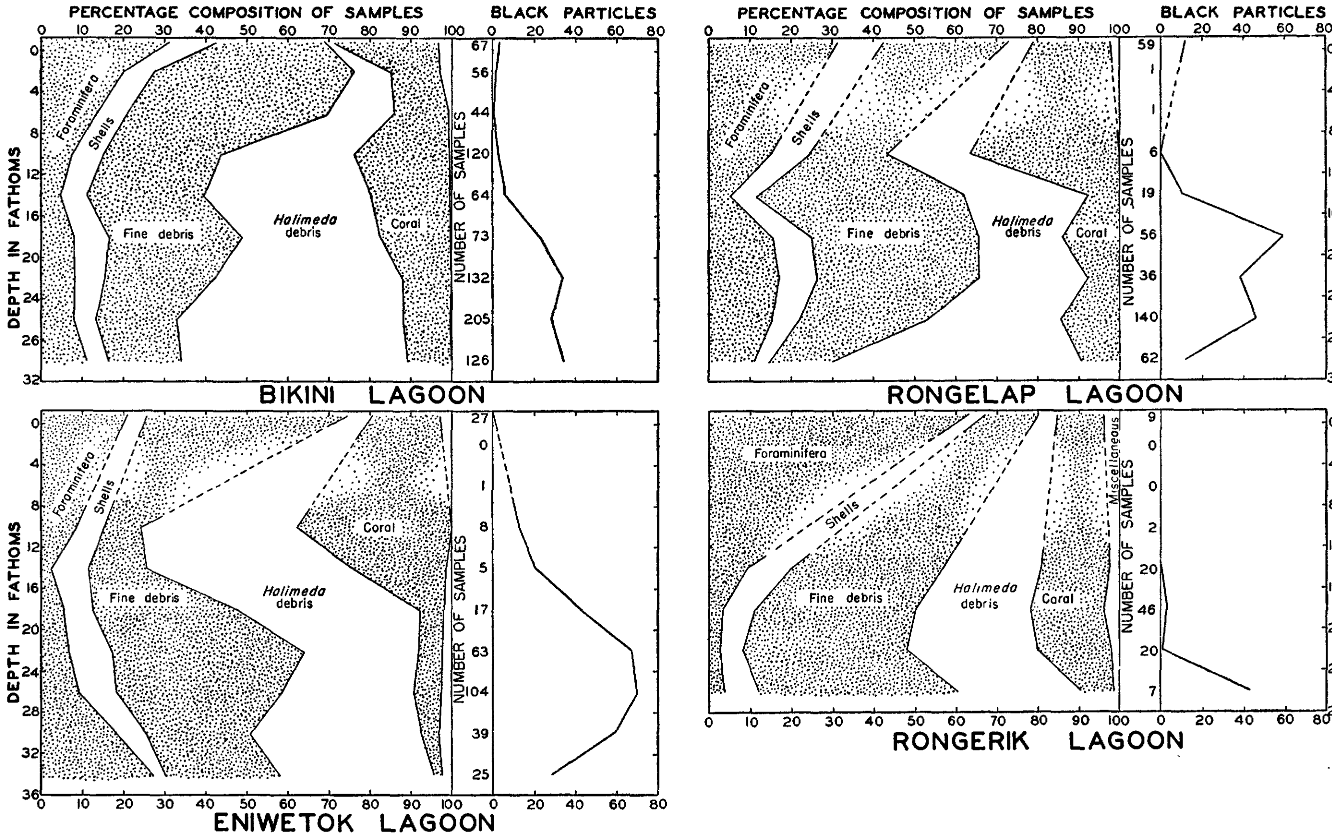

FIGURE 24.—Variation in composition of lagoon sediments with depth.

knolls of plate 20 but also as bramblelike thickets (pl. 24, fig. 3) at intermediate depths. Two large expanses of such coral occur less than a mile from Bikini island. *Halimeda* debris forms a relatively flat mat of green living *Halimeda* mottled by the loose white segments beneath.

In addition to the direct observations, topography also proved useful in delimiting some of the bottom materials, especially coral. Observations made during diving operations as well as ordinary sampling methods showed that the coral knolls consist almost entirely of coral with living specimens at the top and dead ones usually forming a fringing talus slope. Some of the interstices were found to be partly filled with *Halimeda* debris and other fine sediments, but these total only a few percent of the bulk of each coral knoll. Accordingly, all sharp topographic highs can be safely designated on a sediment chart as areas of coral.

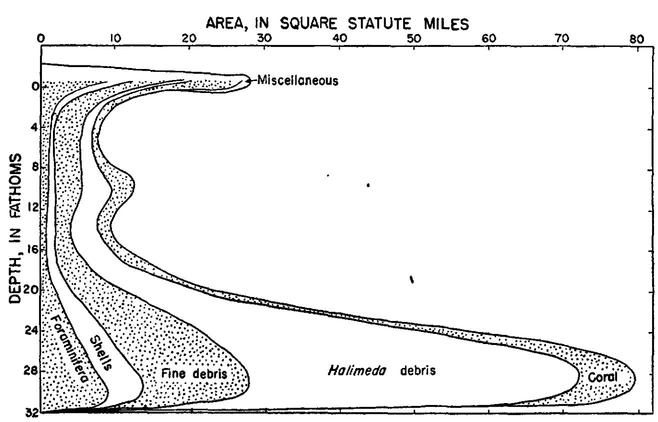

FIGURE 25.—Over-all depth distribution of sediments, Bikini Lagoon.

Most of the Japanese soundings atop the coral knolls are accompanied by bottom notations of coral (Co). Other coral notations were found in areas between coral knolls. It, therefore, appears that the Japanese designated as coral any relatively large fragments of calcareous material including *Halimeda* segments. Chart notations of sand (S) were found to be mostly restricted to areas known from our samples to be sand, but some of them occur in known areas of *Halimeda* debris. As these notations were all based on the very small leadline samples they are not very reliable and are of limited usefulness.

Data from all of these sources were used in constructing plate 67 which, in general, follows the trends suggested by figure 22. Foraminiferal sand from the reef flat is most abundant on the beaches and bars to which it is swept along with fragments of coral, calcareous algae, etc. from the reef flat by waves and currents. Wave action breaks the material of the beaches into fine debris which is carried into the lagoon for distances mostly less than 2 miles. The greater wave action on the downwind side of the lagoon is reflected in a much wider belt of fine debris there than along the up-wind end near Bikini island. The medium and fine sand in deeper water is composed of *Halimeda* debris comminuted by wave action as well as material transported from shore. In still deeper water the depth is too great for effective wave abrasion and the distance from shore too great for contributions from the beaches; accordingly, the bottom sediments there are composed chiefly of *Halimeda* debris. In water deeper than about 30 fathoms, light is so reduced that plants such as *Halimeda* do not flourish, or are absent. In their place there is an accumulation of benthonic and pelagic Foraminifera. These constituents are deposited all over the lagoon but in moderate depths they are masked by the more active growth and deposition of *Halimeda* debris. In shallower depths the *Halimeda* debris itself is partly masked by sand carried from shore and partly destroyed by wave action.

By measuring the percentage area covered by each of the four different major kinds of sediment on plate 67, one finds that the most abundant sediment is *Halimeda* debris followed in turn by fine debris, coral, and Foraminifera (table 8). Such a listing, however, omits the minor constituents that are known to be present in each sample but are ignored when the sample is named from the major constituents only. The minor constituents can be included by basing the estimate on actual sample descriptions weighted according to the area of different depth zones. This method is essentially a totalling of the area covered by each constituent on figure 25. This tabulation (table 9) again shows *Halimeda* debris most abundant, followed by fine debris, coral, Foraminifera, mollusk shells, and miscellaneous. The constituents are in the same order as before but have somewhat different values. However, it should be remembered that the samples over coral bottoms are not very representative because the fragments are large and some are too well attached to be broken off. Many of the misses or "no samples" probably resulted from trials made on coral knolls. Accordingly, the latter method yields values undoubtedly low for coral. If one arbitrarily adds most of the coral-knoll area determined by topography to the coral percentage determined by sample study, and thereby obtains a total coral area of 20 percent, then the remaining constituents can be recomputed to figures believed to be somewhat closer to actual conditions. The weighted and recomputed average composition is also shown in table 9. In it the constituents still are in the original order but are more nearly of equal value. The need of such manipulation underlines the difficulty and uncertainty of estimating the composition of lagoonal sediments, even where numerous samples and soundings are available.

TABLE 8.—*Composition of lagoon floors, estimated from charts*

Atoll	Percent occupied by—			
	Foraminifera	Fine debris	*Halimeda* debris	Coral
Bikini	5	30	56	9
Rongelap	3	53	36	8
Eniwetok	9	52	26	13
Rongerik	3	36	27	34
Average	5	43	36	16

TABLE 9.—*Composition of Bikini Lagoon*

Basis of computation	Percent occupied by—					
	Foraminifera	Fine debris	*Halimeda* debris	Coral	Mollusk shells	Miscellaneous
Chart (estimates)	5	30	56	9	0	0
Depth zones (weighted by area)	11	25	43	13	7	1
Coral knolls (weighted by area)	10	23	40	20	6	1
Wells	10	[1] 70	5	5	3	7

[1] Includes 20 percent paste.

ORGANIC CARBON

Organic carbon was determined for 14 sediment samples from Bikini Lagoon using Allison's (1935) method. This consists of the oxidation of the organic material by an excess of potassium dichromate in concentrated sulfuric acid heated to 175° C., cooling and titrating the unused chromic acid with 0.2 N. ferrous ammonium sulfate using diphenylamine as an indicator. Four tests with blanks showed a range of error of 0.03 percent.

The results, shown on figure 26, range from 0.18 to 0.62 percent organic carbon in the sediments. The lowest value, 0.18 percent, was found in a beach sand from Bikini island. A closely similar sand from 5 fathoms just off another beach was also low, 0.31 percent. Eleven other analyses were distributed amongst fine debris, *Halimeda* debris, and deep lagoon foraminiferal sand. No clear-cut difference between the organic carbon of the different kinds of sediment could be detected. The eleven results varied between 0.33 and 0.62 percent and averaged 0.46 percent. The highest value of all, 3.86 percent, was found for some specimens of *Halimeda* which were green and alive when sampled.

In comparison, Trask (1932) found a range of organic carbon from 0.2 to 4.2 percent in about 100 samples of Recent sediments and a similar range for 15 older sediments. The calcareous sediments from Bikini Lagoon are, therefore, very low in organic carbon, averaging only one-fourth that of Trask's near-shore sediments. When converted to total organic matter (organic carbon times 1.7) the Bikini sediments exhibit almost exactly the same range of low organic content as deep-sea sediments. Analyses of total organic matter by Dr. Donald Johnstone (personal communication) yielded similar average values of 0.60 percent at Bikini and 0.68 percent at Rongelap Lagoon. The organic content of soils from both atolls is also very low (Johnstone, 1947).

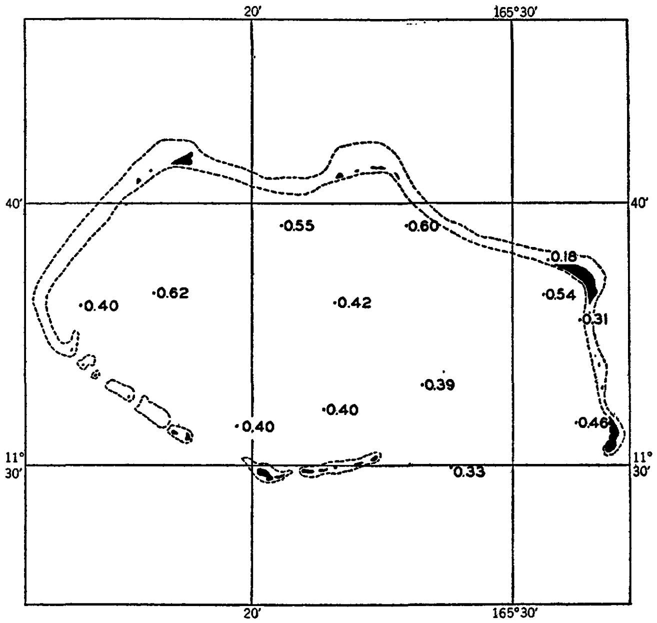

FIGURE 26.—Percentage of organic carbon in sediments of Bikini Lagoon.

CLAY CONTENT

Mechanical analyses of the calcareous sediments, particularly *Halimeda* debris, commonly showed the presence of 5 to 20 percent by weight of grains finer than 1/16 millimeter in diameter. Some of this material is finer than 0.004 millimeter and is insoluble in acid, thus suggesting the presence of clay minerals in the sediments. A 1-gallon sample of *Halimeda* debris collected from a depth of 30 fathoms in Bikini Lagoon at latitude 11°34′30″ N., longitude 165°28′30″ E. was sent to Dr. Ralph E. Grim of the Illinois Geological Survey for study of the clay content. The sample contained only 0.12 percent material other than carbonate and carbonaceous organic remains. Because this residue contained only a small amount of clay, it was necessary to dissolve a large quantity of the sediment, 500 grams, in order to obtain enough material for thermal analysis. Grim believed that by the time all of the carbonate was dissolved the clay mineral may have become much altered. He found that the illite type clay mineral was the most abundant and the only one definitely identified though it is possible that small amounts of kaolinite and montmorillonite were also present.

POROSITY AND SPECIFIC GRAVITY

Microscopic examination of *Halimeda* segments and of foraminiferal tests showed that each contains large internal cavities and also that their walls have many very small covered or partly covered pores. These cavities and pores constitute a porosity in excess of the ordinary interstitial porosity of most sediments. Because the resulting high porosity doubtlessly is reflected in some of the mass properties of the sediment and may be a factor controlling the depth of burial at which the sediment is compacted to limestone, an effort was made to measure each of the three forms of porosity separately, as well as combined.

METHODS

Several samples, each a few grams in weight, were obtained by picking over some of the original sediment samples. For example one picked sample was composed only of tests of *Marginopora* sp., another of *Calcarina* sp., another of whole segments of *Halimeda,* and still another of weathered and broken segments of *Halimeda*. The specific gravity of each picked sample was measured in a pycnometer filled with distilled water to which a drop of wetting agent, Aerosol, was added. Each sample was then dried and crushed and the specific gravity of the powder was measured. This value was assumed to be an approximation of the specific gravity of the wall material of the grains. Knowing the specific gravity of the whole grain and that of the wall material, it is a simple matter to compute the percentage volume of the main cavities of the grains using the equation,

$$P=\frac{\frac{1}{SG_{gr}}-\frac{1}{SG_{wall}}}{\frac{1}{SG_{gr}}}\times 100$$

where P is porosity, SG_{gr} is grain specific gravity, and SG_{wall} is wall specific gravity. It was noted that the specific gravity of the powdered wall material was much lower than that of calcite or aragonite, probably because of the presence of minute pores between the calcium carbonate crystals. According to Clarke and Wheeler (1922) *Halimeda* and coral are composed of aragonite, while most Foraminifera are of calcite. Their chemical analyses show the presence of variable but small amounts of other elements including magnesium, iron, and strontium. By using the measured specific gravity of the wall material and the accepted value of 2.94 for aragonite and 2.71 for calcite, the wall porosity was computed for each of the materials.

The sediments, themselves, are characterized by intergranular porosity in addition to that within the grains. During the collection and transportation of the samples the intergranular porosity was disturbed so that it was necessary to attempt to reproduce the original packing to a reasonable approximation. Dried and weighed samples of each of the main kinds of sediment were introduced slowly into a small graduated cylinder containing a known volume of water with wetting agent. At the same time, the cylinder was jarred so that the sediment would settle to a minimum packing. For sediment containing much fine-grained material several hours were required to introduce the sediment. The volume of sediment and of sediment plus overlying water were read on the graduated scale. After the overlying water was decanted, the saturated sediment was weighed. Thus, the following measurements were made:

W_{gr}=dry weight of grains
W_{gr+w}=weight of grains plus intergranular water
V_w=volume of water alone
V_{gr+w}=volume of grains plus intergranular water
V_{wo}=volume of overlying water

From these measurements the volume of the grains,

$$V_{gr}=V_{gr+w}+V_{wo}-V_w,$$

and the grain specific gravity,

$$SG_{gr}=\frac{W_{gr}}{V_{gr}},$$

can be obtained. Specific gravities measured by this method agreed well with duplicate tests by pycnometer. The total internal grain porosity was computed from the equation,

$$P_{gr}=\frac{\frac{1}{SG_{gr}}-\frac{1}{SG_{cal,arag}}}{\frac{1}{SG_{gr}}}\times 100$$

where $SG_{cal,arag}$ was based on an estimate of the relative proportion of organic debris composed of calcite and of aragonite. Intergranular porosity was computed from the equation,

$$P_i=\frac{V_{gr+w}-V_{gr}}{V_{gr+w}}\times 100.$$

The total porosity is, of course, the sum of the intergranular and the internal grain porosity after the latter is expressed as percentage volume of the total sediment. From the total porosity, the over-all specific gravity of the sediment was computed, assuming that all pore spaces were filled by sea water of density 1.025.

RESULTS

The porosity measurements for selected grains are summarized in the first half of table 10. The highest grain porosity of all, 41.8 percent, was obtained for a sample of *Halimeda* collected alive and preserved in formaldehyde solution. Presumably, the soft tissue still covered many of the openings and prevented the entrance of much water. Other *Halimeda*, which were alive when collected but which were allowed to dry thoroughly, had a lower porosity. Segments which were dead but unbroken when collected had a porosity lower than that of living segments but much higher than worn and broken segments. Presumably, after the plant dies the grain porosity decreases continuously as the softer tissues made of chitinous filaments decompose and as wear and breakage of the grain exposes more and more cavities. Thus, in time, some of the internal grain porosity would be converted to external or intergranular porosity. Samples of picked Foraminifera also yield interesting comparisons. Both *Marginopora* sp. and *Calcarina* sp. in an unweathered state have almost identical internal grain porosities of 22.5 and 22.3 percent, respectively. However, as in the case of *Halimeda*, this porosity is in two parts: the main cavities and the small wall pores. Both microscopic examination and the specific gravity measurements showed that most of the internal grain porosity of *Calcarina* sp. is in the main cavities, while that of *Marginopora* sp. is in the very small pores of the test. It is notable also that the powdered Foraminifera had a lower specific gravity than the powdered *Halimeda* substantiating the dominantly calcitic ccmposition of the Foraminifera and the dominantly aragonitic composition of *Halimeda*. Individual coral branches were found to have, as expected, the lowest porosity of all the tested organic materials.

The second half of table 10 gives the porosity and specific gravity measurements of the typical sediment samples. The sediments are arranged roughly according to distance from shore with deeper sediments listed first. The overall grain porosities of the sedimens are lower than those of the picked samples because of the presence of much broken and worn debris in the samples. The grain porosity ranges between 4.9 and 13.1 percent of the volume of the grains, or between 2.4 and 6.1 percent of the whole sediment. Measurements were not made of the ratio of the porosities of the main cavities and of wall pores. The intergranular porosities ranged between 49.5 and 57.8 percent, with values for *Halimeda* debris about 5 percent higher than for the sand, as a result of the more irregular shapes of *Halimeda* segments. Total porosity, the sum of grain and intergranular porosities, ranges between 53.4 and 61.3 percent, with *Halimeda* debris having the higher values. All of the values are far higher than those normally encountered in sands, since porosity of the latter rarely exceeds 40 percent (King, 1898, p. 209–211; and others).

TABLE 10.—*Porosity and specific-gravity measurements of lagoonal sediments*

Material and sample No. (Bik.)	Porosity, in percent						Specific gravity		
	Grain—internal			Whole sediment					
	Main cavities in grains	Pores in grain walls	Percentage of total	Grain—internal	Intergranular	Total	Grain	Wall	Whole sediment with sea water
Picked grains									
Halimeda, preserved			41.8				1.71		
Halimeda, dried	23.1		29.3				2.08		
Halimeda, whole segments	18.7		25.3				2.20		
Halimeda, worn segments	5.4	21	13.0				2.56	2.71	
Marginopora, sp	8.6	15.2	22.5				2.10	2.30	
Calcarina, sp	14.5	9.1	22.3				2.11	2.46	
Coral	4.0	3.4	7.3				2.51	2.62	
Sediments									
Halimeda, debris 547							2.16		
Do 499			11.3	5.2	54.4	59.6	2.57		1.78
Do 510			13.1	6.1	53.1	59.2	2.52		1.79
Do 131							2.44		
Do 216			8.2	3.5	57.8	61.3	2.66		1.75
Offshore sand 195							2.52		
Do 199							2.43		
Do 500			4.9	2.4	51.0	53.4	2.58		1.81
Near shore sand 497							2.48		
Do 60							2.58		
Do 64			12.5	6.1	50.7	56.8	2.37		1.76
Do 157							2.51		
Beach sand 52							2.50		
Do 26							2.65		
Do 493							2.68		
Do 71			9.0	4.5	49.5	54.0	2.47		1.81
Average values									
Halimeda debris			10.9	4.9	55.1	60.0	2.47		1.77
Sand			8.8	4.3	50.4	54.7	2.52		1.79

Marine sediments of higher porosity are known but such sediments have a high clay content—far greater than that of the Bikini sediments. The high values of the latter are due to the internal grain porosities plus the very irregular grain shapes which give rise to high intergranular porosities.

Grain specific gravities are fairly close. *Halimeda* averages 2.47, offshore sand 2.50, and beach and near-beach sand, 2.55. It is notable that grain specific gravities show a general increase with closer approach to shore, possibly because of greater breakage by wave action. The overall sediment specific gravities are subject to even more errors than the other measurements. Computation of this value was based on the assumption that all pore spaces were filled with water originally. Least certain to be filled are, perhaps, the wall pores, for these may represent only a loose packing of the calcium carbonate crystals between which there may not be enough space for the entrance of water; however, even with this uncertainty, the values for overall specific gravity are probably correct to within a few hundredths. It is notable that all computed values lie within a small range, 1.75 to 1.81.

There is a wide difference between the grain specific gravity of picked Foraminifera (2.10) and of the whole sand (mostly higher than 2.45) as shown by table 10. This difference indicates that the sediment contains much material of specific gravity considerably higher than 2.45 mixed with the lighter Foraminifera. This range of grain specific gravities is so great that high concentrations of whole foraminiferal tests can be made by flotation on heavy liquids. Such liquids were made by mixing bromoform with alcohol until the desired value of specific gravity was obtained. A small dried sample was placed on the liquid and stirred so that all of the denser grains sank to the bottom of the container and only the less dense grains remained floating. Use of a 2.4 specific gravity liquid allowed about 40 percent by weight of the sand samples to float, while only 10 percent floated on a liquid of 2.3 specific gravity. For both liquids the light fraction was dominantly of Foraminifera with some *Halimeda* and gastropods; however, the 2.3 specific gravity liquid was so light that many Foraminifera sank. Relatively few Foraminifera sank in the 2.4 specific gravity liquid. The heavy fraction for that liquid was composed chiefly of the less porous organic debris: well worn coral, echinoid spines, *Gorgonia* spicules, mollusca, and small unidentified debris. Similar tests made with *Halimeda* debris showed that the light fraction contained mostly whole segments, and the heavy fraction had worn and broken segments.

Compaction of Halimeda *debris*.—The discontinuity in seismic velocities at a depth of 2,000 to 3,000 feet beneath Bikini Lagoon may be ascribed either to a difference in type of deposit or to crushing of the sediment at that depth owing to weight of overburden. The high original porosity and the brittle nature of *Halimeda* debris suggested that crushing of this widespread sediment might well be significant. Accordingly, a laboratory test of compaction at various pressures was made.

Two preliminary tests served to establish a technique. Part of a core sample of *Halimeda* debris (Bikini 219, 4 to 8 inches) was introduced into a steel sleeve having a length of 5.28 inches and an inner diameter of 1.77 inches. In order to secure the tightest packing, or lowest original porosity, small portions of dried sediment were added to the water-filled sleeve, until at the end of about 5 hours a total of 3.08 inches of *Halimeda* debris was deposited. Occasional tapping of the sleeve during the filling process aided in the packing. The excess water was drained away and the sediment in the sleeve was dried several days at 110° C. Removal of the water was considered necessary in order to prevent it from limiting compaction, during the later unnaturally accelerated loading.

A steel rod of slightly smaller diameter was pushed into the sleeve until the lower end rested on the surface of the sample, and the whole apparatus was placed in a materials testing machine. Compressive loading was applied at a slow rate. At intervals the load was held constant until no further compaction was measureable. These periods ranged between 6 and 20 minutes, though little or no compaction was observed beyond about 2 minutes after load was reached. At the end of each period the load and the length of the column of sediment was recorded. Altogether, the final experiment required 3½ hours. At the end of this time, no elastic lengthening of the column could be detected on removal of the load.

The measurements of length were converted to porosities and the measures of both length and load were used to compute the depths of overburden that would exert such loads in nature. The resulting "porosity-depth" curve is presented in figure 27. It is evident that there is no indicated sharp discontinuity at 2,000 to 3,000 feet or at any other depth, suggesting that the seismic discontinuity found at Bikini Atoll may reflect a change of sediment rather than from mere crushing of *Halimeda* debris though the single deep drill hole that was carried to 2,556 feet found no important change in material below 2,000 feet. It should, however, be pointed out that compaction carried out in the laboratory differs from that in nature in three respects. Possibly most important is that the duration of the experiment is much shorter than the geological time available in nature. Of uncertain but possibly great significance is the fact that in nature the sediment is saturated with water and that it is heated in the geothermal gradient.

The porosity of *Halimeda* debris decreases much less rapidly with depth than does the porosity of shales (Athy, 1930). In fact, after compaction at 10,000 pounds per square inch (equivalent to a depth of burial of 29,100 feet) the *Halimeda* debris still retained a porosity of 40 percent. Shale under these conditions would have had a porosity of only about 1 percent. This difference probably indicates a greater resistance to deformation and repacking of the calcareous *Halimeda* debris than of marine clays. A similar relationship was obtained by Terzaghi (1940) in low-pressure compaction tests of lime mud as compared with clays.

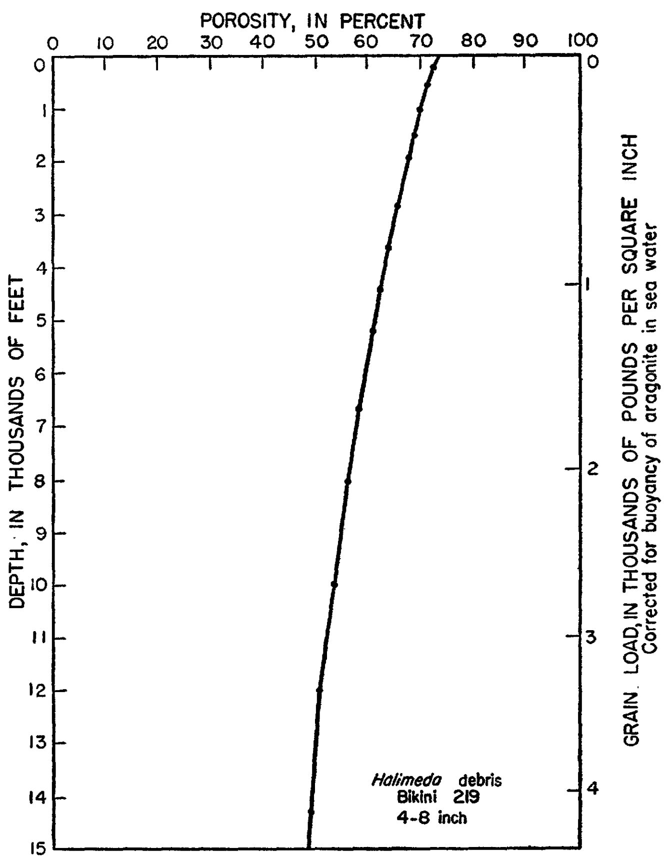

FIGURE 27.—Porosity versus depth for *Halimeda* debris, as computed from laboratory stress-strain test.

CHEMICAL ANALYSES

Chemical analyses were made of picked Foraminifera, *Halimeda*, and calcareous red algae, and of several sediment samples from the beaches and the lagoon floor. These analyses are shown in table 11. No corals were analyzed but an average coral analysis from Clarke and Wheeler (1917) is shown for comparison.

In all of the analyses carbonates comprise 97 percent or more of the inorganic constituents. Carbon dioxide is low by 0.2 to 1.5 percent of balancing all oxides of calcium, magnesium, and strontium as carbonates. Much less than half of this deficiency is made up by acid-soluble sulfate. Perhaps some of the remaining anions are balanced by acid-insoluble sulfate or by chloride, neither of which was investigated.

The ratio of magnesium oxide to calcium oxide ranges from 0.6 to 19.7 percent as contrasted with the ratio of 71.9 percent characteristic of pure dolomite. In spite of the relatively high percentages of magnesium oxide present in some of the samples, no dolomite was identified in the X-ray analyses made by Axelrod. The organisms, thus, consist chiefly of either aragonite or calcite. The Foraminifera and calcareous red algae are of calcite, whereas *Halimeda* and coral are of aragonite. The table shows, as has long been known, the close correlation between aragonite and low-magnesium oxide. Also, as pointed out by Rankama and Sahama (1949, p. 478-481), aragonite appears to be a carrier of strontium. The occurrence of magnesium in these substances is under study in the laboratory of the Geochemistry and Petrology Branch of the Geological Survey.

The analyses show that *Halimeda* has the lowest content of magnesium oxide and the highest of strontium oxide. Coral probably is similar though analyses are less complete. Foraminifera have intermediate values of magnesium oxide and the lowest strontium oxide. Calcareous red algae have the highest magnesium oxide and low-strontium oxide. Calcium oxide varies chiefly in response to changes in magnesium oxide. Silica and sesquioxides are less than 0.5 percent in all analyses and are of little diagnostic value.

The analyses of mixed sediments appear to be closely related to those of the pure organisms. The coarse beach sand consisting chiefly of the large Foraminifera, *Calcarina spengleri* and *Marginopora vertebralis*, with a minor amount of coral, has a chemical composition between that of Foraminifera and coral but nearer the former. The fine beach sand, consisting chiefly of grains of resistant coral with minor numbers of Foraminifera, is of a chemical composition closer to that of coral. *Halimeda* is changed little during its weathering, but the purest sample of *Halimeda* debris contains slightly more magnesium oxide and slightly lower strontium oxide than the picked *Halimeda* segments, possibly because of the admixture of some small pelagic Foraminifera. Samples 9, 11, 12, and 13, taken from progressively deeper water, change from dominantly Foraminifera to dominantly *Halimeda*. The analyses

TABLE 11.—*Analyses (percent) of sediments from Bikini Atoll*

[Analyses 1, 2, 5, 6, 7, 9 by Charlotte M. Warshaw; analyses 3, 4, 10, 11, 12, 13 by A. C. Vlisidis. Final SrO determinations with flame photometer by W. W. Brannock. X-ray determinations by J. M. Axelrod]

	Foraminifera		*Halimeda*		Calcareous red algae			Corals	Sediments				
	1	2	3	4	5	6	7	8	9	10	11	12	13
SiO_2	0.20	0.12	0.50	0.14	0.18	0.24	0.10	0.06	0.12	0.16	0.20	0.20	0.20
$(Al, Fe)_2O_3$	.30	.22	.30	.34	.40	.46	.34	.06	.36	.28	.26	.28	.18
MgO	5.52	5.67	.32	.38	8.01	8.25	6.73	.24	4.95	1.32	2.26	.82	.54
CaO	46.90	47.86	54.51	53.25	42.20	41.85	42.91	53.08	47.78	52.28	50.31	52.84	52.64
SrO	.18	.16	.90	.87	.24	.24	.22	----------	.28	.72	.46	.82	.73
CO_2	42.64	43.16	42.66	41.46	41.08	40.43	39.75	41.68	42.36	41.57	41.65	41.60	41.28
Acid sol. SO_3	.32	.68	.16	.25	.70	.64	.70	(?)	.44	.34	.55	.29	.37
Acid insol. org	.26	.16	----------	.15	1.27	1.60	2.01	} 3.21	{ .28	.17	.21	.16	.32
Water sol. org	.45	.87	----------	----------	1.98	2.73	2.47		----------	----------	----------	----------	----------
Water	.40	.50	.20	.30	1.53	1.48	1.52		.48	.28	.28	.24	.44
Total	97.17	99.40	99.55	97.14	97.59	97.92	96.75	98.33	97.05	97.12	96.18	97.25	96.70
Acid insol. inorg	0.18	0.09	----------	0.38	0.35	0.38	0.36	----------	0.12	0.20	0.05	0.43	0.25
X-ray	Cal.	Cal.	Arag.	Arag. very little cal.	Cal.	Cal.	Cal.	(Arag.)	Cal and little arag.	Arag. and little cal.	Arag. and cal.	Arag. and little cal.	Arag. and little cal.
SiO_2	0.21	0.12	0.50	0.14	0.19	0.28	0.11	0.06	0.12	0.16	0.21	0.20	0.21
$(Al,Fe)_2O_3$	.31	.22	.30	.35	.43	.53	.37	.06	.37	.29	.27	.29	.19
$MgCO_3$	12.03	12.12	.67	.82	18.00	18.54	15.41	.52	10.72	2.83	4.95	1.76	1.17
$CaCO_3$	87.18	87.30	97.25	97.42	81.02	80.28	83.77	99.38	88.38	95.66	93.88	96.55	97.35
$SrCO_3$	.27	.24	1.28	1.27	.36	.37	.34	----------	.41	1.06	.69	1.20	1.08
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	----------	100.00	100.00	100.00	100.00	100.00

1. Picked Foraminifera (*Calcarina spengleri*). Lagoon beach.
2. Picked Foraminifera (*Marginopora vertebralis*). Lagoon beach.
3. Picked unweathered *Halimeda* segments.
4. Picked weathered *Halimeda* segments.
5. *Lithophyllum (Porolithon) gardineri.*
6. *Lithophyllum craspedium.*
7. *Porolithon onkodes.*
8. Average of 15 analyses of madreporarian reef corals (Clarke and Wheeler, 1917).
9. Coarse foraminiferal beach sand (Bik. 3).
10. Fine beach sand (Bik. 5).
11. Medium sand—lagoon, 69 feet (Bik. 51).
12. Medium sand and *Halimeda* debris—lagoon, 108 feet (Bik. 713).
13. *Halimeda* debris—lagoon, 156 feet (Bik. 548).

of these samples show a decrease in MgO and an increase in CaO and SrO. The series is also characterized by a transition from calcite to aragonite, as one might predict.

OUTER SLOPES

SHALLOW TERRACE AND UPPER PART OF SLOPE

In order to map in fair detail the shallow terrace fringing the outer edge of the reef, sonic soundings over it were taken from three minesweepers, whose relatively shallow draft and short turning radius enabled them to venture into shallow water. The bulk of the work was done by YMS *463*, which made radial lines across the terrace from depths as great as 450 fathoms inward to less than 3 fathoms. Other soundings were taken aboard YMS *354* and YMS *358* while they carried out their regular assignment as test fishing boats. These latter ships followed courses roughly parallel to the reef and between 25 and 300 yards distant from it. Positions for the surveys were determined by pelorus bearings to islands or to beacons, and by vertical sextant angles between horizon and reef edge taken at 30-second time intervals. Depths were read at 15-second intervals from nonrecording echo-sounders.

Accuracy of position and depth of the remaining soundings is shown by the generally close agreement of depth where radial and concentric sounding lines cross. All but two of about 20 crossings are within about 2 fathoms, even though some of the slopes are so steep that a small error of position would result in a large depth error. It is believed that most of the radial sections are correct to within about 30 yards, or 5 fathoms, except for slope corrections which were not made.

The sonic profiles, drawn with equal vertical and horizontal scales, are shown in plate 68. The exact depth of the break in slope at the edge of the terrace is not known because of the relatively wide spacing of the soundings. However, the outermost soundings on the terrace inshore from a clearly steep bottom may be used as a rough measure of the terrace-edge depth. A selection of such terrace-edge soundings probably includes some deeper soundings from the top part of the slope as well as other shallow ones from coral masses rising a short distance above the terrace. None of the large shallow coral mounds so characteristic of the lagoon floor were found anywhere on the outer terrace, although broad low irregularities are shown by the profiles. Soundings were taken from 68 places where sounding lines, either radial or parallel to the reef, crossed the terrace edge. The average depth was 45 feet. The terrace edge shown by the index map plate 68 was taken at 8 fathoms, or 48 feet.

As shown by both chart and profiles, the terrace reaches a maximum width of 400 yards between Bikini and Romurikku islands, and nearly as much just southeast of Namu island. Other fairly wide places occur in the reef indentations between Enyu and Bikini islands and also near Enirik island. It appears to be absent in only a few of the profiles: one southwest of Romurikku, another at the westernmost projection of the leeward reef, and a last off Ariikan island. It is notable that the widest areas of terrace lie in the broad reef indentations, and the narrowest are generally off major reef projections, the reverse of the terrace positions in the lagoon.

Beyond the terrace the bottom slopes downward very abruptly. Measurements were made of the average slopes and the maximum slopes of the profiles. The average slope was taken as the angle from the horizontal of the best-fit straight line through the points beyond the terrace down to 200 fathoms; and the maximum slope, the angle from the horizontal of the steepest part having a depth range of 50 fathoms or more. The steepest average slope, thus measured, was 53° off Bikini island, and the steepest maximum slope 68° off Arriikan, and 67° again off Bikini. For all profiles the average slope is 37.5° and the average maximum, 49.2°. Three of the steepest profiles occur off the major reef projections: namely, off Enyu, Bikini and Romurikku islands. For the three profiles off these points the average and the maximum slopes are 44.0° and 54.8°, respectively. It should also be noted that the profiles off the leeward reef are steeper than those off the windward reef by an average of about 6° (plate 68). Thus, the average slopes for the leeward profiles 13 through 24 and the windward profiles 1 through 12 are 40.2° and 34.8°, respectively. The corresponding maximum slopes are 52.2° and 45.9°, respectively. A profile of the upper part of the steep leeward slope of Bikini Atoll—where the shallow terrace does not exist—is shown in figure 51.

LOWER SLOPES

The character of the bottom depths around Bikini Atoll and Sylvania Guyot was determined through surveys chiefly aboard U. S. S. *Sylvania,* but supplemented by additional soundings from other ships. More than 40 radial lines extending from near the reef to depths of 1,800 or more fathoms were obtained, and these were tied together by 4 concentric sounding lines. Additional soundings were obtained along random lines followed by ships enroute to or from Bikini Atoll and by ships which happened to pass through the area before Operation Crossroads, and by ships of the 1950 Mid-Pacific Expedition. Altogether, about 7,000 soundings in the vicinity are available. Chart 4, having a 100-fathom contour interval, is based on these soundings.

Thirty-six radial profiles across the slopes around Bikini Atoll are shown in figure 28. These profiles, with no vertical exaggeration, extend 5.5 statute miles outward from the reef edge to depths of about 1,800 fathoms. The shallow part of many of them was based on the more accurate soundings obtained by YMS *463* but below 250 fathoms the soundings are entirely those of U. S. S. *Sylvania*. Each profile is controlled by 25 to 40 soundings. It will be noted that the steepest slopes are those nearest the surface and that at progressively greater depths the slopes become flatter. This flattening continues beyond the outer ends of the profiles. Many minor irregularities are shown. Unfortunately, the automatic depth recorder was inoperative during much of the survey; consequently, a part of the irregularities are doubtlessly the result of inexpert reading of the echo sounder. When echoes are indefinite, some recorder men have a tendency to record repeatedly the last clear echo, whereas others may wait until the next clear echo arrives and record it for all of the past time-intervals when no sounding was obtained. Both errors give rise to "apparent" terraces. It is believed, however, that many of the irregularities do exist and that they may have been caused by local slumping of the steep slopes. Comparison of the profiles also shows that the steeper slopes usually are from the spurs opposite reef projections.

The slopes surrounding Bikini Atoll reflect in a general fashion the roughly rectangular shape of the main reef. Opposite some of the reef projections, as at Bikini island and Aomoen island, are broad rounded spurs which clearly extend to below 2,000 fathoms. Less well developed spurs occur off reef projections at Enyu island and Eninman island. Even more important than these spurs in breaking up the smooth shape

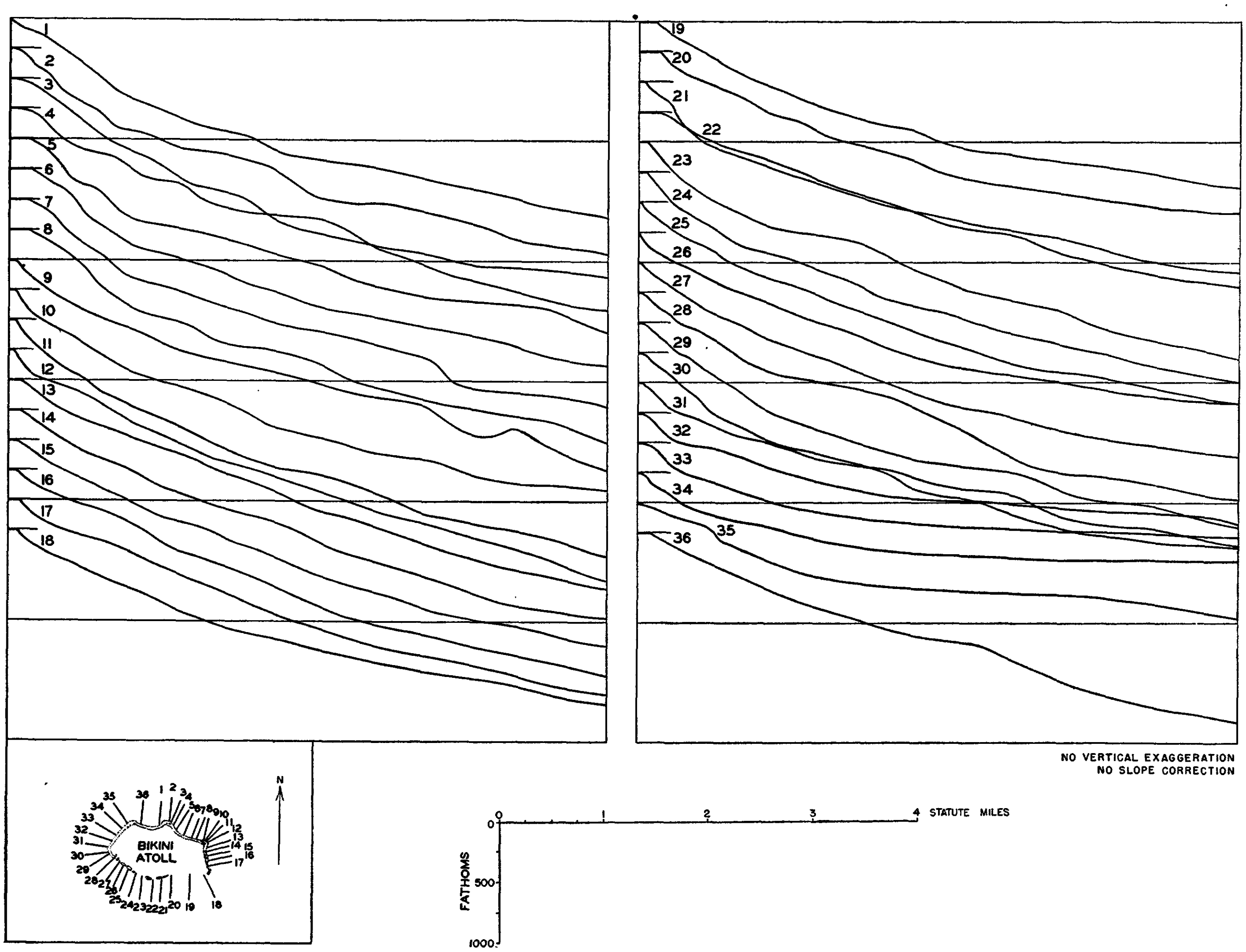

FIGURE 28.—Deep sonic profiles of outer slopes, Bikini Atoll.

of the slopes is the neck which connects Bikini Atoll with the adjacent Sylvania Guyot. In comparison with the much greater width of both atoll and guyot, the neck is similar to the handle connecting the knobs of a dumbbell. The deepest point along the axis of the neck is 790 fathoms, but contours of the atoll slope shallower than 600 fathoms show no bulge or other indication of the neck.

Between the reef projections and their submarine continuations as spurs are broad reef indentations that are reflected at depth by wide hollows between the spurs. Two of these on the north side of the atoll are between Bikini and Aomoen islands and between Yurochi and Namu islands. At least three causes for these peripheral spurs and hollows should be considered. One might ascribe the reef projections to local more than ordinarily rapid reef growth, but this is probably refuted by the fact that the reef projections continue as spurs reaching to great depth. It is conceivable, however, that talus from a more rapid organic growth near the surface could result in the building of a spur beyond the projections. Secondly, Fairbridge (1950) has suggested that the hollows may be the result of large landslides. His belief is based on Emery's (1946) preliminary contour chart from which he redrew slightly modified 1,000- and 2,000-fathom contours and added a hypothetical 2,600-fathom contour as a dashed line. The final contour chart of Bikini Atoll (chart 4)—which was not available to Fairbridge—gives much less support to the landslide interpretation than does his chart because shallow indented contours and deeper bulged ones are less evident. However, the greater steepness of the spur slopes may be the effect of landsliding or creeping on oversteepened slopes. A third possible origin of the hollows and spurs is the original shape of the guyot on which the atoll is built. For example, the outline of Sylvania Guyot is far more irregular than that of Bikini Atoll with several hollows indented more than 5 miles between spurs. Possibly original irregularities exert lasting control on the shape of an atoll such as Bikini.

IGNEOUS ROCKS

Igneous rocks—olivine basalt, basaltic ash, and lapilli tuff—were dredged from the southeastern slopes of Bikini Atoll at depths between 1,000 and 2,010 fathoms in 1950. These were the first samples of igneous rock ever to be recovered from the slopes of a central Pacific atoll and, as Macdonald points out, they constitute the first direct evidence of the volcanic nature of the base on which an atoll is built. On pages 120–124, the rocks are described in detail by Macdonald together with similar rocks dredged from Sylvania Guyot; exact locations are included in table 12.

DISTRIBUTION OF SEDIMENTS

During the 1946, 1947, and 1950 expeditions 58 cores, snapper samples, and dredgings were obtained from deep water around Bikini Atoll (pl. 29). These fall into three categories by area: Atoll slopes shallower than 500 fathoms (24 samples—mostly in table 13), lower atoll slopes and adjacent deep-sea floor (10 samples—table 12), and Sylvania Guyot and adjacent deep-sea floor (24 samples—table 24). The latter samples are described in the section on guyots.

TOP OF OUTER SLOPE

Among the shallow group of samples are ten that are too small to be useful, these are not considered in the following discussion. The positions of the remaining 22 samples are indicated on figure 29. Examination showed that they are highly variable, but that the components belong to two size categories. Because of their size limitation most of the smaller samples consist only of fine-grained material. Some attempts at additional sampling with the small gear recovered nothing. The larger samples contain variable amounts of fine-grained material, and, in addition, they include many large blocks. Practically all of the blocks were obtained in 1947 when a large dredge was employed. The presence of the two widely differing sizes of debris indicates an abundance of blocks in a matrix of finer material. Because of the wide range of particle size it was not considered desirable to estimate the overall percentages of the components, but, instead, to base such estimates only on the finer grained material—that finer than about 1 centimeter (table 13). The size and nature of the coarser constituents are listed separately.

Examination of the data in table 13 shows that most of the constituents are present at most depths. The *Halimeda* debris consists of large curved and slightly folded oval segments not like the smaller sub-round and flat segments from the *Halimeda* growing in the lagoon. Also, included amongst the Foraminifera are occasional specimens of a flat or warped disklike form (*Cycloclypeus*) that reaches diameters as great as 5 centimeters. Present also are several specimens of a small, fragile, pink, corallike hydrozoan (*Distichopora*) not found in the lagoon. Much of the fine debris is gray and very fine-grained—of almost silt size.

A comparison of the sediment found in the top inch or two of the cores and in the snapper and dredge samples is given by figure 30. It is clear that the coarsest sediments of all are those that are shallowest and nearest to the reef edge, and that the finest sediments are at about 600 fathoms near the junction between Bikini Atoll and Sylvania Guyot. Some irregularity in the grain-size graph results from the fact that sample Bik 1482 is a dredging that contains a mixture of material

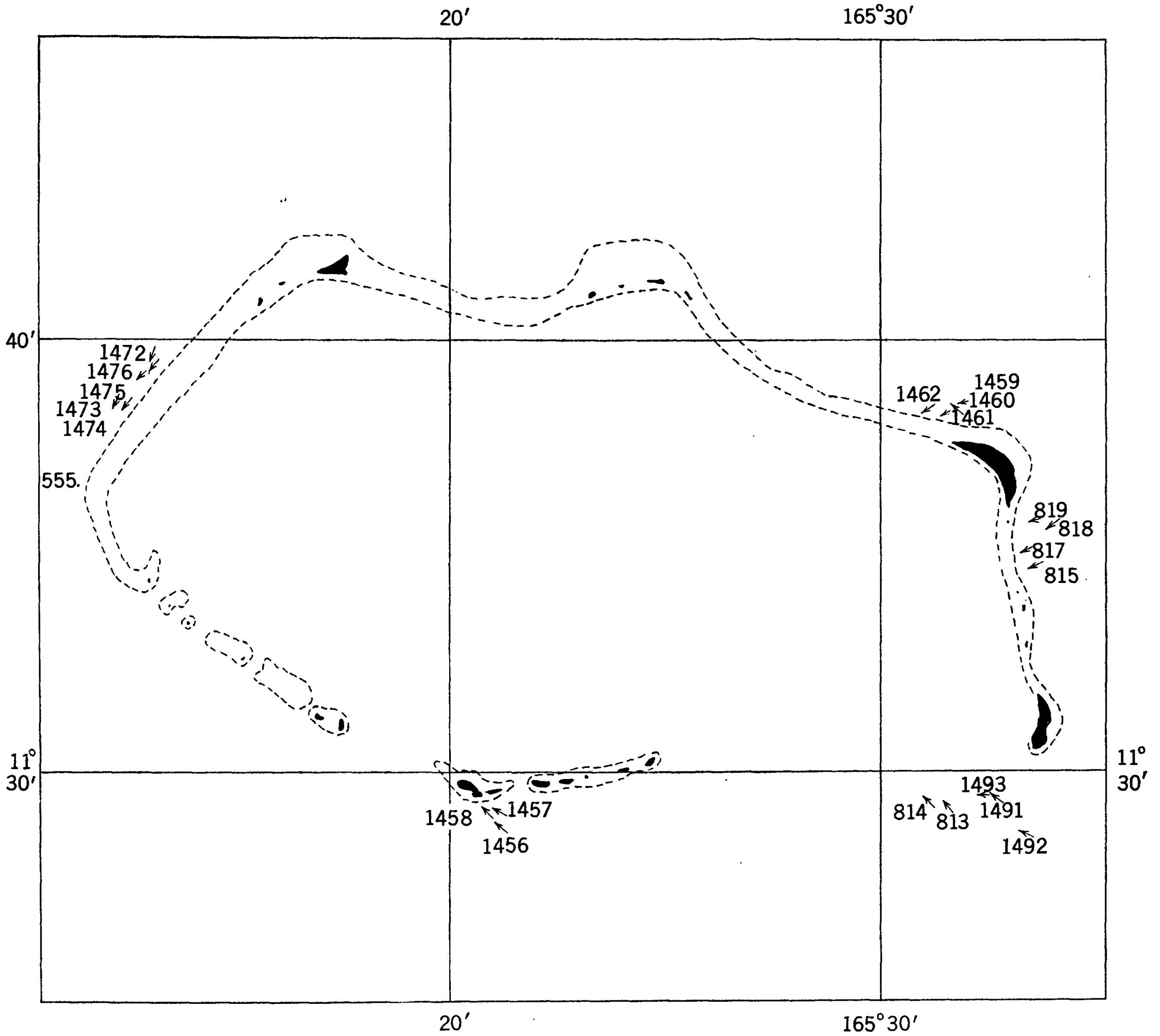

FIGURE 29.—Location of samples collected from outer slopes of Bikini Atoll at depths shallower than 800 feet.

from several inches of depth in the sediment. Sediments found farther away from Bikini atop the guyot are of intermediate coarseness.

Estimates of the percentage composition of the samples, made in the same manner as for the lagoonal sediment samples, reveal the reason for this size variation. The samples that are highest on the slope and contain the coarsest material are composed chiefly of *Halimeda* debris and coral. These are the same components that characterize the sediments from the intermediate depths in the lagoons. The large Foraminifera (pl. 36) are restricted to the outer slope samples. Fine debris, containing some silt-size grains, increases from only 1 percent in the shallowest sample to 60 percent in specimen Bik 1175 at 640 fathoms. Examination showed that this material consisted largely of finely broken *Halimeda*. It, together with the abundant larger pieces of *Halimeda* segments, clearly reflects derivation from shallower depths. In its transportation down the slope it has been accompanied by Foraminifera that are characteristic of shallower depths (Fred Phleger, personal communication). Samples from the top of Sylvania Guyot present a distinct contrast to those on the atoll slope, for they are composed entirely of Foraminifera, nearly all of pelagic species. One sample (core Bik 1170, pl. 29, fig. 4) contained about 25 percent of fine

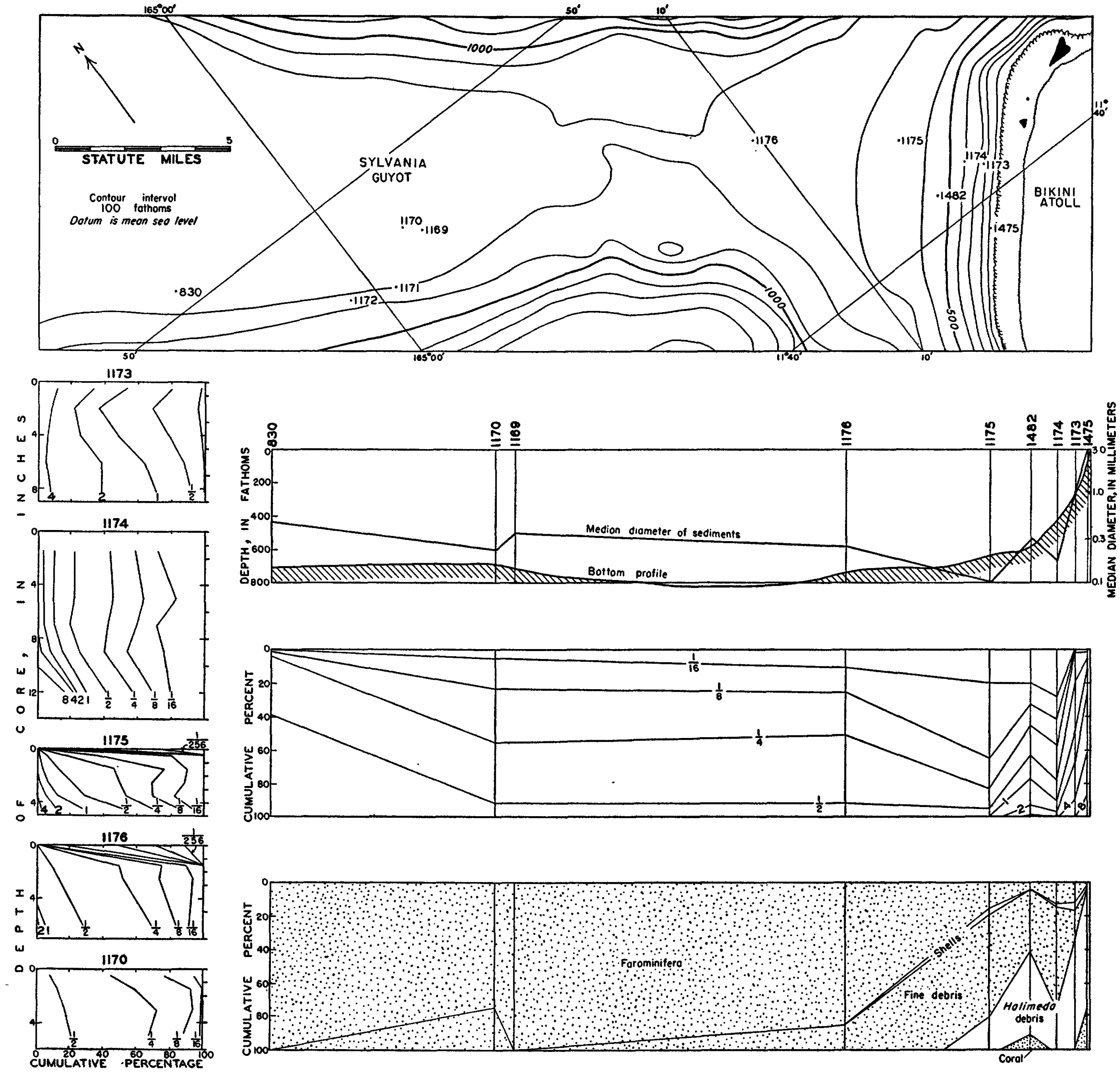

FIGURE 30.—Composition of bottom samples along profile from Bikini reef to the edge of Sylvania Guyot. Station numbers on plan at top of figure are shown above the profiles drawn below.

debris that was composed of fragments of similar tests that were mostly destroyed by solution. Such sediments are known as *Globigerina* sand.

The steeper slopes are partly covered down to 500 feet with large blocks of limestone that apparently have been broken off by waves from the edge of the reef. Most of the blocks are heavy fragments of coral. Others are composed of *Halimeda* debris, pieces of coral, Foraminifera, and sand all cemented together into a solid mass. The cementation far surpasses similar effects noted in lagoon-floor sediments. Several of the blocks are as well cemented as solid beach rock, and they resemble specimens of cemented detrital rock from the reefs.

Russell, in 1947, found that the size of the blocks appeared to decrease with depth. Some near the surface appeared to weigh several tons, because a dredge attached by a 1-inch chain to a ½-inch steel cable was lost when the chain broke after it had hooked to a large block. Russell reported that large blocks seemed to be rare below 200 fathoms, the bottom consisting of limestone boulders and sand, but he expressed the opinion that blocks weighing several hundred pounds extended to more than 350 fathoms because a 3/32-inch stainless-steel airplane cable carrying a small dredge was broken when the dredge became caught at that depth. The amount of debris encountered at higher levels suggests that the obstruction was a block, but the possibility of bedrock being exposed at that depth must be considered. Below 500 feet there is an appreciable decrease in the profusion and variety of marine life.

DEEP SLOPE AND ADJACENT DEEP-SEA FLOOR

During the 1950 Mid-Pacific Expedition 10 deep cores were taken southeast of Bikini Atoll (table 12). These show that the calcareous debris found in the shallower slope samples grades into *Globigerina* ooze at a depth of about 1,000 fathoms. Samples 44A and 44B, below that depth, consist of *Globigerina* ooze with little or no admixture of debris from shallower slopes. Sample 44B is of especial interest because it includes 6½ inches of volcanic agglomerate, ash, and dense rock beneath 4½ inches of *Globigerina* ooze. A slow rate of deposition of calcareous materials on the slope at 1,550 fathoms is indicated. Moreover, the core presents at least a maximum depth for the top of the volcanic basement on which the atoll has formed by organic growth. Another core on the lower slope contains a piece of pumice which may have floated from a distant source.

Manganese oxide was encountered in two deep cores: 44J and 44L. The presence of only chips of this material caught in the core nose, which was smashed at one of the stations, indicates hard rocky bottom. This conclusion is supported by another deep core (no. 44K) which contains only a few rounded pieces of coral and some cemented *Globigerina* ooze. The corals were identified by J. W. Wells as species of *Montipora* and *Porites*, both genera being exclusively reef types. The specimens are much worn as though rolled but are unweathered and not even stained by manganese oxide. The samples were examined spectrographically by Charles Annell of the Geological Survey with the following results, expressed in percent:

>10	Ca	0.01–0.1	Si, Fe
1-10	----------	0.001–0.01	Al, Cu, Ba
0.1–1.0	Na, Sr, Mg	0.0001–0.001	----------

This analysis indicates clearly that the corals have had only a short period of exposure on the sea floor. They have been transported a distance of 21 miles east of the reef over 10 miles of flat sea floor 2,300 fathoms deep by some form of landslide or by a turbudity current.

The deepest core southeast of Bikini is of *Globigerina* ooze (No. 45) having a reddish color. This color probably results from the fact that the sampling depth was 2,445 fathoms, near the average depth of transition from *Globigerina* ooze to red clay (2,400 fathoms) that is characteristic of other deep samples in the region. The boundary between *Globigerina* ooze and red clay appears to be shallower north of Sylvania Guyot because cores 43K and 43L sampled only red clay, at 2,300 and 2,555 fathoms respectively (table 24).

TABLE 12.—*Deep samples southeast of Bikini Atoll*

[Core measurements in inches]

44A Phleger core: lat. 11°16′ N.; long. 165°30′ E.; 2,010 fathoms.
- 0–2 Buff *Globigerina* ooze.
- 2–4½ Light-gray *Globigerina* ooze.
- 4½–6 Green-gray *Globigerina* ooze.
- 6–9½ Buff *Globigerina* ooze.
- 9½–13 Light-gray *Globigerina* ooze.
- 13–15½ Buff *Globigerina* ooze.
- 15½–16½ Light-brown *Globigerina* ooze (contains weathered basalt).
- 16½–24½ Light-gray stiff *Globigerina* ooze.

44B Phleger core: lat. 11°22.5′ N.; long. 165°31′ E.; 1,550 fathoms.
- 0–4½ Light-buff *Globigerina* ooze, ½-inch pebble of tuft-breccia.
- 4½–5½ Light-brown granular ash.
- 5½–6½ Dark-brown ash with 1/16-inch grains of black volcanic glass.
- 6½–7 Light-brown, fine-grained ash.
- 7-7½ Green ash with 1/16 inch grains of rock.
- 7½–9 Dark-brown ash with 1/16 inch grains of black volcanic glass.
- 9–11 Oxide lapilli tuff with 1/16 crust of manganese.

44C Phleger core: lat. 11°27.5′ N.; long. 165°32′ E.; 1,000 fathoms.
- 0–1 *Globigerina* ooze, *Halimeda* and other calcareous debris.

44D Phleger core: lat. 11°28.5′ N.; long. 165°32′ E.; 630 fathoms.
- 0–3 Broken coral.

44H Phleger core: lat. 11°31′ N.; long. 165°36′ E.; 750 fathoms.
- 0–½ *Halimeda*, echinoid spines and plates, other calcareous debris.

44I Phleger core: lat. 11°31′ N.; long. 165°37′ E.; 1,000 fathoms.
- 0–1 *Globigerina* ooze with subangular fragment of olivine basalt (1 x 1 x ¾ inch) covered with 1/16 inch manganese oxide.

44J Phleger core: lat. 11°32′ N.; long. 165°39′ E.; 1,565 fathoms.
- 0–¼ Manganese oxide; nose smashed.

44K Kullenberg core: lat. 11°32′ N.; long. 165°57′ E.; 2,350 fathoms.
- 0–1 Round to subangular fresh coral fragments to 1 inch; fragile pieces of slightly cemented *Globigerina* ooze to 1 inch.

44L Kullenberg core: lat. 11°27′ N.; long. 165°51′ E.; 2,390 fathoms.
- Small chips manganese oxide.

45 Kullenberg core: lat. 9°57′ N.; long. 166°54′ E.; 2,445 fathoms
- 0–5 Reddish *Globigerina* ooze.

TABLE 13.—*Composition of samples from top part of outer slope of Bikini Atoll*

Bikini (Bik) sample No.	Depth (feet)	Percentages of finer material						Remarks
		Foraminifera	Mollusk shells	Fine debris	*Halimeda* debris	Coral	Others	
Bik 815	55	20	0	70	10	0	0	
1477	80	10	10	45	15	20	0	Blocks of coral and rock.
1493	135	0	0	0	100	0	0	Fragments of live coral.
814	136	15	5	35	25	20	0	
817	144	10	5	30	30	15	10	
Av	------	11	4	36	36	11	2	
1461	205	----	----	----	----	----	----	Blocks of coral and rock.
1476	210	10	5	15	70	0	0	Large rock and living coral.
813	280	0	15	5	80	0	0	
1458	245	5	3	2	80	10	0	Coral fragments.
819	315	10	5	35	40	10	0	
1491	375	20	5	60	15	0	0	
Av	------	9	7	23	57	4	----	
1475	450	2	2	1	70	25	0	Living coral and sponges.
1492	425	0	5	0	45	50	0	Coral fragments.
1457	440	----	----	----	----	----	----	Fragments of coral and coralline algae
1460	445	10	0	0	80	10	0	Fragments of coral.
818	500	10	3	80	5	2	0	
1474	600	0	0	0	0	100	0	Blocks of rock.
Av	------	4	2	16	40	38	----	
555	660	5	0	10	80	5	0	
1462	690	----	----	----	----	----	----	Blocks of rock and coralline algae.
1456	750	----	----	----	----	----	----	Do.
1472	750	----	----	----	----	----	----	Fragments of coral to 3 inches; large Foraminifera.
1473	800	----	----	----	----	----	----	Fragments of rock, coralline algae, and coral. Many large Foraminifera.

SUBSURFACE GEOLOGY

DRILLING OPERATIONS

The U. S. S. *Chilton* arrived at Bikini Atoll on July 15, 1947, and on the following day the rig was taken ashore in a landing craft, was assembled, and was set up on location for hole 1 on the northeast side of Bikini island (figs. 31, 32).

The hole was located on a sand flat at the top of the beach, and about 2,700 feet from the edge of the reef.

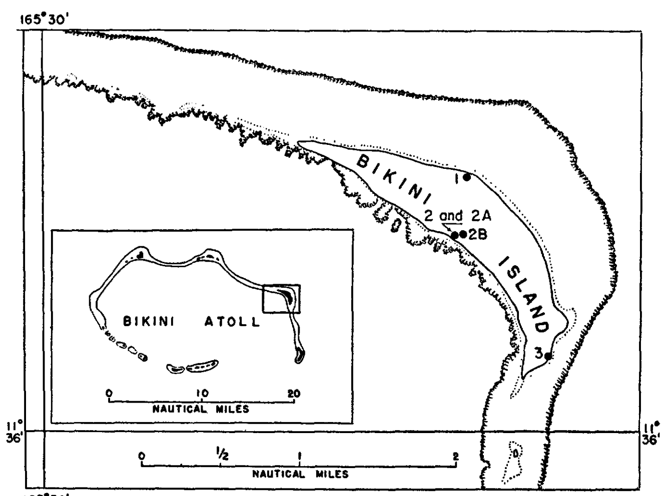

FIGURE 31.—Location of drill holes on Bikini island.

The collar of the hole was 13 feet above the level of the reef flat, or approximately 15 feet above low-tide level; total depth was 300 feet. Except in discussing correlations between holes and geologic history in later sections of this report, all depths mentioned will refer to the actual depth below the hole collar, rather than to depths below sea level. Exact figures on depths, core recovery, and other drilling records are given in table 14.

TABLE 14.—*Drilling data, Bikini Atoll*

Hole No.	Depth (feet)	Casing (ft.)		Drilling time (hours)	Footage cored	Core recovery	
		6-inch	4-inch			Feet	Percent
1	300	19	--------	46	281	33.5	12
2	190	41	--------	23	153	29.5	19.3
2A	1,346	190	--------	162	271	41.0	15.1
2B	2,556	28	804	190	0	0	0
3	118	6	--------	40	107	31.0	29
	4,510	284	804	461	812	135.0	16.6

The hole was started on July 18, and was drilled by a 6⅝-inch rock bit through 13 feet of beach sand. Hard rock was drilled from 13 to 19 feet, and 19 feet of surface casing was set to prevent caving of unconsolidated surface material. The remainder of the hole down to 300 feet was cored with a 4½-inch core barrel. Core recovery was poor, as can be seen in the table; in four successive core runs from 95.5 to 137.5 feet (42 feet) only 0.3 foot of core was recovered in the last run. The best recovery for a 10.5 foot run was 3 feet. The hole was completed on July 20, and the total drilling time was 48 hours.

The rig was moved to the lagoon side of Bikini island to drill hole 2, which was to be the deep hole. For this a heavy wooden platform was erected to provide solid footing for the drill truck. The hole was located 63 feet from the vegetation line at the crest of the beach, on a sand flat about 16 feet above extreme low tide level (fig. 31). The location was about 2,400 feet from hole 1 and 4,800 feet from the seaward margin of the reef.

The hole was spudded in on the morning of July 22. It was drilled by rock bit through 14 feet of beach sand to beach rock. A core of the beach rock was taken, and the hole was drilled by rock bit to 43 feet, at which depth 6-inch surface casing was set on firm limestone. Drilling was continued to 190 feet by coring with the 4½-inch core barrel. While reaming the hole to set 190 feet of casing, a pipe wrench was dropped to the bottom. As the hole was rather crooked and would have been difficult to case, the rig was moved forward 5 feet and the hole was redrilled as hole 2A.

Hole 2A was begun on July 23. It was drilled to 190 feet by 6⅝-inch rock bit, and 6-inch casing was set to this depth. Below 190 feet the hole was cored to

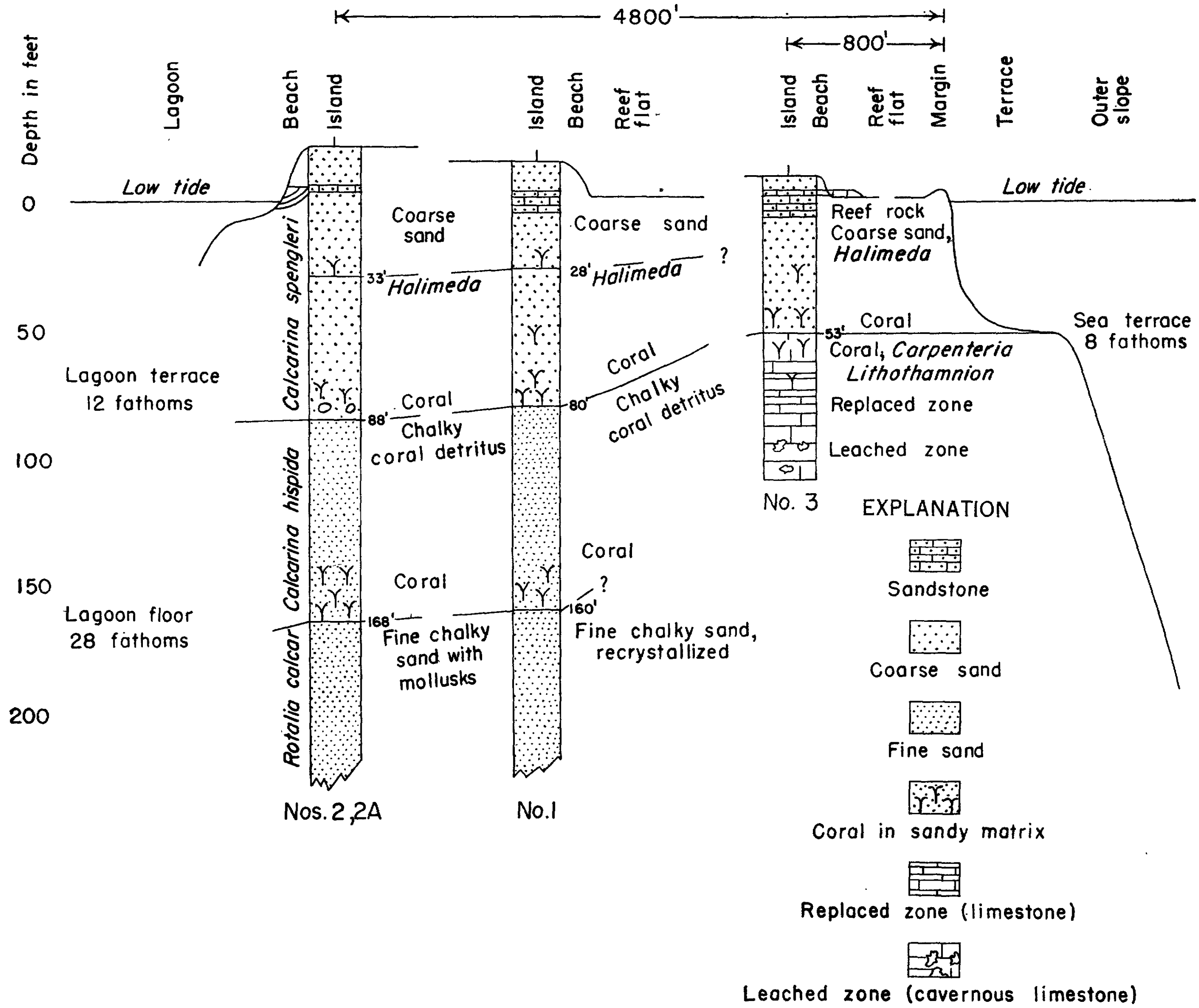

FIGURE 32.—Diagrammatic section at Bikini island, showing drill holes and their relation to reefs and lagoon. Distance of each hole to the reef margin is shown at top of figure; the section shows correlations between lithologic or faunal zones in each hole and the sea terrace, lagoon terrace, and lagoon bottom of the atoll.

347.5 feet, but so much drilling mud was lost in porous, unconsolidated material below 300 feet, that at 347.5 feet it was decided to ream the hole and continue drilling by rock bit, taking a 10.5-foot core every 50 to 100 feet. This change in procedure was made because drilling by rock bit might allow a mud wall to form and protect the hole from caving, whereas in continuous coring, much caving is caused by pulling the rods from the hole and returning them after each core run.

From 347.5 to 925 feet the hole was drilled by rock bit, but in this interval 10.5-foot core runs were made at 442 feet, 514.5 feet, 567.5 feet, 631.5 feet, 694.5 feet, 757.5 feet, and 862.5 feet. The hole continued to absorb drilling mud, and little core was recovered in most of the runs.

A core run at 925 feet recovered about 2.5 feet of brown, unconsolidated very fossiliferous material. The fossils were in an excellent state of preservation, and coring was continued to 957.5 feet, but because of serious loss of mud in the unconsolidated material, it was necessary to resume drilling by rock bit.

At 1,090 feet an extremely soft interval was encountered that seemed almost like an empty cavity. The rods dropped seemingly without resistance to 1,103 feet and mud circulation was completely lost. The "cavity" was cemented with 4 barrels of cement. When drilling was resumed after 24 hours, mud circulation was poor, and a variety of absorbent materials such as rice hulls and corn meal were used in attempting to seal the walls of the hole. Drilling by rock bit progressed to a depth of 1,346 feet, on August 2, when it was decided that the hole must be cased if drilling were to continue. Four-inch casing, procured from the Navy base at Kwajalein, arrived by ship on August 5. In attempting to case the hole, however, the casing stuck at an offset at a depth of 400 feet, and in attempting to pull the casing the bottom joint of 4-inch pipe broke off in the hole, which consequently had to be abandoned.

Because of the difficulties and the length of time taken in drilling Holes 2 and 2A, it was necessary to revise the plans for the 3 weeks of drilling time remaining. It was planned to drill another hole as deep as possible by rock bit, coring only if solid rock were encountered. The location chosen for hole 2B was 179 feet inland from holes 2 and 2A (see fig. 31) on a knoll about 19 feet above low tide level. Drilling started on August 7. The hole was drilled to 33 feet, 6-inch surface casing was set, and drilling was continued with a 5⅝-inch rock bit. By August 11, the hole was drilled to 1,324.5 feet, and an attempt was made to case the hole with 4-inch casing. The casing stuck at 804 feet, and drilling had to be resumed with a 3⅞-inch rock bit. No further difficulties arose, and by August 16 the hole bottomed with all drill rods in the hole at 2,556 feet, in unconsolidated fine sand. No core runs were made, for no hard rock was encountered below 1,346 feet.

It would have been most desirable to take a core of the sand at the bottom of the hole, but that was not attempted for several reasons. Because of the 4-inch casing in the upper part of the hole, it would have been necessary to use a small core barrel that cut a core a little more than an inch in diameter. The drillers believed that it would be almost impossible to recover any of the unconsolidated fine sand using such a small barrel, especially at a depth of more than 2,500 feet with a drill that was designed for 1,500 feet. More important, the Geotechnical Corporation was to make a series of seismic vertical velocity measurements at intervals to the bottom of the hole to get accurate data on changes of velocity with depth, in order to interpret the seismic refraction survey made in 1946. The possibility of making these measurements was considered good if they were made at once, but poor if a core were taken first, for coring at so great a depth increased the chances of caving in the hole.

The hole was kept open by rotating the rods and by circulating the drilling mud until the seismic velocity apparatus was assembled. The drill rods were then withdrawn and the geophone was lowered to 1,820 feet, at which depth the hole had bridged when the rods were withdrawn. A total of 72 successful measurements were made at intervals of 50 to 300 feet, between depths of 1,820 and 50 feet in the hole.

On August 21 the rig was moved to the south end of Bikini island (fig. 31) to drill hole 3. The drill was located on a sand berm 6 feet above the reef flat and 800 feet from the seaward margin of the reef. The site was chosen instead of a previously planned location half way between holes 1 and 2, in order to determine whether shallow rocks under Bikini island were as unconsolidated near the reef edge as they were in the first two holes at some distance from the edge.

Six feet of beach sand was drilled to hard rock and surface casing was set. The hole was then cored to a depth of 117.8 feet. With the exception of the first core run in which 5.3 feet of reef rock was obtained, core recovery was poor to a depth of 58 feet. Below this depth core recovery was relatively good and averaged 29 percent for the entire cored interval. Most of the rock was moderately to well consolidated, but porous and cavernous. At 80 feet the rock was hard, but so porous that mud circulation was lost, and except for a few periods when circulation was briefly regained, the rest of the hole was drilled "blind". When the driller put the rods in the hole for a core run at a depth of 107.3 feet, the hole was so choked with rock fragments that it was almost impossible to get the core barrel to the bottom. Accordingly, drilling was halted at the end of the run at a depth of 117.8 feet, on August 23.

The next few days were spent in dismantling the rig and putting it aboard ship, and in packing specimens and cores. On August 28 the Bikini Scientific Resurvey was completed and the U. S. S. *Chilton* departed for Honolulu.

SAMPLING METHODS

CUTTINGS

When the drilling was done with rock bit, cuttings returned to the top of the hole in the drilling mud were caught in a wire strainer, washed, and put in cloth bags. Cuttings were collected once or twice during the drilling of each 10.5 foot interval. Cuttings were labelled with the depth of both top and bottom of the interval sampled. When a rod length was drilled down starting at 1,135 feet, for example, cuttings collected would be labelled 1,135–1,145.5 feet.

Cuttings were also collected during each core run in order to compare rock-bit cuttings with cored material, but results were unsatisfactory. In the first place, the core bit ground the rock considerably finer than the rock bit; in the second place, during coring operations the mud had to be circulated at a low pressure in order not to wash away the core, and as a result relatively few cuttings were brought to the surface. Also, pulling and returning the rods between core runs resulted in the caving of the wall of the hole, and cuttings were badly contaminated.

When the drilling was done by rock bit the cuttings were more reliable, but even at such times there was contamination from higher levels. An additional and most serious difficulty arose during the drilling of the lower part of hole 2B. Below about 1,150 feet the cuttings became continuously finer until at 1,500 feet only a small part of the cuttings were coarse enough to be caught in the wire strainers used. It was then necessary to catch the samples in cloth bags, and wash out the drilling mud through the cloth. The material was so fine and so completely unconsolidated that the drilling mud had to be kept thick and heavy to prevent caving in the hole; so thick, in fact, that much of the fine material did not settle out in slush pits, but stayed in suspension and was recirculated through the hole, possibly several times.

The reliability of cuttings for interpreting the lithology of a drill hole can, therefore, be very low under some circumstances, and cuttings must be used with caution. For some parts of the deep drilling at Bikini, the principal interpretations that could be made were based on the first appearance of fossils, chiefly the larger Foraminifera. For other parts, changes in the action of the drill were helpful in interpreting the lithology. The roughness or smoothness of drilling, the drilling time for each 10.5-foot interval, and the action of the pump, which varied with the nature of the rock, all gave useful if veiled hints of changes in lithology.

CORES

In each core run the distance drilled was normally 10.5 feet, which was the length of the drill rods and also the approximate maximum length of core that could be held by the barrel. In an attempt to hold unconsolidated material in the barrel, in some core runs, the last few inches of core were "blocked," or jammed into the bit by cutting off mud circulation and forcing the core barrel down dry. The barrel was then pulled up, the core, if any, removed, and the barrel returned to the bottom for another run. Although the length of a core run normally was 10.5 feet, several runs in friable material were only 5 feet long, and a few 21 feet long were tried with the hope that more core might be recovered.

The core pieces, fragments, or sandy detritus were removed from the barrel, washed, and packed in sequence. The tops of cylindrical pieces were marked to show their position in the barrel. Fine material was packed in sample sacks immediately, without washing, although it was usually possible to remove most of the drilling mud that adhered to the surface. Each core piece was labelled with the hole number, the number of the core run, and the number of the piece in the run. Specimen 2A–26–3, for example, is the third piece, counting from top to bottom, of the twenty-sixth core run in hole 2A. Fragments or fine detritus were sacked and labelled the same as core pieces.

The reliability of cores as an index of the lithology and of the fossil content is in general very good, although at Bikini Atoll unusual lithology, excessive caving in the hole, and poor recovery made the core less representative and more difficult to interpret than in more conventional coring operations.

In coring unconsolidated rock containing large brittle coral colonies and patchy consolidated masses, it was found that much of the unconsolidated material washed away in the circulating mud, resulting in a selective recovery of harder material. In some core runs after some core had passed into the barrel, a hard fragment lodged in the bit and prevented more core from entering.

Excessive caving in the hole, especially caving between core runs while the tools are withdrawn may result in fine detritus and larger fragments from higher levels falling to the bottom of the hole and being picked up in the following core run. Although caved fine material can usually be distinguished from freshly cut core by its mucky appearance, larger caved pieces are more difficult to differentiate, especially if the freshly cut core consists only of broken pieces worn and rounded by the core bit.

The difficulties inherent in drilling other coral limestones have been reported by Sollas and David (1904) who discussed the Funafuti drilling, by Richards and Hill (1942) who discussed two borings on the Great Barrier Reef, and by Endo (1935) and Sugiyama (1936) who discussed the drilling operation on Kita-Daito-Zima (North Borodino Island).

METHODS OF STUDY

In the laboratory each sample of cuttings was halved, one half to be kept intact for future reference, the other half to be studied. Many of the samples were sieved through a 1-millimeter screen, to facilitate picking of fossils. The material was picked for Foraminifera, mollusks, calcareous algae, and corals. The coarse fractions in particular were examined under the binocular microscope and a few thin sections were made of chips or fragments that seemed representative. Chemical analyses of three samples, and X-ray analyses of one were made, but as a rule an intensive study of the lithology was not possible. The cuttings proved to be of especial value in hole 2B where successive samples from 425 through 550 feet seemed to show that a change from white to tan limestone observed in cores from hole 2A, was a gradation and not an abrupt lithologic break. The essential continuity of deposition from 750 to 1,080 feet, in beds ranging in age from probable Pliocene to Lower Miocene, was likewise indicated by study of the cuttings and by watching the action of the drill, which is more responsive to changes in lithology when a rock bit is used than when coring. Lastly, in the interval 957–2,556 feet, in which only cuttings were available, and many of them poor, it was possible in places to estimate at least roughly the proportions of major fossil groups and detrital grains. At several places these estimates proved to be of value, especially in changes from coral-molluskan to foraminiferal sand at 1,755 feet, and from foraminiferal to algal sand at 2,070 feet.

All cores that were substantial enough were halved with a diamond saw. Some poorly consolidated specimens were impregnated with canada balsam before sawing. Solid core as well as loose material was picked for foramanifers, mollusks, corals, and algae, and much of the highly fossiliferous material from 925 to 957 feet in Hole 2A was broken down and washed for fossils. The sequence of cores was examined and described piece by piece under the binocular microscope. Particular attention was given the fossil assemblages, the nature of the detrital matrix, alteration of organic remains, and kind of cementation. Thin sections of selected specimens, including some of friable cores, were studied by means of a petrographic microscope and were compared with thin sections of rock from present-day beaches and from various zones of the reef.

No infallible criteria were found for distinguishing in drill core samples, rock formed on the reef from that formed on beaches. However, in the series of rock types ranging from coral-algal reef limestone containing remains in position of growth, to sorted, bedded beach sandstone with well developed acicular carbonate cement, the extreme types are easily differentiated. To distinguish between coarse detrital reef limestone and unsorted beach conglomerate is more difficult and for some specimens may be impossible. As a general rule, rock that is formed on the reef flat contains a moderate to large proportion of finely detrital limy paste filling cavities and pores. In a hand specimen, the paste is white, chalky to porcelaneous, and it fills cavities at some depth from the exposed surface of the rock. In a thin section the paste is gray to brown, microgranular but containing fine detrital fragments, and it is altered along grain borders and in scattered spots to clear, finely granular to microgranular carbonate. Acicular carbonate binding grains or lining cavities may be present but is not strongly developed. The surface of the rock is spongy and riddled by borings of small organisms. Rock formed on beaches in the intertidal zone is generally better sorted. Grains are cemented by a veneer of well developed acicular carbonate, and pore spaces and cavities are generally empty. Chalky to porcelaneous limy paste fills only a small proportion of the cavities, but may be abundant for a few millimeters below the exposed surface of the rock.

Rock that forms the flat-lying island platforms or groins on the reef shows lithologic characteristics of both beach conglomerate and detrital reef rock. In a general way, this rock is similar to reef rock in the amount of limy paste in the intergranular spaces, but it differs from most reef rock in the large proportion of rounded pebbles and boulders it contains.

No hard-rock samples were obtained from the lagoon bottom, so no direct comparison can be made between lagoon samples and reef and island samples. One would expect to distinguish lagoon samples in a core by the similarity of its lithologic and organic constituents to one of the several zones discussed under lagoon sediments. Although fine silt or limy mud are rare in recovered samples from the lagoon, it is possible that buried sediments might receive a considerable amount of fine material, which would filter through the porous surface layers of *Halimeda* or detritus, and which would be difficult to recover by the usual sampling methods.

Chemical analyses were made of representative core pieces taken at intervals throughout the deep hole. F. J. Flanagan of the U. S. Geological Survey, analyzed 12 samples from hole 2A, and two cuttings samples from hole 2B, for $CaCO_3$ and $MgCO_3$ in a preliminary study in the fall of 1947, to determine whether any significant section of dolomite existed at Bikini. In the spring of 1950, 13 more samples were analyzed by Mrs. Charlotte M. Warshaw, to complete the series through the cored interval. J. M. Axelrod, made X-ray analyses of 22 specimens of core. Some of these were of representative samples of the limestone, others were of specimens of unaltered and altered organic remains and of recrystallized material, to determine the carbonate minerals. Spectrographic analyses of 11 specimens of fresh, altered, and recrystallized material were made by A. T. Myers of the U. S. Geological Survey. In addition, H. T. Odum of Yale University determined quantitatively by comparative spectrophotometer the ratio of strontium to calcium atoms in three core samples and in specimens of material from the present-day reef and lagoon bottom.

The X-ray results of a limited number of samples provided a check on calcite-aragonite determinations made by Tracey in studies of thin sections, in examinations of powdered material in immersion oils with indice of 1.66 and 1.68, and in staining tests of sawed core specimens boiled in dilute cobalt nitrate (Meigen's solution). No thin sections were stained. As no dolomite was identified by X-ray analyses, and as no specimens chemically analyzed were found to contain more than a few percent of $MgCO_3$, no additional microscopic or staining tests were used for differentiation of calcite and dolomite.

ORGANIC CONSTITUENTS

CORALS

Although the occurrence in the core of unusual species of coral may be significant, particularly as regards age, the association of common types are indicative of the environment in which they lived. The most numerous corals in the core are *Acropora*, *Astreopora*, *Porites*, *Seriatopora*, and *Stylophora*, all common genera on the present reef, lagoon, and outer slopes. The occurrence, however, of several or all of these, many in position of growth, in a cored interval in which coral is dominant, strongly suggests an origin on a reef, or in a coral-rich zone of the lagoon in shallow water near the reef. A depth of 12 to 15 fathoms is probably a maximum for such profuse growth.

On the other hand, if the corals be limited to delicate, branching types of *Acropora* and *Seriatopora*, then quiet, sheltered water is indicated and a lagoonal environment seems most probable. They are found in most abundance in the present lagoon at depths of 12 to 18 fathoms, and less commonly to 25 fathoms. They also occur in pools on the reef flat, but are invariably associated with other more abundant corals. Massive heads of *Porites* are abundant both on the reef flat and in the lagoon, but branching types of *Porites*, especially fragile, thin-branched types, appear to be limited to shallow waters of the lagoon.

CALCAREOUS ALGAE

Massive, nodular, or encrusting growths of coralline algae such as *Porolithon*, *Goniolithon* and *Lithophyllum*, which will be grouped here under the name *Lithothamnion*, are found today in greatest abundance on the seaward margin of the reef where they commonly form 90 percent or more of the reef constituents. They grow in abundance to depths of 50 or 60 feet on the seaward slopes and their detritus is carried down considerably deeper. They are important rock formers of the reef surface several hundred feet behind the reef edge, for they bind and encrust corals and debris into a solid mass even where they are a subordinate constituent. *Lithothamnion* is scarce over most reef flats that are exposed at low tide, for it requires a constant supply of fresh ocean water to exist, but in the lagoon it binds the bases of corals on shallow knolls, and it has been dredged alive at least to depths of 22 fathoms (132 feet) as a thin coating on coral fragments and other debris. Fragments and particles of *Lithothamnion* form a large part of the sands in shallow pools on the reef, on island beaches, and on both seaward and lagoon slopes of the reef. Very fine grained particles, comminuted by organisms or by wave action, are carried for several miles into the lagoon by currents across the reef, but the presence in cores of any considerable amount of *Lithothamnion* detritus is indicative of deposition reasonably close to a reef.

The calcareous green alga, *Halimeda*, is the most abundant organic constituent of the lagoon. It is sparsely distributed on the reef edge and also on the reef flat, where its calcareous segments are abundant in the sandy bottoms of some shallow pools. It likewise forms a considerable part of the detritus recovered in dredge hauls from seaward slopes. The segments of *Halimeda* from reef and lagoon are typically small, thin, and flat, ranging from 3 to 5 millimeters in length, whereas those of the seaward slopes are thick, curved, and are 5 to 10 millimeters in length. The thin, small lagoonal variety was recognized in much of the core. Moderately large slightly curved segments were found in some core pieces but were of a size and form that suggested the lagoonal rather than the seaward variety.

Although *Halimeda* is common in the lagoon at a few places near the reef, it is most profuse in the broad reaches of the lagoon at depths of 20 to 30 fathoms. *Halimeda* forms 75 to 100 percent of most samples in the deepest part of the lagoon. Chapman (1901, p. 166) reported that in Funafuti lagoon, samples below 20 fathoms consist 80 to 100 percent of *Halimeda*. The occurrence of a continuous section of core having such a great proportion of *Halimeda* would indicate that the material accumulated in the central basin of a lagoon, in water probably 20 to 30 fathoms in depth.

FORAMINIFERA

The tests of these simple organisms are a major component of the atoll, and they may rank next to *Halimeda* as a rock former. The most common species on present-day reefs and beaches of the northern Marshall Islands is *Calcarina spengleri*, a spiny foraminifer whose worn tests are a major component of most of the beach sands at Bikini. The living foraminifer appears to be restricted to the reef, especially to barren flats carpeted by a thin veneer of a filamentous alga in which the tests are packed, usually one layer thick. The species is found in lagoon sands bordering the reef, rarely 2 or 3 miles from the reef and in moderately deep water, but on beaches the tests are almost invariably worn and the delicate spines are broken. Unworn tests of a similar species, *Calcarina hispida*, are abundant in lagoon samples from depths below 10 fathoms. The occurrence in the core of either or both of these species, and the state of preservation of the tests, are significant indicators of conditions governing the accumulation of the sediments, both as to depth of water and proximity to reefs. Both species are found, although not in great abundance, on seaward slopes to depths of several hundred fathoms, so that their presence alone does not indicate reef or lagoonal deposition as opposed to deposition on outer slopes.

Other "beach" foraminifers abundant at Bikini are *Marginopora* and *Amphistegina*. These are found in samples from the lagoon and from outer slopes, but large unworn tests of *Marginopora* appeared to be most numerous on sandy reef flats in a few feet of water, either in pools on the reef or at the lagoon edge of the reef.

Globigerinids and other pelagic types that make up *Globigerina* oozes are found in lagoon samples, but they are not abundant because their aggregate bulk is insignificant compared to the mass of other tests, shells, and detritus. M. W. Johnson (1949) has shown, however, that because of the circulation of lagoonal waters at Bikini atoll, and because of continual replenishing of the lagoonal water by ocean water over the reefs, an increase in pelagic fauna takes place in the lagoon as compared to the ocean water. He estimates that living Globigerinas are roughly twice as abundant in the lagoon water as in the ocean water to windward of the atoll. Emery found that small areas at depths of 30 to 32 fathoms in Bikini Lagoon consist largely of tests of lagoonal and pelagic foraminifers. At Eniwetok atoll, a relatively large area in the deepest part of the lagoon below 32 fathoms consisted mostly of such tests. Their abundance in the core suggests accumulation at depths of 30 fathoms or more, but it is also possible that pelagic tests might accumulate in shallow lagoon water in an area protected from detritus swept from the reef.

The encrusting foraminifers, *Homotrema*, *Carpenteria*, and *Miniacina* are abundant on reefs at Bikini atoll, where they encrust small cavities in the rock, but they do not seem to be rock formers. In the lagoon and on outer slopes they are found encrusting coral and detrital fragments to considerable depths. Chapman (1904, p. 80) is reported to have shown that they are present-day rock formers on the *Lithothamnion* ridge at Funafuti. They form a considerable percentage of the core from the Funafuti drill hole.

In the Bikini core, the finding of massive intergrowths of encrusting foraminifers with *Lithothamnion* is considered good evidence of reef or near-reef conditions. Thinly encrusting intergrowths would indicate accumulation in water probably no more than 25 fathoms in depth if the material can be shown on other evidence to be lagoonal. Nodular *Lithothamnion* and encrusting foraminifers are rather abundant on outer slopes and can be carried down to depths of several hundred fathoms.

MOLLUSKS

A few samples indicate that small shallow areas of Bikini Lagoon, especially near the sill of Enyu Channel, contain more than 12.5 percent shells and fragments of mollusks, but in general samples from reef, lagoon, and outer slope do not contain more than a few percent of shells. Nevertheless, mollusks are significant indicators of ecologic conditions. On reefs, *Trochus*, *Drupa*, *Turbo*, *Chama*, and *Cypraea* are common, whereas on the lagoon bottom, especially at depths of 12 to 25 fathoms, such forms as *Cerithium*, certain species of *Strombus*, and tellinids are found. In the core, a mixture of worn reef types and unworn lagoon types would indicate deposition in water of shallow to moderate depth not far from a reef.

SUMMARY OF THE SECTIONS DRILLED

The following abbreviated logs of the drill holes are summaries of the detailed descriptions to be found in the section on description of cores and cuttings (p. 214). Changes in fauna or lithology within major intervals are stated here, but all descriptions of smaller units, petrographic descriptions of individual core specimens, and ecologic interpretations of lithologic intervals are contained in the detailed descriptions.

Drill hole 1

[Elevation 13 feet above reef level, and approximately 15 feet above low-tide level. The location is shown in figure 31. A diagrammatic section is shown in figure 33.]

	Depth (feet)
Beach sand and gravel	13
Well-consolidated algal, coral, and foraminiferal reef rock	21
Unconsolidated sand, mostly unworn tests of *Calcarina spengleri*, fragments of *Lithothamnion* and coral. Reef detritus	43
Reef detritus. The top foot is moderately consolidated coral rock. Below is unconsolidated to poorly consolidated detritus of corals, some in position of growth and encrusted by formanifers and mollusks; *Lithothamnion* fragments, *Halimeda* segments, tests of foraminifers, especially *Calcarina spengleri* and *Marginopora*, and coarse to fine angular detrital grains. Acicular needles of aragonite fill some pore spaces in corals, and near the bottom of the interval they form a cementing coat on detrital grains. A slight disintegration of *Halimeda* grains and of corals was seen near the base of the interval	95
Poorly consolidated, chalky coralliferous detritus. *Calcarina spengleri* is absent, *Calcarina hispida* is present in abundance. *Halimeda* segments are abundant especially in the upper part of the unit; coral colonies in position of growth are common, especially from 158 to 175 feet. Many corals are friable and in thin section appear to be disintegrated. Patchy, irregular areas are recrystallized. In the top part of this unit, needles of aragonite penetrate gray microgranular paste that fills pore spaces; in the bottom part, small areas are recrystallized to a mosaic of calcite, or are replaced by brown calcite	175

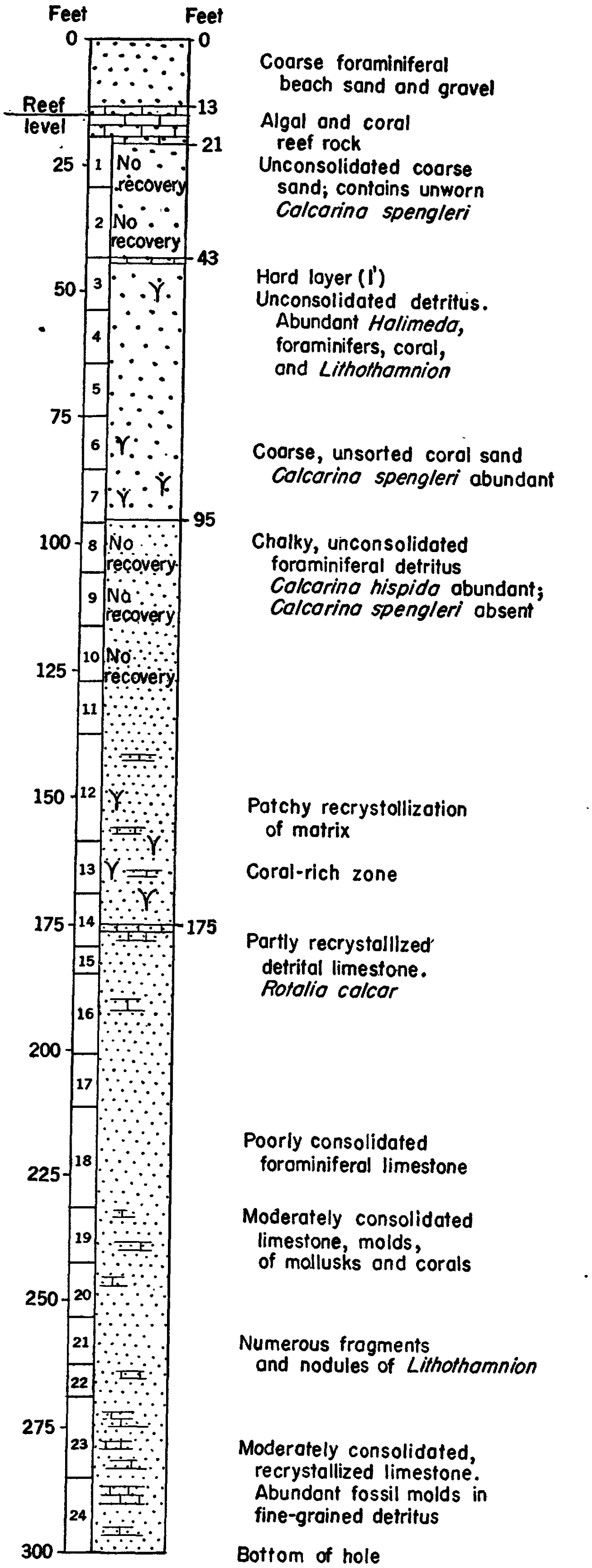

FIGURE 33.—Diagrammatic section of drill hole 1, Bikini island. Depths to significant lithologic or faunal zones are shown on right. Numbered insets to left of column represent cored intervals.

Depth (feet)

Poorly to moderately consolidated, coralliferous detritus. *Rotalia calcar* is present. Corals are common but are distributed irregularly. Many are coated by encrusting foraminifers, and from 253 to 269 feet by encrusting *Lithothamnion*. Original skeletons as well as molds of mollusks and corals are present above 284 feet, but below this depth all mollusks and corals are molds. Some organic remains and limy paste of the matrix are recrystallized to a mosaic of calcite. The degree of recrystallization increases irregularly from top to base of the interval. In a few places organic remains are disintegrated to a brown microgranular material 300

Drill holes 2 and 2A

[Elevation about 17 feet above low-tide level. The location is shown in figure 31. A diagrammatic section is shown in figure 34]

Depth (feet)

Coarse beach sand and gravel 14

Bedded, well-consolidated beach sandstone 16.5

Unconsolidated foraminiferal and coral detritus. From 16.5 feet to 42 feet is mostly foraminiferal sand. A moderately consolidated rock from 42 to 43 feet overlies coarse coralliferous detritus to the bottom of the unit 50

Poorly consolidated to unconsolidated coralliferous detritus. *Halimeda* is abundant and forms most of the material from 80 to 88 feet. *Calcarina spengleri* is abundant. Some corals are coated with *Lithothamnion*. The material is very coarse and there are some rounded coral pebbles at the base of the unit.

Some aragonite has broken down into microgranular crystals, and some pores are lined with aragonite needles. Near the bottom of the unit, a thick coat of acicular aragonite cements grains to form a moderately consolidated limestone 105

Partly consolidated coralliferous limestone containing *Calcarina hispida*. Corals are abundant, some of them in position of growth, and near the bottom of the interval they form more than half of the rock. A rich molluscan fauna consisting of lagoonal species is found at the base of the unit, together with a few altered pebbles from the unit below.

Centers of some corals are disintegrated and chalky; others have recrystallized to a mosaic of calcite 185

Unconsolidated to moderately consolidated fine chalky detritus containing *Calcarina hispida* and *Rotalia calcar*, and lagoon-type mollusks and corals.

At the top, the unit is unconsolidated and shells are well preserved. The chalky matrix is recrystallized in a few places to calcite, and the amount of consolidation increases irregularly with depth. Near the base, some mollusks and corals are molds, and others are altered to a chalky aragonite powder 293

White, cavernous, moderately consolidated limestone grading to poorly consolidated tan limestone. At the top, corals and mollusk molds are abundant in a hard fine-grained matrix but some intervals consist of unconsolidated foraminiferal sand. From 327 to 447 feet most aragonite is altered to calcite. A poorly consolidated interval from 447 to 473 feet overlies a moderately consolidated interval from 473 to 504 feet. Below 504 feet the rock contains lagoon-type corals that are disintegrated to an aragonite powder, and cavities are

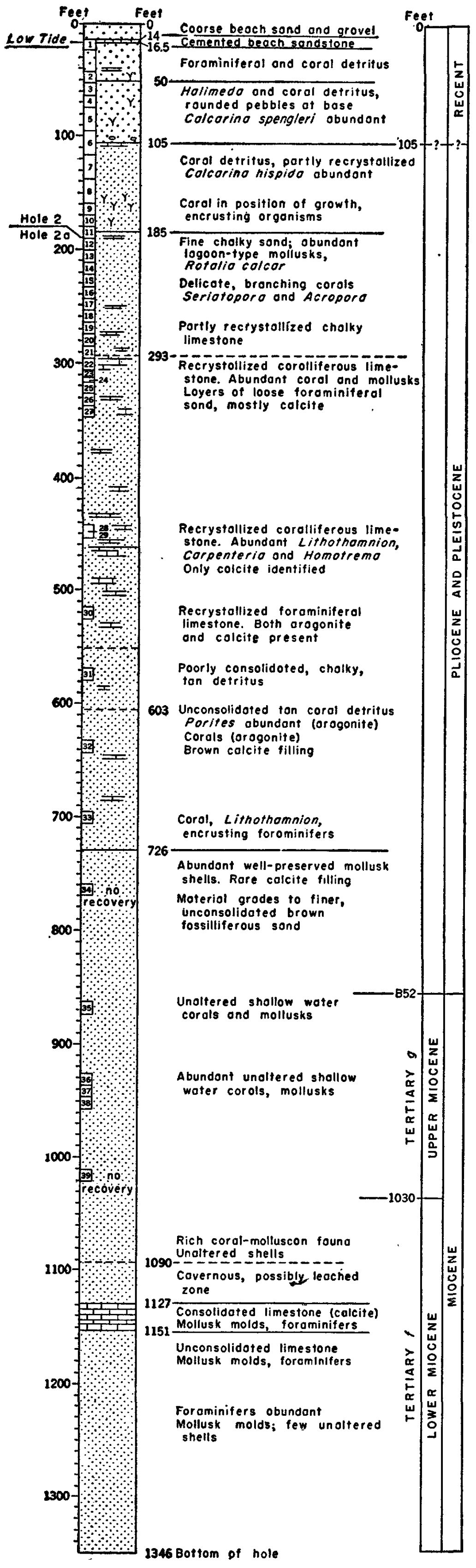

FIGURE 34.—Diagrammatic section of drill holes 2 and 2A, Bikini island. Depths to lithologic intervals are shown to left of descriptions; depths to faunal zones are shown in column on right. Numbered insets represent cored intervals.

	Depth (feet)
lined or filled with coarsely crystalline calcite. Both alteration of original remains and recrystallization to calcite are less than from 327 to 447 feet	603
Porous, unconsolidated tan to brown coarse detritus. Shallow-water corals are abundant and are well preserved. They are especially numerous in the upper part of the unit. In the lower part nodular *Lithothamnion* and encrusting foraminifers are present, and they may form a considerable portion of the rock. Brown crystalline calcite fills large corallites and encrusts open cavities. It diminishes in abundance below 700 feet, and it is practically absent at 726 feet	726
Unconsolidated brown detritus. Numerous well-preserved mollusk shells, corals, and foraminiferal tests are in an uncemented, unsorted, fine-grained sandy matrix. The top of the upper Miocene in the hole is tentatively placed at 825 feet, and the top of the lower Miocene at 1,030 feet	1,090
Porous, unconsolidated material. No cuttings were obtained as the drill struck a "cavity" and mud circulation was lost	1,127
Consolidated brown foraminiferal limestone containing numerous molds of small mollusks	1,151
Unconsolidated fine brown detritus. Mollusk molds are abundant in some porous fragments, but rare original shells and corals are present near the top of the unit and they increase with depth	1,346

Drill hole 2B

[Elevation about 19 feet above low-tide level. The location is shown in figure 31. A diagrammatic section of the hole is shown in figure 35]

	Depth (feet)
Unconsolidated foraminiferal sand and gravel	26
Consolidated layer 1.5 feet thick at top of unit; beach rock or reef rock. The rest of the unit is unconsolidated white detrital limestone containing numerous thin hard layers	187
Poorly consolidated, chalky detrital limestone	290
Poorly to moderately consolidated recrystallized white limestone, containing molds of mollusks. Cavities are coated with calcite crystals	425
Poorly consolidated porous limestone, white at the top, grading to light tan at the bottom	550
Poorly consolidated porous tan to light-brown detritus containing coral and molds of mollusks. Crystalline calcite fills some cavities	715
Light- to medium-brown fossiliferous sand containing original shells, corals, and foraminifers. Much fine sand below 750 feet. This unit is gradational into the next	832
Unconsolidated tan to brown very fossiliferous sand containing abundant shells with original nacreous luster, corals, and foraminifers. The top of the upper Miocene is tentatively placed at 852 feet, based on small foraminifers, and the top of the lower Miocene is tentatively placed at 1,080 feet, based on the larger foraminifers	1, 120
Compact brown limestone containing molds of small mollusks	1, 155
Unconsolidated light-brown detritus containing mollusk molds at the top, but very few original shells. Below 1,219 feet, tests of larger foraminifers are abundant	

	Depth (feet)
to 1,314 feet; from 1,314 to 1,755 corals and mollusk shells are common but foraminiferal tests are relatively rare	, 755
Unconsolidated brown sand. Mollusks and corals are rare, larger foraminifers are abundant in a fine-grained detrital matrix	1, 870
Unconsolidated medium-brown sand. Larger foraminifers are less abundant than in the preceding unit, but mollusks and corals are more abundant	2, 070
Unconsolidated medium-brown sand. Corals, mollusks and foraminifers are moderately abundant at the top of the unit, but decrease in abundance with depth. Small rods of calcareous algae (*Lithophyllum*) are common to exceedingly abundant. The top of the Oligocene (?) is tentatively placed at 2,070 feet by Cole.[1] (chapter O of this report)	2, 070–2, 401
Unconsolidated medium-brown fine sand. Fossils are rare except for abundant calcareous algae	2, 556

Drill hole 3

[Elevation 6 feet above reef level, and approximately 8 feet above low-tide level. The location is shown in figure 31. A diagrammatic section is shown in figure 36]

	Depth (feet)
Beach sand and gravel	6
Consolidated coral-algal rock, probably coral conglomerate in the upper 2 feet, equivalent to the lithified rock bar near the drill hole; and algal reef limestone in the bottom 8 feet, containing *Lithothamnion* in position of growth, unworn *Calcarina spengleri*, and coral	16
Unconsolidated foraminiferal sand containing coral and *Lithothamnion* fragments, and segments of *Halimeda*. Corals near the base of the interval are in position of growth, and are encrusted by *Homotrema*, *Carpenteria*, and *Lithothamnion*. Unworn tests of *Calcarina spengleri* are abundant. Acicular aragonite needles fill a few coral pores and cement some grains. At the base of the interval there is an apparent slight recrystallization to microgranular calcite	61
Moderately consolidated coral rock. *Calcarina spengleri* is absent. Encrusting *Lithothamnion* and *Carpenteria* are very abundant, and in places *Carpenteria* forms 40 percent of the rock. Corals are in position of growth; reef type mollusks are common. The rock is cemented by fine-grained calcite and there is some recrystallization to a mosaic of fine calcite	80
Cavernous coral limestone filled and replaced by coarsely crystalline brown calcite. Coral and *Lithothamnion* are abundant. Detrital material is present but fills only a few of the cavities between corals. The cavities are thickly encrusted or filled by brown crystalline calcite and by tan, compact, coarsely crystalline calcite that is marked by agatelike concentric rings. Outlines of some of the corals are altered and replaced by the brown calcite. In thin section, some of the coral is seen to be completely replaced by a coarse mosaic of clear calcite	95

[1] The tentative reference of the beds below 2,349 feet to the Oligocene was based entirely on the occurrence of one species of *Halkyardia*. This species has since been found by W. Storrs Cole in rocks of unquestioned late Eocene age on Saipan in the Mariana Islands. It is possible, therefore, that the portion of the "Oligocene(?)" referred to Tertiary "c" of the Bikini section may eventually be assigned to the late Eocene.

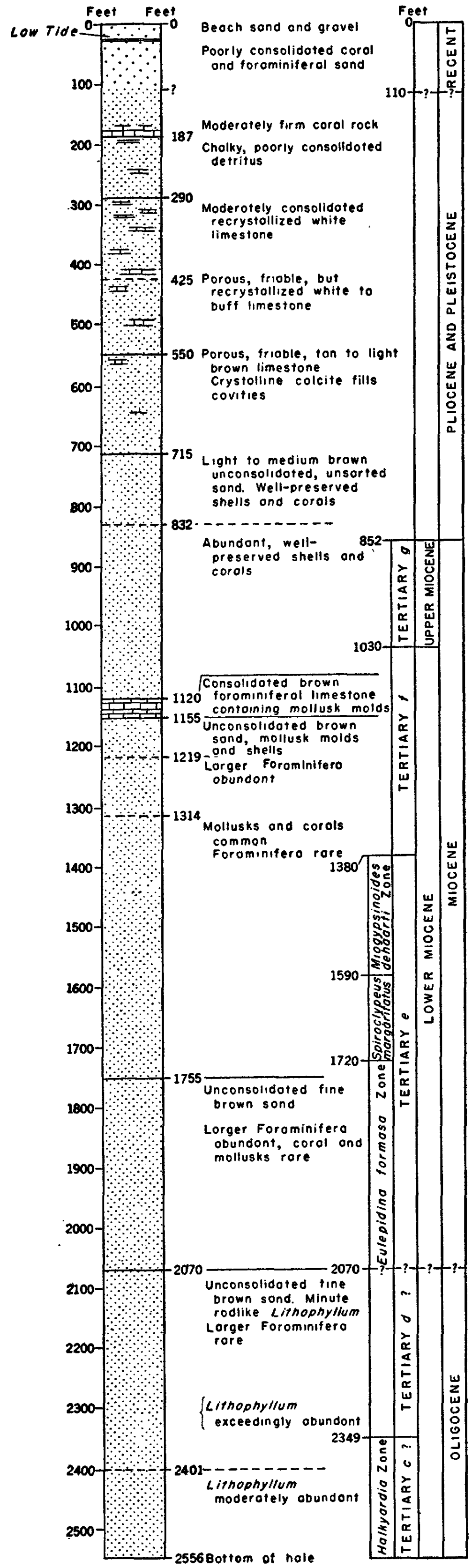

FIGURE 35.—Diagrammatic section of drill hole 2B, Bikini Island. Depths to lithologic intervals are shown to left of descriptions; depths to faunal zones are shown in column on right.

	Depth (feet)
Leached zone of hard white porous limestone. The rock is full of small cavities that appear to be molds, possibly of *Halimeda* and mollusks. Recognizable organic remains are rare, although a few foraminifers can be seen. In thin section the rock appears to be a fine-grained to microgranular dark-gray paste, partly recrystallized to a fine mosaic of calcite	117

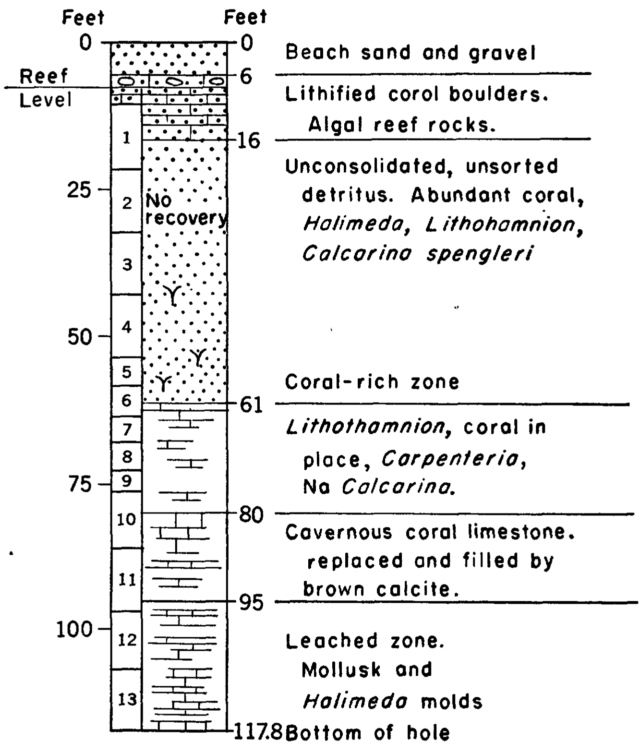

FIGURE 36.—Diagrammatic section of drill hole 3, Bikini island. Depths to lithologic intervals are shown to right of column; numbered insets at left of column represent cored intervals.

CHEMISTRY AND MINERALOGY

CHEMICAL ANALYSES

A representative series of 18 samples taken at intervals throughout the Bikini drill core were analyzed in the chemical laboratory of the U. S. Geological Survey for carbonates (table 15). Four samples of brown limestone (table 16), one of which was a surface rock, and two samples from the replaced and leached zones in hole 3 were also analyzed (table 17).

All the analyses reported above are of samples considered by the writer to be representative of the core run from which they were taken. All samples except the last three are fragments of cores. Sample 2A–1135 consisted of rock-bit chips picked from cuttings collected in the interval 1,135 to 1,145.5 feet, and the sample is probably as free of contamination as any of the core samples. Samples 2B–1600 and 2B–2510 were aliquot splits of cuttings collected from the intervals 1,597.5 to 1.608 feet and 2,503.5 to 2,514 feet, respectively. Both samples contain much fine material, but both contain polished white grains and worn foraminiferal tests that are obviously surface contamination. Though contaminated, they are considered to be fairly representative of the material drilled, and they show that there is no marked increase in magnesium carbonate toward the bottom of the hole. Sample 2B–2510 shows a slight increase to 3.46 percent in magnesium carbonate, which is possibly due to contaminating particles from the surface, but which is more probably due to the presence of rodlike *Lithophyllum* that was so abundant from 2,070 to 2,556 feet in hole 2B, and that formed at least 10 percent of this sample.

TABLE 15.—*Representative chemical analyses of Bikini cores*

[Analyses that include percent insoluble residue by Charlotte M. Warshaw; others by F. J. Flanagan]

Sample No.	Approximate depth (feet)	$CaCO_3$	$MgCO_3$	Insoluble residue
2-1-4	15.5	87.66	8.27	----------
2-3-3	55	93.46	3.26	0.28
2-7-1	116	96.39	.84	----------
2-9	160	97.21	1.13	.35
2A-13-4	205	96.52	.77	----------
2A-16-1	240	94.89	.75	.21
2A-25-1	316	97.18	.92	----------
2A-27-1a	340	98.60	.71	.15
2A-28-16	450	97.05	1.76	----------
2A-30-1	520	97.85	.89	.51
2A-31-1	578	97.27	1.11	----------
2A-32-1	640	96.17	.54	1.19
2A-33-5	705	97.48	1.53	----------
2A-35-1	870	95.97	.24	----------
2A-37-15	946	94.32	1.33	----------
2A-1135	1,135	97.25	2.09	.38
2B-1600	1,600	94.04	2.58	----------
2B-2510	2,510	94.23	3.46	----------

The only other samples showing more than 3 percent of magnesium carbonate are specimen 2–1–4, beach sandstone containing abundant foraminiferal tests and fragments of *Lithothamnion*, and specimen 2–3–3 containing abundant *Halimeda* and coral fragments, in a detrital matrix formed largely of tests of *Calcarina spengleri*.

Clark (1924, p. 573) reported that in a series of analyses of foraminiferal tests, magnesium carbonate ranged from 3.67 to 11.22 percent. He also reported a series of analyses of the calcareous algae *Lithothamnion*, *Lithophyllum*, etc., in which the proportion of magnesium carbonate ranged from 10.93 to 25.17 percent, whereas the calcareous green alga, *Halimeda*, is nonmagnesian. Corals range from 0.09 to 0.77 percent, and mollusk shells contain 0 to 2.58 percent magnesium carbonate.

We may conclude, then, that the small amount of magnesium carbonate throughout the 2,556-foot section at Bikini Atoll is a function of the proportions of organic remains in the rock, and that no significant addition or subtraction of magnesium carbonate has occurred.

Several special analyses were made by Mrs. Warshaw on brown limestone from several depths, and on a brown rock collected from the middle of one of the small southwest islands.

TABLE 16.—*Analyses of brownish carbonate rocks*

Specimen [1]	$CaCO_3$	$MgCO_3$	R_2O_3	P_2O_5	Total insol.	Insol.[2] organic
A	94.68	1.17	0.28	0.06	0.78	0.47
B	97.57	.75			.40	[3].3
C	95.53	.89			.30	.18
D	94.03	2.97	[3].5	.76	.46	.32

A. Specimen 2-2-10, depth 50 feet, brown laminated porous carbonate.
B. Specimen 2A-23-10, depth 310 feet; brown laminated carbonate.
C. Specimen 2A-37-7, depth 943 feet; medium-brown detrital sand.
D. Specimen B-316, surface of Orukaen island; brown detrital sandstone.

[1] Description of specimens:
[2] Determined by treatment with 30 percent H_2O_2.
[3] Estimated.

All the samples are calcium carbonates low in magnesium carbonate. Phosphate is highest in *D*, the surface sample, but it is in no sense a phosphate rock. The insoluble residue is a little larger in *A* than in the other samples. About 60 percent of the insoluble residue is organic matter. Mrs. Warshaw reported that not all organic matter was collected in the insoluble residues, for some was colloidal or very finely suspended and could not be collected even by using a centrifuge. She reported that two other specimens, 2A-1135 (analysis reported in table 15 page 84) and 3-10-13 (table 17), contain an estimated 0.3 percent organic matter.

Specimen 2A-1135 was consolidated brown limestone from a depth of 1,135 feet; specimen 3-10-13 is brown coarsely crystalline calcite from hole 3 at a depth of 83 feet. The insoluble residues of two other samples, 2-3-3 and 2-16-1, were analyzed for organic matter. Both specimens were white, chalky, fine-grained detritus and both contained only 0.08 percent insoluble organic matter. Thus it appears that the very small percentage of organic matter in the brown carbonates, ranging from 0.18 to 0.47 precent, may be responsible for the tan to brown color in both unaltered and recrystallized rocks. The amount of organic matter is about half that obtained for the lagoonal sediments (fig. 26). Mrs. Warshaw reported that the insoluble residue from specimen 2A-37-7 was dried at 110° C. and ignited. The loss of weight on ignition was 60 percent, and the ignited residue consisted of 70 percent silica.

Two specimens from hole 3 were analyzed by Mrs. Warshaw. One was from the zone replaced and filled by brown coarsely crystalline calcite, 80 to 95 feet, the other from the leached zone, 95 to 117 feet.

TABLE 17.—*Analyses of limestone from hole 3*

Specimen No.	$CaCO_3$	$MgCO_3$	Insoluble residue
3-10-13 [1]	97.00	1.42	0.40
3-13-5 [2]	98.07	1.84	.19

[1] 3-10-13, depth 83 feet; coarsely crystalline brown calcite.
[2] 3-13-5, depth 115 feet; porous leached limestone.

The carbonates in the two rocks are not significantly different, but the insoluble residue is greater in the brown calcite. The total insoluble organic matter in the brown carbonate is probably two or more times that in the leached carbonate, but the actual amounts were not analyzed.

X-RAY ANALYSES

A group of 22 samples was submitted to J. M. Axelrod of the U. S. Geological Survey. Some were representative samples of core specimens, but others were samples of unaltered, disintegrated, or recrystallized mollusk shells and corals (table 18).

TABLE 18.—*X-ray analyses of Bikini cores*

[The unidentified mineral X is the same substance in all samples; mineral T is a new manganese oxide mineral not yet fully identified. The unit-cell size variation is with respect to Iceland spar and was measured nearly along the rhombohedral face diagonal]

Sample	Depth (feet)	Minerals	Description
2-7-1	116	Aragonite, calcite, very little X.	Coralliferous limestone.
2-11-1	180	Aragonite, tr. calcite, tr. X	Mollusk shell.
2A-12-5	195	Aragonite, calcite	Chalky fine sand.
2A-13-3a	205	Aragonite, very little calcite	Chalky fine sand.
2A-13-3b	205	Aragonite, tr. calcite	Chalky coral.
2A-16-1	240	Aragonite, calcite	Chalky silt.
2A-23-10	310	Calcite (cell 0.5 percent short) very little aragonite.	Brown carbonate.
2A-26-1	330	Calcite (cell 0.6 percent short) little aragonite.	Chalky coral.
2A-28-17	447	Calcite (cell 0.7 percent short)	Limy paste.
2A-30-1a	520	Aragonite, tr. calcite	Powder, mollusk shell.
2A-30-1b	520	Aragonite, calcite (cell 0.3 percent short).	Powder, coral center.
2A-31-3	578	Calcite, aragonite, very little X.	Chalky sand.
2A-32-1a	640	Aragonite, tr. calcite	Coral (*Porites*).
2A-32-1b	640	Calcite (cell 0.4 percent short) and aragonite.	Coral (*Goniastrea*) and brown calcite.
2A-35-1	870	Aragonite	Coral (*Stylophora*).
2A-36-3	930	Aragonite, tr. calcite, tr. X	Mollusk shell.
2A-37-15	946	Aragonite, little calcite, little X.	Fine sand.
2A-1135	1,135	Calcite (cell 0.1 percent short)	Hard limestone chips.
2A-1135a	1,135	Calcite (cell 0.5 percent short)	Mollusk shell in limestone chip.
3-10-8	81	Aragonite, little calcite	Chalky coral.
3-10-13	82	Calcite (cell 0.1 percent short)	Brown calcite crystals.
3-11-4	90	Mineral T, little X	Black coating on coral.

Aragonite and calcite are the principal minerals. No trace of dolomite was found, and the only other minerals found were mineral T, in one sample from hole 3, a new manganese oxide mineral reported from several localities but not yet fully identified, and the unidentified substance X. Traces of the unidentified substance were found in several samples but there is no apparent reason for the random distribution.

Of the 22 samples 8 are of limestone, sand, silt, or limy paste, and can be considered reasonably representative of the material in the core specimen. Aragonite is dominant at some levels, and calcite is the principal or only mineral in others. Furthermore there are several degrees of alteration of shells and corals. Some are unaltered and consist of aragonite. Others are altered to a chalky aragonite powder (specimens 2A–13–3b, 2A–30–1a). Another is chalky powder that consists of calcite (specimen 2A–26–1—pl. 62, fig. 3). Corals consisting of both aragonite and calcite, such as specimens 2A–30–1b and 2A–32–1b, have friable cell walls of aragonite, and pore spaces are filled by crystalline calcite.

The proportions of aragonite and calcite in the limestone in holes 2 and 2A may be roughly estimated from the X-ray analyses, and from the staining and oil-immersion tests that were made by Tracey concurrently with examination of thin sections:

Depth (feet)	*Minerals (estimated)*
0– 105	Aragonite, some calcite.
105– 185	More aragonite than calcite.
185– 195	More calcite than aragonite.
195– 250	More aragonite than calcite.
250– 294	More calcite than aragonite.
294– 447	Calcite, little aragonite.
447– 603	Calcite and aragonite.
603– 631	Aragonite, some calcite.
631– 725	Aragonite and calcite.
725–1,127	Aragonite, some calcite.
1,127–1,151	Calcite.
1,151–1,346	Calcite, some aragonite.

SPECTROGRAPHIC ANALYSES

Eleven samples (table 19) were submitted to A. T. Myers of the U. S. Geological Survey for spectrographic analysis. Most of them are similar or identical to the samples submitted for X-ray analysis.

TABLE 19.—*Spectrographic analyses (in percent) of Bikini cores*

[Looked for but not found: Ag, As, Be, Bi, Cb, Cd, Co, Cu, Ga, Ge, In, La, Mo, Ni, P, Pb, Sb, Sn, Tl, Th, U, W, Zn, and Zr. Y was found in only one sample; 0.00X percent in 2A–32–1a]

Sample No.	Mg	Sr	Ba	Si [1]	Al [1]	Fe	Mn	Na	Cr	B
2–2–7 [2]	1.2	0.9	0.002	0.4	0.05	0.007	0.002	0.4	0.000X	0.000X
2–3–5 [3]	1.0	.6	.001	.08	------	.008	.001	.3	.00X	.000X
2A–12–5 [4]	.66	.8	.002	.2	.01	.02	.0006	.6	.00X	.000X
2A–13–3b	.16	.6	.001	[5] ndt	.006	.02	ndt	ndt	--------	.000X
2A–23–10	.35	.1	.001	.05	.002	.01	.0005	.1	.00X	--------
2A–26–1	.33	.4	.001	.8	.09	.1	.002	.7	--------	.000X
2A–32–1a	30	.8	.002	1.5	.1	.2	.003	1.0	--------	.000X
2A–32–1b	30	.08	------	.2	.008	.02	.0005	.1	--------	--------
2A–37–15	.49	.6	.001	.08	.002	.01	------	.3	.00X	.000X
2A–1135	.90	.03	------	.2	.004	.02	.0004	.07	.00X	--------
3–10–13	.60	.08	.001	.1	------	.007	------	.07	--------	--------

[1] Very approximate determinations.
[2] Depth about 45 feet; unaltered coral.
[3] Depth about 60 feet, unaltered *Halimeda* and fine sand.
[4] For descriptions and depths of samples 2A–12–5 to 3–10–13, see table 18.
[5] Not determined.

Spectrographic analyses of carbonates are not considered to be as accurate as those of some other types of rock, but the results are probably consistent and show accurately the relative variation between samples. Two specimens were analyzed by flame photometer for strontium by W. W. Brannock. He reports that sample 2–2–7 contains 0.75 percent SrO (approximately 0.63 percent Sr), and that sample 2A–32–1a contains 0.72 percent SrO (approximately 0.61 percent Sr). Analyses by flame photometer are consistently somewhat lower than those by the general spectrographic method in which a large number of elements are determined simultaneously.

The percentage of strontium in the samples shows a considerable variation that may be correlated with the mineral analyses. Those samples containing 0.6 to 0.9 percent strontium are specimens of coral or unconsolidated sand that consist mostly of aragonite. The corals are either unaltered or they are friable, disintegrated aragonite, and there is very little recrystallization to calcite. Samples containing 0.1 percent or less of strontium consist mostly of calcite that has recrystallized or replaced aragonitic material. Sample 2A–23–10 is brown, laminated microgranular calcite; samples 2A–32–1b and 3–10–13 are brown, coarsely crystalline calcite, and sample 2A–1135 is fine paste recrystallized to calcite. Sample 2A–26–1 containing 0.4 percent of strontium, an intermediate amount, is a coral center that has altered to microgranular calcite powder but has not recrystallized to granular calcite. The percentage of strontium in samples appears to bear an inverse relationship to the degree of alteration and recrystallization of aragonite to calcite.

Two samples, 2A–26–1 from 330 feet, and 2A–32–1a from 635 feet, contain more silicon, aluminum, iron, manganese, and sodium than other samples, but these elements are possibly due to contamination by drilling mud.

The amount of boron in the samples appears to vary in the same manner as strontium, for it is absent in those specimens that contain 0.1 percent or less of strontium, and it is present in other samples.

The use of strontium as an index of the recrystallization or replacement of limestones has been suggested in a personal communication by H. T. Odum of Yale University, who has determined by spectrophotometric methods the strontium-calcium ratio in many groups of Recent and fossil shells. He states that the degree of exclusion of strontium in the skeletons of marine organisms has a definite taxonomic pattern. Coral skeletons have a high ratio of Sr to Ca by atoms, 3 to 6/1000; mollusk shells have lower ratios of 1 to 2/1000, but ratios in limestones as a whole are less than 1/1000, and in Cambrian dolomites they range from 0.05/1000 to 0.3/1000. The ratio Sr/Ca by atoms for ocean water is 8.16/1000.

The writers submitted several samples to Mr. Odum both from the surface and the subsurface at Bikini. He reports the following determinations of Sr/Ca:

TABLE 20.—*Strontium-calcium ratios from Bikini Atoll*

Recent specimens:	*Location*	*Ratio per 1,000*
Heliopora	Reef	3. 82
Astreopora	Reef	4. 56
Acropora digitifera	Reef	6. 00
Acropora cymbicyathus	Reef	4. 50
Lithophyllum	Reef	2. 14
Halimeda sand	Lagoon	5. 12
Detrital sand	Lagoon	4. 40
Core specimens:	*Depth (feet)*	*Ratio per 1,000*
2-7-1	116	2. 56
2A-31-3	578	. 91
2A-37-15	946	3. 92

Two samples from the Bikini drilling show moderate to high ratios at 116 and 946 feet, in material that is dominantly aragonitic and unaltered. The intermediate sample at 578 feet has a relatively low ratio of 0.92/1000, in material that is chalky sand partly recrystallized to calcite.

Mr. Odum's determinations by spectrophotometer are in general lower than those of Mr. Myer using the general spectrographic method. Each series of determinations, however, is probably consistent in the relative variations of strontium shown.

There has not been enough spectrographic work done on the Bikini material to differentiate all the types of recrystallization and alteration found, but the determination of the proportion of strontium or of the strontium-calcium ratio seems to be a most valuable tool for further research. This much seems to be established:

1. Corals and detrital sand that show little or no alteration have relatively high percentages of strontium (0.6 to 0.9 percent in Myers' analyses).
2. Corals and detrital sand that are broken down to microgranular aragonite have high percentages of strontium, probably somewhat less than in unaltered material (0.6 percent).
3. Corals that are broken down and recrystallized to microgranular calcite have intermediate amounts of strontium (0.4 percent).
4. Corals and detritus that are completely recrystallized to crystalline calcite have low percentages (0.03 to 0.1 percent).

PETROLOGY

CONSTITUENTS

The section of rock drilled at Bikini, from top to bottom, consists of very pure calcium carbonate. Magnesium carbonate forms at the most a few percent of the material, and only exceptional samples have more than 1 to 2 percent other components including organic matter and sesquioxides.

The constituents of the limestone are calcareous organic remains and fragments, roughly 30 percent; fine to coarse detrital grains, 50 percent; and calcareous mud or paste, 20 percent. Organic remains are mostly coral, foraminifers, *Halimeda*, mollusks, and *Lithothamnion*. Detrital grains, so far as could be determined, are formed of fragments and finely comminuted particles of organic skeletons. Most of the calcareous paste seems to be derived from organic material. No conclusive evidence for the presence of calcareous precipitates was found, but it is possible that a part of the paste is inorganic in origin.

Among the organic constituents, corals are the most abundant in the recovered core, and they form roughly 20 percent of the materials studied. As coral is recovered more easily than smaller constituents in coring, however, it probably forms no more than 10 percent of the rock above 1,100 feet, less than 5 percent of the rock from 1,100 feet to 1,700 feet, and is rare or absent from 1,700 feet to the bottom of the hole.

Foraminiferal tests form about 10 to 15 percent of the recovered core. They amount to 40 percent of the rock in certain beds, but throughout the section they probably do not average more than 10 percent of the material.

Halimeda segments are very abundant in some shallower zones, and they form more than 10 percent of the material above 900 feet, but they do not form more than 5 percent of the entire section.

Lithothamnion, although it is a common constituent in many core specimens, and although it is the chief constituent at some levels, probably does not average more than 5 percent of the rock.

Mollusk shells rarely form more than 5 to 10 percent of core specimens, and probably do not form more than 2 or 3 percent of the entire section.

About 50 percent of the rock, through the 2,556 feet explored, consists of unsorted detrital grains 0.1 to 2 millimeters in size. The coarser part of this detritus is recognizably organic, and the finer part is presumably of organic origin.

The remaining 20 percent of the rock consists of fine calcareous paste, some of it consisting of detrital grains recognizable in thin sections, the rest of it consisting of microgranular material. If it is assumed that the detrital grains and calcareous paste are derived solely from the 5 principal rock-making organisms, and in the same proportions as in the recognizable fragments, the percentage that each group contributes to the 2,556-foot section underlying Bikini Island would be as follows: corals, 25 percent; Foraminifera, 35 percent;

Halimeda, 15 percent; *Lithothamnion*, 15 percent; mollusks, 10 percent.

The rough approximations above are given to indicate the general composition of the limestone. Accurate analyses and averages of the components were not made because of the poor core recovery and because of the selective recovery of certain constituents in the cores and cuttings.

Several types of changes in the rock since its deposition are recognizable. These include disintegration, or breaking down of crystalline to microgranular and cryptocrystalline material, and consolidation of the rock both by addition of calcite (cementation) and by recrystallization.

DISINTEGRATION

Much of the fine-grained detritus and the calcareous paste is probably derived from the attrition of organic remains by waves and water currents, and by the action of holothurians, echinoids, and burrowing mollusks and worms. After burial, however, there is also much decomposition of crystalline skeletal material. Coral and mollusk fragments have disintegrated to a chalky powder. In thin section the original fibrous crystalline structure of aragonitic organisms is seen to be altered to finely granular or microgranular material. *Halimeda* segments in particular are altered from brown microgranular to brown cryptocrystalline material. Unaltered *Halimeda* in thin section shows a mat of minute needles about 1 micron in size, but altered segments of the alga have scattered needles of high birefringence in a brown isotropic matrix. The calcite tests of small foraminifers are likewise changed from fibrous calcite, oriented normal to the cell walls, to brown isotropic material. Some of the gray microgranular paste shows a similar alteration to brown nearly isotropic paste.

The disintegration or decomposition of material is seen in a few places in specimens of rock from the beaches and reefs. In the drill holes from the surface to a depth of 50 feet or more rare small areas of corals and of *Halimeda* are partly decomposed. The amount of decomposition increases irregularly with depth to about 300 feet where most of the small calcitic foraminifers seen in thin section are composed of gray to brown microgranular material. Below 600 feet and especially below 725 feet, mollusk shells are perfectly preserved and at some levels they have an original nacreous luster and traces of color patterns, but in thin section the laminated aragonite layers are seen to be less well crystallized than in Recent shells. The septa and dissepiments of corals are likewise perfectly preserved, but the original fibrous aragonite is broken down to microgranular material at most levels.

The decomposition of organic skeletons apparently increases irregularly with depth, but the material at 950 feet shows little more disintegration of crystalline material than that at some higher levels.

X-ray analyses indicate that there is no change in the mineral content of the altered corals and shells, and spectrographic studies revealed no apparent change in the amount of strontium contained in the carbonate. The process of disintegration therefore appears unrelated to such factors as circulation of ground water. The process seems somewhat more complete in older, more deeply buried rocks, but there is no clear evidence that the disintegration depends only on age or depth of burial.

CEMENTATION

Consolidation of the rocks at Bikini by addition of carbonates into open pores and cavities is moderately common above 725 feet. Rarely, as at 74 to 95 feet in hole 2, the detrital grains in some core specimens are well cemented by a thick growth of aragonite needles normal to the margins of the grains, similar to the cementing aragonite seen in beach sandstones. More commonly the cement is granular calcite that coats or fills cavities and pore spaces. At 80 to 95 feet in hole 3 a thick encrustation of coarsely crystalline brown calcite in some core pieces has replaced parts of corals, shells and detrital grains. The brown crystalline calcite that occurs from about 630 to 725 feet in hole 2A, seen in specimens 2A–32–1b and 2A–33–1, fills large corallites and replaces parts of the coral, but many of the delicate septal walls are neither filled nor replaced.

RECRYSTALLIZATION

The most widespread type of consolidation seen at Bikini is the recrystallization of both aragonitic and calcitic organisms and grains to calcite. The recrystallization is rarely very advanced, but in a few cores some organic remains are almost obliterated by the growth of a mosaic of clear calcite, and corals and mollusks can be recognized only by fine "dust lines" that trace the outlines and cellular structures.

The fossils seem to follow about the same order of decreasing susceptibility to change as that reported by Crickmay (1945, p. 239), namely corals, mollusks, *Halimeda*, thin-walled (pelagic) foraminifers, thick-walled (beach) foraminifers, larger foraminifers, echinoids and *Lithothamnion*. Corals recrystallize readily to a mosaic of calcite, but there is some evidence (specimen 2–6–6, 95 to 116 feet in Hole 2) that they first break down to microgranular aragonite. Mollusks also recrystallize readily. In *Halimeda* segments the central pores and boundaries are attacked first. Only rarely is the whole segment completely recrystallized to a calcite mosaic. Thick-walled foraminifers such as *Calcarina* and *Amphistegina* recrystallize from fibrous compact calcite to coarsely crystalline calcite that has a more or less radial orientation. Echinoids and *Lithothamnion* are rarely recrystallized.

The microgranular gray or brown paste recrystallizes readily to a calcite mosaic that starts in small spots and spreads over the paste. In some places, gray paste that fills pores is attacked first on the borders of grains, and the mosaic of calcite spreads through the paste in branching veinlets. In other places the paste is recrystallized to a coarse mosaic in the centers of filled spaces, but the edges near grains and shells are microgranular.

LIMITS OF ALTERATION

In hole 1 there is a little decomposition of aragonite, and a moderate amount of calcite filling above 95 feet. From 95 to 175 feet, there is more decomposition of aragonite, and some has recrystallized to calcite. Below 175 feet the material is increasingly recrystallized to the bottom of the hole at 300 feet, but the limestone is well consolidated only in patches.

In holes 2 and 2A, acicular aragonite cement is strongly developed in some places between 54 and 105 feet. From 105 to 185 feet, minor recrystallization is present in patchy areas. There is a moderate recrystallization from 185 to 190 feet, but the rock from 190 to 250 feet is recrystallized only in small, scattered patches. The rock from 250 to 294 feet is moderately recrystallized, and the development of calcite, although it is scattered and patchy, increases with depth to 447 feet. From 447 to 603 feet the amount of recrystallization is less, and it decreases with depth. Recrystallized calcite apparently is absent from 603 to 631 feet. From 631 to 725 feet calcite fills pores and cavities. From 725 to 1,127 feet, neither calcite filling nor recrystallized calcite are present.

At 1,127 to 1,151 feet the rock is again moderately recrystallized, but below this depth there is little addition or recrystallization of calcite to the bottom of the hole at 1,346 feet. Below 1,346 feet to 2,556 feet in hole 2B, cuttings showed no further evidence of recrystallization. A minor amount of calcitic cement was seen in a thin section made from a rock chip at 2,338.5 to 2,349 feet, but this is not considered evidence for any significant cementation or recrystallization because the rock on the whole was totally unconsolidated, extremely porous sand below 1,155 feet.

In hole 3, there is a little filling of pore spaces by carbonate above 80 feet. From 80 to 95 feet, there is a great deal of coarsely crystalline brown calcite filling and encrusting cavities and replacing some organic skeletons. Corals are disintegrated to chalky aragonite, and some are recrystallized to a coarsely crystalline mosaic of calcite. Below 95 feet the rock is apparently leached and altered, and in thin section the microgranular gray paste is seen to be partly recrystallized.

CORRELATION OF SUBSURFACE ROCKS

In holes 1 and 2, there are three recognizable stratigraphic units (fig. 32), each characterized by distinctive species of Foraminifera: *Calcarina spengleri*, the spiny reef foraminifer so abundant on the present reefs, occurs in the uppermost zone; *Calcarina hispida*, a species that is abundant in the present lagoon in 10 fathoms or more of water, occurs in the middle zone; and *Rotalia calcar*, a species not found today at Bikini but common in other parts of the Pacific, is found in the lowest zone. The zones in hole 2 resemble those in hole 1, but in hole 2, which is closer to the lagoon, there are fewer corals and *Lithothamnion*, more *Halimeda*, and the average grain size is relatively smaller.

In hole 3, nearest the existing reef, the uppermost zone may be recognized. The *Calcarina spengleri* zone is made up of reef-type coral-algal detritus; in the second zone no *Calcarina hispida* is present but *Calcarina spengleri* is absent and the rock contains 30 percent or more of encrusting *Carpenteria*. Inasmuch as hole 3 is close to the reef edge, it is inferred that the *Carpenteria* rock was a growing reef at the time that the *Calcarina hispida* rock in holes 1 and 2 was accumulating in a lagoon. The correlation is strengthened by the fact that the lithologic break between the upper and middle zones in hole 3 is at 61.5 feet, or about 53 feet below sea level—approximately the same depth as the present seaward terrace at Bikini, whereas the lithologic break in hole 1 at 95 feet, and in hole 2 at 105 feet, is 80 and 88 feet, respectively, below low-tide level—a little below the present lagoon terrace which is well developed off Bikini island.

The lower lithologic break, between the *Calcarina hispida* and the *Rotalia calcar* zones, occurs at about 175 feet in hole 1, and 185 feet in hole 2, or 160 and 168 feet, respectively, below low-tide level. This is 30 feet higher than the deepest part of the lagoon—32 fathoms or 192 feet—but it is at almost the exact depth—28 fathoms or 168 feet—of the greatest area of the lagoon bottom.

It seems likely that the three zones described above may be explained in terms of existing physiographic features (lagoon basin, lagoonal and seaward terraces, and reef surface) as three successive late stages in the growth of Bikini Atoll. The present lagoon floor formed or was truncated to the level of the top of the *Rotalia calcar* zone. With later submergence and emergence the reefs grew and were truncated to form a lagoon and seaward terrace at the top of the *Calcarina hispida* zone. Most recently the present reefs have grown to the surface. This hypothesis is supported by the following facts: first, the basal part of the *Calcarina spengleri* zone contains coarse detritus and abundant corals in holes 1 and 2, and it contains worn pebbles in hole 2; second, the basal part of the *Calcarina hispida* zone in both hole 1 and hole 2 is rock extremely rich in corals, many of which are in position of growth, and pebblelike bodies are present that contain *Rotalia calcar* from the zone below; lastly, both the *Calcarina hispida* zone and the *Rotalia calcar* zone show a general decrease in grain size from bottom to top. These facts suggest that emergence alternated with submergence several times, and that with each submergence there was a marked stimulation of coral growth followed by deposition of increasingly fine detritus as the atoll became relatively stable before the next submergence.

PALEOECOLOGY

It is believed that the entire 2,556-foot section of limestone at Bikini accumulated in a shallow lagoonal, or near-reef, environment. Some parts of the section, especially in hole 3 that is only 800 feet from the present reef edge, probably accumulated on a growing, near-surface reef.

The environment of deposition of small units in the rock have been summarized at the end of the descriptions of individual core runs (pp. 214–259). For any one core the environment can be determined only broadly, but for the whole section of rock the accumulation of evidence is compelling. The reasons are summarized as follows:

1. The presence of abundant shallow-water corals, of stout types similar to those found on the present reef, or of delicate branching types similar to those of the present lagoon, at intervals from the surface to a depth of 1,080 feet. These are common to rare from 1,300 to 1,700 feet, but only a few genera can be recognized in cuttings. The coral-rich intervals at upper levels, especially from 600 to 1,000 feet, suggest that most of the deposition was in lagoonal waters very close to a reef.

2. The abundance of shallow-water Foraminifera throughout. Rita Post and Ruth Todd state that all the cores suggest deposition in an environment not much different from that now existing inside the lagoon. They believe that the presence of Miliolidae throughout and of Peneroplidae and Alveolinellidae in the lower parts of the core indicate shallow water, probably not more than 60 fathoms, and more likely less—possibly around 5 or 10 fathoms. They found no true *Globigerina* oozes in the core. Globigerinids and other pelagic species are rare except at one depth, 316 to 326.5 feet, and there they probably indicate nothing more than access to oceanic water, for similar assemblages are found inside the lagoon at the present time.

In hole 2A from a depth of 673 to 678.5 feet Cole identified *Cycloclypeus*, a large foraminifer that occurs in abundance on the outer slopes of Bikini at depths between 500 and 800 feet (see p. 135) but which was not found living in the lagoon. At Funafuti, *Cycloclypeus* was found on the outer slopes from 180 to 1,800 feet, most abundantly at about 480 feet; a few examples were also obtained in the lagoon. In other areas it has been reported at a depth of 120 feet (David, Halligan and Finckh, 1904, pp. 155–156, including footnote by editor, T. G. Bonney).

3. The abundance of shallow-water mollusks at many places in the section. Ladd identified mollusks from 7 horizons in cores from the upper 300 feet of holes 2 and 2A. All of the mollusks from this interval that have been determined to date are identical with living species, and with 2 exceptions all of them are represented in the collections of Recent shells made at Bikini. Most of the pelecypods and many of the gastropods are types that live more or less completely buried in sand and silt, and their occurrence in the upper horizons strongly suggests a shallow lagoonal environment. This interpretation is supported by the fact that many of the forms are specifically identical with shells dredged from Bikini's lagoon and by the fact that the few intertidal or reef species that are recognizable among the fossils are badly worn. Many of the gastropods that characterize the reefs and reef flats in the Bikini area (*Trochus*, *Turbo*, *Conus*, *Drupa*) have not been found in the upper cores while others of this group (*Cypraea*, *Columbella*) are represented by single worn specimens. Gastropods that are particularly abundant in the lagoon today (*Cerithium*, *Strombus*) are well represented among the fossils. The evidence of the pelecypods found in the upper 300 feet is similar: 7 species of fossil tellinids were found to be identical with Recent shells dredged from Bikini and Eniwetok Lagoons at depths of 12 to 25 fathoms.

Preliminary studies of the rich molluscan fauna obtained from a core at 925 to 935.5 feet in hole 2A indicate that it is appreciably older but the assemblage appears to represent a shallow-water environment, probably only tens of feet in depth, and possibly close to intertidal levels.

4. The presence of *Halimeda* to a depth of at least 950 feet, and its abundance in parts of the core is suggestive of a lagoonal environment. On the other hand, so far as can be determined, the drill did not penetrate any considerable thickness of nearly pure *Halimeda* such as would be expected if the environment were consistently at depths of 25 to 30 fathoms (fig. 22).

5. The presence of *Lithothamnion* as algal reef rock in hole 3, and as algal nodules and encrustations in holes 1 and 2. *Lithothamnion* is especially abundant at depths of 442–452.5 feet and at 694.5–705 feet in hole 2A, indicating that the rock of these intervals accumulated at very shallow depths. The alga is not

abundant below 705 feet to a depth of 2,070 feet, but in the interval 2,070–2,556 feet a new species of *Lithophyllum* is very abundant, and a very shallow lagoonal or near-reef environment at this level is indicated.

6. The absence throughout the core of any deep-water organisms, or of any limestone blocks or accumulations such as were found in the dredgings at Bikini is negative evidence for a lagoonal environment.

7. The proportion of fine detritus in the core, and more particularly the dominance of fine sand from 725 feet to the bottom of the hole, strongly suggests accumulation in a marginal zone of the lagoon comparable to the fine-debris zone normally less than 2 miles wide found around the lagoon margin of the reef (table 9).

If the material from top to bottom of the section is lagoonal, then it may be concluded that none of the rocks in the deep hole accumulated more than 2 miles from the seaward edge of a reef. The rock at the top of the hole is 4,800 feet from the present seaward margin, and the rock at the bottom of the hole is less than 2 miles from a point at corresponding depth on the seaward slope. Inasmuch as a considerable thickness of the outer slope is formed of talus from the reef margin, most of the 2,500-foot section of limestone in the drill hole probably accumulated less than a mile from the lagoon margin of a reef.

GEOLOGY OF ENIWETOK ATOLL

Eniwetok Atoll is located about 190 statute miles west of Bikini Atoll. It consists of a chain of about 30 small low islands surrounding an oval lagoon 25 miles long by 20 miles wide, and elongate in a northwest-trending direction. The total area of the islands is only 2.5 square statute miles. Most of them are less than 13 feet high but are covered by coconut palms reaching up to about 80 feet above low-tide level. Three entrances penetrate the reef. Deep Entrance, at the southeast side, is only about three-quarters of a mile wide but it has a depth of 31 fathoms between Parry Island and Muti (Japtan). South Channel, on the other hand, is very wide, about 6 miles, but the charted depths are only 6 to 12 fathoms. Southwest Passage, on the west side, is even shallower, only about 1 fathom. Maximum tidal currents of 2 knots in Deep Entrance and of 1 knot in South Channel have been observed.

According to the Hydrographic Office publication "Sailing directions for the Pacific islands" the atoll in 1930 supported 121 inhabitants, who raised chiefly pigs, chickens, and coconuts, and caught the abundant fish. Eniwetok Atoll was a large Japanese base early in the war and it was captured by American forces in 1944 in a costly landing operation. It was then made into a U. S. naval base and during this period an excellent echo-sounding survey was made by personnel of the U. S. S. *Bowditch* (AGS 4).

The rainfall is about 60 inches annually with occasional spring droughts. The mean tide range is 2.8 feet, the spring tide range 4.8 feet. A local magnetic disturbance of about 1° noted in the vicinity of the atoll may be related to basement rocks.

REEFS

Detailed traverses were made across the reefs of Eniwetok in 13 localities (fig. 37) as described in a later section. Both Tracey and Ladd made flights completely around the atoll to get an overall view. Many similarities to the reefs of Bikini Atoll were apparent on the ground and from the air but there were also some rather striking differences and these are stressed in the brief account that follows.

The windward reefs of Eniwetok Atoll are narrower than those of Bikini Atoll and zonation does not appear

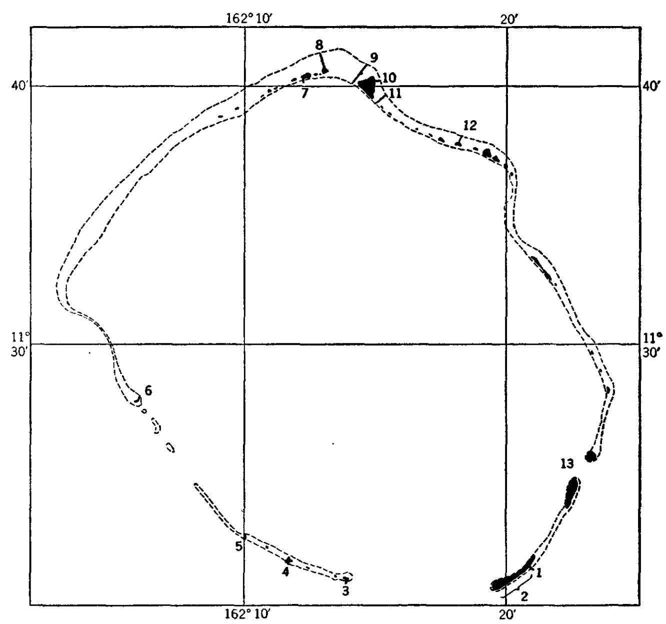

FIGURE 37.—Location of measured reef traverses, Eniwetok Atoll.

NOTE.—In 1944 the Board on Geographical Names published Decision List No. 4414 dealing with place names in the Caroline, Marshall, and Mariana Islands (except Guam). Most of the island and pass names in the northern Marshalls that were approved are the same as those appearing on the charts issued by the Hydrographic Office. In the case of Eniwetok Atoll, however, there are numerous discrepancies. Of the 34 names on the Hydrographic chart 13 were approved, 5 were ignored and the names given for the remaining 16 differ from those of the chart. Some of the differences are minor, such as Rujiyoru for Rujoru I., others are major, such as Lidilbut for Teiteiripucchi I.; the island called Japtan I. on the chart is labeled Muti by the Board and the island called Aniyaanii I. on the chart is called Japtan. Unfortunately the HO Chart (No. 6033) and the Board's list (No. 4414) were both issued during the month of August 1944. No names were changed in a second edition of the chart issued in March 1946 but it is understood that when a new chart is published it will follow the Board's decisions. To avoid as much confusion as possible the authors of the present report have accepted the Board's decisions and have used approved names placing the more widely used names of the charts in parenthesis.

to be so well developed. The reef margins resemble those of Bikini in general form and outline but in most places lack the pink and purple coloration so conspicuous at Bikini.

During a wartime visit to Eniwetok Atoll, Stearns noted (1945a) that the reef off Eniwetok Island appeared to be decadent, a condition also noted by Tracey when he visited the area in 1946. Tracey (Ladd and Tracey, 1949, p. 300) believed that the reef organisms had been largely killed off as a result of the bombardment of the reef in the battle of the Marshalls and the release of fuel oil from ships damaged during the invasion, etc. He, however, noted signs of new growth. When Ladd visited the atoll in 1950 and 1952 he found that the drab appearance of the reef off Eniwetok Island and others along the windward coast, including Engebi which was the scene of heavy bombardment, persisted. Parts of the reef margin showed potholes and irregular depressions partly filled with sand and worn coral boulders. Only off Japtan (Aniyaanii) island did the buttresses of the *Lithothamnion* ridge of the windward reef show a deep pink coloration. Yet on this same windward coast the reefs between islands (Eniwetok traverses 9 and 11) were flourishing. To leeward, reefs in the vicinity of Rigili island supported a marginal growth of corals and algae comparable to that seen on the leeward reefs of Bikini Atoll.

The grooves bordering the windward reef between Parry and Engebi Islands were observed many times from the air at levels of 500 to 700 feet. As at Bikini, many of them bifurcate, in some places downslope toward the sea, in others upslope toward the reef. Many are narrow near the reef becoming broader to seaward. The flat-topped ridges that separate the grooves are 6 to 8 times as wide as the grooves. Many of the broader ridges show one or more small circular to elongate-oval pockets near their centers. On other ridges there are larger square-ended depressions with the longer axis paralleling the axis of the ridge. To seaward as the water gradually deepens, the sharp boundaries between ridges and grooves become less distinct and the ridges merge into a mottled pattern of dark subcircular masses that appear to be narrower than the sharply defined ridges. In the border zone the circular masses are arranged in lines along the seaward projections of the ridges. The occurrence of potholes and worn coral heads in the reef surface near its seaward edge indicates clearly that some erosion of the reefs is taking place but it is difficult to explain the features mentioned above in terms of erosion under existing conditions.

The windward reefs of Eniwetok are characterized by an extensive development of rock bars or groins (pl. 30, fig. 1). The typical groin consists, as described in traverse 12, of an outer truncated platform of lithified boulder conglomerate, cut to a rough plane averaging about 3 inches above low water. This presumably rests upon the algal limestone of the reef flat. The inner part of the structure is less eroded and dissolved, and many of the boulders cemented to the platform stand up above the general level. Farther shoreward the boulders are packed closer and higher, and at least the top layer is loose and uncemented. The size of the boulders decreases shoreward to cobble and pebble size, and the shoreward 500 feet is a gravel bar with much sand on the inner edge. Where the groins are separated from the shore by channels, currents through the channels may limit shoreward growth but in many cases the groins are connected with the islands. They apparently are best developed on the northeast (windward) side of the atoll, and attain their greatest size and number at convex bends in the reef.

As noted from the air, the islands and the sandbars between them lie on the inner half of the reef, nearer the lagoon than the belt of groins. The sand bars are almost perfect crescents with their horns pointing toward the lagoon. Many appear to have patches of reef in the shallow waters between the horns, the larger bars bear vegetation.

The reef from Grinem island to Rigili island on the southwest side of the atoll is about 7 miles long. Of this, about 4 miles nearest Rigili appear to be submerged from one to 4 fathoms even at low tide. Parts of the submerged strip are navigable by small ships, but currents, due both to tides and to cross-lagoon winds, are strong and treacherous.

The reef ranges from about 1,400 to 2,000 feet in width. It is covered by parallel or subparallel ridges or trains of coral, aligned nearly at right angles to the reef and parallel to the current flow. The coral ridges on a part of the reef may be seen in the aerial photograph shown in plate 30, fig. 2. They are dark patches on the light background of the sandy reef floor. Individual patches of coral range from a few feet to 1,500 feet in length, and most appear to be 500 to 1,000 feet long. They range in width from a few feet to 200 feet, and most of them are 50 to 100 feet wide. They are separated by barren, sandy areas 40 to 200 feet wide. The length of reef was examined from the air at an altitude of 500 feet, and the writers gained the impression that the reef floor was covered by 10 to 20 feet of water over most of the submerged part, and that the coral ridges rose 5 to 10 feet off the floor. In a few places the tops of the ridges and the reef floor appeared to be nearly awash.

The seaward margin of the submerged reef dips steeply. Most of the submerged rim is covered by dark coral growth. In some places the coral growth along the edge of the reef and the coral ridges normal to the reef merge to form a substantial reef margin of coral. Near the southeastern part of the drowned area the reef margin shoals and grades to a normal *Lithothamnion* margin 3 miles northwest of Grinem island. As the reef margin shoals, light-colored *Lithothamnion* begins to dominate the dark coral.

The impression gained both by flying over the reef, and by studying aerial photographs, is that the submerged reef shows a progressively greater degree of development from northeast to southwest as it shoals and merges imperceptibly with the surface reef near Grinem island.

ISLANDS

BEACHES

COMPOSITION

Thirty samples were collected from the beaches of 10 islands of Eniwetok Atoll by various land parties. These samples as well as field inspections indicate that the lagoon beaches at Eniwetok are generally somewhat finer-grained than lagoon beaches at Bikini Atoll. Half of the samples contain more than 60 percent fine debris. Correspondingly, the Eniwetok Lagoon beach samples contain fewer Foraminifera.

RIPPLE MARKS

Large ripple marks were observed on the lagoon beaches of Eniwetok as they were on those of the other atolls visited but such marks were never found on the seaward beaches, even though both types of beaches were composed of sediment of about the same grain-size. Waves striking the lagoon beaches usually range between 1 and 4 feet in height, whereas those on the seaward beaches are only a few inches high except during storms. Thus, the development of the large ripple marks appears to be related to wave height. A special study was made by C. C. Bates of ripple marks near the north end of Eniwetok Island.

RIPPLE MARKS ALONG LAGOON BEACH, ENIWETOK ISLAND

By Charles C. Bates

Wave-formed ripple marks occur along practically all lagoon beaches on the eastern, upwind side of Bikini, Eniwetok, and Rongelap Atolls. Ripple marks of this type were studied in detail at the Officer's Club landing on Eniwetok Island between high and low tide on June 7, 1946. The field investigation was conducted by making 5 surveys during a 7-hour period. The survey technique consisted of noting the location of each crest and trough according to an anchored, graduated tape, and of determining the trough depths with a ruler. Underwater measurements were possible by use of face masks. In addition, the beach profile was measured, (pl. 69, profile 19), and 16 sand samples were collected in a line from the zone above the storm tide level out to that portion of lagoon bottom too deep to exhibit ripple marks. Mechanical analyses of these samples were subsequently made by the Department of Geology, University of Southern California.

The ripple marks were present during a period of low waves on a beach slope of about 1 in 10. Heights of the waves at time of breaking were 6 to 12 inches, and the period averaged 4½ seconds, although the range was from 3 to 7 seconds. The ripple mark closest to shore began as a trough formed by the back-rush at a point 5 to 14 feet lagoonward from the line of mean water level. Beyond this trough, well-defined ripple marks ran parallel to shore for hundreds of yards in either direction. However, the system extended only into water 3 to 5 feet deep, depending upon the stage of the tide; beyond those depths, the bottom consisted of slight, irregular sandy hummocks 1 or 2 inches high and was littered with fragments of coral and shell. As far as could be determined, the lowering of water level caused by tidal fluctuations did not affect ripple marks in the deeper water; inshore, however, the trough closest to shore migrated down the beach a distance of 18 feet during the 7-hour period and 7 ripple marks were destroyed in the process. During the measurements, the ripple marks tended to become disturbed and ill-defined; they did not markedly re-form between observations with the exception of several ripple marks close to shore.

Table 21 presents the various characteristics of all ripple marks existing along the measured profile at the survey's beginning. It will be noted that the wave heights ranged from 0.10 to 0.44 feet, wavelengths from 0.75 to 4.1 feet, and ripple index from 3 to 17. Although wave ripple marks are supposedly symmetrical, the ratio between wavelengths on the lagoon and shore side of the crests ranged from 0.33 to 3, with the steeper face occurring almost 3 times as frequently on the lagoonward as on the shoreward side. With the exception of wave length, there was no clear-cut progression of ripple-mark characteristics along the profile; the wavelength, however, reached its greatest value in the two ripple marks closest to shore, whereas lengths greater than 2 feet did not occur in water much deeper than 2 feet.

The sand grains derived from coral, *Halimeda*, and shell fragments, show a clearly marked gradation in size along the profile. Figure 38 illustrates this gradation; for example, it will be noted that samples taken above the zone of existing uprush exhibit the smallest grain sizes of the entire profile (medians of 0.25 to 0.52 mm). Grain sizes increase in the swash zone (lagoonward) and maximum coarseness is reached in ripple troughs near shore (median diameter of 2.70 mm). In

TABLE 21.—*Ripple-mark characteristics, as determined for each ripple crest*

Ratios: L, length; H, height; Ls, length (shore side); Ll, length (lagoon side)

[Eniwetok Island, 1030 local time, June 7, 1946]

Distance from waterline (feet)	Mean depth of water (feet)	Waves height (feet)	Wave length (feet)			Ripple index L/H	Ls/Ll
			Total	Shore side	Lagoon side		
5.0		0.44	4.1	2.6	1.5	9.5	1.6
7.5		.42	4.2	1.0	3.2	10	.3
11.5	1	.38	1.25	.7	.55	3.0	1.3
13.6		.20	2.4	1.8	.6	11.0	3
14.5		.17	1.6	.4	1.2	9.5	.3
16.8		.33	1.4	.9	.5	4.0	1.8
17.9		.20	1.7	.7	1.0	8.5	.7
20.2	2	.30	2.5	1.3	1.2	8	1.1
23.0		.24	2.5	1.7	.8	10	2.0
24.4		.25	1.05	.7	.35	4	2.0
25.4		.25	1.1	.6	.5	5	1.2
26.5		.25	1.5	.6	.9	6	.7
38.1		.25	1.2	.6	.6	5	1.0
29.9	3	.30	1.9	1.1	.8	6	1.3
32.0		.35	1.7	1.1	.6	5	1.8
32.5		.25	1.4	1.0	.4	5.5	2.5
34.9		.17	1.6	1.0	.6	10	1.7
35.8		.17	.75	.35	.4	4.5	.9
36.9		.25	1.4	.66	.7	5.5	.9
38.2		.35	1.0	.5	.5	3	1.0
39.4		.40	1.2	.6	.55	3	1.1
40.7	4	.42	1.4	.8	.6	3.5	1.3
41.9		.33	.9	.6	.3	3	2.0
43.1		.10	1.7	1.0	.7	17	1.5
44.4		.14	1.1	.6	.5	8	1.2
Average		0.28	1.7	0.9	0.8	6.7	1.4

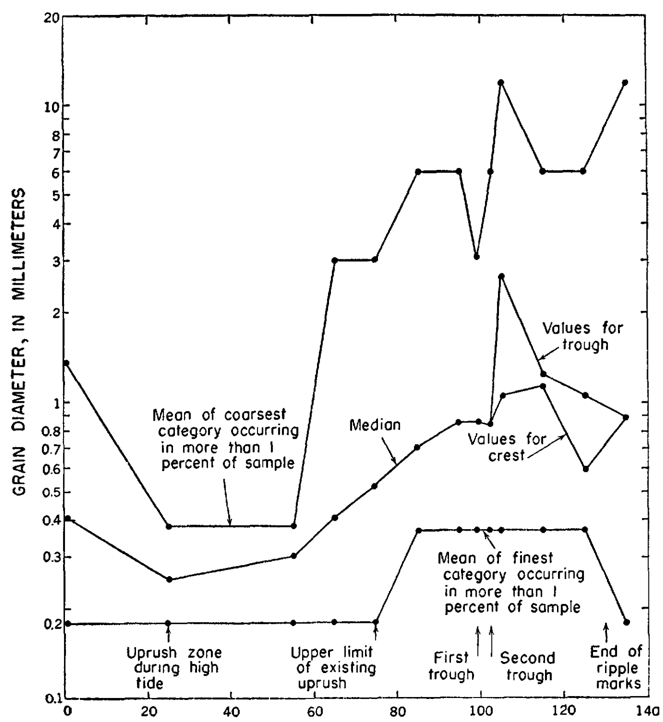

FIGURE 38.—Distribution of grain sizes for sand samples taken at 1700 (5 p. m.) June 7, 1946, on Eniwetok Island.

deeper water just before the ripple marks disappear, the median for the trough is 1.14 mm and 0.58 mm for the crest. Material from crests exhibit marked sorting with a mode of about 0.75 mm, while material gathered from troughs proves to be poorly sorted with a mode of about 1.0 mm (see fig. 39). The greater coarseness of sand from the ripple troughs is illustrated by underwater photographs (pl. 32, fig. 2).

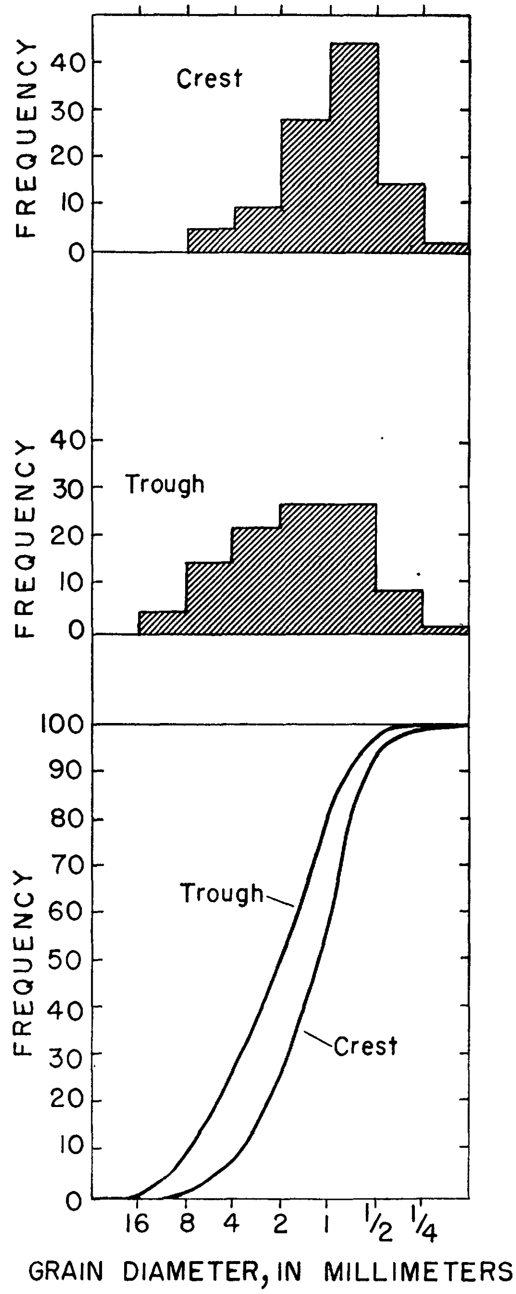

FIGURE 39.—Histograms and cumulative curves for mean of three samples from crests and troughs of ripple marks.

To summarize, the data from Eniwetok indicate that the ripple marks frequently observed along lagoon beaches of the Marshall Islands are relatively permanent in water between 3 and 5 feet deep during spells of low waves, although ripple marks existing between high and low-water mark are destroyed whenever the tide goes out. The re-formation of these ripple marks appears to be quite rapid when the water level rises again. Because of the sensitive hydrodynamical process which forms ripple marks, the crests are composed of well-sorted material, while troughs are composed of poorly sorted and slightly coarser sands. Grain size progresses from fine to coarse when proceeding lagoonward with a slight decrease in average grain size occurring where ripple marks cease because the water is too deep to allow pronounced wave action on the bottom.

SLOPES

Profiles across the beaches of 7 islands of Eniwetok Atoll were measured by C. C. Bates incidental to other investigations. The method was the same as that used at Bikini. Because the stay at Eniwetok was short, only one profile was repeated to determine cyclic changes. One profile across the lagoon beach and one across the seaward beach were measured for 4 islands: Runit, Chinimi, Bogen (Jieroru), and Buganegar (Mui). Seven profiles radiate in all directions around Muti Island, and several cross both sides of Parry and Eniwetok Islands, as shown by plate 69.

It is noteworthy that most of the profiles across the lagoon beaches show the presence of sand with very little gravel-size debris. On the other hand, nearly all of those crossing the seaward beaches consist exclusively of gravel. This may be the result of rare large storm waves which can strike only the seaward beaches. The profiles that cross gravel are much steeper than those on sand. The latter are similar in steepness to those at Bikini, all of which were intentionally selected to cross sand (pl. 66). Many of the profiles of sandy lagoon beaches cross zones of large sand ripples just below the water surface. All of the usual minor sedimentary features seen at Bikini were observed, including beach cusps on sandy lagoon beaches. As at Bikini the lower parts of most of the profiles consist of rock. Some of the rocky part is gently sloping; this part is beach rock—cemented sand or gravel of a former beach. Usually, it contains solution basins and pot-holes formed after cementation and exposure. Rock in the flat level lower part of some of the seaward profiles is reef rock of different origin.

LAGOON

PHYSIOGRAPHY

A detailed contour chart of Eniwetok Lagoon was drawn on the basis of soundings made by the Navy in 1944. About 180,000 soundings from recording echo sounder tapes had been plotted by Hydrographic Office personnel on large-scale boat sheets of parts of the lagoon. These charts were contoured at 4-fathom (24-foot) intervals and the resulting sections were reduced to a common scale and joined together (Emery 1948). The final chart (chart 5) shows markedly irregular topography due largely to abundance of coral knolls. Approximately 12,000 additional soundings were taken during Operation Crossroads but these were not plotted because this number is insignificant compared to the number of earlier ones.

TERRACE

The contours show the presence of a wide terrace between the 8- and the 12-fathom contours. As the most frequent sounding on its surface is 10 fathoms, it is usually referred to as the 10-fathom terrace. It extends from Chinieero island north and west to Bogallua island beyond which, after a gap of a few miles, it continues southward to Rigili island. The terrace is also present in a very small area near Eniwetok Island. Thus, it borders most of the east, north, and west margins of the lagoon. The greatest widths of about 2 miles occur within reef projections, or points where the reef bends seaward markedly, as for example near Aranit island (Aomon), Engebi Island, and between Bogallua and Rigili islands. Near Aranit island the terrace contains a number of shallow irregular depressions. None of these low areas extend more than 2 fathoms below the terrace surface. An entirely different sort of depression, however, occurs in the wide terrace surface between Bogallua and Rigili islands. This depression is 2½ miles long but less than ½ mile wide and its trend is roughly parallel with the terrace edge. The depth is fairly great, as its bottom is 8 fathoms below the terrace surface. The slope from the reef and islands to the 10-fathom terrace is gentle, averaging only 2.5°. An even gentler slope separates the terrace from the deep basin of the main lagoon. This slope averages 1.25° between the 12- and 24-fathom contours. Along the south side of the lagoon, where the terrace is absent, the slopes extend directly from the reef to the lagoon basin and are intermediate in steepness.

BASIN

The shape of the main basin, if its margin be taken at about 20 fathoms, is a nearly perfect ellipse, in contrast to the subrectangular outline of the outer reef edge. The long axis of the lagoon trends northwest, its maximum depth is 35 fathoms and there is a fairly large area deeper than 32 fathoms. More than 90 percent of this deepest area is in the northwestern half of the lagoon, the area farthest from the main passes through the reef. If the numerous superimposed coral mounds were ignored the bottom contours would show a smooth slope of only 0°06′ from a depth of 24 fathoms near Eniwetok Island northwestward to the deepest point of the lagoon. Indeed, the bottom appears to be quite flat between the coral mounds, so that where the mounds are spaced some distance apart, as in the northern half of the lagoon, contours are widely spaced. There appears to be no indication whatever of submerged terraces or cliffs on the lagoon floor below the slope from the 10-fathom terrace. Numerous depressions are scattered about the basin floor but none are deeper than 1 or 2 fathoms and all probably are merely depositional irregularities.

CORAL KNOLLS

Within Eniwetok Lagoon a large number of coral knolls can be shown by the contours. These rise above the basin, the slope, and the terrace. Some of the coral knolls are large enough so that many soundings were taken on them and their shapes are indicated by several contours. Other coral knolls are so steep and narrow that they were indicated by only one or two soundings. Contours are impractical for such knolls, so they are shown on chart 5 by rough hachures. Still others, probably the majority, are so small that they were shown as only a single or double echo on the sounding tape and so low that they rise only 1 or 2 fathoms above the general bottom level. Most such knolls were completely ignored and not shown on the sounding sheets. There is some suggestion on Chart 5 that the coral knolls which can be shown by contours or hachures belong to 2 distinct size categories: nearly all the large coral knolls have a diameter in excess of 1 mile whereas nearly all the rest are smaller than ⅛ mile, and intermediate sizes are not common.

Many of the larger knolls rise near enough to the sea surface so that they can be clearly distinguished from shipboard, but only one breaks water at low tide. The depth distribution of the tops of 2,293 coral knolls which were measured is presented in figure 40. The depth of

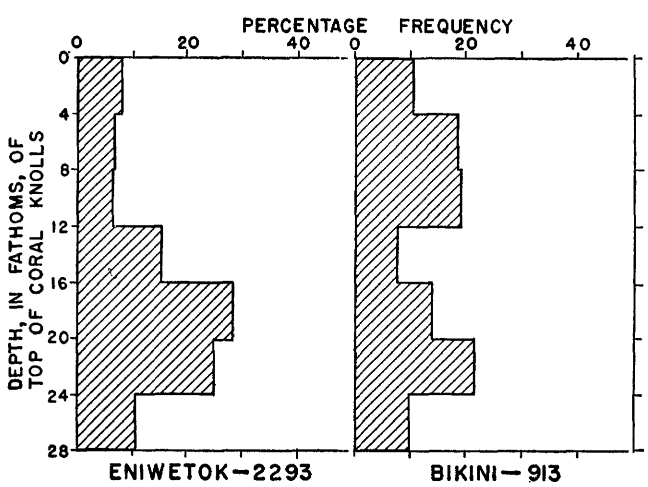

FIGURE 40.—Depth distribution of tops of coral knolls of Eniwetok and Bikini Lagoons.

greatest frequency is 16 to 20 fathoms. The more detailed depth data given by figure 41 shows that some coral knolls reach to near the surface regardless of the depth from which they rise. Only a small percentage of the coral knolls in each zone rise to near the surface, between 0 and 4 fathoms. Only a few more rise to 4–8 fathoms. It is noteworthy that the histograms of top

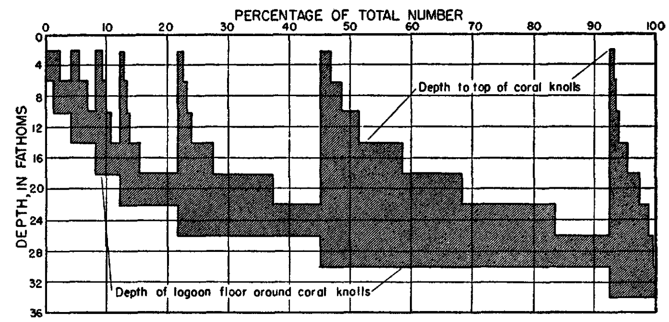

FIGURE 41.—Percentage of depth frequency of tops and bases of 2,293 coral knolls in Eniwetok Lagoon.

depths for each bottom depth zone are of similar shapes, more or less concave upward, or logarithmic. The histograms also show no indication whatever of a greater depth frequency at 10 fathoms, the depth of the lagoon terrace. Examination of Chart 5 reveals no preferred side of the lagoon for either large or small coral knolls. In fact, the 20 coral knolls having diameters of more than a mile show a strikingly even spacing.

REEF OPENINGS AND DEEP CHANNEL

The reef at Eniwetok Atoll is pierced by three openings, or passes. The widest of these faces southward and has a sill lying mostly between 8 and 12 fathoms, a depth corresponding to that of the lagoon terrace. On the west side of the atoll is another wide pass but of much shallower depth, so that it appears to be an area of slightly submerged reef. On the southeastern side of the atoll is a narrow pass between Parry Islands and Muti (Japtan). It is through this pass that a deep channel from the lagoon extends to the ocean. A fathogram across the channel is shown by plate 31, fig. 1. The maximum depth of the channel in the pass is 32 fathoms, roughly corresponding to the maximum depth of the lagoon, 35 fathoms. Toward the lagoon the channel becomes progressively shallower so that its axis intersects the bottom slope profile about 3 miles lagoonward of the reef. Beyond that point a number of depressions below 28 fathoms suggest a continuation in a loop convex to the south. That part of the channel may have become largely filled with sediment. It is of interest that the shallowest depth of the channel, 26 fathoms, coincides with the base of the slope below the 10-fathom terrace. About 1½ miles from the point where it fades out, the channel splits, one branch passing on either side of Bogen (Jieroru) island, as though 2 stream tributaries had joined and flowed thence outward through the reef opening. The triangular shape of the submerged platform around Bogen island north of the deep channel is characteristic of islands just inside the narrow passes of other atolls.

DISTRIBUTION OF DEPTHS

The percentage frequency of depth zones throughout the atoll was determined as for Bikini Atoll. Both the frequency histogram and the cumulative curve (figure 19) show that depths between 24 and 32 fathoms are most common in the lagoon. The mean depth is 26.2 fathoms. The small bulge of the histogram between 8 and 12 fathoms is due to the 10-fathom terrace. It is noteworthy that the islands, above high-tide level, occupy only 0.6 percent of the atoll's area of 392 square statute miles. The reef area, essentially intertidal, is much larger—7.5 percent, an area not exceeded by any of the 4-fathom-interval zones shallower than 20 fathoms. The total volume at low tide was computed at 5.5^{10} cubic yards, of which 60 percent lies below the surface of the 10-fathom terrace, and only 11 percent below the 26-fathom sill of the deep channel through the reef.

SMOOTHNESS COEFFICIENT

Smoothness coefficients were estimated from the fathograms that were made in Eniwetok Lagoon in the same manner that was followed at Bikini Atoll (page 150). Although Eniwetok Lagoon is much larger, fewer fathograms were made, especially in shallow water near the shore. Probably the latter factor is the one chiefly responsible for the lack of high smoothness values around the periphery (fig. 42) unlike at Bikini. The low smoothness values that occur nearest shore at Eniwetok, then, correspond to those a few miles from shore at Bikini. However, a new characteristic is present at Eniwetok—the middle area here is fairly flat. Evidently, this flatness indicates a decreased abundance of small coral knolls at great depth. The absence of such a zone at Bikini may be related to the lesser maximum depths there. The average smoothness coefficient at Eniwetok Lagoon is 4.3, a slightly lower value than that found at Bikini.

SEDIMENTS

GENERAL

Bottom samples and photographs were collected during about 10 days of the stay at Eniwetok Atoll. A total of 97 underwater photographs were taken—about half of them in shallow water near Eniwetok island—from aboard a whaleboat. The remaining photographs were taken in deep water from the U. S. S. *Gilliss* (AGS *13*). Owing to the demands of the survey of Bikini Atoll the *Gilliss* was unable to carry out sampling operations and most of the geological operations, therefore, were transferred to the U. S. S. *Blish* (AGS *10*). Most of the 365 bottom samples from Eniwetok were obtained while the *Blish* was engaged in other work for which prior commitments had been made. Nearly all of the samples were taken by an underway sampler, only 10 or 15 being recovered in the larger capacity snapper or on the anchor. Only one dredging was obtained. About 28 sand samples from beaches were contributed by various land parties.

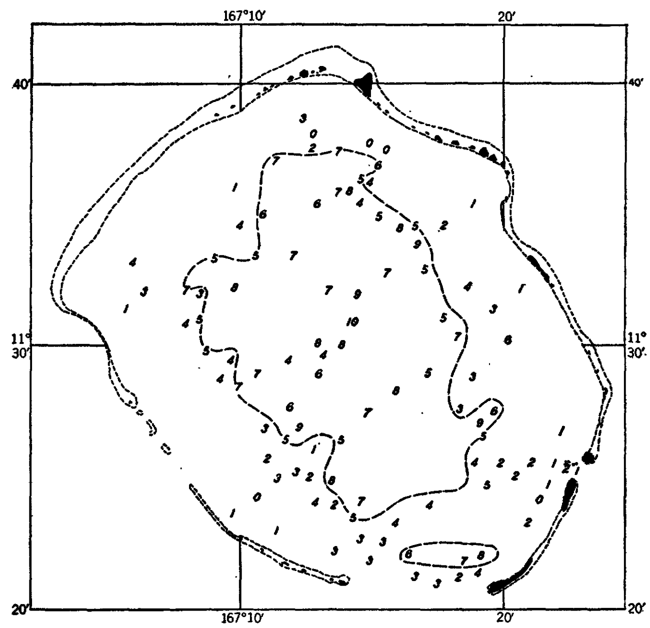

FIGURE 42.—Map showing percentage of flat area (smoothness coefficient) in Eniwetok lagoon. The smoothness coefficient shows the percentage of flat floor covered by a fathogram made in a 1½- to 2½-mile interval. The percentages are expressed in units between 1 and 10, each unit representing 10 percent. Dashed lines in lagoon separate the more level areas from those that are rougher.

PERCENTAGE OF COMPONENTS

As at Bikini Lagoon the sediments were found to contain the following chief components: *Halimeda*, coral, Foraminifera, and shells. Grains finer than ¼ millimeter in diameter were not classified as to source organism but were lumped together as fine debris. The percentage weight of each of these components plus another, Miscellaneous, was estimated for each sediment sample. Percentage weights for Foraminifera, *Halimeda*, fine debris, and shells were plotted at the mapped position of each sample. Coral was not plotted because as at Bikini the samples were not considered representative. Miscellaneous, composed mostly of *Lithothamnion*, echinoid spines, sponge spicules, and crab parts, was also omitted because it rarely amounted

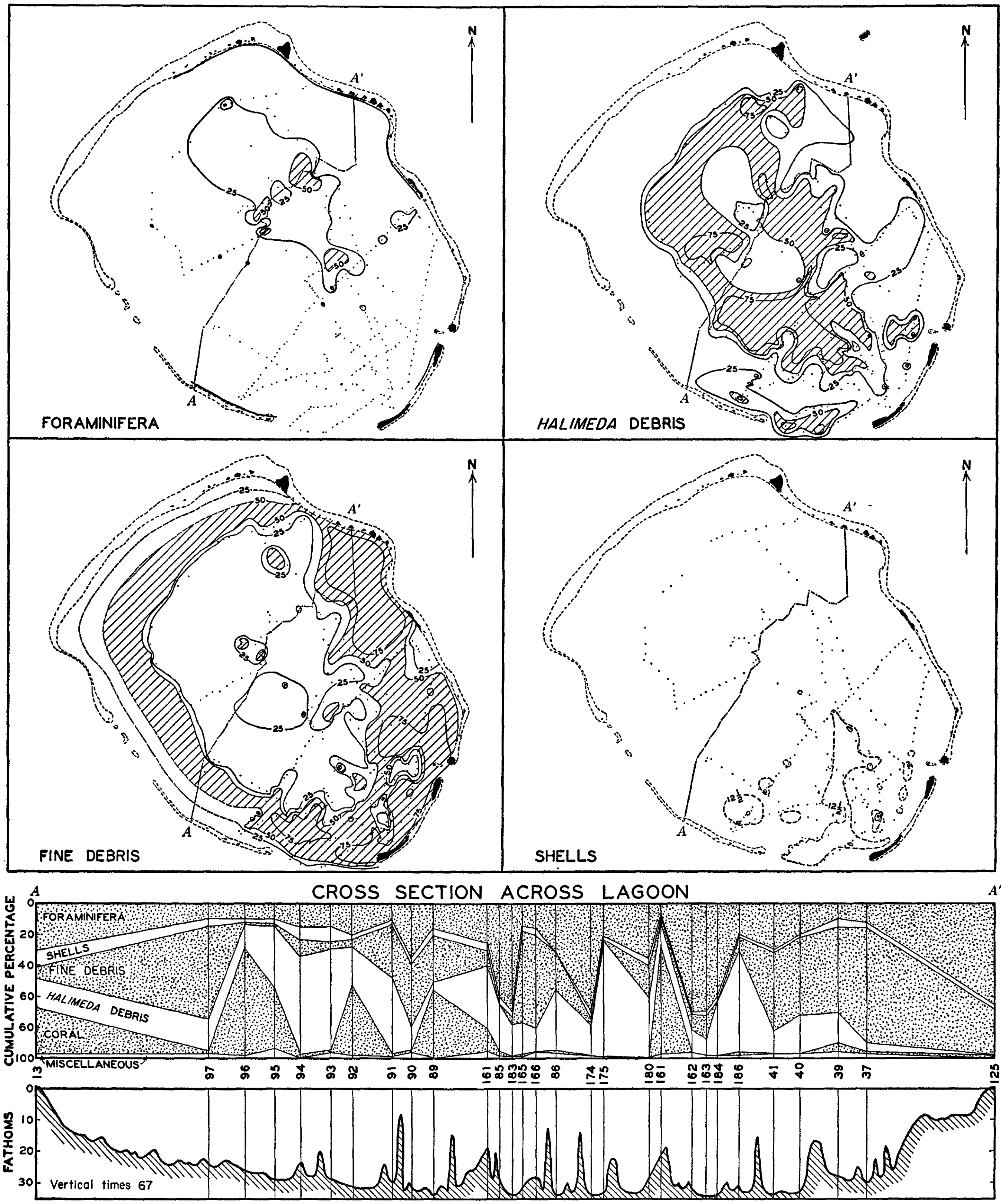

Figure 43.—Maps showing the percentage abundance of the important constituents in the sediments of Eniwetok Lagoon. Lines of equal abundance are drawn through the 25-, 50-, and 75-percent values. Reef boundaries are shown by dashed line. Dots mark sample localities. Locality numbers of the samples used in constructing the cross section are shown above the profile.

to more than a few percent. The resulting 4 percentage charts were contoured with the 25-, 50-, and 75-percent lines as shown by figure 43. Areas in which any component amounts to more than 50 percent in the samples are cross-hatched to simplify interpretation of the distribution pattern.

Foraminifera are most abundant in 2 different environments. Most of the beach sand samples contain more than 25 percent of foraminiferal tests, and some of them have as much as 65 percent. The Foraminifera are abundant also in samples from the middle of the lagoon, generally from deeper than 33 fathoms. The assemblages from the two environments are entirely different, those from the beaches being mostly *Calcarina* and *Marginopora,* while those from the deep water are mostly much smaller forms.

Halimeda debris is most abundant in a ringlike pattern surrounding the deep water area of Foraminifera. It ranges up to about 80 percent in depths of 27 to 32 fathoms, but is unimportant in samples shallower than about 20 fathoms. Surrounding the ring of abundant *Halimeda* is another ring of fine debris which is generally abundant to within a few hundred feet of the shore. Many of the shore samples also consist dominantly of this material.

Many of the sediment samples contain a number of black grains that contrast with the more abundant white or cream colored grains. The black grains are most abundant in samples from between 20 and 32 fathoms. Between 24 and 28 fathoms, 75 percent of the samples contain black grains and in 30 percent of them the black grains amount to between 2 and 20 percent of the whole sample—giving rise to a salt and pepper texture. Microscopic examination revealed that the dark grains had the same original source as the lighter ones, i. e., coral shell, *Halimeda,* foraminiferal fragments. As in the case of the Bikini sediments, the blackening is ascribed to a boring alga.

OVER-ALL COMPOSITION

In order to present an overall picture of the composition of Eniwetok Lagoon floor each of the 365 bottom samples was designated as chiefly coral, Foraminifera, *Halimeda* debris, or fine debris. Additional information was provided by the 97 underwater photographs and by the 26 bottom notations found on the Navy field survey sheets of the atoll. The topography of the lagoon floor supplemented these spot indications because the coral knolls shown by the contours are known to consist chiefly of coral.

The beach sands, most of which consist chiefly of tests of Foraminifera, form a narrow belt around the lagoon. Fine debris is dominant in a belt 2 to 5 miles wide extending inward from the foraminiferal sand, or from the shore itself where foraminiferal sand is absent. Sources are foraminiferal tests, coral, *Halimeda* segments, and shell broken to bits on the beach or in shallow water and then transported lagoonward. Relatively little of the sand reaches as far as 4 miles from the reef. Altogether the sand covers 52 percent of the lagoon floor. Beyond the area where the waves and currents are able to break up and transport sand, *Halimeda* live most abundantly and contribute their remains to the bottom. The *Halimeda* debris forms an almost complete ring inside the sand belt ranging in width up to about 6 miles. It is the second most abundant bottom material, comprising about 26 percent of the lagoon area. Within the belt of *Halimeda* debris, and occupying the deepest part of the lagoon is a large circular patch consisting mostly of abundant tests of Foraminifera. The species are different from those found on the shore and reef flat. They owe their abundance to the water depth, more than 32 fathoms, which absorbs so much of the sunlight that the *Halimeda* cannot thrive and mask the Foraminifera. The deep and shallow areas of Foraminifera together cover 9 percent of the lagoon; however, owing to scarcity of samples in the deep north half of the lagoon this figure may be in error. The last of the main components of the lagoon is coral, which exists chiefly on coral knolls. As a result, coral has a spotty distribution and covers a total of 13 percent of the lagoon area.

The typical character of the lagoon components is shown by the underwater photographs of plate 32. Some of the sandy areas are covered by finely drawn trails, while other areas present a fluffy appearance as though shaped by some burrowing organisms. Areas of *Halimeda* debris have a texture somewhat coarser than the sand areas and they also contain numerous sprigs of algae. Other photographs show coral at depth as well as on shallow coral knolls.

OUTER SLOPES

GENERAL

The topography around Eniwetok Atoll was revealed mostly by 85 radial and 5 partially complete concentric lines of soundings made by U. S. S. *Bowditch* (AGS *4*) in 1944. During Operation Crossroads several additional lines were taken in order to chart the adjoining guyots more completely while other soundings were collected en route to and from the atoll by U. S. S. *Bowditch* again and by U. S. S. *Sylvania* (KA *44*). There was no opportunity to collect detailed soundings near the reef edge as at Bikini Atoll. Altogether, about 6,700 soundings available in the area around Eniwetok were used in drawing the 100-fathom contour interval of chart 6.

The chart shows that from the reef edge down to about 600 fathoms the slopes are similar in outline to the reef edge. Below 800 fathoms the outline of the slopes changes from nearly circular in the shallow depths to roughly rectangular. This change is produced by two guyots which fringe the slopes. One guyot fringes 15 miles of the south side and it extends southward 12 miles from the general slope. Inshore, the guyot depths gradually merge into those of the general slope, but most of its surface is at about 700 fathoms. Another guyot fringes 18 miles of the northwest side of the atoll. It extends northwest for 8 miles and like the other guyot its surface is at about 700 fathoms. On the east and the southwest sides of the atoll between the guyots the slope profiles show no indication whatever of a flattening of the slope.

Twenty-five of the radial lines of soundings were used as control for the profiles shown in figure 44. Each profile has 30 to 45 soundings. It is readily apparent that there are two main kinds of profiles: those which cross an unbroken slope and those which cross a fringing guyot. At shallow depths in the steepest part of the profile, both kinds are identical. Between the reef edge and 250 fathoms the profiles appear to range in steepness between 18° and 49°, averaging 33°. Actually, the slopes are probably somewhat steeper, because slopes measured by more accurate soundings on other atolls were found to be steeper than those indicated by soundings collected by the large ships. The lack of detailed near-reef data also precludes determination of the exact character and extent of a shallow terrace like that around each of the other atolls. Such a terrace is shown by some of the profiles and from the air may be seen extending almost continuously along the windward side. Its presence was noted particularly from Runit island south to Eniwetok Island. At some points it is half a mile wide and looks much like the 8-fathom terrace present around parts of Bikini Atoll.

SEDIMENTS

Only a few samples were collected from the outer slopes of Eniwetok Atoll. Most of these were fairly large, weighing several hundred grams. As shown by figure 45 fine debris is the most abundant constituent at the shallow depths as well as at 500 fathoms. Sample 119 from 500 fathoms contained about 5 percent material of silt size. The sample was grayish, contrasting with the usual cream color of the sediments. At intermediate depth along the single profile sampled, *Halimeda* debris made up the bulk of the material, and it was a major component of all samples, evidently having slumped or been otherwise transported down the slope from its growth zone. As at Bikini Atoll the *Halimeda* debris of the outer slope is different from that of the lagoon. The segments are larger, averaging about 12 millimeters in width, and are folded (pl. 29, fig. 1). Foraminifera are not abundant but they include large forms that are restricted to the outer slopes. Only a few pieces of coral were recovered and most of them were of a small branching type.

GEOLOGY OF RONGELAP ATOLL

Rongelap Atoll is about 70 miles east of Bikini Atoll. Its shape approximates a square 20 miles on a side, with a rectangle of 5 by 9 miles adjoining the northeast corner. About 40 islands surround the lagoon. Most of them are small, but one, Rongelap island, is the longest island (4½ miles) in the Marshall Islands. The total land area of the atoll is 3.2 square miles. Nine entrances penetrate the reef. South Pass, adjoining Rongelap island is 4 miles wide and mostly less than 10 fathoms deep, but at one spot it is about 30 fathoms, making this the deepest entrance to the atoll. Most of the other entrances are relatively narrow and shallow.

According to "Sailing directions for the Pacific Islands" there were 92 inhabitants in 1930, mostly living on Rongelap and Eniaidokku islands. Some of those on Rongelap island were isolated in a leper colony. During the war the Japanese established a meteorological station with a large radio tower on Rongelap island. In 1944 this was destroyed by bombing operations. Only the eastern half of the lagoon had been sounded by the Japanese who set out only a few buoys and beacons for navigational aids.

Ailinginae Atoll is southwest of Rongelap Atoll a distance of 9 miles from the nearest point. It is rectangular in shape with dimensions of 4 by 17 miles. It contains about 22 islands, mostly on the south side. None of them are very large and few support coconut palms. There are two shallow entrances. The deeper, Mogiri Pass, is charted as 6 fathoms deep and is studded by shoals in the lagoon end. No soundings are available for the lagoon except near Mogiri Pass. Because of the small size of the islands and lagoon the atoll is uninhabited.

REEFS

The reefs of Rongelap were examined in a dozen places (fig. 46) and observations are given in the section on detailed reef traverses (p. 190–201). The windward reefs are narrower than those of Bikini, and are similar to those of Eniwetok. A more striking similarity to Eniwetok is the presence of many groins or rock bars on the windward reefs. Most of these extend from the seaward beaches of islands toward the reef edge but some are found on the reefs between islands. The lagoon margin of the eastern or windward reef of Rongelap in several places terminates in a ledge of reef rock that overhangs a sandy lagoon floor lying at a

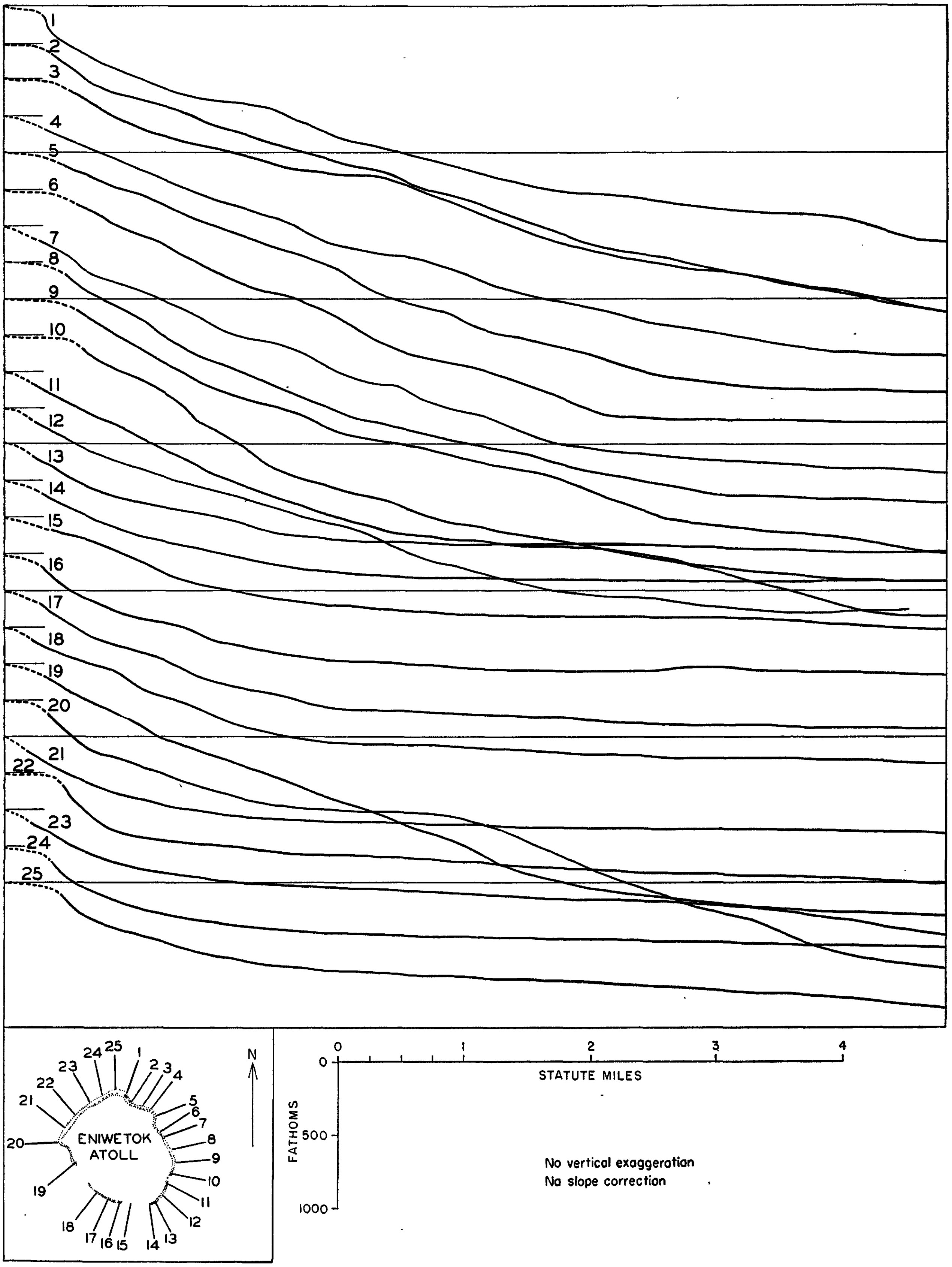

FIGURE 44.—Deep sonic profiles of outer slopes, Eniwetok Atoll.

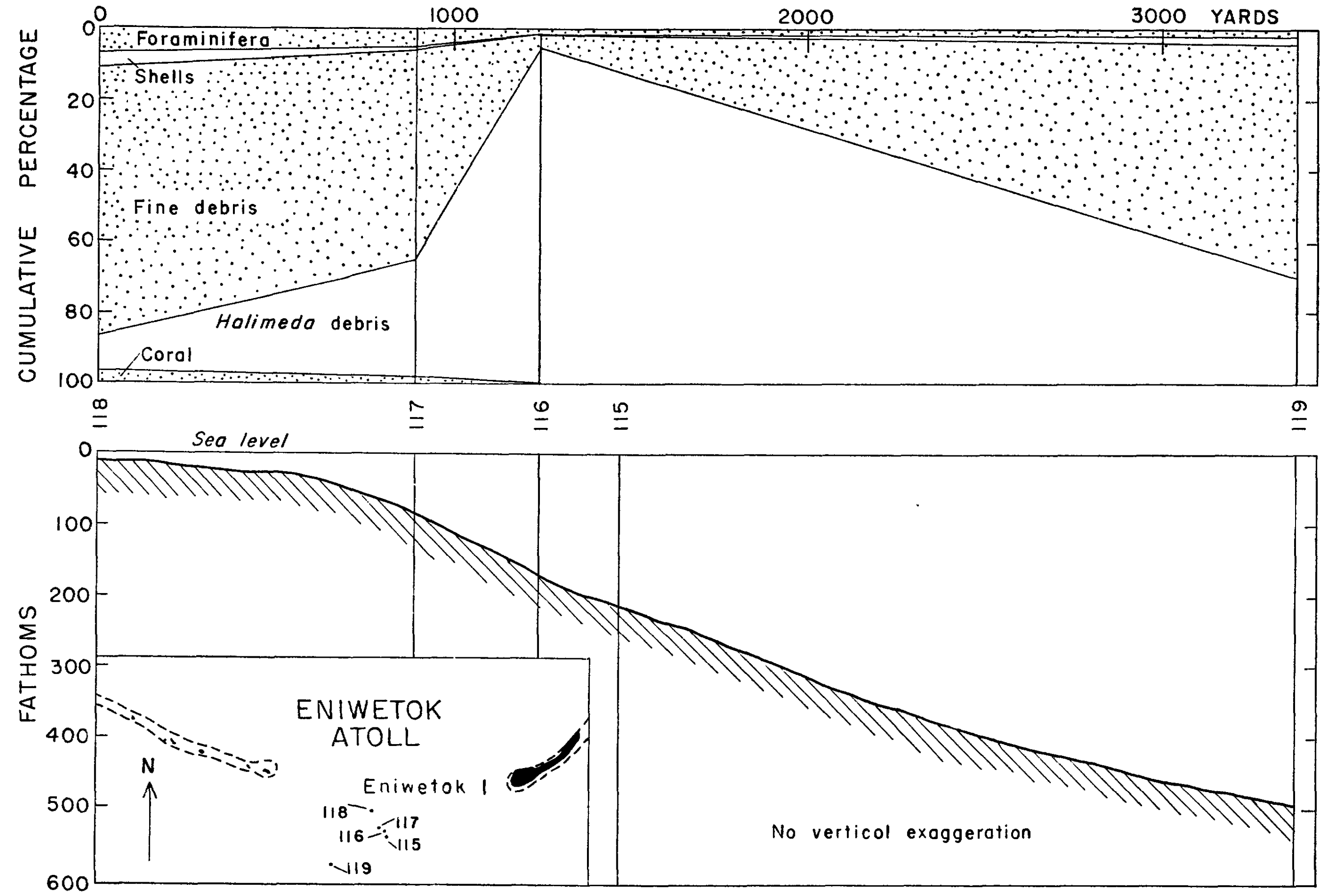

FIGURE 45.—Composition of bottom samples from outer slopes of Eniwetok Atoll. Station numbers on plan in lower left corner are shown above the profile in the lower half of the figure.

depth of 15–25 feet. In such places the reef edge is eroded, and large blocks of reef rock have been dropped to the lagoon floor. Eroded lagoon reefs of this sort were not observed on the other atolls studied.

The reefs of Ailinginae were not studied as no landings were made on the atoll.

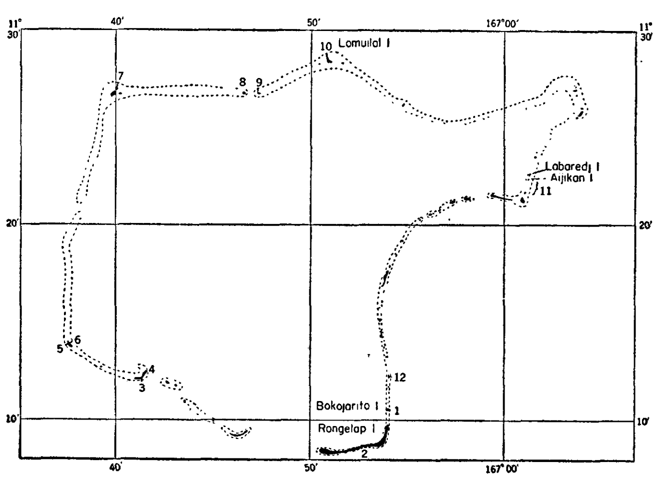

FIGURE 46.—Location of measured reef traverses, Rongelap Atoll.

SAND OF REEF FLAT

As at Bikini and the other atolls, much of the reef flat at Rongelap is covered by a feltlike layer of sand about one-eighth inch thick. This is commonly well-developed as a lining of tide pools. Within many of the pools are holothurians that eat the sand and digest the included organic debris. In order to learn what effect the holothurians have on the sediments, the intestines of several were collected along with samples of the sand mat of three pools, and of loose sand found in the bottom on one tide pool. Mechanical analyses gave an unexpected result—in each instance the sand from within the holothurians was coarser than the sand mat of the same pool (table 22).

Microscopic examination of the sand mat, however, revealed an abundance of small articulated fibers of a calcareous red alga, *Jania* sp. that forms a feltlike mass capable of binding the sand together. This alga gives the sand a light-green color. Only a few of the fibers were present in sand from the holothurian intestines, indicating that they had been dissolved and digested. Their loss, of course, resulted in the observed increase of median diameter of the remaining sand. The loose sand is even coarser than that from inside the holothurians, because after it is excreted from the animal the sand was subjected to winnowing action from the currents that resulted in further loss of finer grain sizes.

TABLE 22.—*Sand from reef-flat tide-pools*

Sample No.	Source	Median diameter of grains (mm.)	*Jania* sp. (est. percent)	Organic carbon (percent)
412	Holothurian	1.35	0.1	1.02
413	Loose Sand	2.20	0	.60
414	Sand Mat	.43	2.0	1.36
415	Holothurian	.81	.2	1.24
416	Sand Mat	.39	2.0	1.55
417	Holothurian	.31	.4	1.39
418	Sand Mat	.27	3.0	2.57

Dr. E. Y. Dawson identified infrequent specimens of the green algae, *Valonia* sp. and *Boodlea* sp., in addition to the abundant red alga, *Jania* sp. All of these must serve as food for the holothurians. An estimate of the abundance of *Jania* is presented in table 22. Analysis for organic carbon showed a much higher organic carbon content in the sand mat than in any of the sediment samples from within the lagoon at Bikini that were similarly analyzed. Ingestion of the sand by the holothurians resulted in a decrease in organic carbon content. Had the sand-filled intestines not been extracted before the holothurians had finished digesting their food, the organic carbon loss would have been even greater. The loose sand contained even less organic carbon. The fibers of *Jania* sp. have a thin wall of calcium carbonate which must have been dissolved by digestive juices in order to expose the protoplasm inside. However, no obvious solution effects could be detected on the sediment grains, which are larger and less easily attacked by solution.

During the 1950 expedition, the pH of the stomach and the anal end of the intestine of each of four holothurians from the reef flat off Bikini Island was measured. The results (table 23) show that the digestive juices are acid enough to lower the normal pH of sea water (8.0 to 8.2) to an average of 7.38 at the anus and 6.81 at the stomach. The latter value is certainly low enough to cause solution of calcium carbonate.

TABLE 23.—*The pH of intestinal tract of holothurians*

Specimen	pH	
	Stomach	Near anus
1	6.71	7.16
2	6.88	7.60
3	6.93	7.43
4	6.72	7.34

ISLANDS

On Rongelap Atoll, well-defined boulder ramparts are found on islands associated with the channels on the east side of the atoll between Mellu and Gabelle islands where the reef faces south. On this and other atolls, some of the islands along the eastern side are only 300 or 400 feet from the reef edge, and where the reef is narrow the island beach is commonly formed of boulders or coarse gravel. True boulder ramparts, however, seem generally confined to islands or reefs having a strong southerly component, especially those islands adjacent to channels or passes.

Nineteen beach profiles at Rongelap Atoll were measured by C. C. Bates between June 18 and June 21. As shown by plate 70, these profiles are about equally distributed on the lagoonward and seaward sides of Kabelle, Mellu, Bokujarito, and Rongelap islands. Somewhat steeper slopes are present on the seaward sides of the islands. All of the seaward profiles were made across gravel beaches and, in contrast to profiles measured at Bikini and Eniwetok Atolls, many of the lagoonward profiles were also made across gravel. Beach rock is common on both sides, and a wide stretch of reef rock forms the flat surface beyond seaward beaches.

Profiles at nearly an equal number of points on beaches at Bikini, Eniwetok, and Rongelap Atolls were measured (pls. 66, 69, 70). All profiles from lagoonward beaches and all from seaward beaches were traced in a superimposed position and the median and limiting profiles were drawn (fig. 47). The 50-inch elevation was used as control point because many profiles do not extend all of the way to lowest low water. The limiting profiles show the position of the envelope within which the profiles fall. The lagoonward and the seaward compilations are somewhat similar in general but several points of difference exist. The seaward median profile is somewhat the steeper, because of the inclusion of relatively steep gravel profiles from Eniwetok and Rongelap Atolls. The steepest portion of the seaward median profile is 9.5° as compared to 8.6° for the lagoonward median profile. The upper part of the seaward profiles also show a greater spread—wider limiting profiles—and the lower part is flatter than the lagoonward ones. This flatness is a reflection of the presence of reef rock beyond the loose sand or gravel beach.

LAGOON

PHYSIOGRAPHY

The Japanese, during their occupation of Rongelap Atoll, took more than 4,000 lead-line soundings about one-fourth mile apart in the southeast part of the lagoon. None were taken in the west half or along

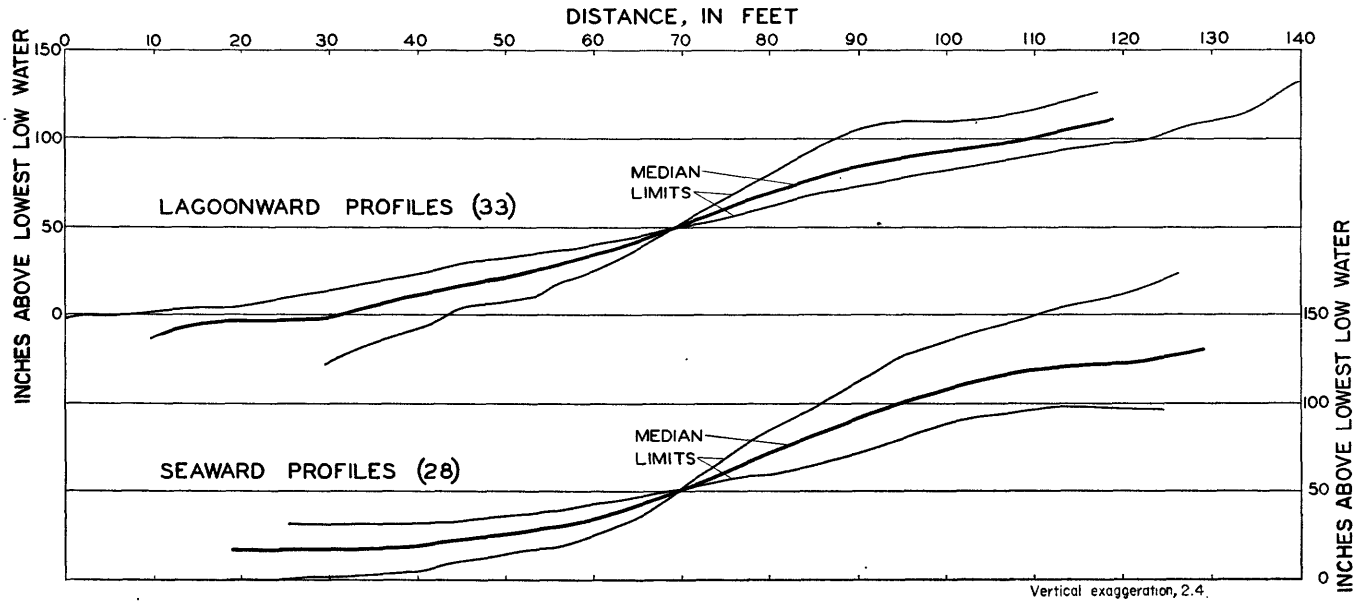

FIGURE 47.—Median and limiting beach profiles at Bikini, Eniwetok and Rongelap Atolls.

the north margin. A strip about 2 miles wide was also wire-dragged from South Pass to Northeast Pass. No further surveys were made either by the Japanese or the Americans until Operation Crossroads. At that time it was found feasible to combine sounding and bottom sampling operations with the biologist's work, and as a result 10,400 additional soundings were obtained by echo-sounder along lines generally 1 to 2 miles apart throughout the entire lagoon. This work was done aboard U. S. S. *Blish* (AGS *10*). Some additional radial sounding lines about 5 miles apart were run into very shallow water along the lagoon margins by Ens. Barney Timmer using a 50-foot sound boat. Because of the greater control yielded by the presence of both Japanese and American soundings in the southeast part of the lagoon, contours could be drawn there in greater detail than elsewhere. It should not be assumed, therefore, that chart 7 is accurate in portraying a flatter bottom and fewer coral knolls in the west and north parts of the lagoon. A further uncertainty comes from the fact that only a few lead-line checks against the echo-sounder were made, so the chief control of depth error had to be made by comparison of our soundings with Japanese soundings. As these agreed well elsewhere, it is believed that no serious error is introduced.

Both in the field and in the drafting laboratory considerable difficulty was found in the plotting of position fixes at Rongelap Atoll. This is due to the poor mapping of the islands on the Japanese base charts. Some improvement of the chart resulted from our survey during which we attempted to locate more accurately some of the islands along the west and north reef. The best positions, as shown in chart 7, are still not very good. The original reef outline also was very badly drawn on the Japanese chart but this was corrected, relative to the islands, by the use of aerial photographs. Rongelap Lagoon is the least well sounded of the four lagoons studied, but there are sufficient data to yield at least a general picture of the character of the sea-floor.

TERRACE

The periphery of the lagoon is not well sounded but neither the Japanese soundings nor about 11 echo-sounder lines that extend into depths less than 5 fathoms show any indication of a 10 fathom lagoon terrace paralleling the reef as at both Bikini and Eniwetok Atolls. The only suggestion of a flattening at that depth is to be found in the numerous soundings on the floor of the widest entrance of the atoll, between Rongelap and Arubaru islands. Because of the same scarcity of sounding the steepness of the slope leading to the basin floor is known at only a few places. The average slope obtained along the shallow echo-sounder lines is 3.0°, about the same as at Bikini and Eniwetok Atolls.

BASIN

The basin of Rongelap Lagoon has the same roughly square shape as the reef outline, with the floor beginning at about 20 fathoms around the entire circumference. Near the center of the lagoon is an irregular area deeper than 32 fathoms. The deepest Japanese sounding, which is in this area, is 35 fathoms, while our deepest one is 206 feet, or 34.3 fathoms. The latter will be considered the maximum depth of Rongelap Lagoon. In contrast to these depths of the main part of the lagoon, the northeastern corner, which projects nearly 10 miles outward, has floor depths of less than 26 fathoms.

CORAL KNOLLS

Most coral knolls of the area are known from Japanese soundings. Others were discovered on the echo-sounding tape, while still additional ones off the sounding track were noted because of their characteristic light-green color. The latter were judged to lie at depths between 2 and 6 fathoms according to the color of water above them. A few more were shown by the aerial photographs. The depth distribution of coral knolls at Rongelap Atoll appears from chart 7 to be shallower than those at Eniwetok and Bikini; but this, of course, is merely a reflection of the relative preponderance at Rongelap of shallow coral knolls identified by color of water either by the Japanese or by ourselves. Had sonic soundings been more abundant, a higher percentage of deep coral knolls would have been discovered. This accentuates the need for adequate sounding density for proper interpretations of sea-floor physiography.

A detailed survey of each of two coral knolls near Rongelap island was made by allowing a motor launch to drift slowly past a buoy that marked the coral knoll. Positions at 1-minute intervals were obtained by estimating the bearing to the buoy and measuring with a sextant the vertical angle from the horizon to the water-line of the buoy. This angle is a measure of distance from the buoy. Soundings were recorded continuously by the recording echo-sounder and the tape was later read at 15-second time intervals. The resulting spot soundings, plotted in chart form relative to the buoy, are shown in figure 48. The 2-fathom contours based on the soundings show that the side slopes are steepest near the surface in the zone of active coral growth, but that they are gentle on the talus slope at depth and finally merge into the flat lagoon floor.

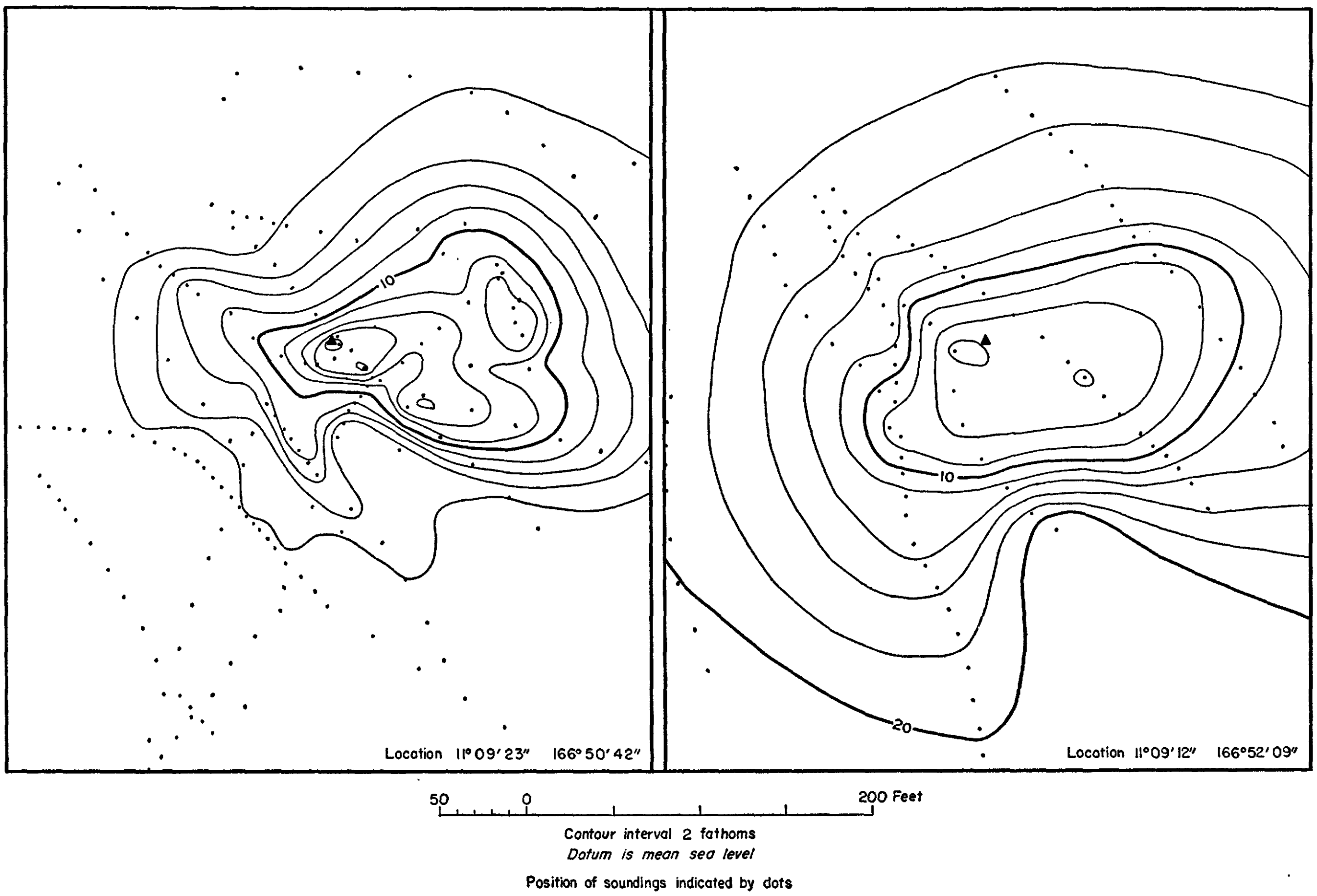

FIGURE 48.—Sonic surveys of coral knolls in Rongelap Lagoon. The positions of the soundings are indicated by dots; solid triangles mark the position of buoys. Positions at one-minute intervals were obtained by estimating the bearing to the buoy and measuring with a sextant the vertical angle from the horizon to the waterline of the buoy.

REEF OPENINGS

The main reef at Rongelap Atoll is penetrated by 9 passes, only 1 of which is on the north side and 1 on the west. The widest opening, South Pass, is nearly 4 miles wide and along most of its length the depth is roughly 10 fathoms. Within this pass, however, and within 2 other passes, deep channels are present. The best surveyed one, at South Pass, is deeper than 28 fathoms at the entrance but along its axis the shallowest point, or sill, is 160 feet, or 26.6 fathoms. A photograph of a fathogram across it is given in plate 31, figure 2. Another deep channel is at Enybarber Pass, where again the depth in the entrance is 28 fathoms, and the sill is 26.6 fathoms or perhaps somewhat deeper. Rongelap, then, is the only one of the 4 atolls which has 2 deep channels. A third channel is at West Pass, but it appears to be shallower, with a sill depth of 22.5 fathoms.

DISTRIBUTION OF DEPTHS

Rongelap is the largest of the 4 atolls studied, having an area of 430 square statute miles. As at the other atolls, the islands comprise only a small percentage of the area, 0.8 percent, whereas the outer reef amounts to 7 percent. The remainder, 396 square miles, is the area of the lagoon. As shown by the histogram and cumulative curve of figure 19, most of this area lies between 24 and 32 fathoms, and the mean depth is 27.3 fathoms. Thus, Rongelap is the deepest as well as the largest of the four atolls. The histogram, unlike those for Bikini and Eniwetok Atolls, shows no bulge between 3 and 12 fathoms for a 10 fathoms terrace. This absence may be due to the relatively sparse soundings at Rongelap. The cumulative volume curve of figure 19 shows that this is the largest in volume of the four atolls. The total volume is 6.1×10^{10} cubic yards, of which only 7 percent is below the sill depth.

SMOOTHNESS COEFFICIENT

The smoothness coefficients determined from the fathograms of Rongelap Lagoon show a high degree of smoothness near the shore and in the reef projection to the northeast, and a low smoothness in the main area of the lagoon (fig. 49). This distribution of values

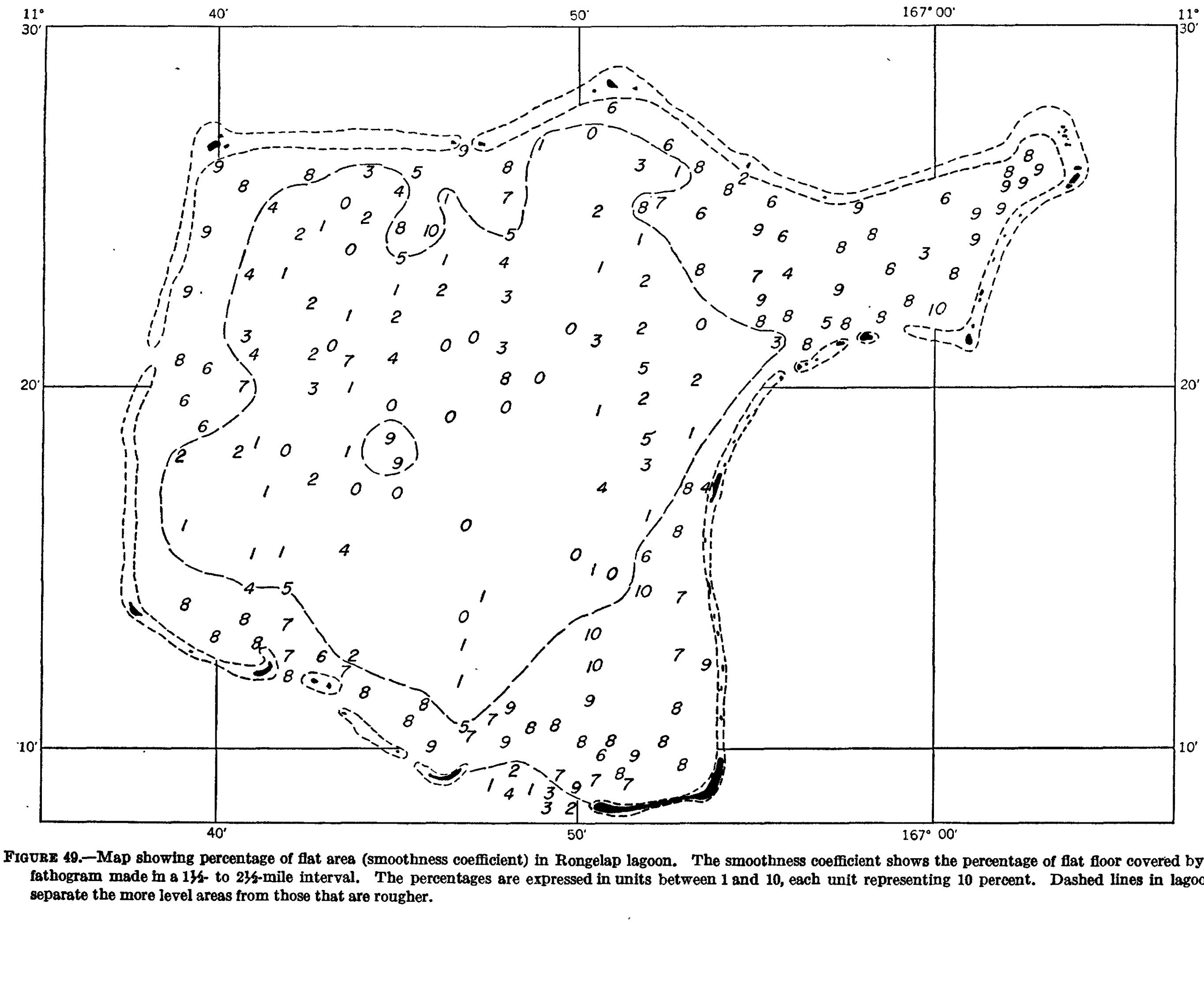

FIGURE 49.—Map showing percentage of flat area (smoothness coefficient) in Rongelap lagoon. The smoothness coefficient shows the percentage of flat floor covered by a fathogram made in a 1½- to 2½-mile interval. The percentages are expressed in units between 1 and 10, each unit representing 10 percent. Dashed lines in lagoon separate the more level areas from those that are rougher.

corresponds to that at Bikini Lagoon and it evidently reflects the smoothing ability of the fine debris around the edge of the lagoon. As at Eniwetok Lagoon, there appears to be a small area of high smoothness in the center and deepest part of the lagoon. The average smoothness coefficient is 5.0, showing that 50 percent of the lagoon floor is flat within 1 fathom. This is higher than the average values obtained for the other lagoons, probably in response to the exceptionally wide flat floor of the northeastern projection of Rongelap Lagoon.

SEDIMENTS

Sampling operations conducted during 3 separate visits to Rongelap Atoll, totaling about 15 days, resulted in the collection of 492 bottom samples from the lagoon floor and beaches and 37 others from the outer slopes. Nearly all of those from the lagoon were taken with an underway sampler and thus are small. A number of underwater photographs were made, 9 during diving operations on a lagoon coral knoll, 24 others from a wherry operated just outside the reef edge, and 32 others were snapshots taken by swimming in shallow water along the beaches. Nearly all of the shipboard work at Rongelap Atoll was done aboard U. S. S. *Blish* (AGS *10*).

PERCENTAGES OF COMPONENTS

Each of the samples from Rongelap Lagoon was examined briefly under a binocular microscope and an estimate was made of the percentage abundance of *Halimeda*, coral, Foraminifera, and shells. Finely comminuted fragments were listed as fine debris. These percentages were plotted at each sampling position on a chart. Coral distribution, as usual, is spotty, partly because of greater relative difficulty of sampling. The other four components, however, have a fairly systematic distribution, as shown by the percentage contours of figure 50.

Sands composed chiefly of Foraminifera are mostly restricted to beaches. Some of the beach samples have more than 80 percent foraminiferal tests. Patches of sediment containing somewhat more than 25 percent of Foraminifera are scattered about the deeper part of the lagoon; however, most of the samples from the lagoon contain less than 10 percent of Foraminifera. These tests are much smaller and belong to different species than those of the beaches.

The fine debris forms a ring around the periphery of the lagoon just beyond the beach. It is most abundant between 1 and 4 miles from shore, where it locally constitutes as much as 90 percent of the sediment. Toward the middle of the lagoon it decreases to less than 10 percent.

Inside the ring of abundant fine debris is still another ring, one of abundant *Halimeda* debris. This sediment is most abundant between 20 and 34 fathoms, constituting as much as 95 percent of some samples.

Shells rarely comprise more than 25 percent of a given sample. Many samples, however, contain more than 10 percent and these samples are almost entirely restricted to the lagoon floor bordering the passes just as at Bikini and Eniwetok Atolls. Thus, shells are fairly abundant in a long belt paralleling the wide passes at the south end of the lagoon and in smaller patches near the eastern passes. Many of the samples contain black grains, as at Eniwetok and Bikini Atolls.

OVER-ALL DISTRIBUTION

In addition to data from the samples collected during Operation Crossroads, the topography was considered a useful criterion of coral bottom and all hills, or coral knolls, are considered areas of coral bottom. Only minor aid was provided by the Japanese lead-line bottom notations, because the Japanese failed to differentiate between *Halimeda* and coral.

In Rongelap Lagoon the Foraminifera, concentrated along the beaches, cover 3 percent of the area. Wave and current action breaks up the foraminiferal sand and carries the fragments out to maximum depths of 15 to 20 fathoms where they are added to *Halimeda* fragments also comminuted on the bottom by the waves. This ring of fine debris constitutes 52 percent of the lagoon area. Beyond the zone of destructive wave action the unbroken *Halimeda* debris accumulates unmasked by sand. In samples from the deeper water, below about 34 fathoms, *Halimeda* is less abundant probably because of the low intensity of light at those depths. There, the smaller species of Foraminifera appear to be more abundant because of the restricted growth of *Halimeda*, but in none of the samples do these Foraminifera constitute more than 50 percent of the total. Thus, even the deep samples are still chiefly of *Halimeda* debris. Altogether, *Halimeda* debris covers 36 percent of the lagoon area.

Coral, as at Eniwetok Lagoon, is very patchily distributed in numerous relatively small spots. One large patch in the west side of the lagoon is listed as coral but the samples from that area are rather poor and may not be diagnostic. Altogether, the coral covers only 8 percent of the lagoon area.

OUTER SLOPES

REEF EDGE

Several detailed profiles of the upper part of the slope fringing the outside of the reefs were made at Rongelap and Bikini Atolls. These profiles were made from lead-line soundings, and because only a small boat could be used, all of the profiles are on the leeward sides

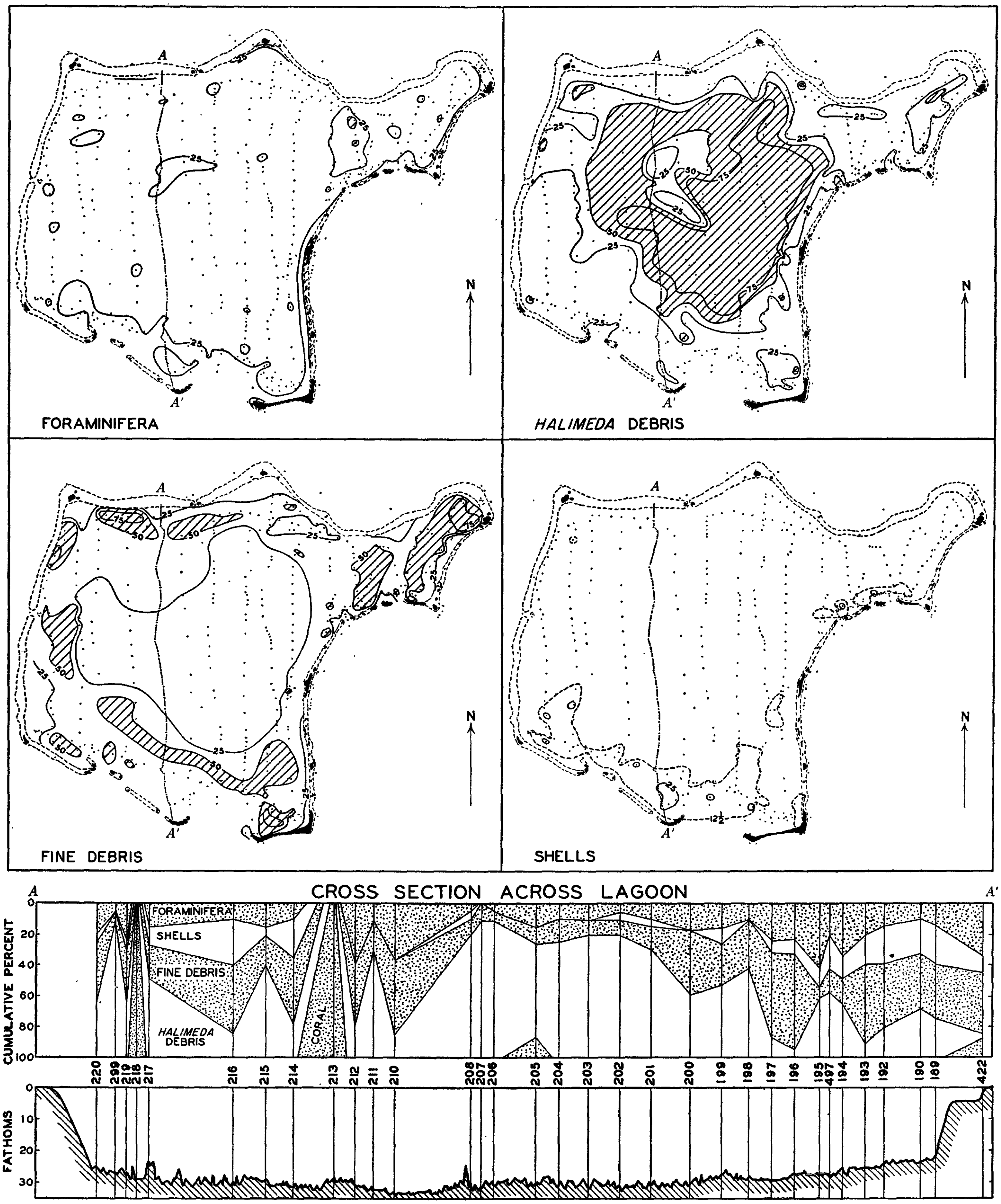

FIGURE 50.—Maps showing the percentage abundance of the important constituents in the sediments of Rongelap lagoon. Lines of equal abundance are drawn through the 25-, 50-, and 75-percent values. Reef boundaries are shown by dash line. Dots mark sample localities. Locality numbers of the samples used in constructing the cross section are shown above the profile.

of the atolls. The best results were obtained with a 14-foot wherry carrying 3 men: one to row and record, one to handle the 60-fathom sounding lines, and one for another 60-fathom sounding line which was used to measure horizontal distance. This latter line had a grappling hook attached to the usual 10-pound sounding lead. The procedure was to toss the hook onto the rough reef edge and using it as an anchor, to pay out the line gradually, while the boat was held in proper position by rowing. When the boat reached each successive fathom mark a sounding was made with the other line. Before and after the sounding work some time was devoted to taking under-water photographs and to studying the bottom with the aid of face masks.

The profiles that were made (fig. 51) show that the leeward sides of both Rongelap and Bikini Atolls are fringed by precipitous slopes, which locally (profiles 1, 4 and 5) have nearly vertical cliffs more than 100 feet high. All of the profiles except numbers 6 and 7 are at least 45°. Profiles 6 and 7 were taken off reefs at Kaeroga Pass, Rongelap Atoll, which are inset about a quarter-mile from the general line of the reef edge. Profile 5 was made across the middle of an area off Burok Island where aerial photographs indicated that slumping due to erosion of the reef margin had occurred. Inspection at the site supported this view because under-water in the reentrant of the reef there were several blocks jumbled together which had outlines similar to that of the broken reef edge. The profile adjacent to the gap, given by dashed line, shows the probable former shape of the reef profile before the slumping took place. Most of the dislodged material may have gone down beyond the end of the profile. A net total of 3,000 cubic yards is estimated to have slid away from this one site. As discussed elsewhere, there are many other such slump areas on the south sides of Bikini, Rongelap, and Ailinginae Atolls (pl. 73).

While it proved unfeasible to make lead-line soundings off the windward side of the atolls, sonic soundings from YMS's and inspection while swimming revealed no such steep slopes, but a more gradual slope fringing the reef edge.

SHALLOW TERRACE AND UPPER PART OF SLOPE

At Rongelap Atoll an opportunity was found to conduct a brief field survey of the shallow outer terrace from aboard AGS *10* and YMS *463*. The terrace is 400 yards wide locally on the windward side but is absent or very narrow on the leeward side of the atoll. One sounding line was run roughly parallel to the reef edge while underway bottom samples were being collected. Other soundings were read visually at 15-second intervals on radial lines. Positions were determined by both vertical angles between the horizon and the reef edge and by bearings on island tangents. Thirty radial profiles were made but 8 of these (mostly on the south and east sides) were discarded because too few positions were obtained for reliability. The remaining 22 profiles are presented in plate 71. Unfortunately, even these are not as reliable as those at Bikini Atoll and some are incomplete because the ships usually did not run closer than 300 yards from the reef. The innermost portions of profiles 14, 18, 19, 20, 21, and 22 are supplemented by the data from lead-line soundings of figure 51. The sonic soundings are shown by dots.

True terraces were covered by six profiles (nos. 1, 4, 5, 7, 11, and 12) whereas the inner portions of three other profiles have the appearance of terraces only because they extend into passes through the reef. It is notable that the terrace is well developed off both the northeastern reef projections as well as in reef indentations. In 10 instances the depth of the outer edge could be determined from the profiles and from the sounding line parallel to the reef. The measurements of depth ranged between 28 and 47 feet, averaging 40 feet. This compares with the 45-foot average depth of the terrace off Bikini; the 5-foot difference is about the probable error of measurement so to all intents and purposes the terraces are of equal depth.

Beginning at the outer edge of the terrace the slope steepens. Measurements of the maximum slope and average slope were made in the same manner as at Bikini Atoll. A maximum slope of 62° was found at the northeasternmost reef projection. Maximum slopes of 70° and 61° were found at two places off the leeward reef, also resembling the conditions found at Bikini Atoll. For all profiles the maximum and average slopes are 46.3° and 35.7° respectively. The leeward profiles (nos. 2, 3, and 14–22) have maximum and average slopes of 49.6° and 37.1°, whereas these values for the windward profiles are 42.7° and 33.4° respectively. Thus, as at Bikini Atoll, the leeward slopes are steeper than those to windward.

LOWER SLOPES

In addition to the soundings taken at the top of the outer slopes of Rongelap Atoll by YMS *463*, about 8,200 deeper soundings were obtained mostly by U. S. S. *Sylvania* (KA *44*). The latter soundings are along radial and concentric lines around each of the three atolls: Rongelap, Rongerik, and Ailinginae. Other soundings were collected by U. S. S. *Sylvania* and U. S. S. *Bowditch* (AGS *4*) en route between Rongelap and Bikini Atolls. A negligible number of soundings were available in the area before Operation Crossroads.

Chart 9 with a 100-fathom contour interval shows the slopes and sea floor around the group of atolls. As at Bikini and Eniwetok Atolls the slopes are broken by spurs lying seaward of major reef projections. Especially long and narrow spurs are indicated for the two smaller atolls. Deep terracelike structures are poorly developed, but they are present. A small one at 1,100 fathoms occurs on the south side of Rongelap Atoll; and another one at 750 fathoms is northwest of Rongerik Atoll. The chart shows also that the three atolls are so close to each other that their slopes intersect—at

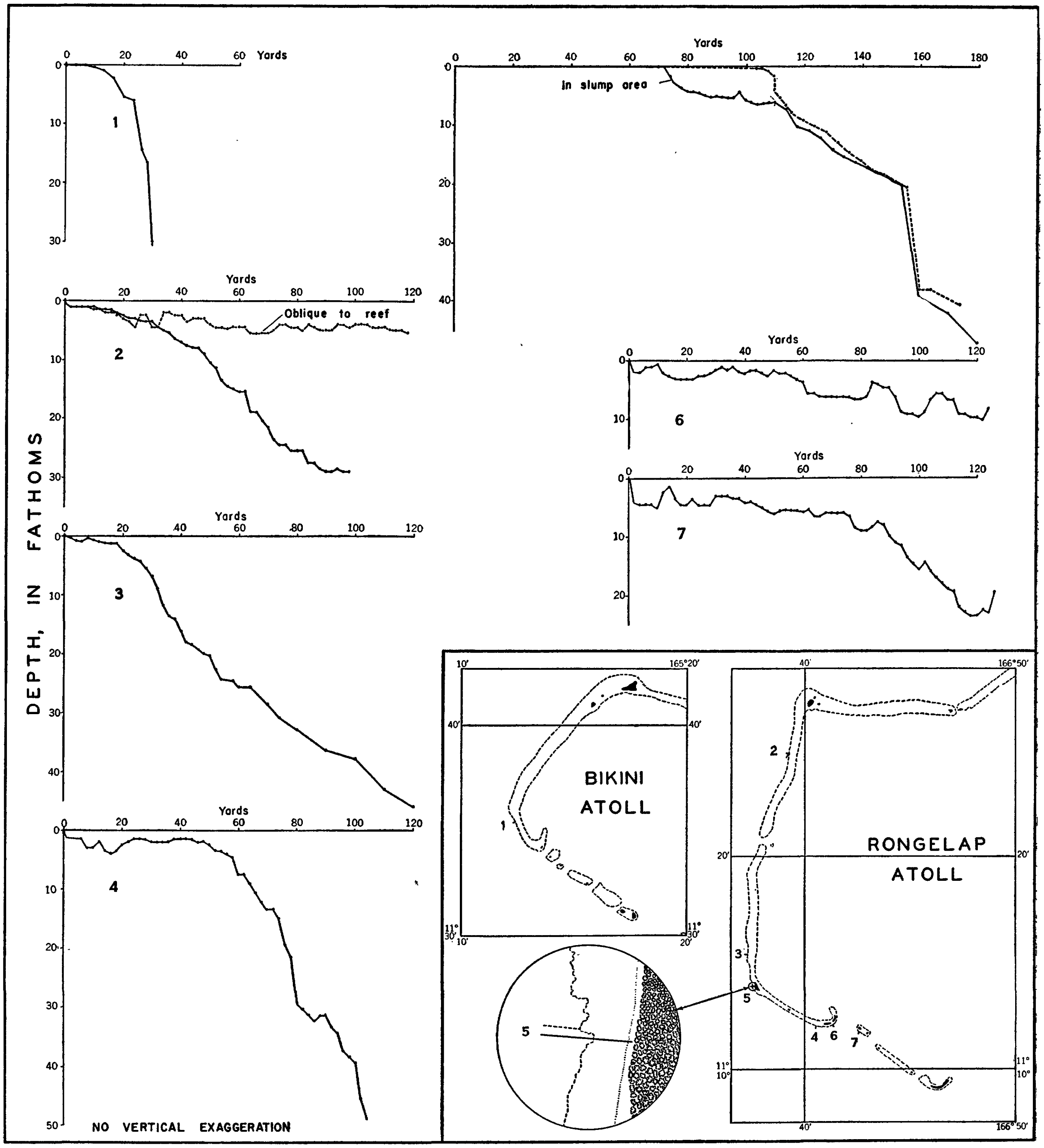

FIGURE 51.—Profiles from lead-line soundings off leeward reefs, Bikini and Rongelap Atolls.

about 1,000 fathoms. Thus, the bases are joined in a continuous curved bulbous chain. The divide between Ailinginae and Rongelap Atolls is simple and like the line between two cones whose bases intersect. The divide between Rongelap and Rongerik Atolls, however, is less simple for a small hill is located in what would otherwise be the lowest point of the divide. It extends 180 fathoms above the adjoining axis of the divide.

The slope profiles of Rongelap, Rongerik, and Ailinginae (fig. 52) like those of the other atolls, are steepest near the surface. Between the reef edge and 250 fathoms the slopes range between 15° and 43°, averaging 31° for Rongelap, 31° for Rongerik, and 35° for Ailinginae Atoll. As at Bikini more accurate soundings by a smaller ship would show the slopes to be somewhat steeper than these figures, which are based on only a few profiles taken with a large ship. At greater depth the slopes gradually decrease in steepness so that they merge with the deep sea floor at 2,000 to 2,500 fathoms.

SEDIMENTS

During the 2 days that soundings were obtained near the reef on the outer slopes of Rongelap Atoll aboard U. S. S. *Blish* 30 bottom samples were collected with an underway sampler. Depths range from 24 to 500 feet. The sampler was too small to secure representative samples of coral or rock fragments and all of the samples are small but about half weigh more than 5 grams and some more than 10 grams. It is probable that a number of misses or "no samples" can safely be ascribed to the sampler encountering large coral or rock surfaces. Even the larger samples are fairly variable with no clear-cut relationship to exposure to waves or to the character of the reef edge. Some tendency toward dependence on depth was present however, with changes in the character of the sediment at about 100 and 200 feet. Accordingly, the 15 large samples were divided into 3 groups having depth limits of 0 to 100, 100 to 200, and 200 to 300 feet. The average composition of the samples from each zone is shown in figure 53. From this is appears that the shallower samples are composed mostly of coarse material, chiefly *Halimeda* debris, while between 100 and 200 feet the sediments are finer, consisting largely of tests of Foraminifera, and fine debris. The samples from 200 to 300 feet again are coarse, consisting chiefly of *Halimeda* debris.

GEOLOGY OF RONGERIK ATOLL

Rongerik Atoll is only 20 miles east of the closest point of Rongelap Atoll. It has a roughly triangular shape, about 11 miles on a side, and with the apex pointing southward. There are 10 islands, only two of which, Rongerik and Eniwetak, are large enough to support many coconut palms. The total area of the islands is only 0.53 square statute mile. One of the islands is reported to have a 28-foot elevation. This figure, which is unusually high for the Marshalls, was not verified by the writers. Three passes penetrate the reef. South Pass, adjacent to Eniwetak island, appears to be the deepest but it is only about 400 yards wide. Bock Pass on the west side is wide but mostly shallow and filled with shoals. The lagoon was sparsely sounded prior to Operation Crossroads and is considered dangerous for navigation because of numerous shoals.

According to "Sailing directions for the Pacific Islands" there were only 11 inhabitants in 1930, but exports of copra, turtle, and pearls are mentioned. These natives apparently left the atoll, which was then uninhabited until the settling of the 167 natives from Bikini Atoll in March 1946. Because the atoll was found to be too small to support so many people, they have been since transferred elsewhere.

REEFS

The reefs of Rongerik were examined in only four places (fig. 54); observations made are given on pages 201–202. Data are insufficient for detailed comparisons with other atolls but certain broad similarities and differences may be pointed out. The southeast reef at Eniwetak island is similar to the corresponding reefs bordering Eniwetok Island on Eniwetok Atoll, Rongelap island on Rongelap Atoll, and Enyu island on Bikini Atoll, in its narrowness and in the occurrence of eroded blowholes. The north and northwest reefs of the several atolls are similar in surface features but those of Rongerik differ from the others considerably in marginal features.

At Rongerik there is a broad seaward terrace at depths of only 20–50 feet. Because of this terrace the reef margin is irregular and wide spurs and channelways exist. These are considerably larger than the windward surge channels and may be erosional in origin.

The lagoon reefs at Rongerik consist of broad platforms at depths of 4–10 feet that support a prolific coral growth. Similar reefs occur on the other atolls but not over such wide areas as at Rongerik. All of the differences between Rongerik's reefs and those of the other atolls appear to be connected with the shallowness of the lagoon. This condition may have been caused by a relative uplift of a few fathoms or by an abnormally high rate of sedimentation resulting from a high ratio of reef length to lagoon area.

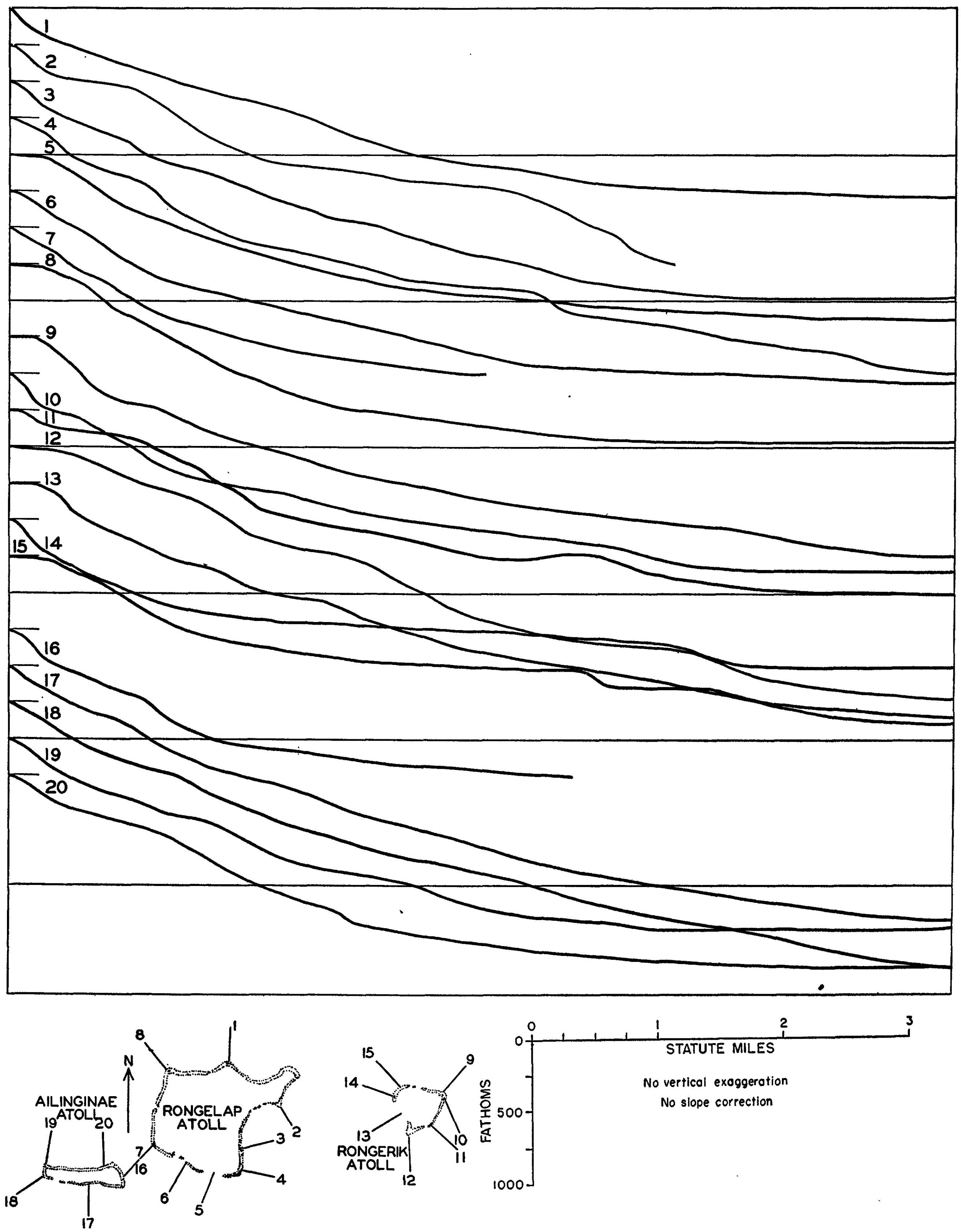

FIGURE 52.—Deep sonic profiles of outer slopes of Rongelap, Rongerik, and Ailinginae Atolls.

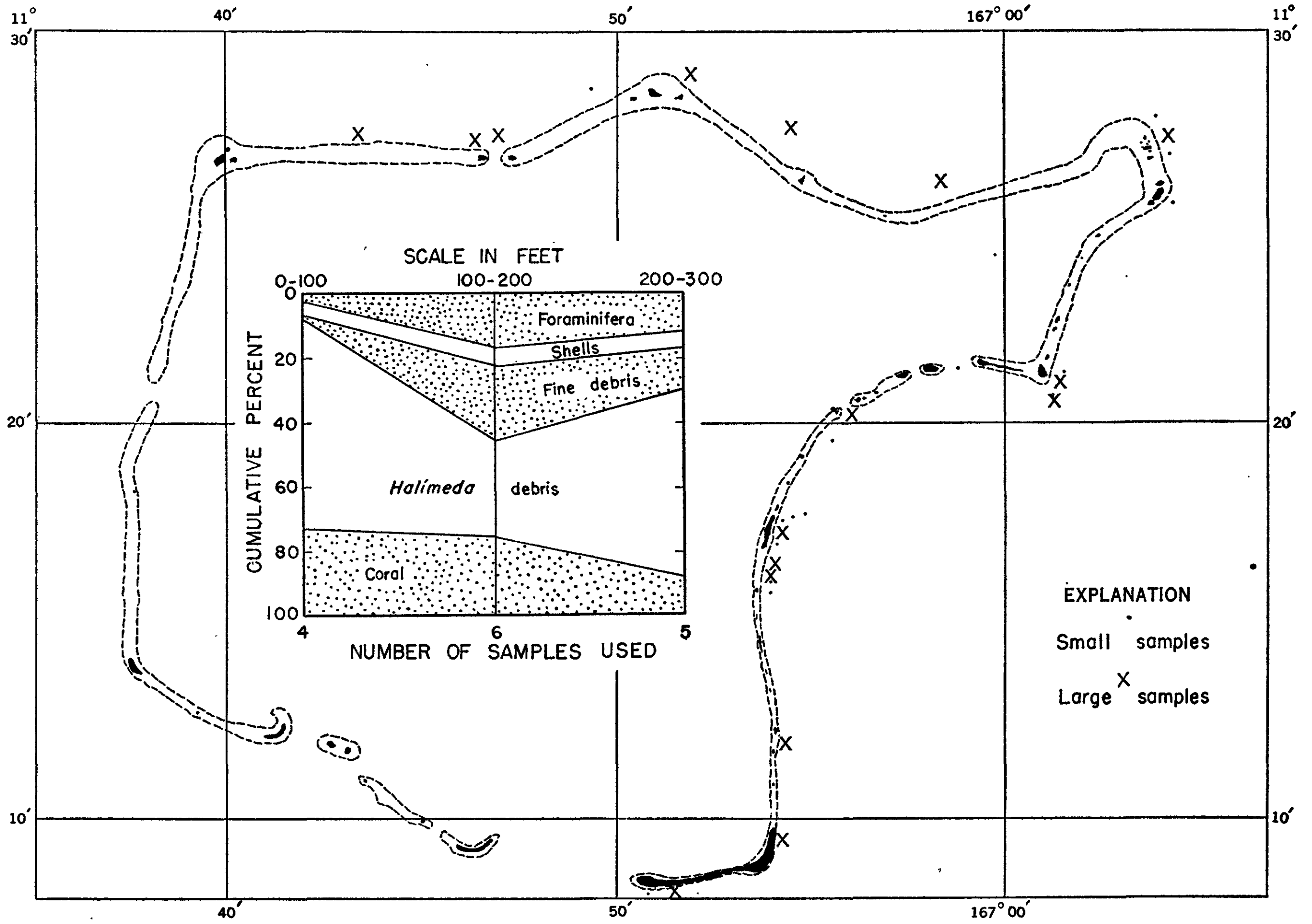

FIGURE 53.—Composition of bottom samples from the outer slopes of Rongelap Atoll.

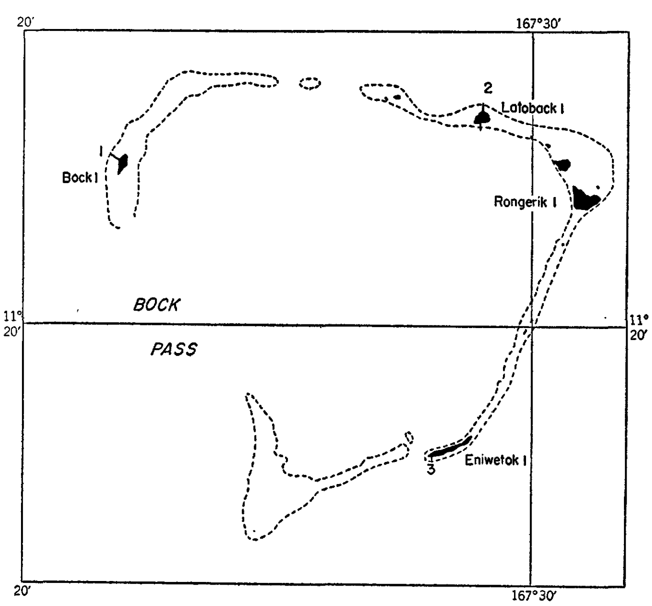

FIGURE 54.—Locations of measured reef traverses, Rongerik Atoll.

LAGOON

PHYSIOGRAPHY

On June 23 and 24 a brief investigation of the topography and sediments of Rongerik Lagoon was made aboard the U. S. S. *Blish* (AGS *10*). About 870 soundings were read from the fathograms. These soundings, together with the 765 Japanese lead-line soundings from Hydrographic Office Chart No. 6026 served as a basis for the contour chart of the lagoon (chart 8). In general the two sets of soundings are in agreement. However, the maximum sonic sounding was found to be 153 feet, or 25.5 fathoms. Thirteen Japanese soundings exceeded this value, but only 3 of them were 30 or 31 fathoms. As these were lead-line soundings which could have been affected by drift of the sounding boat, they are discounted, so that the maximum depth in the lagoon is believed to be close to 26 fathoms. Altogether, the soundings comprise an average of only 30 per square mile of lagoon area, a density which is low compared to the 500 per square mile in Eniwetok

Lagoon. Nevertheless, the soundings are sufficiently abundant to give a fairly good general picture of the bottom topography. To some extent the soundings were supplemented by knowledge of the positions of a number of shallow coral knolls near the courses followed by the *Blish* and also by indications of others on aerial photographs. The contour interval of the Rongerik Lagoon chart like those of the other atolls is 4 fathoms.

TERRACE

Inspection of chart 8 reveals no indication whatever of the 10-fathom terrace which is very well developed at both Bikini and Eniwetok Atolls. It is replaced, apparently, by a shallower terrace lying between 0 and 4 fathoms. This terrace is widest along the southeast side between Rongerik and Eniwetak islands, in the south corner west of Eniwetak island, and just east of Bock island. In all three areas the depths are based entirely on soundings made by the Japanese. The *Blish* did not investigate them because of the obvious shallowness shown by wide expanses of green water. An examination of the actual soundings from which the contours were drawn suggests that the mean depth of the terrace is close to 20 feet. Thus, it is approximately 40 feet shallower than similar terraces of the other atolls. Bordering the edge of the lagoon terrace is a relatively steep slope extending to the main basin.

BASIN

The bottom depths of the lagoon begin at about 18 fathoms at the base of the slope fringing the terrace. The basin is roughly elliptical, with the long axis trending west-northwest, and it shows no reflection whatever of the triangular shape of the outer reef edge. In detail, the basin might more properly be called two basins for it is divided into two subequal parts by a broad low ridge which extends diagonally across it in a northwest-southeast direction. The top of the ridge lies mostly at about 18 or 19 fathoms. The two basins are of about the same depth, sonic soundings of 26 fathoms having been found in each. The eastern basin is discontinuous as indicated by a number of 24 fathom depression contours.

CORAL KNOLLS

Coral knolls are shown by the contours to be far more common on the east side of the lagoon, where a great many of them rise from the bottom depths of the basin to near the surface. Many smaller coral knolls were observed rising above the general level of the shallow lagoon terrace and making large areas practically unnavigable by even small ships. The chart shows contours around all of the higher coral knolls but these contours do not in any sense indicate their true side slopes because nearly all of the coral knolls were marked by only one sounding, which was made at the top. Soundings were too few in the lagoon for making a valid statistical examination of the coral knoll characteristics as was done for Bikini and Eniwetok Atolls.

REEF OPENINGS

Three openings or passes cut through the Rongerik reef. The widest of these is the one south of Bock Island, but while wide, this opening is mostly shallow, with numerous coral knolls reaching to near the surface. The deeper middle part of the opening has complicated topography which may not be correctly shown by chart 8; however no evidence of a very deep channel through this opening was found.

Another opening, in the north reef, is also fairly wide but extremely shallow, probably less than 4 fathoms. The third, and last, opening in the reef is just west of Eniwetak island. While this is the narrowest, it appears also to be the deepest opening. A *Blish* sounding of nearly 22 fathoms was found on a line which probably paralleled the axis of a deep channel but did not cross it. Farther out in the main opening in the reef, there is a Japanese sounding of 25 fathoms and it is entirely possible that still greater depths are present. The channel was not completely investigated because its axis is less than about 100 yards from the Eniwetak island beach and currents in the area were strong enough to make routine surveying dangerous. As far as the present data go this channel appears to be similar to the deep channels found penetrating the reefs at each of the other atolls.

DISTRIBUTION OF DEPTHS

The frequency of 4-fathom depth zones in Rongerik Lagoon is shown in figure 19. The histogram shows that islands comprise 0.7 percent of the atoll's area, a value similar to that found for the other atolls; however, the intertidal reef area is 17.4 percent, more than twice as great a percentage as at the others. Below low water, the histogram shows the 0 to 4 fathom zone to be far more extensive than other zones shallower than 16 fathoms. This prominence reflects the presence of the 20-foot terrace. The widest zone of all is that between 20 and 24 fathoms, the main lagoon floor. The volume of the lagoon was computed to be only about one-tenth that of Eniwetok, because of the smaller diameter and depth.

SMOOTHNESS COEFFICIENT

As in the case of the other atolls the smoothness coefficients of Rongerik Lagoon were estimated from the fathograms. Because of the smaller size of this lagoon each value was based on the tape drawn during intervals of only 10 minutes or 1 to 2 miles. Perhaps because figure 55 is drawn on a larger scale than figures showing smoothness coefficients for the other lagoons, it indicates a rather clear-cut distinction between a high coefficient of smoothness near shore and a low coefficient in the main part of the lagoon. This is ascribed to the mantling effect of fine debris around the periphery of the lagoon. The average smoothness coefficient for Rongerik Lagoon is 4.3, indicating that 43 percent of the lagoon floor is flat or has irregularities projecting less than 1 fathom above the floor.

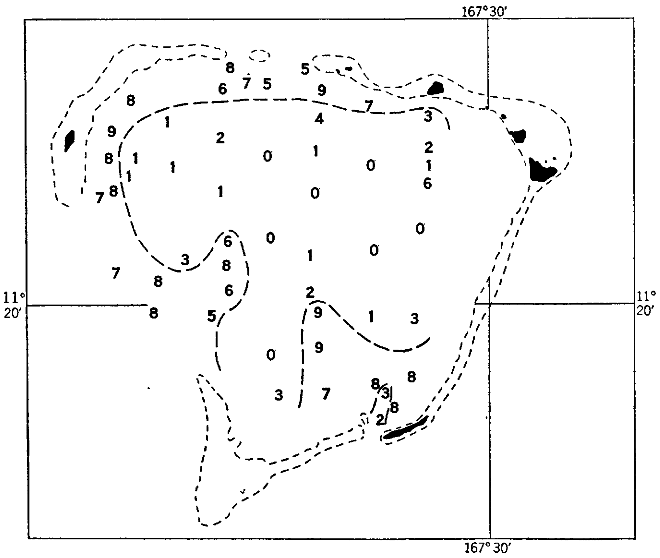

FIGURE 55.—Map showing percentage of flat area (smoothness coefficient) in Rongerik Lagoon. The smoothness coefficient shows the percentage of flat floor covered by a fathogram made during a 1- to 2-mile interval. The percentages are expressed in units between 1 and 10, each unit representing 10 percent. Dashed lines in lagoon separate the more level areas from those that are rougher.

SEDIMENTS

During 2 half days spent in surveying Rongerik Lagoon 95 bottom samples were collected. All but two of these samples were taken by the underway sampler and thus are small, mostly less than 50 grams each. Only two samples were taken by a snapper, and no cores, dredgings, or bottom photographs were obtained. Nine beach samples collected by landing parties during other visits to the atoll add to the sediment distribution picture.

The percentage distribution of the main components in sediments from the flat areas between coral knolls are shown in figure 56 in both chart and cross-section form. Foraminifera are most abundant in the beach sands where they constitute as much as 85 percent of the grains, and consist mainly of *Calcarina* and *Marginopora* tests 1½ to 3 millimeters in diameter. The percentage abundance decreases very rapidly lagoonward from the beach so that practically all samples from deeper than 10 fathoms contain less than 5 percent and average about 3 percent of Foraminifera. The tests in these deeper areas are thin walled and mostly about ½ millimeter in diameter. Some of them are even less than ¼ millimeter and are included in the fine debris classification but the total bulk of the very small tests is only a fraction of one percent of the total sample and can be ignored for the present purposes.

Shells of pelecypods and gastropods are very abundant in only four samples, all near the west edge of the lagoon. The chart plot of shells suggests the presence of a narrow band of shelly sediments extending around the southwest, west, and northwest lagoon margin.

Halimeda debris is very abundant in most samples from deeper water in the main east-central area of the lagoon. A secondary patch of *Halimeda* debris is in the deep spot in the northwest corner. In some samples recognizable *Halimeda* debris constitutes as much as 85 percent. Undoubtedly, the fine-debris component of these samples contains additional comminuted or corroded remains of *Halimeda* segments.

Percentage of coral was not plotted in chart form, but nearly all samples contain some coral, averaging about 8 percent. Samples containing a much higher percentage probably were derived from the top or side of coral knolls, and as only a relatively small percentage of the coral knolls were sampled, the data for percentage distribution of coral are incomplete, so no attempt was made to show it in chart form.

As in the other lagoons fine debris is most abundant at intermediate depths where it makes a doughnut shaped distribution pattern.

The distribution data are also shown in figure 56 on a cumulative-percentage cross section. This section brings out the rapid decrease in abundance of Foraminifera near the beach beyond which it is succeeded chiefly by fine debris, which in turn is replaced in deeper water chiefly by *Halimeda* debris and coral. Some of the irregularities of the cross section are due to relative scarcity of samples because of which adequate samples for the section had to be selected on a zig-zag course varying between deeper and shallower water.

Classified according to the chief constituent in the samples, supplemented by topography, fine debris is the most abundant sediment, constituting 36 percent of the total area and covering most of the west half of the lagoon but continuing in a strip at intermediate depth around the whole basin. Coral is next in abundance and it covers 34 percent of the lagoon, where it certainly occurs as small patches coinciding with coral knolls and less certainly occurs as large areas of the 20-foot terrace in the east and south corners of the lagoon. The presence of coral in these broad shallow areas is based only on Japanese lead-line bottom character notations. *Halimeda* debris, the third most abundant component, 27 percent, occurs in deep water

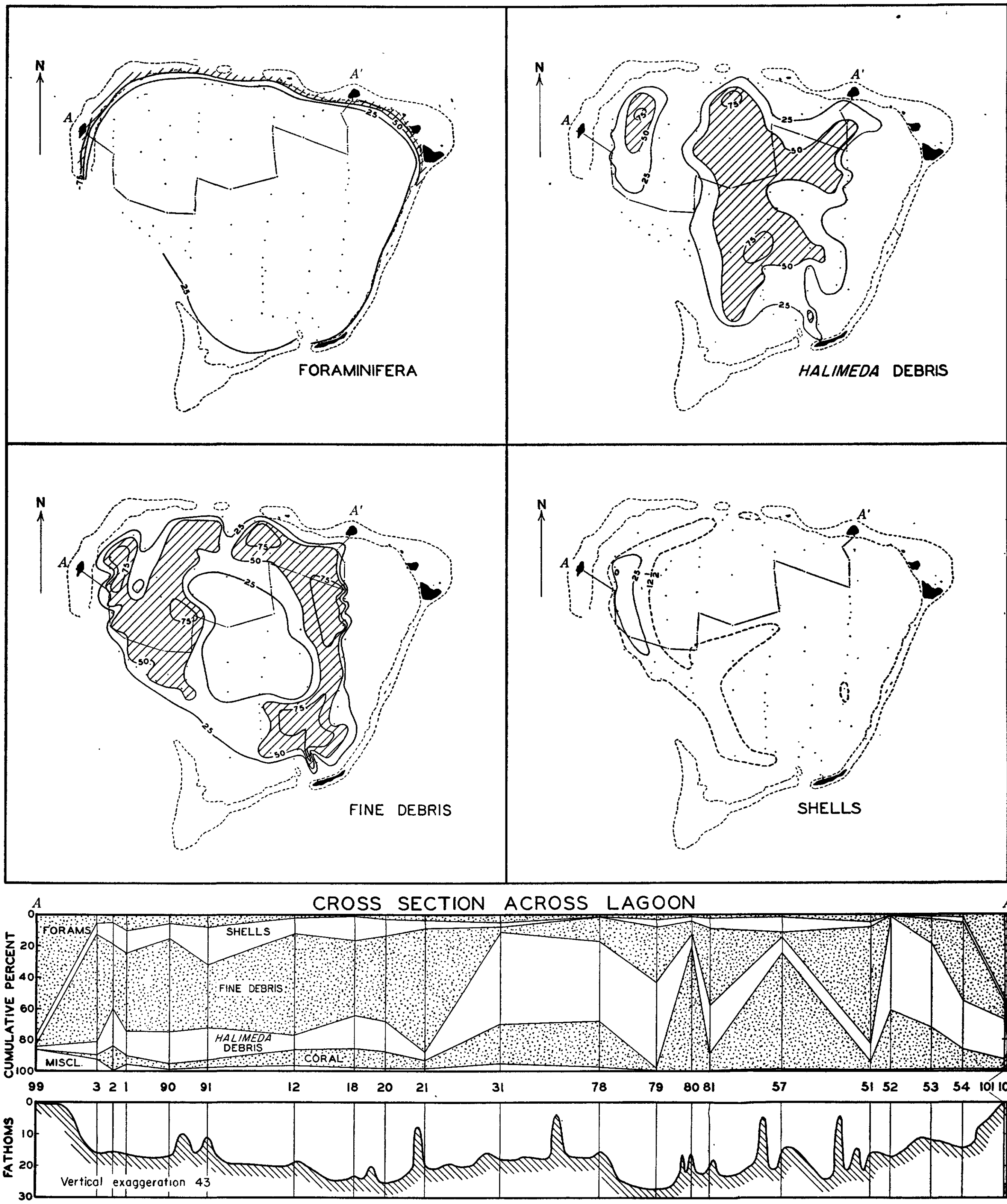

Figure 56.—Map showing the percentage abundance of the important constituents in the sediments of Rongerik Lagoon. Lines of equal abundance are drawn through the 25-, 50-, and 75-percent values. Reef boundaries are shown by dash line. Dots mark sample localities. Locality numbers of the samples used in constructing the cross section are shown above the profile.

in a large area near the middle of the lagoon and a smaller area in the northwest corner. Foraminifera are abundant only in a peripheral zone in beach sands around the islands and on sand bars of the reef.

OUTER SLOPES

No field studies were made of the terraces fringing Rongerik Atoll but such terraces were observed on aerial photographs. The terrace at Rongerik—both outside the atoll and in the lagoon—is so sharply defined that it is believed to be shallower than the 8-fathom terrace at Bikini. It is best developed along the north side of Rongerik where it reaches a width of 500 yards.

GEOLOGY OF GUYOTS (FLAT-TOPPED SEAMOUNTS)

SYLVANIA GUYOT

PHYSIOGRAPHY

The deep northwesterly projection of Bikini Atoll (chart 4) was found in 1944 by Hess (1948, p. 298) who made four profiles across it. In the present report it is named Sylvania Guyot in honor of the U. S. S. *Sylvania* (KA *44*) aboard which most of the deep soundings outside of the lagoons were obtained during Operation Crossroads. This guyot was sounded during night runs intervening between the daytime surveys of the outer slopes of Bikini Atoll. Additional soundings were obtained with recording echo sounders aboard the U. S. S. *Horizon* and the U. S. S. EPCE(R) *857* during the 1950 Mid-Pacific Expedition.

The guyot has a flat top that is larger than the area of Bikini Lagoon and reef—462 square miles as compared to 273 square miles. The maximum width and length are 14 and 30 miles respectively. In outline, Sylvania Guyot differs from Bikini Atoll in the presence of four long radial projections that extend much farther beyond the main central mass than do the buttresses opposite the reef projections at Bikini. The guyot is separated from the bulk of Bikini Atoll by a saddle that is only 6 miles wide. The deepest part of the saddle appears to be about 790 fathoms, about 50 fathoms deeper than most of the flat top of the guyot.

The top of the guyot is very flat, with a number of shallowest soundings of 705 fathoms. One pre-1946 sounding was 698 fathoms, but this one has not been duplicated in the recent surveys. Most of the fathograms crossing the top of the guyot show no irregularities on the general incline that exceed 2 fathoms. One fathogram (pl. 6, fig. 1), however, shows a small hillock that rises 6 fathoms above its surroundings near the middle of the guyot.

Two different aspects are presented at the edges of the guyot. Fathograms that cross the four projections or the neck that joins it to Bikini Atoll show a deep gently rounded edge. Others that cross the edge of the main mass between the projections, indicate a shallower and generally sharper break in slope. Some, particularly those that cross the southeastern half of the guyot, reveal a marginal rise, probably a ridge (pl. 6, fig. 2). The height of the ridge above surroundings, as well as its absolute depth, is highly variable but it is believed to be a real structure, not one created by defects in the sounding equipment. The presence of the marginal ridge suggests coral reef structure, but some of the fathograms (fig. 57, fathograms 9, 24, and 25) were made close to dredging stations that almost certainly would have contained some calcareous material had it been present. No alternative explanation is offered. In general, even with the marginal ridge, the edge of the guyot is not so sharp as the edge of an atoll. Instead it presents a fairly well rounded curve. Beyond the edge the side slopes become steeper, reaching an average of about 12° at depths between 1,000 and 1,500 fathoms. The slopes of Bikini Atoll have about the same steepness at that depth but are much steeper at depths shallower than the top of the guyot. To an unknown extent the gentler slopes of the guyot are due to the greater distances between them and the echo-sounding gear on the ship's hull.

SEDIMENTS

Three main kinds of material were obtained from the top of Sylvania Guyot: *Globigerina* ooze from the flat top, calcareous debris from the area adjoining Bikini Atoll, and volcanic rocks and manganese oxide from the edges (pl. 33, fig. 1).

Coarse *Globigerina* ooze was found in most samples from the guyot. Near the edges it is thin, patchy, and mingled with rocks and manganese oxide nodules (pl. 34). Near the middle, it probably was penetrated to a depth of 10 feet by the Kullenberg corer on 2 trials but the long core was lost in each attempt. Short cores of it were obtained from the southeastern part of the flat top mostly during the 1946 expedition. Figure 30, based on these cores, shows that this foraminiferal sand is coarser than the fine debris that reaches the lower slopes of the atoll from the reef edge. There the abundant fine debris masks the foraminiferal sand. Of especial interest is an underwater photograph of the sediment at a depth of 750 fathoms (pl. 35), showing nearly symmetrical ripple marks having a wavelength of about 1 foot (Menard, 1952). Such ripple marks, seen in ancient sediments would often be assumed to indicate a shallow water environment of deposition. They appear to be of the wave-formed type, but they are far below wave base. Perhaps they were developed by

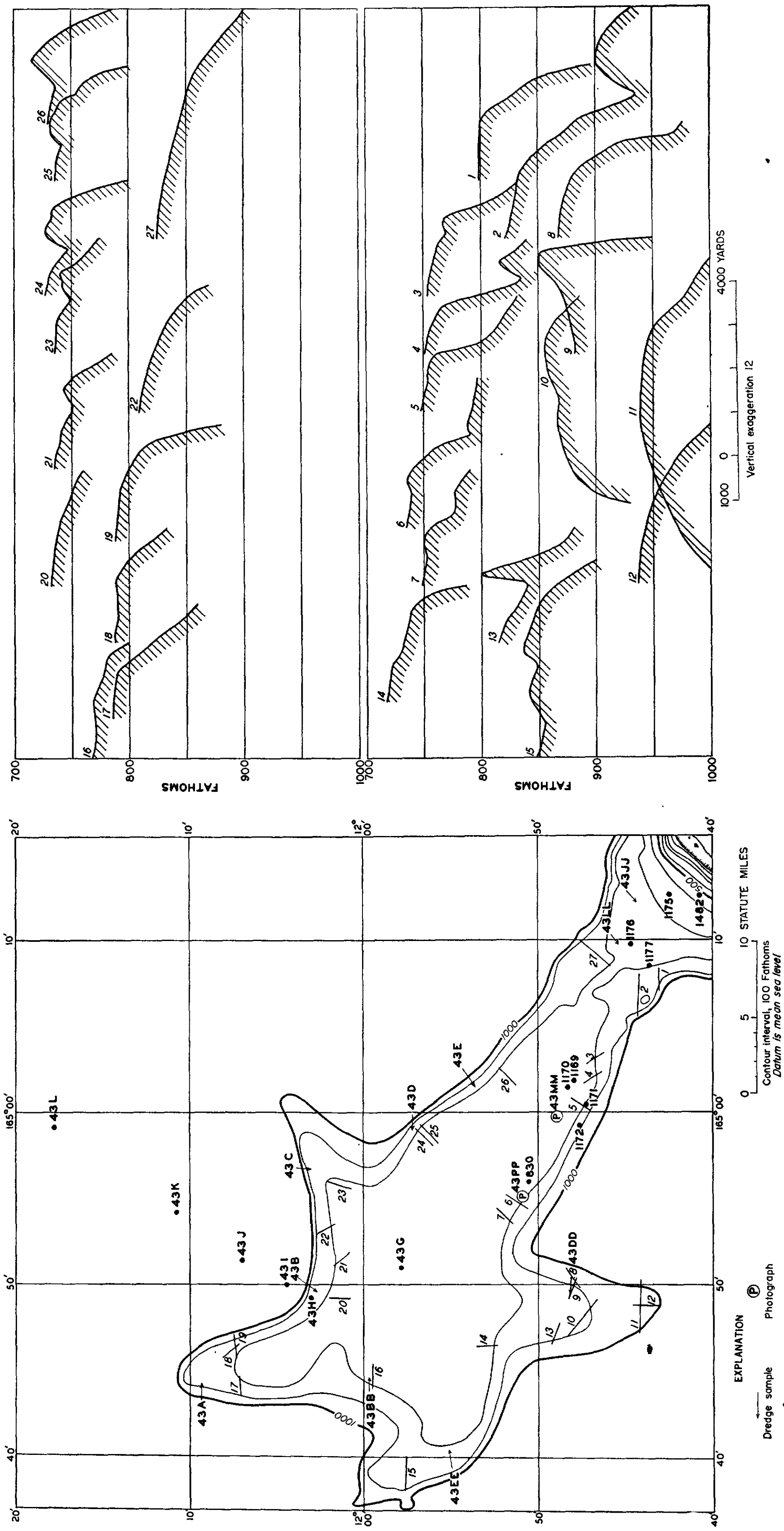

FIGURE 57.—Sylvania Guyot, bottom samples and fathograms of edge.

internal waves, or by changeable currents in the known eddy west of Bikini Atoll.

The fine debris near Bikini Atoll forms part of the second class of material recovered from the guyot. Associated with it are larger pebbles, cobbles, and blocks. A dredging, 43JJ, recovered more than 200 pounds of calcareous material mostly reef coral that was rounded to some extent by abrasion. Possibly, it was transported by rolling or sliding, whereby large blocks sank into the sediment and stopped and finer material, put into suspension, travelled farther.

The third, and most interesting, kind of material was that obtained from the guyot's edge. During the 1946 expeditions, the light gear permitted the taking of only small samples. Manganese oxide crusts recovered then from the edge indicated an area of nondeposition of sediment favorable to recovery of rock. The heavier equipment used in 1950 obtained volcanic rock at 6 places and thick manganese oxide crusts at others (table 24). Most of the rock was brown, and highly weathered.

Cores taken beyond the edge of the guyot show the presence of progressively finer *Globigerina* ooze down to 1,800 fathoms. Two deeper cores are of red clay (table 24).

TABLE 24.—*Deep samples from Sylvania Guyot and adjacent deep-sea floor*

43A Dredge. Lat. 12°09′ N.; long. 164°44′ E.; 1,030–810 fathoms.

1. Yellow and brown tuff breccia covered by 1/16- to 1/4-inch crust of manganese oxide and containing crack fillings of white chert and cemented Foraminifera. Two-hundred-pound piece 24 inches long, loose.
2. Yellow and brown tuff breccia covered by 4 1/4-inch crust of manganese oxide. Twelve inches long, loose.
   Crust (inches):
   0–1/2 ---- Black, bumpy, dense.
   1/2–1 3/4 --- Black, brown, gray, porous, granular.
   1 3/4–2 1/8 -- Dark brown to black, slightly fibrous.
   2 1/8–2 7/8 -- Black, massive, dense to granular.
   2 7/8–4 1/4 -- Black, massive, dense.
3. Four pieces of dense gray basalt. One inch long, angular.
4. One pound loose chips of manganese oxide.
5. One-eighth pint *Globigerina* ooze, coarse.

43B Dredge. Lat. 12°03′ N.; long. 165°00′ E.; 1,140–820 fathoms.

1. Gray tuff breccia covered by manganese oxide. One inch long.
2. Manganese oxide crust. 8 x 8 x 4 inches, freshly broken:
   Crust (inches):
   0–1/4 ---- Black, crackly, dense.
   1/4–1 ---- Bluish, black, granular.
   1–1 1/2 --- Tan, granular.
   1 1/2–2 --- Black, crackly.
   2–2 3/4 --- Tan, granular.
   2 3/4–4 --- Black, massive, dense.
3. One-half pound loose chips of manganese oxide.
4. Two pints *Globigerina* ooze, coarse.

TABLE 24.—*Deep samples from Sylvania Guyot and adjacent deep-sea floor*—Continued

43C Dredge. Lat. 12°03′ N.; long. 164°57′ E.; 1,150–850 fathoms.

1. Four pieces gray to brown basalt, hard, angular, freshly broken. As much as 2 1/2-inch length. One piece is broken round pebble. All are covered on one side by manganese oxide. (See pl. 33, figs. 2, 5.)
2. One pound loose chips of manganese oxide.
3. One pint *Globigerina* ooze, coarse.

43D Dredge. Lat. 11°57′ N.; long. 164°59′ E.; 1,150–820 fathoms.

1. Three pieces of brown dense basalt with tan feldspar phenocrysts, subangular to sub-round. As much as 4 inches long. Manganese oxide crust.
2. Two pieces of green tuff breccia 4 inches long. Manganese oxide crust.
3. Two pieces of light-gray rhyolite pumice. 1 1/2 inches long. When dried, they floated 2 weeks in jar of sea water.
4. Manganese oxide, lensy, layered. 6 x 4 x 2 inches.
5. Three pounds loose chips of manganese oxide.
6. Three pints *Globigerina* ooze, coarse.

43E Dredge. Lat. 11°47′ N.; long. 165°11′ E.; 1,150–860 fathoms.

1. Gray basalt with feldspar phenocrysts, angular. 1 inch long.
2. Brown basalt, freshly broken, covered by 2 1/2-inch crust of manganese oxide.
3. One-half pound loose chips of manganese oxide.
4. Four pints *Globigerina* ooze, coarse.

43G Core. Lat. 11°58′ N.; long. 165°01′ E.; 711 fathoms.
Phleger core: 14 inches uniform coarse *Globigerina* ooze.
Kullenberg core: Penetrated about 10 feet but core was lost. Two trials.

43H Core. Lat. 12°03′ N.; long. 164°49′ E.; 830 fathoms.
Phleger core: Hit rock, nose bent, two trials.

43I Core. Lat. 12°04.5′ N.; long. 164°50′ E.; 1,300 fathoms.
Phleger core (inches):
0–5 ------- Dark-buff *Globigerina* ooze.
5–8 ------- Light-buff *Globigerina* ooze containing light-gray layers at 7 3/8 to 7 1/2 and 7 5/8 to 7 3/4 inches.
8–12 ------ Light-gray *Globigerina* ooze.

43J Core. Lat. 12°07′ N.; long. 164°52′ E.; 1,800 fathoms.
Phleger core (inches):
0–1/8 ------- *Globigerina* ooze containing 1/2-inch manganese oxide nodule.
1/8–1 1/2 ----- Red clay.

43K Core. Lat. 12°11′ N.; long. 164°54′ E.; 2,300 fathoms.
Phleger core: 0–30 inches—red clay.

43L Core. Lat. 12°18′ N.; long. 164°59′ E.; 2,555 fathoms.
Kullenberg core: 0–175 inches—uniform light-brown clay.

43BB Dredge. Lat. 11°59.5′ N.; long. 164°44′ E.; 840 fathoms.
Three pints *Globigerina* ooze.

43DD Dredge. Lat. 11°48′ N.; long. 164°50′ E.; 880 fathoms.

1. 200-lb. green coarse-grained olivine basalt lapilli tuff, angular, fragile, weathered, freshly broken by dredge. As much as 20 inches long. Many have cover of manganese oxide.
2. Few brown dense pieces of olivine basalt, sub-round, covered by manganese oxide.

TABLE 24.—*Deep samples from Sylvania Guyot and adjacent deep-sea floor*—Continued

43EE Dredge. Lat. 11°55′ N.; long. 164°43′ E.; 800–900 fathoms.
Few Foraminifera and grains of manganese oxide.

43JJ Dredge. Lat. 11°45′ N.; long. 165°12.5′ E.; 740 fathoms.
1. 226-lb. subangular reef coral fragments with about ½ lb. shells, echinoid spines, and plates. Median diameter is 1.2 inches, but ranges up to 12 inches. Slightly weathered with thin stain of manganese oxide on one-quarter of pieces.
2. Two pieces of rhyolite pumice, round, 1 and 2 inches long.
3. 4 pints *Globigerina* ooze.

43LL Dredge. Lat. 11°46′ N.; long. 165°10′ E.; 730 fathoms.
Manganese oxide. Three inches long.

43MM Camera. Lat. 11°49′ N.; long. 165°00′ E.; 750 fathoms.
Ripple-marked *Globigerina* ooze.

43PP Camera. Lat. 11°51′ N.; long. 164°55′ E.; 750 fathoms.
Manganese nodules imbedded in *Globigerina* ooze.

830 Core. Lat. 11°50.5′ N.; long. 164°56′ E.; 710 fathoms.
Gravity core: *Globigerina* ooze, coarse.

1169 Core. Lat. 11°48′ N.; long. 165°02′ E.; 710 fathoms.
Gravity core: *Globigerina* ooze, coarse.

1170 Core. Lat. 11°48.5′ N.; long. 165°01.5′ E.; 680 fathoms.
Gravity core: 0–6 inches—*Globigerina* ooze, coarse.

1171 Dredge. Lat. 11°47.5′ N.; long. 165°00.5′ E.; 800 fathoms.
Manganese oxide.

1172. Dredge. Lat. 11°48′ N.; long. 164°59.5′ E.; 835 fathoms.
Globigerina ooze, coarse.

1175 Core. Lat. 11°42.5′ N.; long. 165°13′ E.; 592 fathoms.
Gravity core: 0–5 inches—fine calcareous sediment and *Globigerina* ooze.

1176 Core. Lat. 11°44.5′ N.; long. 165°10′ E.; 720 fathoms.
Gravity core: 0–7 inches—*Globigerina* ooze, coarse.

1482 Dredge. Lat. 11°41′ N.; long. 165°12.5′ E.; 575 fathoms.
Halimeda debris and fine calcareous sediment.

IGNEOUS ROCKS

By GORDON A. MACDONALD

INTRODUCTION

Fourteen samples of igneous rock, collected by the Mid-Pacific Expedition of 1950 at ten separate localities on the lower slopes of Bikini Atoll and the adjoining Sylvania Guyot, have been examined megascopically and under the microscope. These are the first samples of igneous rock found on the slopes of any of the atoll islands in the central Pacific, and constitute the first direct evidence of the volcanic nature of the base on which the limestone islands were built. The locations and depths at which the samples were taken, and the general nature of the rock materials, are listed in the table 25. The locations are shown on the map (fig. 57). With the exception of sample 43JJ, all the samples of the 43 series came from Sylvania Guyot, and all those of the 44 series from the southeastern slope of Bikini Atoll.

Because of the small number of samples and the unique nature of the collection, each sample is described in detail in the following pages. Optic axial angles were estimated from interference figures. Refractive indices were determined by immersion in liquids of known index, using white light, and are believed to be accurate within 0.003.

TABLE 25.—*Location and description of igneous-rock samples*

Sample No.	Location		Depth of water (fathoms)	Type of rock
	Latitude (N.)	Longitude (E.)		
43A-1	12°09′	164°44′	1,030–810	Basaltic tuff-breccia.
43A-2	12°09′	164°44′	1,030–810	Scoriaceous olivine basalt.
43B	12°03′	165°00′	1,140–820	Basaltic tuff-breccia.
43C-1	12°03′	164°57′	1,150–850	Basalt.
43C-2	12°03′	164°57′	1,150–850	Basaltic glass.
43D-1	11°57′	164°59′	1,150–820	Rhyolite pumice, probably exotic.
43D-2	11°57′	164°59′	1,150–820	Much altered basaltic lava, possibly nepheline basalt.
43DD-1	11°48′	164°50′	880	Olivine basalt lapilli tuff.
43DD-2	11°48′	164°50′	880	Olivine basalt.
43E	11°47′	165°11′	1,150–860	Altered basaltic lava, possibly nepheline basalt.
43JJ	11°45′	165°12.5′	740	Rhyolite pumice, probably exotic.
44A	11°16′	165°30′	2,010	Weathered rock debris, probably olivine basalt.
44B	11°22½′	165°31′	1,150	Core, the lower portion consisting of basaltic ash and lapilli tuff.
44I	11°31′	165°37′	1,000	Olivine basalt.

DESCRIPTIONS OF ROCK SAMPLES

Sample 43A. Basaltic tuff breccia and scoriaceous olivine basalt.—The sample consists of three parts, as follows: one fragment of tuff-breccia 60 cm across, covered with 0.5 cm of manganese oxide; one fragment of similar tuff-breccia 30 cm across; and 4 angular fragments of volcanic rock 2 to 4 cm across.

The two large fragments of tuff-breccia are yellowish brown, and easily friable. The tuff is much altered to clay minerals. The freshest surfaces show many angular fragments, some of them as much as 3 cm across but most of them less than 1 cm, embedded in a fine-grained matrix. Irregular cracks are filled with pale brown to white chert, some of which contains the remains of Foraminifera.

The small fragments of volcanic rock are brownish gray scoriaceous olivine basalt, enclosed in a crust of black manganese oxide averaging about 2 mm thick. Two thin sections of the rock were examined. Microphenocrysts of labradorite, altered olivine, and magnetite lie in a matrix of altered brown glass. The labradorite grains are lath-shaped, and range up to 0.4 mm long. They commonly show albite and Carlsbad twinning, and some also show pericline twinning. The large grains are zoned from labradorite-bytownite in the middle to intermediate labradorite on the outside. A few olivine microphenocrysts attain lengths as great as 0.7 mm, but most are less than 0.2 mm long. They are entirely altered to bright red iddingsite. Few microphenocrysts of magnetite exceed 0.1 mm across. The glassy matrix is clouded with very fine grained alteration products.

The vesicles are nearly round in cross section and constitute about 55 percent of the rock. Most are lined with a very thin layer of isotropic material, probably opal, as much as about 0.01 mm thick, within which is a slightly thicker layer of pale-green fibrous chlorite. Some vesicles are filled with analcite, for the most part isotropic but rarely very weakly anisotropic. Irregular or rounded masses of opaque black manganese oxide also were observed in some of the vesicles, and a few secondary veinlets of analcite and manganese oxide have formed along fractures. From its structure, the rock appears almost certainly to be pyroclastic.

Sample 43B. Basaltic tuff-breccia.—This sample is very similar to the large fragments of 43A.

Sample 43C. Basalt and basaltic glass.—Four angular fragments of volcanic rock and one rounded fragment were examined. The angular fragments are as much as 6 cm across, partly covered with manganese oxide. The rounded fragment is possibly a pebble.

The rock of the angular fragments is a grayish-brown lava, sparingly vesicular. The vesicles are very irregular in outline. From its general structure the rock appears probably to have come from an aa flow. Megascopically, the rock is nonporphyritic. It has not been studied in thin section, but crushed fragments examined in oils proved to be of basaltic composition. Microphenocrysts of labradorite lie in a groundmass composed of labradorite, slightly greenish monoclinic pyroxene, and opaque iron oxide, in a fine-grained altered matrix which probably was originally glassy. The larger grains of pyroxene are augite, but the nature of the smaller grains was not determined. A few reddish-brown grains appear to be iddingsite formed by the alteration of olivine.

The slightly rounded fragment (pl. 33) is variegated in color, ranging from light brown to black. The rock is volcanic glass, with a refractive index of 1.609 ±0.003, containing a few grains of labradorite. Some patches of the glass show weak devitrification. In small fragments under the microscope the glass is pale brownish green. The composition, as determined from George's (1924) curves is about 47.5 percent silica, with the proportions of lime, magnesia, and iron high, and of potash low. The large size (2 by 2 by 2½ cm) of the glass fragment as compared to subaerially chilled glass fragments in the volcanic rocks of Hawaii may be related to under-water eruption.

Sample 43D. Rhyolite pumice and much altered basaltic lava (nepheline basalt?).—The sample consists of 2 parts: two rounded pebbles of pumice 3 cm in diameter; and three freshly broken angular fragments of lava as much as 10 cm across.

The fragments of pumice are pale gray and highly vesicular. The vesicles show only moderate stretching. No megaphenocrysts are present, but microphenocrysts of quartz, sanidine, oligoclase, and hypersthene reach a length of 0.7 mm. The glass of the matrix is colorless, with a refractive index of 1.498 ±0.003, which according to George (1924) corresponds to a silica content of about 72 percent. The pumice therefore is classed as rhyolitic.

The angular fragments of lava are brownish gray and dense. They are enclosed in a shell of manganese oxide averaging approximately 2.5 cm thick. The lava contains moderately abundant yellowish to brownish white phenocrysts as much as 2 mm across which have the characteristic outlines of olivine. In thin section the former olivine phenocrysts are completely altered, very largely to a mixture of fine fibrous chloritic and serpentinous material. Microphenocrysts of augite as much as 0.8 mm long also are present. The augite is slightly purplish, with strong dispersion, and is probably titaniferous. The groundmass consists largely of subhedral grains of slightly purplish brown monoclinic pyroxene and less abundant magnetite, between which are small irregular masses of chloritic material probably derived by alteration of olivine, a few irregular patches of colorless isotropic material which appears to be glass, and many tiny irregular pores into which project grains of pyroxene. The texture of the rock resembles that of some nepheline basalts of the island of Kauai, in the Hawaiian group. However, although staining with methylene blue produced abundant coloration in the slide, all of the stained material appears to be alteration products rather than feldspathoid.

Sample 43DD. Olivine basalt lapilli tuff and olivine basalt.—The sample consists of two parts. One, weighing about 200 pounds, is a soft, friable greenish-brown igneous rock, covered with a shell of manganese oxide. Several freshly broken angular pieces of this rock were recovered, one of them 50 cm long. The other portion of the sample consists of a few subrounded pieces of grayish-brown igneous rock, as much as 7 cm across, with a coating of manganese oxide 1 to 2 mm thick.

The large fragments of greenish brown igneous rock are olivine basalt lapilli tuff. The thin section shows the rock to consist largely of fragments of brown glass, much altered to green chlorite, within which lie abundant phenocrysts of feldspar and some of altered olivine as much as 2 mm long. The former olivine phenocrysts are recognizable only by their outlines and the preservation of some of their characteristic fracture pattern. The original mineral has been entirely altered to chlorite and serpentinous material, with a little fibrous zeolite. The feldspar is in part fairly fresh, and in part altered to chlorite. The fresh portions are calcic labradorite to labradorite-bytownite. Subspherical vesicles are filled with chlorite and analcite.

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The fragments of this altered glassy olivine basalt are angular, and in part show distinct arcuate outlines characteristic of pyroclastic shards. The spaces between the shards are filled with an aggregate of chlorite and analcite. In the hand specimen some of the fragments are as much as 2 cm across.

The small subrounded fragments also are olivine basalt. The rock contains moderately abundant phenocrysts of altered olivine and scattered phenocrysts of feldspar as much as 1 mm long, in a dense groundmass. No thin section of the rock was cut. Under the microscope, fragments crushed in oil showed phenocrysts of olivine entirely altered to reddish brown iddingsite, phenocrysts of plagioclase, and microphenocrysts of monoclinic pyroxene, in a groundmass of glass heavily clouded with finely granular iron ore. The pyroxene is augite, with about $+2V=55°$. The larger grains of plagioclase show normal zoning from sodic bytownite ($\beta=1.570 \pm 0.003$) to labradorite-bytownite ($\beta=1.567 \pm 0.003$).

Sample 43E. Altered basaltic lava (nepheline basalt?).—Fragments of brownish-gray nonporphyritic sparingly vesicular lava, with a coating of manganese oxide as much as 2 mm thick.

The thin section shows abundant microphenocrysts of olivine totally altered to aggregates of chlorite and serpentinous material, analcite, and a birefringent zeolite. Microphenocrysts of augite also are present, and show no signs of alteration. The augite has $+2V=60°$, and strong dispersion with r greater than v. It is slightly purplish brown in color, and may be titaniferous. The microphenocrysts grade into a groundmass consisting of augite, magnetite, chlorite, analcite(?), and possibly a little unaltered glass. No feldspar or feldspathoid could be recognized, but they may have been destroyed in the alteration of the rock. Some of the patches of analcite(?) in the groundmass have a somewhat square outline like that of nepheline grains in the groundmass of some Hawaiian lavas. The texture and general appearance of the rock also is strongly reminiscent of the ultramafic nepheline basalts ("ankaratrites") of the island of Kauai. It could be that the rock was originally an "ankaratrite."

Sample 43JJ. Rhyolite pumice.—Two rounded pebbles of white pumice, one 2 cm and the other 5 cm across.

The rock is rhyolite pumice closely resembling that of sample 43D. Rare phenocrysts of andesine ($\beta=1.556$), approximately 0.5 mm across, are present. The smaller specimen also contains a few slender phenocrysts of hypersthene up to about 1 mm long, and a few phenocrysts of magnetite. The rest of the rock is glass, colorless under the microscope, with a refractive index of 1.498 ± 0.003. The larger specimen is much the same as the smaller one, except that no hypersthene was observed in it. Shells of Foraminifera are embedded in the vesicles in the outer portions of the fragments.

Sample 44A. Weathered rock debris, probably olivine basalt.—One gram of powdery reddish-brown material.

Under the microscope the material appears to be weathered igneous rock debris. Small grains of augite are fairly abundant, and larger reddish brown grains appear probably to be iddingsitic material formed by alteration of olivine. Foraminiferal tests are fairly abundant. The original rock was probably an olivine-bearing basaltic lava.

Sample 44B. Core, largely ash and tuff.—Twenty-eight centimeters of core, as follows (measurements from top of core):

	Centimeters
Light-buff *Globigerina* ooze, with a pebble of volcanic tuff-breccia 1 cm across 2.5 cm below top	11.5
Light-brown fine-grained palagonitic ash, containing abundant Radiolaria, Foraminifera, and other calcareous organic debris	14
Dark-brown ash, like that above, but the volcanic grains a little coarser. Black grains as much as 0.7 mm across are scattered throughout the sample and appear to be altered volcanic glass heavily impregnated with very fine dusty iron ore	16.5
Light-brown fine-grained ash, like that from 11.5 to 14 cm	18
Greenish-gray fine-grained ash, containing black fragments as much as 1 mm long. Microscopically, it is similar to the overlying ash but contains little palagonite. The volcanic grains are pale brown, and show very fine-grained crystallization owing to devitrification. The black grains are similar to those between 14 to 16.5 cm. All the material above 19 cm is easily friable	19
Reddish-brown ash mottled with green ash and white organic debris. The ash is composed largely of reddish-brown palagonitized glass, with less abundant pale-brown devitrified glass, and abundant organic debris. The black grains are glass heavily charged with dusty iron ore. The material is moderately friable	23
Moderately well cemented reddish-brown lapilli tuff, consisting of angular fragments of vesicular glass as much as 8 mm across, in a matrix of finer volcanic grains and zeolites. The cementation apparently is the result of deposition of zeolites between the volcanic grains. Most of the zeolitic material is isotropic, but some is weakly anisotropic and very finely fibrous, the length-slow fibers commonly radiating from a central point. The refractive index of the isotropic form is about 1.48, and that of the anisotropic form about 1.50. The isotropic zeolite is probably either analcite or faujasite. The anisotropic zeolite is probably epistilbite. Most of the glass fragments are altered to brownish-red palagonite, but a few of pale, slightly greenish-brown color show no alteration other than slight devitrification. Calcareous organic debris is present in some spaces between the volcanic grains	28

Sample 44I. Olivine basalt.—One subangular fragment of moderately vesicular brownish-gray volcanic rock 3 cm across, with a coating of manganese oxide as much as about 0.5 mm thick.

The rock is a much altered olivine basalt. Under the microscope it is seen to consist of an altered pilotaxitic groundmass, containing scattered phenocrysts of olivine completely altered to reddish-brown iddingsite. Former feldspar grains in the groundmass, recognizable by their lath-shaped outlines, are largely altered to fine-grained sericite. Pyroxene is no longer recognizable, but is probably represented by very fine-grained masses of chlorite, clay minerals, and iron oxide.

Approximately 50 percent of the volume of the rock consists of subspherical vesicles. Some of the vesicles contain a weakly birefringent zeolite. Others are lined with chlorite, or partly filled with manganese oxide or calcite. Some of the calcite in vesicles near the edge of the fragment is recognizable as organic debris. Some vesicles contain an outer shell of pale-green chlorite, either directly in contact with the walls or separated from them by a thin layer of colorless isotropic zeolite(?), and an inner shell of weakly pleochroic brown or greenish-brown material, possibly prochlorite, which has a weakly fibrous structure with negative elongation of the fibers, absorption Z' greater than X', and birefringence, approximately 0.008.

In general structure the rock could have originated either as a highly vesicular portion of a pahoehoe flow, or as pyroclastic cinder. The fact that the groundmass apparently was originally very largely crystalline would, on the basis of comparison with Hawaiian volcanic rocks, strongly indicate a flow origin for the rock.

DISCUSSIONS AND CONCLUSIONS

Except for the two samples of rhyolite pumice, all of the igneous rocks collected on the Bikini-Sylvania Guyot are of general basaltic character. Several are typical mid-Pacific olivine basalts. Two of the samples, 43D–2 and 43E, bear a strong resemblance to nepheline basalts of the island of Kauai in the Hawaiian group, but are too much altered to permit positive identification. There appears to be little doubt that the rock suite as a whole belongs to the general mid-Pacific petrographic region (Macdonald, 1949, pp. 1588–1592), characterized by predominant olivine basalts with associated lesser amounts of nepheline-bearing lavas and sodic andesites and trachytes.

The samples of rhyolite pumice are almost certainly exotic—drifted in from some rhyolite-producing volcano along the Pacific border. Similar rounded rhyolite and dacite pumice fragments occasionally are found on the present-day beaches of the Hawaiian Islands, and have been found by C. K. Wentworth (personal communication) in elevated Pleistocene reefs on the windward side of the island of Oahu. Two other pieces were picked up on the beaches of Bikini. Rhyolite pumice may float for long distances before it becomes sufficiently saturated with water to sink. The pebbles found in Hawaii are believed to have drifted in probably from Aleutian volcanoes, or possibly from Japan or Kamchatka. It is not improbable that the rhyolite pumice in the Bikini area came from one of the same sources, drifted by the great current loop formed in the north Pacific by the Japan, California, and North Equatorial Currents.

The presence of essentially unaltered glass in some of the specimens (e. g., sample 43C–2) is significant. Volcanic glass is unstable, and crystallizes with the passage of time. Fresh undevitrified glasses of great geologic age are rare or unknown. Grout (1932, p. 233) states that there are no fresh glasses of Archean age, and few older than Carboniferous. Tyrrell (1929, p. 82) also believes that practically no undevitrified glasses are of pre-Carboniferous age. It has been suggested that volcanic glass formed beneath the ocean and never subsequently exposed to atmospheric action might remain vitreous for longer periods than ordinary subaerial glasses. However, devitrification is not essentially a process of weathering, but is merely the delayed crystallization of a highly viscous supercooled liquid. It does not appear probable that submersion beneath water would materially slow up this process. Indeed, absorption of water by the glass might well increase the rate of crystallization. Therefore the presence of fresh glass in the samples makes it improbable that the volcanic rocks of the Bikini-Sylvania Guyot are older than late Paleozoic, and very improbable that the Sylvania Guyot is pre-Cambrian in age (Hess, 1946).

Four of the basaltic specimens, constituting one-third of the specimens believed to have originated in the Bikini-Sylvania area, are certainly pyroclastic, and 2 more may be. The proportion of pyroclastic rocks in Mid-Pacific subaerial basaltic volcanoes is very small, of the order of 1 percent or less of the total volcanic structure. Thus the proportion of pyroclastic rocks among the Bikini specimens is disproportionately large as compared, for example, to the Hawaiian area. The greater proportion of pyroclastic material in the Bikini area may be the result of submarine eruption, the explosivity of the erupting magma being greatly increased by contact with sea water. In the Hawaiian Islands most of the large pyroclastic cones, such as Diamond Head and Punchbowl on Oahu, are of phreatomagmatic origin, formed where ascending magma came into contact with water-saturated reef rocks. The tuff-breccia and lapilli tuff of samples 43A, 43B, 43DD, and the lower portion of 44B resemble in general structure material of the Hawaiian tuff cones. Palagonitization is, however, much less abundant in the Bikini Atoll than in the Hawaiian tuffs, possibly because of lack of exposure to atmospheric oxygen during underwater eruptions at Bikini Atoll.

Both the abundance of pyroclastic material and the highly vesicular character of some of the lava fragments from the Bikini-Sylvania area indicate that the volcanic eruptions which formed them probably did not take place at great depths in the ocean. Rittmann (1936, p. 52) has pointed out that in deep water the hydrostatic pressure should be so great in comparison with the magmatic gas tension that explosive eruption would be prevented or greatly restrained. The vesicularity of the lava samples from the Bikini area is of the same order as that of Hawaiian volcanic rocks. However, the Bikini samples came from depths averaging about 1,000 fathoms, and at that depth the hydrostatic confining pressure is approximately 178 atmospheres, or more than 178 times as great as the atmospheric pressure during subaerial Hawaiian eruptions. Under such conditions, assuming a perfect gas at a temperature about the same as that of erupting Hawaiian lava, since pressure and volume are reciprocal in the perfect gas equation ($pV=nRT$) the gas content of the Bikini magma would have had to be approximately 178 times as great as that of Hawaiian magma to produce the same degree of vesicularity. Because the perfect gas laws do not hold at such high pressures, the figure has no value beyond indicating that a very large increase in the weight percentage of volatiles, as compared to that of Hawaiian magmas, would be necessary to produce the observed vesicularity in the Bikini volcanic rocks if they were erupted at or near the depth in the ocean at which they were collected. However, because the consolidated rock products are very similar, it does not appear reasonable to assume an original volatile content in the Bikini magma of radically different magnitude from that of Hawaiian magma.

It is possible that the volatile content of the Bikini-Sylvania magma when first erupted may have been increased by the absorption of sea water under the high pressures at depths of several hundred fathoms, but it appears very improbable that such absorption would have increased the volatile content by any such amount as that necessary to bring about the observed vesiculation at depths in the vicinity of 1,000 fathoms.

Instead, it appears probable that the Bikini and Sylvania volcanic rocks were erupted in a depth of water much shallower than that in which they now are found. This, in turn, implies a sinking of the guyot relative to the ocean surface, probably by an amount of several thousand feet. It is reasonable to suppose the sinking to have been isostatic, in response to the great load of material heaped on the earth's crust during the building of the Bikini and Sylvania volcanoes.

Since Darwin first proposed his classical subsidence theory of the origin of coral reefs, evidence of marked subsidence of central Pacific islands has been recognized by many workers. Thus Dana (1864, p. 587) believed that islands over a large portion of the Pacific had subsided not less than 6,000 feet. More recently Hobbs (1944, p. 224) has arrived at a figure of about 10,000 feet for the relative submergence of the ocean floor, and Hess (1946, p. 790) a figure of about 3,000 feet for the relative rise of the ocean surface caused by accumulation of sediments since the end of pre-Cambrian time. On the island of Oahu, Hawaii, alluviated valleys extend 1,200 feet below sea level (Stearns and Vaksvik, 1935, p. 170), indicating a subsidence relative to sea level of at least that amount. Stearns (1945, p. 621, 624) has expressed belief in a general subsidence of the floor of the Pacific basin of great but unspecified amount, possibly as great as 35,000 feet. Geophysical measurements of the thickness of sediments at Bikini led Dobrin, Perkins, and Snavely (1949, p. 826) to hypothesize a sinking of at least 2,000 to 3,000 feet, and possibly 7,000 to 13,000 feet. Ladd (1950, p. 212) cited concentration of unworn shells in cores from Bikini obtained at a depth close to 1,000 feet indicating deposition in very shallow water. In recent general treatments of the geology of the oceans, both Shepard (1948, p. 276) and Kuenen (1950, p. 476–7) have recognized general subsidence as a factor in the formation of coral reefs.

Assuming the density deficiency of the volcanic rocks of the Hawaiian ridge to be 0.4, as compared to the average density of the suboceanic crust, Betz and Hess (1942, p. 109) calculate that complete isostatic adjustment of the Hawaiian Islands would produce a downbowing of the crust of a little more than 20,000 feet. Large positive anomalies suggest, however, that compensation is not complete (Betz and Hess, 1942, p. 111). Recent work by Woollard (1951, p. 367) suggests an actual subsidence of the island of Oahu of about 9,000 feet, with a theoretical total subsidence of 15,000 to 18,000 feet needed to bring about complete isostatic equilibrium. If the composition of the Bikini-Sylvania volcanic mass was similar to the Hawaiian volcanoes and originally of comparable height above the ocean floor, the expectable isostatic sinking there should be similar in amount to that in the Hawaiian area.

Thus the hypothesis of sinking of Sylvania Guyot of several thousand feet is not discordant with general theory, or with geological and geophysical evidence from other parts of the Pacific, and the agreement of conclusions based on petrographic evidence with those based on other types of evidence is gratifying.

GUYOTS ADJOINING ENIWETOK ATOLL

In 1946 Hess described the guyots adjoining Eniwetok Atoll, one on the south, the other on the northwest, pointing out that the atoll appeared to rest in part on these 2 structures at a depth of 700 fathoms. As mentioned earlier in the discussion of Eniwetok's outer slopes, many additional soundings near the atoll were obtained by U. S. S. *Bowditch* in 1944 and by the *Bowditch* and the U. S. S. *Sylvania* during Operation Crossroads. All available data were used constructing chart 6. Radial profiles some of which cross the terrace-like guyots are shown in figure 44.

GUYOT NORTHEAST OF ENIWETOK ATOLL

The U. S. Navy Hydrographic Office Chart No. 5413 of the northern Marshall Islands indicates the presence of an elevated flat area northeast of Eniwetok Atoll. A few additional soundings in the area are given by H. O. Miscellaneous Chart No. 11,851, which is an overlay of Chart No. 5413. In order to learn more about its topography, the course of U. S. S. *Sylvania* en route from Eniwetok Atoll to Bikini Atoll was set to cross the shallowest reported soundings on the guyot, 700 fathoms. Figure 58 shows the results of the brief midnight survey. About 160 soundings were taken by

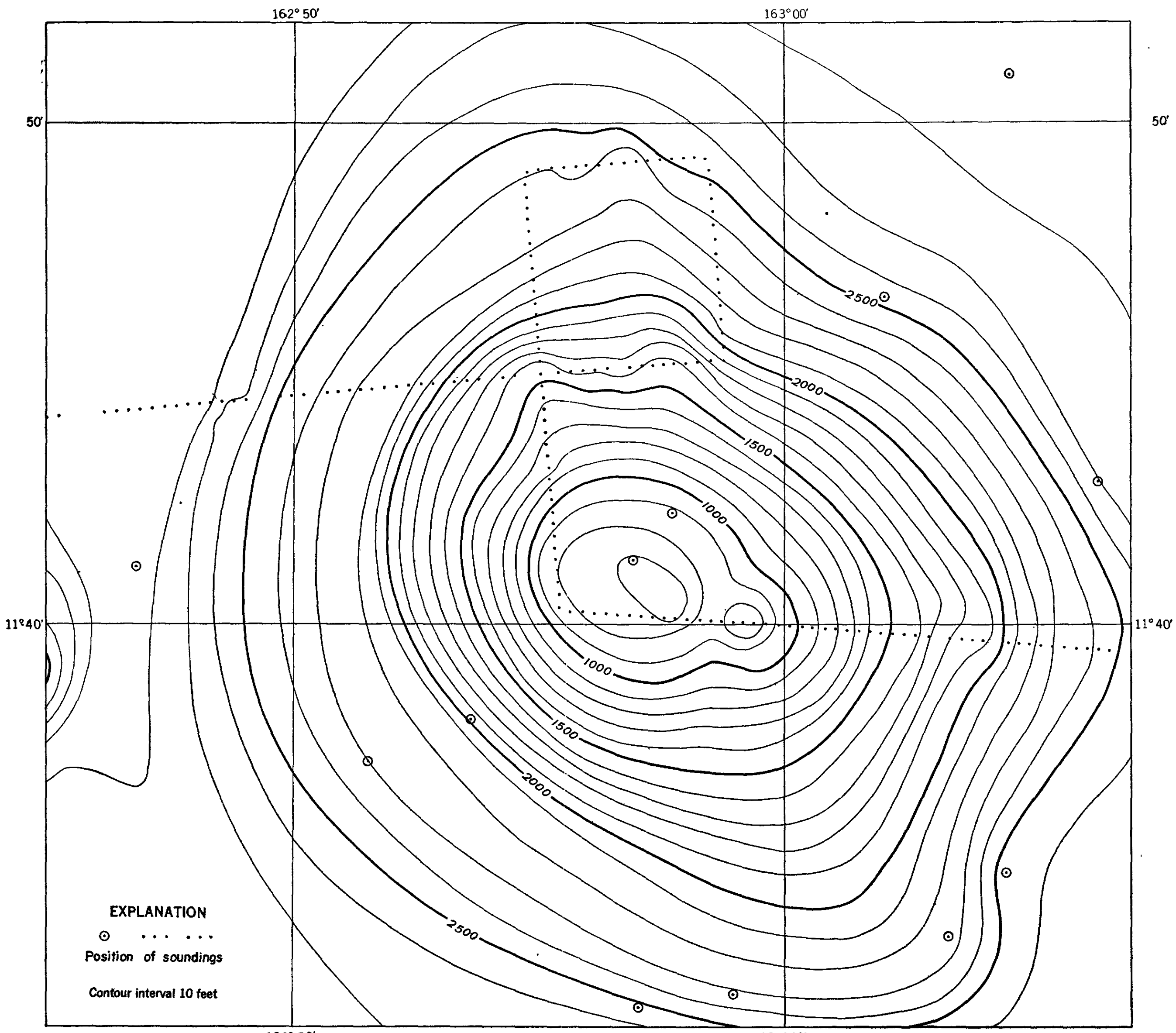

FIGURE 58.—Contour chart of guyot northeast of Eniwetok Atoll.

the *Sylvania* and these are indicated by dots on the chart. About a dozen earlier soundings from H. O. 11,851 were also used. These earlier soundings were collected as a matter of routine by merchant or warships en route probably from Hawaii to Eniwetok Atoll. It was necessary to shift one of the earlier lines about 3½ miles southward so that it would fit the *Sylvania* soundings. Another line had to be omitted because it was completely unreasonable in the light of the relatively accurate *Sylvania* soundings. Because the course of the *Sylvania* was laid out on the basis of the position of the shallowest earlier sounding, which proved to be erroneous, the *Sylvania* nearly missed the guyot.

The final chart shows that the top center of the guyot is located at latitude 11°41′ N., longitude 162°57′ E., about 40 miles east-northeast of the closest side of Eniwetok Atoll. The top is fairly flat, with a shallowest depth of 700 fathoms, indicated by 3 soundings. The edge of the flat top seems to be at about 750 fathoms, and its diameter is 3 to 4 miles. Beyond the edge of the flat top, the sides of the guyot have a slope of about 15° to a depth of 1,500 fathoms, below which the steepness decreases and the cone merges with the deep-sea floor at about 2,800 fathoms.

GUYOTS NORTHEAST OF BIKINI ATOLL

About 50 miles northeast of Bikini Atoll the charts show a sounding of 1,020 fathoms in a region of general depths twice as great. While en route to some of the rehearsals and actual bomb tests, courses of the U. S. S. *Sylvania* were set for crossing this shallow area. The soundings by the *Sylvania*, together with one line by the *Bowditch*, outline the guyot (chart 10). The guyot has a flat top with the shallowest sounding of 496 fathoms near the middle, the shallowest depth of any guyot in the northern Marshall Islands. Depths at the periphery average about 597 fathoms. So far as the data permits interpretation, the guyot appears to be roughly circular in outline with maximum side slopes of about 22°.

Two of the sounding lines show the presence of another guyot located about 20 miles farther eastward. Although this one cannot be considered adequately sounded, it is also flat-topped and has minimum depth of less than 678 fathoms.

GUYOT NORTH OF RONGELAP ATOLL

During the surveys around Rongelap Atoll and while en route to bomb tests, soundings showed the presence of a previously unknown guyot about 20 miles north of Rongelap Atoll (chart 9). This guyot, like the others, is flat-topped, with a minimum depth of 678 fathoms near the middle. It differs from others, however, in rising only about 800 fathoms above its surroundings because of its position atop a broad slope north of the group of atolls.

GUYOTS SOUTH OF RONGELAP ATOLL

About 35 miles south of Rongelap Atoll the chart soundings showed a broad shallow area which was investigated in a 1-night run by the *Sylvania*. Additional soundings were obtained on request by the U. S. S. *Walke* (DD *715*) en route between Bikini and Kwajalein Atolls. Another line of soundings was obtained on U. S. S. *Horizon* in 1950. Scattered soundings by other ships, shown on H. O. Miscellaneous chart 11,851, were also used. The available data, though sketchy, indicates that the area is a grouping of three separate guyots whose bases are joined forming a broad irregular platform (chart 11). Soundings over the easternmost guyot indicate it to be flat-topped with a minimum depth of perhaps slightly less than 963 fathoms. The sounding lines probably did not cross the shallowest parts of the two westernmost guyots but the shallowest recorded depths for these are 1,045 and 1,066 fathoms. The available soundings indicate that two of the guyots together form a nearly continuous ridge trending northeast.

GEOLOGIC HISTORY

In spite of the fact that more is now known about Bikini Atoll and its surroundings than about any other Pacific atoll there are many gaps in its geologic record and any attempt to write a connected account of the atoll's history involves considerable speculation, particularly as regards the earliest stages. The problem of the origin of atolls such as Bikini Atoll has not yet been completely solved but much progress toward such a solution has been made.

GUYOT AND ATOLL FOUNDATIONS

GUYOTS

In the northern Marshall Island region both atolls and guyots are distributed along the same chains. As they have some features in common it is necessary to consider the possibility of a genetic relationship. A comparison of some of the features of guyots and atolls is given in figures 57, 59, 60, 61, and 62. Guyots are generally similar to atolls in size and shape of outline. Several points of difference, however, are apparent: (1) Volcanic rocks have been dredged from the upper part of the rims of guyots but only low on the flanks of atolls. Thus, it is evident that at least some guyots are not merely drowned atolls. (2) The side slopes of the upper 500 fathoms of the atolls are about twice as steep as those of the upper 500 fathoms of the guyots (fig. 61, table 26). (3) The periphery of the guyot is rounded in profile in contrast to the sharp reef edge of

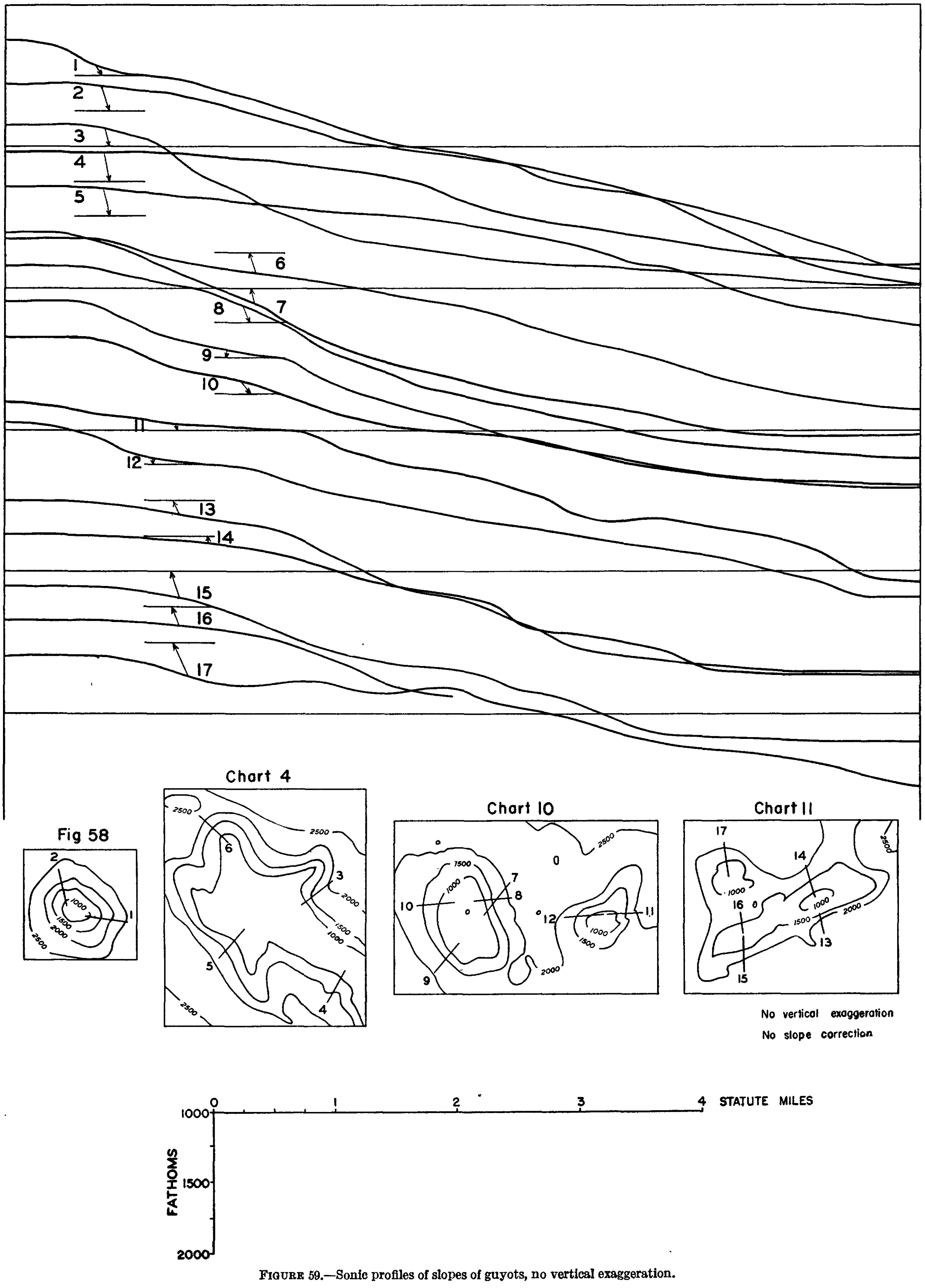

Figure 59.—Sonic profiles of slopes of guyots, no vertical exaggeration.

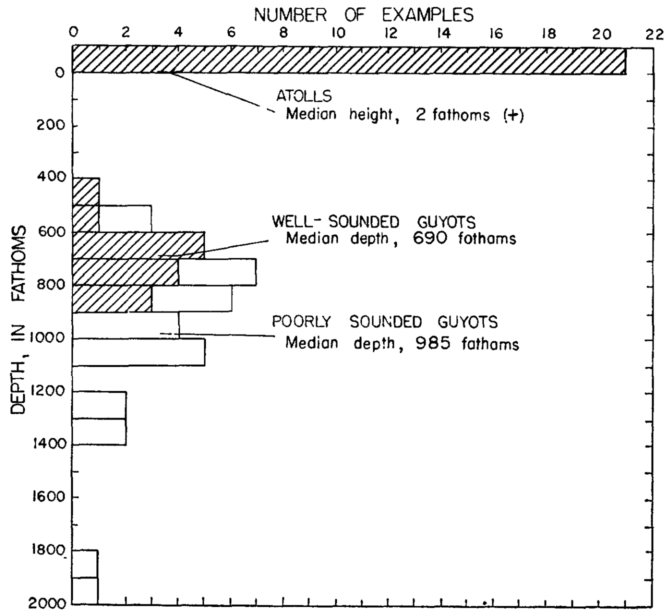

FIGURE 60.—Depth distribution of tops of atolls and guyots.

the atolls (fig. 62; compare fig. 59 with figs. 28, 44, 52). (4) The top of Sylvania Guyot and the tops of others appear to be smoother than the knoll-studded areas in atoll lagoons. (5) The highest point on the guyots is near the center, whereas that of the atolls is at the edge—the islands and main reef (fig. 63).

The presence of volcanic rock suggests that the guyots are either fault blocks, unmodified volcanoes, or volcanoes bevelled by past wave erosion. Fault blocks, like those off southern California (Shepard and Emery, 1941) or like the much larger scale Mid-Pacific Mountains are bounded by straight steep scarps, many of which extend downward into a linear trough. The slopes around the atolls and guyots, however, are roughly circular in plan, with projecting buttresses and broad gentle lower slopes which gradually merge into the deep-sea floor. Some fault blocks, such as that of San Clemente Island (fig. 63), also have tilted surfaces, unlike the guyots.

TABLE 26.—*Average slopes of atolls and guyots*

	Average slopes for indicated depths in fathoms							
	0–250	251–500	501–750	751–1000	1001–1250	1251–1500	1501–1750	1751–2000
Atolls	32°	25°	20°	15°	14°	10°	5°	
Guyots				14°	11°	13°	14°	

If guyots are due to submarine vulcanism, unmodified by subsequent erosion, they should show some similarity to known volcanoes. Comparison with the flat, virtually uneroded top of Mauna Loa, the flattest volcano of which the authors are aware (fig. 63), reveals that the guyots are much flatter. San Juan Seamount off California (fig. 63) is presumed to be a submarine volcano because of the physiographic relationships and the collection of basalt fragments, but it is far steeper and completely unlike the tops of even the smallest guyots in the Marshall Islands. The side slopes of the guyots, however, are of about the same steepness as those of Mauna Loa.

Lastly, the guyots may be volcanoes bevelled by past wave erosion. The elliptical plan and the degree of steepness of the side slopes are similar to known volcanoes and to other inferred volcanoes of the sea floor. The greater flatness of the top of the guyots may be accounted for through bevelling by past wave erosion. Comparison in figure 63 of the cross sections of Sylvania Guyot and Northeast Bank (a submarine bank off California thought to be a wave-bevelled volcano) shows that each has a nearly smooth, very gently sloping top surface. On Northeast Bank the interpretation of former wave action is based on the dredging of numerous rounded cobbles and pebbles; a few rounded fragments of altered basalt have also been obtained from Sylvania Guyot. Hess (1946) in his discussion of

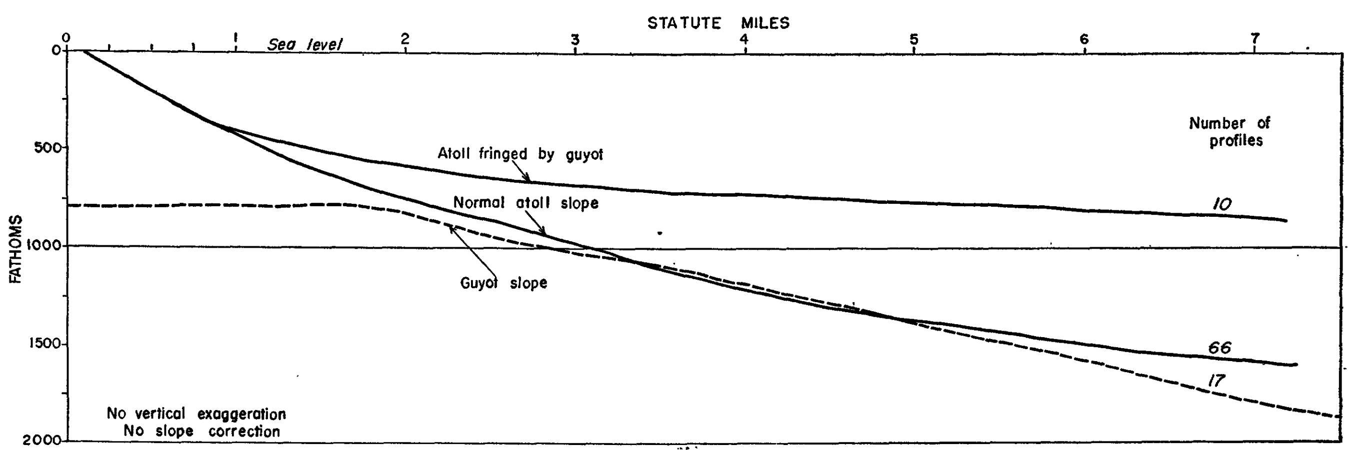

FIGURE 61.—Average slopes of 5 atolls and 5 guyots.

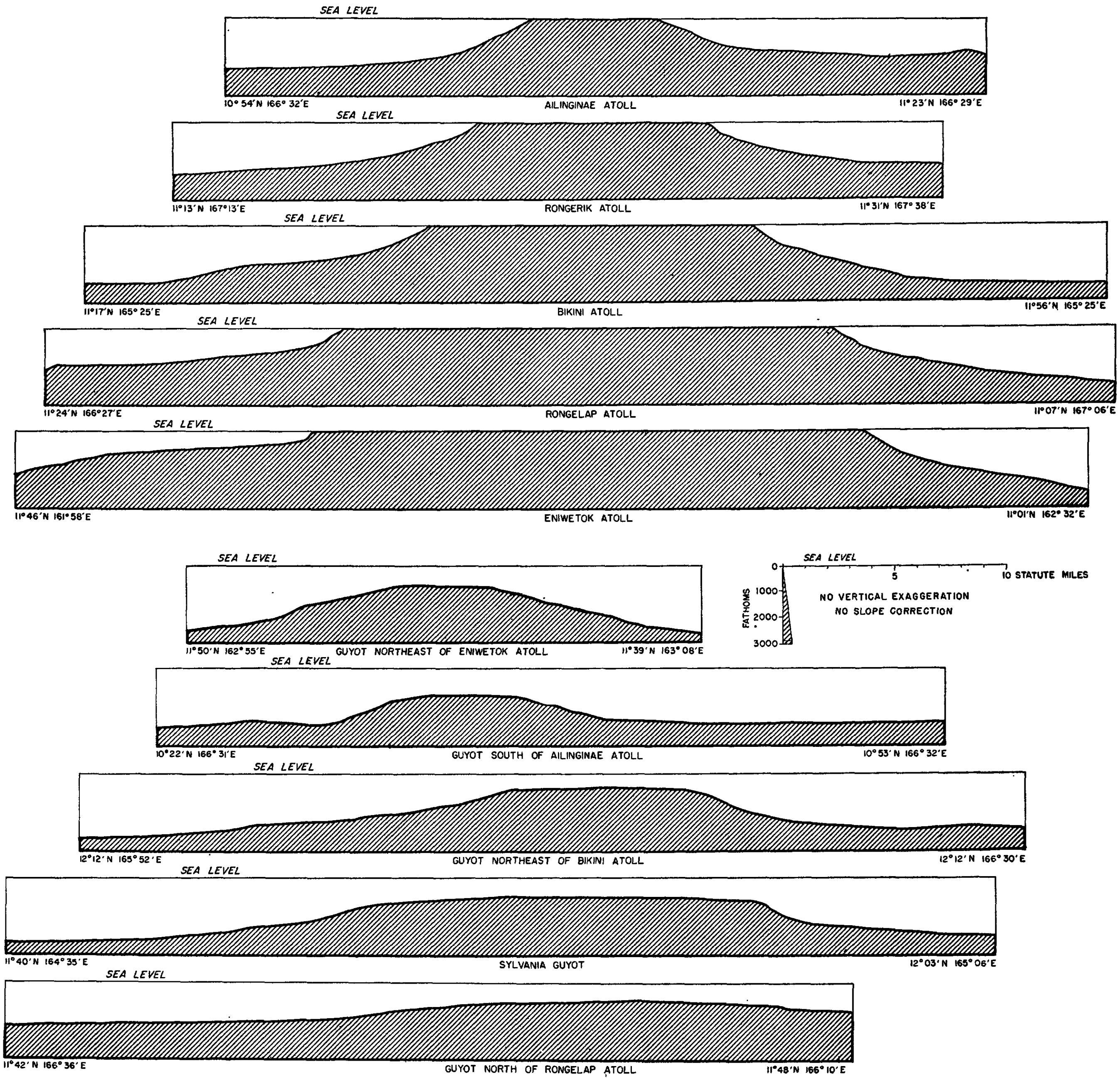

FIGURE 62.—Cross sections of atolls and guyots. The peripheries of the guyots are rounded, those of the atolls comparatively sharp.

guyots suggested the possibility that they were formed and bevelled by wave action during pre-Cambrian time. He estimated that sediments deposited since then would have displaced about 500 fathoms of sea-water. Because of their weight the sediments may also have downwarped the bottom of the ocean several hundred fathoms, thereby submerging well below sea level any banks which had been bevelled by wave action.

The hypothesis outlined by Hess was confirmed in part by the Mid-Pacific Expedition in 1950. Rounded basaltic pebbles, cobbles and boulders were dredged from the flat tops of half a dozen guyots at depth between 700 and 1000 fathoms. One such pebble obtained from Sylvania Guyot is shown on plate 33, fig. 2. The guyots do, therefore, appear to be submarine volcanoes whose tops have been truncated by wave action. However, it now seems clear that most of them were formed long after the pre-Cambrian because the Mid-Pacific Expedition also dredged limestone containing reef corals, mollusks and an echinoid from the guyots and according to E. L. Hamilton, all are of Late Cretaceous age (Revelle, 1951*a* and 1951*b*).

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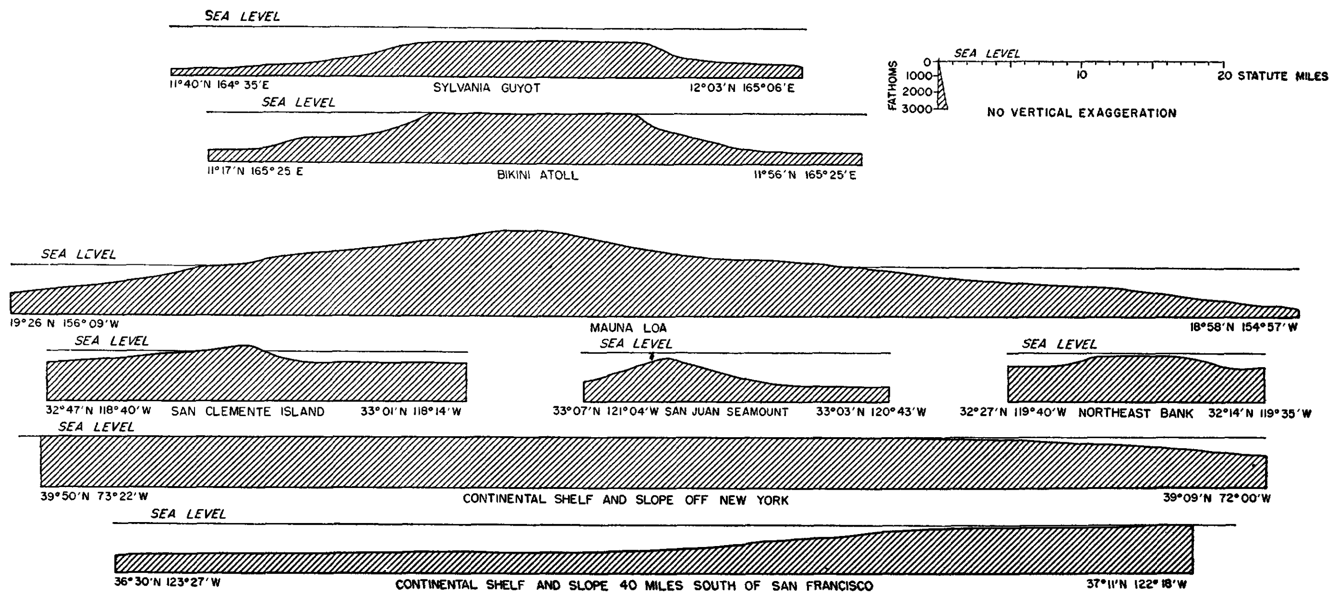

FIGURE 63.—Cross sections through Bikini Atoll and other physiographic features to show submarine slopes.

Macdonald's conclusions based on his petrographic study of the igneous rock dredged from Sylvania Guyot and the slopes of Bikini Atoll add significantly to what is known of the origin of guyots and are entirely compatible with the latest geophysical data and the paleontologic data mentioned above. Thus, Macdonald found the rocks to be basaltic and related to the rocks of the general Mid-Pacific petrographic region. He noted that the glasses were essentially unaltered and concluded that they were no older than late Paleozoic. He likewise pointed out that at least one-third of the samples were pyroclastic and postulated eruption in seawater at shallow depths.

Another point of interest is the depth distribution of the guyots. In the area of Chart 1 are 14 guyots that were considered well-surveyed because the flat top of each contains from 4 to several hundred nearly equal soundings. The depths of these guyots range between 470 and 870 fathoms and average 690 fathoms (fig. 60). The chart also contains 23 other definite guyots, but these are not well surveyed and their depth is very uncertain. The shallowest soundings on most of them may be from the upper part of the side slopes. The average depth of the shallowest sounding of each is 985 fathoms, about 300 fathoms deeper than the average known top depth of well surveyed guyots. Still other guyots may exist in the area as suggested by the presence of a number of soundings a few hundred fathoms shallower than adjacent ones of the deep-sea floor; some of these soundings may be on the lower part of side slopes of other guyots. It is quite possible, of course, that some of these deeper soundings mark the tops of volcanoes of the same age as the guyots but which did not reach to the sea level of that time and thus could not become flattened by wave erosion. Figure 60 shows the concentration of guyots within a range of a few hundred fathoms and the complete absence of them between 400 fathoms and the sea surface. This distribution is similar to that discovered by Hess (1946) for the general region of the Marshall, Caroline, and Gilbert Islands. If they are the result of past wave erosion, the guyots should have been formed at essentially identical depths. Three possible explanations for the depth of the guyots below present sea level are worthy of consideration: increase in amount of sea water, sinking of entire ocean floor, and isostatic sinking of individual guyots. According to Rubey (1951) it is most unlikely that the necessary volume of water, equal to about 30 percent of the total ocean volume, could have been produced since Cretaceous time. Sinking of the entire ocean floor also seems to be out of the question, because of the tremendous area involved. Guyots similar to those of the central west Pacific Ocean are now known from the Gulf of Alaska (Menard and Dietz, 1951), from the North Atlantic Ocean (Tolstoy, 1951), and the Indian Ocean (Anton F. Bruun, personal communication, 1952). The third explanation—individual isostatic sinking—seems to be faced by no great difficulties, and would moreover help to explain the variation in depth of guyots. It is supported by the finding of a peripheral trench around the Hawaiian Islands during the Mid-Pacific Expedition, by the greater steepness of the side slopes of guyots than those of atolls below 1,600 fathoms, and by the probable 40-foot shallower terrace depths of Rongerik as compared to Bikini, Rongelap, and Eniwetok Atolls.

If the flattening of the guyots were due to wave erosion, one might expect to find sea cliffs and uneroded remnants atop some of the guyots. Unfortunately, the sounding density is insufficient to prove clearly the existence of such features, but a fathogram which crossed the outer edge of the deep terracelike guyot northwest of Eniwetok Atoll shows two well-defined narrow and deeper terraces. Another fathogram atop Sylvania Guyot (pl. 6, fig. 1) shows a nipple which may possibly be an erosional remnant. Although wave erosion at a long-past date may have bevelled the tops of the guyots, most of that erosional surface has become buried under subsequent pelagic sediments. It is well known from studies of the sea floor off the United States, Europe, and Asia that submerged hilltops consist of rock only partly mantled by a thin layer of sand and that the outer edge of the continental shelf is commonly a zone of rock or coarse-grained sediment. Both are environments of nonaccumulation of present-day detrital sediments. On the flat top of Sylvania Guyot a number of short cores of *Globigerina* ooze were taken; however, sampling at the periphery revealed volcanic rocks and manganese oxide, a mineral often found coating bare rock surfaces on the sea floor. Evidently the original surface of the guyot is exposed only at the edge. Thus, although pelagic sediment may accumulate in the center of a preexisting flat bank, its thickness is controlled by the width of the bank and the angle of rest under existing current conditions. The shallowest depth, near the middle of the bank, is about 100 fathoms shallower than the minimum depth at which volcanic rock was recovered at the periphery. Thus, if the original wave-cut surface were perfectly flat, a maximum thickness of about 100 fathoms of *Globigerina* ooze would have accumulated since Cretaceous time. This thickness would be sufficient to smooth the surface, burying initial erosional irregularities.

The seismic work done by the Mid-Pacific Expedition under the leadership of Russell Raitt gave a much clearer picture of the foundation of Bikini Atoll and its relation to Sylvania Guyot than had been apparent before. As shown in Raitt's report [1954] and the overall summary, in the same report, given by Perkins, the basaltic mass that forms the guyot continues under the atoll, rising well above the level of the guyot as an irregular surface. This indicates clearly that guyots and atolls are fundamentally alike; it suggests that the atoll foundations were never completely bevelled by wave action and that they thus projected into the zone of reef growth if not actually above the sea and eventually became reef-crowned whereas the guyots remained without such a cap. Whereas guyots and atolls are fundamentally alike, it is entirely possible, as suggested by Hess (1948, p. 298–299), that atoll cores are younger than the youngest guyot surfaces. In his earlier paper Hess noted (1946, p. 781) that the absence of a 700 fathom bench around parts of Eniwetok Atoll strongly suggested that the assumed volcanic core of the atoll was younger than the benches projecting from the southern and northwestern sides.

Raitt's work, however, while clarifying certain relations has raised another problem for which at the present time there seems to be no satisfactory solution. His cross sections, showing the presence of materials of higher sound velocity (basalt) near the margins of the guyot were confirmed by dredging but in the central parts of the guyot his sections indicate from several hundred to several thousand feet of material with a sound velocity comparable to that of the unconsolidated limestones capping Bikini.

In summary, it appears probable that the guyots in the northern Marshall area were formed in late Mesozoic time by eruptions of basaltic materials. Mounds were built up close to the surface of the sea and some probably projected above the sea as pyroclastic cones. These were leveled by wave action in the manner observed at Falcon Island in Tonga (Hoffmeister, Ladd, and Alling, 1929). Pieces of scoriaceous rock were rounded by wave action as the mounds were flattened. Corals and other shallow-water organisms lived on the shoals in Late Cretaceous time. Since then the mounds (guyots) have sunk at similar but slightly different rates to their present positions. This sinking is believed to have been only partly isostatic in nature. Apparently in many cases the guyots sank too rapidly to permit compensatory reef growth.

ATOLLS

The guyots and atolls are distributed along the same northwest-southeast chains and are similar in size and outline. Dredging to date shows that both have basaltic foundations. Seismic data indicate that the basalt of Sylvania Guyot probably extends laterally as a somewhat irregular surface that rises under the adjoining mass of Bikini Atoll. It seems probable that similar relations exist at Eniwetok and that the surfaces of the two deep terracelike guyots adjoining that atoll probably continue laterally to form a single guyot whose center is located beneath the existing atoll. The volcanics of the terracelike guyots and those directly beneath the present atoll may have been erupted from separate centers.

All the volcanoes—including those beneath the existing atolls—were at least partially leveled by wave action in late Mesozoic time and all began to settle at about the same time. Owing to differences in size and density or to some other cause, such as local orogenic movements, they sank at different rates. Those that were incompletely bevelled or those that settled slowly were the sites of vigorous organic growth and reef building kept their upper surfaces in shallow water. This process of limestone accumulation continued through the Tertiary.

DEPOSITION OF TERTIARY LIMESTONE

At Bikini Atoll, seismic data suggest that 1 to 2 thousand feet of sediments underlie the Oligocene(?) beds encountered in drilling. This unknown section is probably lower Tertiary in large part and may contain some Mesozoic rocks.

Starting at least as early as Oligocene(?) time (Tertiary e(?))[2] the deposition of limestone seems to have been essentially continuous through much of the early Miocene (Tertiary $f_{1,2}$). The rocks all appear to be of shallow-water origin, and they probably were laid down in a lagoon not far removed from the margin of a reef. There is no evidence for a hiatus in the rocks from 2,556 to 1,127 feet, but of course such a break would be difficult to recognize from a study of cuttings alone.[3]

As the rocks accumulated, the proportions of organic constituents varied from time to time, but such variations may be explained reasonably by assuming minor local changes in environment rather than regional changes. In Oligocene(?) time, the calcareous alga, *Lithophyllum* was dominant in the facies explored by the drill. The great abundance of algae from 2,370 to 2,288 feet indicates that the accumulation kept pace with or exceeded the rate of submergence of the atoll. The diminishing of the algae near the end of Oligocene(?) time might indicate either a submergence below the zone of most prolific growth (probably a few tens of feet), or the lateral encroachment of a sandier facies that killed off the algae at least locally.

Accumulation through the lower Miocene was marked by periods in which mollusks and corals dominated and periods in which larger Foraminifera were the principal organisms. The nature of the variations that appear to occur in cyclic fashion over several hundred feet of rocks suggests that the rate of submergence of the foundations of the atoll may have varied from time to time, but there is no evidence of major changes in the sedimentation or paleoecology of the rocks below 1,127 feet.

An emergence of possible significance took place during Tertiary f time. The rocks below 1,130 feet are f_{1-2} according to Cole, and those just above are f_3. The rocks now below 1,130 feet were uplifted after deposition, were leached and were recrystallized to calcite, and were resubmerged. With the resubmergence both corals and mollusks grew profusely.

The concentration of mollusks cored at a depth of nearly 1,000 feet under Bikini island points to deposition in waters not more than a few tens of feet in depth. A pocket so rich in shallow-water forms could hardly have been accumulated on a talus slope outside the reef or even in the deeper parts of the lagoon.

Accumulation of the coral-molluscan rock continued with no apparent significant changes through the rest of Miocene and well into Pliocene time. The limestone consists of fine brown sand and silt-sized grains of calcium carbonate and many horizons show abundant well-preserved corals and mollusks. Throughout this time, shallow-water corals and mollusks are very abundant, and they probably lived near the reef in shallow lagoonal water.

DEPOSITION OF QUATERNARY LIMESTONES

It is difficult if not impossible to draw a boundary between Pliocene beds and those formed during the Pleistocene in the Pacific Islands area; it is equally difficult to separate rocks of Pleistocene age from those formed since the close of the ice age.

Lithothamnion is present in abundance at 700 feet thus suggesting a true reef environment. The rock from 700 to 447 feet is represented by several poor cores, and it is impossible to tell whether any significant changes occurred during the time these rocks were deposited. A filling of brown coarsely crystalline calcite from 631 to 735 feet indicates a change in post-depositional conditions, but what the changes were or when they occurred cannot be interpreted at present.

As deposition continued in the rocks above 447 feet, several changes of possible significance are recorded. At 447 feet, the rocks contain abundant encrusting foraminifers, a *Porolithon* different from near-surface samples, masses of alcyonarian spicules, and molds of corals and mollusks. A shallow near-reef or lagoonal environment seems likely. Above 325 feet the rocks appear to have been deposited at somewhat greater depths. A few beds of foraminiferal tests including

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[2] In the East Indies, where Tertiary stratigraphy has been worked out in great detail, the section has been subdivided on the basis of Foraminifera. Major subdivisions, or stages, are designated by letters; minor ones, called zones, by numbers. (See Leupold and Van der Vlerk, 1931.)

[3] Foraminifera that probably are of early Tertiary age were found by Ruth Todd (Cushman, Todd and Post, chap. H of the present report) in a 7-inch core of *Globigerina* sand (Bik 1176) obtained at a depth of 720 fathoms at the break in slope separating Bikini Atoll and Sylvania Guyot. The specimens were present in some abundance in this one sample but were not found in any of the samples obtained from other parts of the guyot. The species, which proved to be new, has been tentatively referred to *Gümbelina*, a genus that ranges from Cretaceous to Oligocene. Miss Todd feels that the Bikini species probably is Tertiary rather than Cretaceous, basing this interpretation largely on its resemblance to a known Oligocene form; this interpretation is supported by the occurrence with it of a Miocene species obtained at a depth of 925 to 1,175 feet in the Bikini deep hole and by the absence of Cretaceous forms known from other parts of the Pacific area. The writers concur in Miss Todd's opinion that the foraminifer in question probably came from the Tertiary rocks that form the slopes of Bikini above the level of the guyot.

abundant pelagic species indicate that there was a free circulation of ocean water. From 294 to 447 feet the rock is much recrystallized to calcite and one or more of the early Pleistocene emergences above sea level is possibly recorded here.

As the rocks from 325 to 185 feet accumulated, there was an increase in the proportion of limy sand and silt, and an increase in the abundance of lagoon-type bivalves and gastropods. The increasing fineness of the limy sand and silt, especially from 250 to 185 feet, may well represent a relatively stable interglacial phase during which the flat floor of the lagoon was filled essentially to its present configuration. The break seen in cores at this level, between the *Rotalia calcar* zone and the *Calcarina hispida* zone, is believed to represent a period of emergence in which there occurred some recrystallization of the *Rotalia calcar* zone and possibly a truncation of the atoll at the level of the present lagoon floor. This period of emergence is probably to be correlated with one of the later eustatic lowerings of sea level during the Pleistocene. When the sea level rose at the end of the glacial stage, the rocks of the *Calcarina hispida* zone accumulated, at first with luxuriant growth of coral in place, and later with medium to fine-grained coralliferous detritus. During the accumulation of these rocks, the reefs grew to the level marked by the present seaward terrace, and by the sill of the wide channel at the southeast end of the atoll.

The present broad lagoon terrace was built up inside the reef, at a depth of 25 or 30 feet, by accumulation of detritus swept off the reefs, and by luxuriant coral growth of the shallow water. The width of the terraces indicates that the sea was relatively stable for a considerable time.

Renewed emergence of the reefs during another period of lowered sea level, possibly the last, resulted in the poor to moderate recrystallization to calcite seen in the rocks of the *Calcarina hispida* zone, between 105 and 185 feet in hole 2. Subaerial erosion at this time may also have produced the large depressions in lagoon terraces of Bikini and Eniwetok Atolls. With resubmergence after this late Pleistocene glacial stage, the reefs were built up 50 feet or more to their present stands, the terraces accumulated some 10 or more feet of Recent sediments and the lagoon floor was covered by a relatively few feet of additional sediments.

The most recent emergence affected the rock of the *Calcarina hispida* zone (fig. 32) below the levels of the lagoonal terrace, at 95 feet in hole 1 and 105 feet in hole 2, and of the seaward terrace at 61 feet in hole 3. The previous emergence affected the rocks of the *Rotalia calcar* zone below the flat bottom of the present lagoon, at 175 feet in hole 1 and 185 feet in hole 2. Below 294 feet in hole 2A, and below about 284 feet in hole 1, there is an increase in the amount of recrystallized calcite in the limestone down to about 447 feet, and from 631 to 725 feet there is considerable addition of brown crystalline calcite. One or more additional emergences between 294 feet and 725 feet might be postulated to explain the two kinds of calcite, but they do not seem to be warranted at this time. Stratigraphic evidence comparable to that obtained for the later emergences might have been obtained if the rocks had been cored continuously with a more satisfactory recovery.

Lastly, the consolidation and the presence of mollusk molds at 1,127 to 1,151 feet in hole 2A indicates a probable Miocene emergence. The consolidated rocks are only 24 feet thick, but the unconsolidated rock from 1,151 to 1,300 feet or lower, contains molds along with unaltered shells, and an emergence of 200 feet relative to sea level at that time is possible.

GROWTH OF EXISTING REEFS

No doubt the first traveler ever to see living sea-level coral reefs observed some of their peculiar features and speculated on their mode of origin. Actual records of this kind go back at least to the earliest days of the last century. In 1821 Adalbert von Chamisso (1821*a*) published his "remarks and opinions" based on 3 years of voyaging with the Russian Otto von Kotzebue, but according to Emil Du Bois-Reymond (1890) at least 2 writers had suggested methods of reef origin before Chamisso. They were Johann Reinhold, who had suggested that the ring walls of atolls were built by polyps from the depths of the ocean, and Henrik Steffens, who had put forth the hypothesis of growth on the rims of submarine craters. The suggestion that atolls were formed by the growth of corals on submarine volcanic craters was cited as a "general opinion" by Captain F. W. Beechey (1832, p. 169). Darwin's ideas involving reef subsidence were first set forth in 1837. He reasoned that a fringing reef growing on a slowly subsiding foundation could be transformed into a barrier and finally into an atoll by organic growth. This hypothesis explained many of the peculiar features of reefs and was widely accepted. No serious opposition appeared until 1863 at which time Carl Semper published the results of his studies in the Palau (Pelew) Islands. His ideas on the whole were the antithesis of those held by Darwin. In later years many followed Semper's lead and a variety of alternate theories for reef origin were brought forth. Since the days of Darwin there has been no widespread agreement on the origin of coral reefs. The history of this controversy has recently been reviewed by Ladd and Tracey (1949) and will not be repeated here, though references to alternate theories, particularly the glacial-control theory so vigorously supported by Daly will be made later.

DISTRIBUTION

As has long been recognized (Vaughan, 1919, p. 189–276, Yonge, 1951) reef organisms need warm water and strong light. They also require some agitation or circulation of the water because they are fixed and the water must bring food to them. These three conditions are most widely developed in the tropic seas at shallow depths. Reef organisms must also, of course, have water of near normal salinity and a type of bottom suitable for fixation. The most influential control of reef growth is temperature, which in large part explains the marked development of reefs in the western parts of the oceans in tropical latitudes; reefs are almost entirely absent from the eastern oceanic areas because of the upwelling of cold water (Sverdrup, Johnson, and Fleming, 1946, p. 855). Plate 72 shows the general distribution of reefs throughout the world. It brings out the relation of reefs to latitude and landmasses and the control exerted by temperature. In general the reefs are within an area of 30° north and 30° south of the equator. There are few places where the reefs or even reef corals extend beyond these boundaries. It will be noted that in places where reefs extend beyond the 30° latitude boundary the isotherms of 70° (farthest north and farthest south extensions for the year in each hemisphere) bend with them.

Most of the data shown on plate 72 were first assembled by Joubin (1912) on a world map drawn on the Mercator projection. Recent investigations indicate that the occurrences of reefs around Baja California shown by Joubin are greatly exaggerated. Joubin's map followed one by Darwin (1842) which showed the distribution of reef types over most of the world. A series of maps showing the distribution of surface temperatures and their relations to coral reefs in the Pacific and Indian Oceans were published by Schott in 1935.

DEPTH OF REEF GROWTH

The distribution of reef corals and associated organisms at the surface is seen to be controlled largely by temperature but the distribution of these same organisms in depth appears to be controlled largely by light. This obviously is a very important point for it limits coral-reef growth to shallow water. Thick sections of coral reef now found beneath the sea or elevated above it must have accumulated on a subsiding foundation as suggested long ago by Darwin.

Systematic dredging has been carried out on seaward slopes of Indo-Pacific coral reefs in only a few areas, such as the Maldives (Gardiner, 1898, 1903), Funafuti (David, Halligan, and Finckh, 1904), and Hawaii (Vaughan, 1909) and the data are still far from reasonable completeness. It has generally been concluded on the basis of available data that most reef-building takes place in depths of 15 fathoms or less, that some hermatypic species extend to 25 fathoms, that a few reach as much as 40 fathoms and that the maximum depth is finally reached at 50 fathoms (Vaughan, 1919; and Vaughan and Wells, 1943). Analysis of the vertical distribution of hermatypic types at Bikini adds confirmatory data to these conclusions but suggests that in some localities the lower limit for living reef-type corals may extend to as much as 85 fathoms (510 feet), although at these depths such corals are scarcely significant contributors to the atoll. From 112 species on the surface reefs at Bikini, the number falls abruptly to about 20 at 15 fathoms, half of these being nonsurface reef species, to about 15 at 45 fathoms, practically all nonsurface species, to about 12 at 70 fathoms, finally dropping to 1 or 2 at 85 fathoms. No hermatypic types were found below this depth, down to more than 120 fathoms.

Below 30 to 40 fathoms the reef-coral fauna is marked by special species or a facies different from those of the surface-reef forms. (*Leptoseris* zone, described in chap. I of this report.) This is the bathymetric faunal zone recognized first by Gardiner (1903) in the Maldives and later at the same depths in the Hawaiian Islands by Vaughan (1907). At Bikini this zone appears to begin at a somewhat greater depth. It also appears in Bikini Lagoon but is not so clearly distinguishable. Ahermatypic corals were found at all depths in small number and variety. Truly "deep-sea" coral types come in at about 80 fathoms and continue on down as far as dredgings extended (in 1947 to 600 fathoms) as the only scleractinians. In some areas these "deep-sea" types are very abundant at depths of 200 to 600 meters (110 to 350 fathoms) (Hyman, 1940, p. 616).

Botanists and others have expressed a variety of opinions regarding the depths to which calcareous algae can exist and the depths to which they flourish and are effective rock builders. Alfred E. Finckh, one of the authors of the Funafuti Report, stated (1904, p. 134) that whereas certain forms of *Lithothamnion* had very limited bathymetric ranges one lichenous or encrusting type was found flourishing on the outer slopes of the Funafuti Atoll even down to depths of 200 fathoms. The validity of these occurrences was established, he said, by the evidence afforded by fragments broken off in situ by the chisel down to such depths and then caught in the tangles and brought to the surface during dredging operations carried on by expeditions both in 1897 and 1898. He found this type of *Lithothamnion* frequently associated with deep-sea corals. Finckh also noted (1904, p. 135) that *Halimeda* was invariably found present alive down to depths of 45 fathoms and in a single instance was found alive at a depth of 80 fathoms.

Weber (Weber and Foslie, 1904, p. 4) reported lithothamnia to depths of as much as 120 meters (393 feet). Swinnerton (1923, pp. 3–4) placed the bottom of the Coralline zone at 400 feet; he says that in this zone light is dim and animals still abundant; below about 400 feet the water is probably no lighter than on a moonless night, and that the only plants on the floor and in the water are minute algae and bacteria.

The records of Funafuti were cited by Setchell (1928, p. 1839) who stated that living nullipores were taken from the reef surface at 200 fathoms and were abundant and actively working in about 100 fathoms. Gardiner (1931, pp. 77, 79) states that *Lithothamnion* is an important builder of shoals in the tropics down to depths of 60 fathoms and that *Halimeda* can exist to 60 fathoms but that vigorous growth is not found below 40 fathoms.

F. E. Fritsch (1950, p. 59) in a lecture before the British Association for the Advancement of Science summarized data on the reef-building Corallinaceae stating, "They require well-aerated water for successful growth and usually occur where there is a fairly strong current. Several are known to thrive at depths of 200 to 350 fathoms in clear tropical waters." No direct references to such occurrences are given.

Observations made in Arctic regions by Kjellman (1883, p. 11–12, 33, 96) indicate that many of the Corallinaceae can flourish with a very limited supply of light. One of the commonest forms was the gregareous *Lithothamnion glaciale* which at Spitzbergen he found covering the bottom in deep layers at depths of 10 to 20 fathoms. On the north coast of Spitzbergen in a latitude close to 80° this species covered the bottom for 4 to 5 square miles in the form of balls from 15 to 20 centimeters in diameter. In describing this area Kjellman states that

> the sun is below the horizon for many months, and consequently the darkness even above the surface of the sea is during a long time so deep that a man cannot find his way, even at noon, without artificial light. It must be still darker, of course, at the bottom of the sea in order to reach which the scanty light would have to penetrate masses of ice several feet thick, covered with a fathom of snow, and besides the layer of water above the bottom.

At Bikini each outer-slope dredging covered an appreciable depth interval, and no very significant data on the depth distribution of living calcareous algae were obtained.

Some of the materials dredged from depths of 500 to 800 feet at Bikini Atoll were composed mainly of Foraminifera with small numbers of a variety of other organisms. A sample of such material is shown in plate 36. Larger Foraminifera (including a *Cycloclypeus*, 1½ inches in diameter)[4] and an encrusting form (*Gypsina*) are associated with smaller Foraminifera, small brachiopods (many alive), ahermatypic corals, bryozoans, worms, fragments of both regular and irregular echinoids, and mollusks. The mollusks are of two groups: heavy-shelled forms such as *Cardium*, *Spondylus*, *Pecten*, *Siliquaria* and *Cypraea* that may have lived at the depth of dredging, and fragile pelagic pteropods (*Cavolina*, *Diacria*) whose shells have drifted downward from the surface. Some of the shells and masses of encrusting Foraminifera appear worn and many have come down the seaward slope of the atoll from comparatively shallow waters but there is a notable lack of *Lithothamnion* and the corals and mollusks that characterize intertidal areas.

The outer submarine slopes of the atoll thus are being built up at a very slow rate by organic growth at all levels and by sediments derived from the upper levels of the reef.

It appears from the records cited above that light effectively controls the distribution of reef corals but that this control is much less effective as regards certain of the reef-type algae. Under proper conditions algae and large foraminifers might extend the limit of reef growth downward for several hundred feet, building a foundation upon which corals could become established. This apparently has happened in Fiji where on many islands elevated coral reefs rest upon bedded rocks composed largely of algae and Foraminifera (Ladd and Hoffmeister, 1945).

THICKNESS OF REEFS

Charles Darwin was, perhaps, the first to speculate about the thickness of coral reefs and to suggest that one or more reefs be tested by the drill. In a letter to Alexander Agassiz written on May 5, 1881 (F. Darwin, 1888, p. 362), he said:

> I wish that some doubly rich millionaire would take it into his head to have borings made in some of the Pacific and Indian Atolls, and bring home cores for slicing from a depth of 500 to 600 feet.

Darwin's modest request was more than fulfilled by the Second and Third Funafuti Expeditions in 1897 and 1898.

To date, deep holes have been drilled on coral reefs and coral islands in 7 places in the Pacific, 4 in what may be called continental areas, and 4 on islands of the open Pacific (fig. 65). In the continental areas 2 holes have been drilled on the Borneo Shelf (Kuenen, 1947) and 2 on the Great Barrier Reef off Australia (Richards and Hill, 1942). Four holes have been

[4] Dye tests (rose bengale) made by Ruth Todd showed that this form at least was alive when collected.

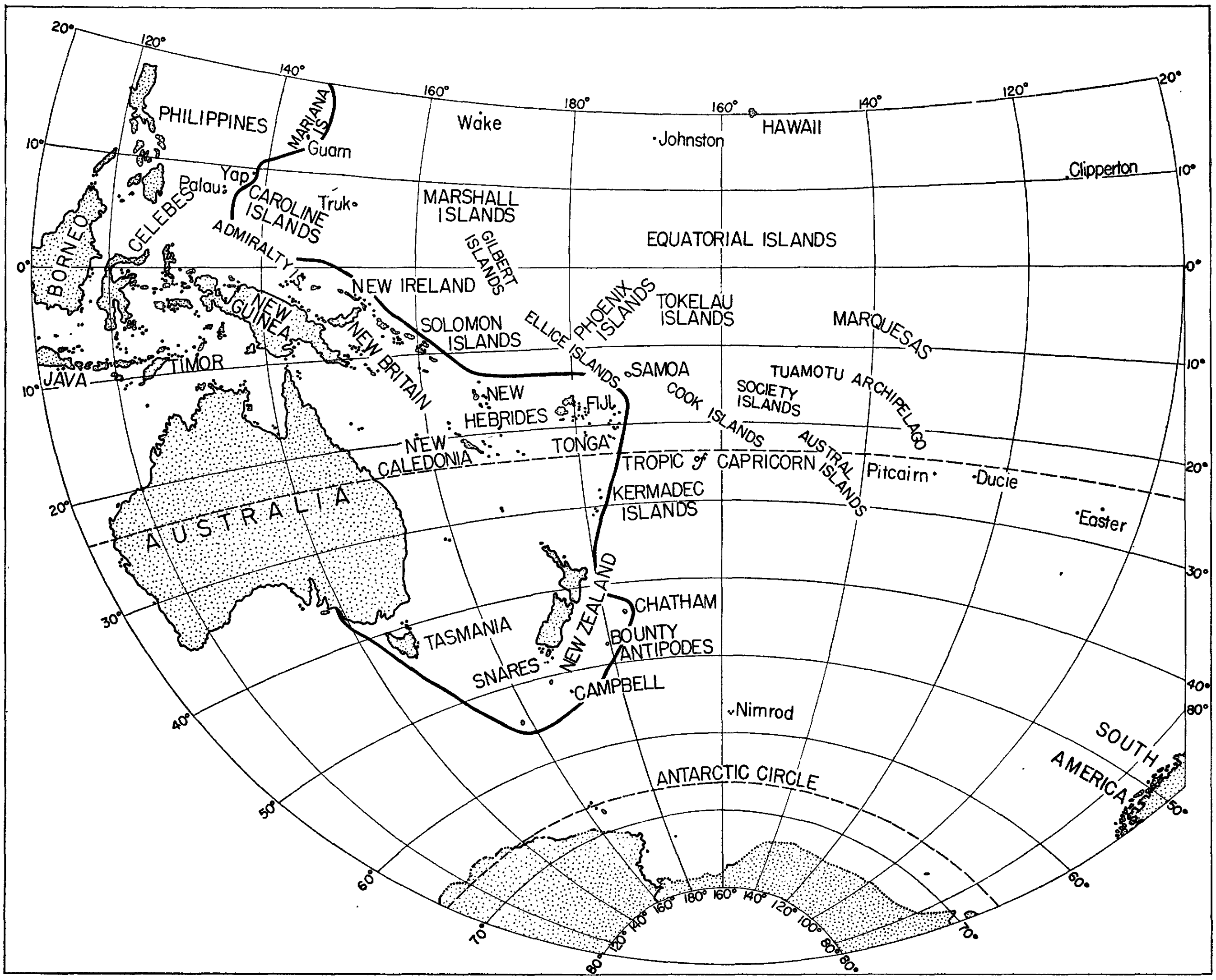

FIGURE 64.—Map of South Pacific showing structural boundary of the Pacific basin.

drilled on small islands: 1 at Kita-daitō-jima east of Okinawa (Hanzawa, 1940) 2 on atolls—Eniwetok and Bikini—in the northern Marshall Islands (Ladd, Tracey and Lill, 1948), and 1 at Funafuti in the Ellice Islands (Funafuti Report, 1904). A summary of the results is given below and shown graphically in figure 66.

The continental holes gave information on the thickness, lithology, and organic constitution of limestone in two important coral reef areas but none of the drill holes penetrated dolomite, Tertiary beds, or hard rock foundation.

Borneo shelf.—Two holes were drilled on Maratoea, described as a horseshoe-shaped elevated atoll, 30 by 7-8 kilometers, lying northeast of Borneo near the seaward edge of the shelf that extends from Borneo to the Celebes Sea (shelf close to island lies at a depth of 270 meters). Highest point on the island is 110 meters; the lagoon is 5-10 meters deep. The drilling was on an islet 2-2½ kilometers inside the outer margin of Maratoea and presumably close to sea level. The first hole was alternately cored and drilled to a depth of 261 meters (856 feet); the second was cored and drilled to 373 meters (1,224 feet), then cored continuously to 429 meters (1,407 feet). A core recovery of 19 percent is recorded from 51.25 meters (168 feet) of sampling from the 250- to 368-meter interval. Coral limestone alternating with a mixture of pieces of coral limestone and coral sand was found to 189 meters (620 feet); from that level to 261 meters (856 feet) there was no hard limestone but mainly cemented reef detritus and soft, marly limestone merging into an olive-green limy marl. Below 260 meters (853 feet) was an irregular alternation of coral limestone detritus and soft, amorphous, nonfossiliferous limestone. No evidence is given of the content of magnesium carbonate, but preliminary studies of some of the finer samples show

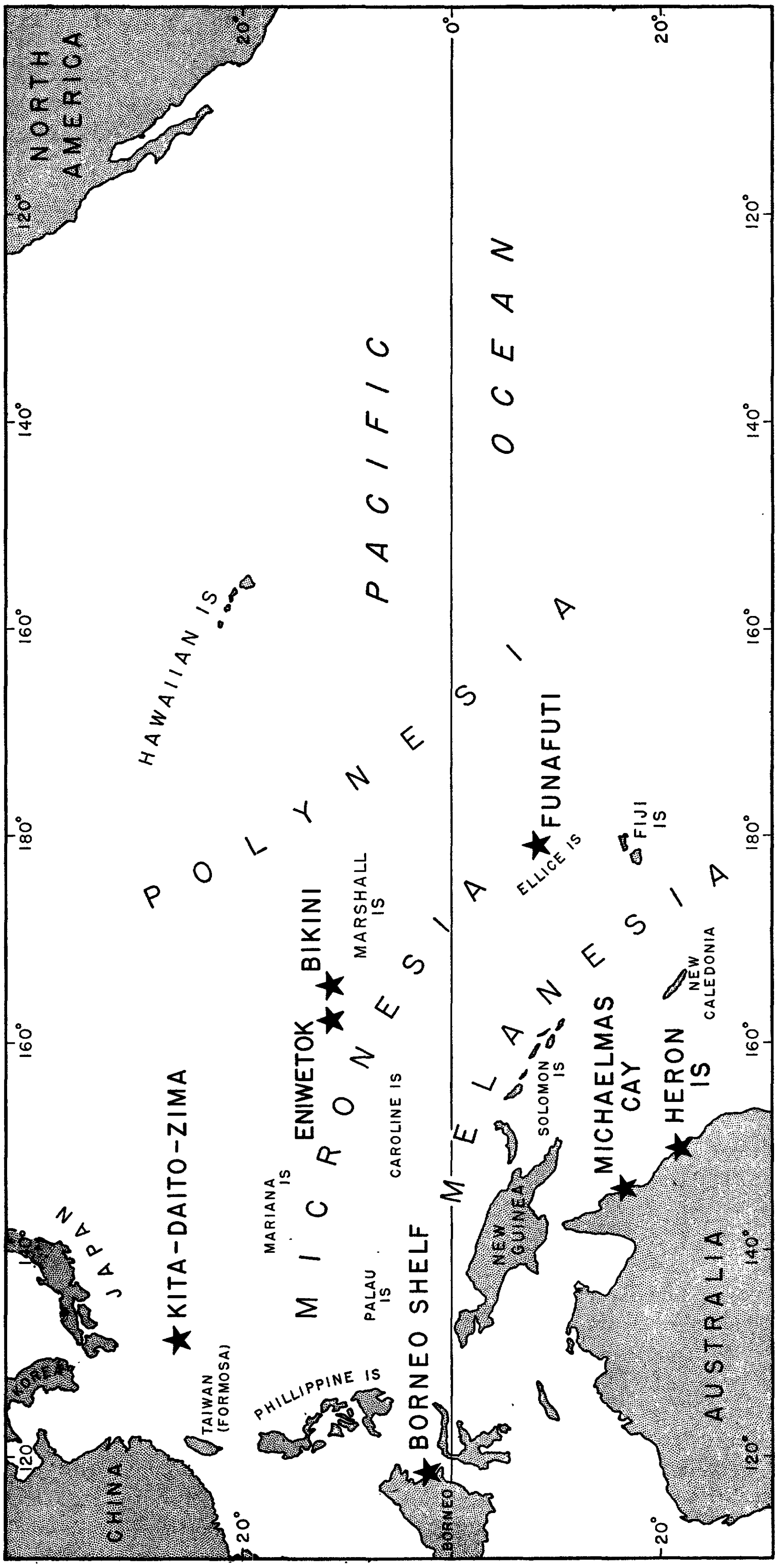

FIGURE 65.—Sites of deep holes drilled on reefs and coral islands in the Pacific.

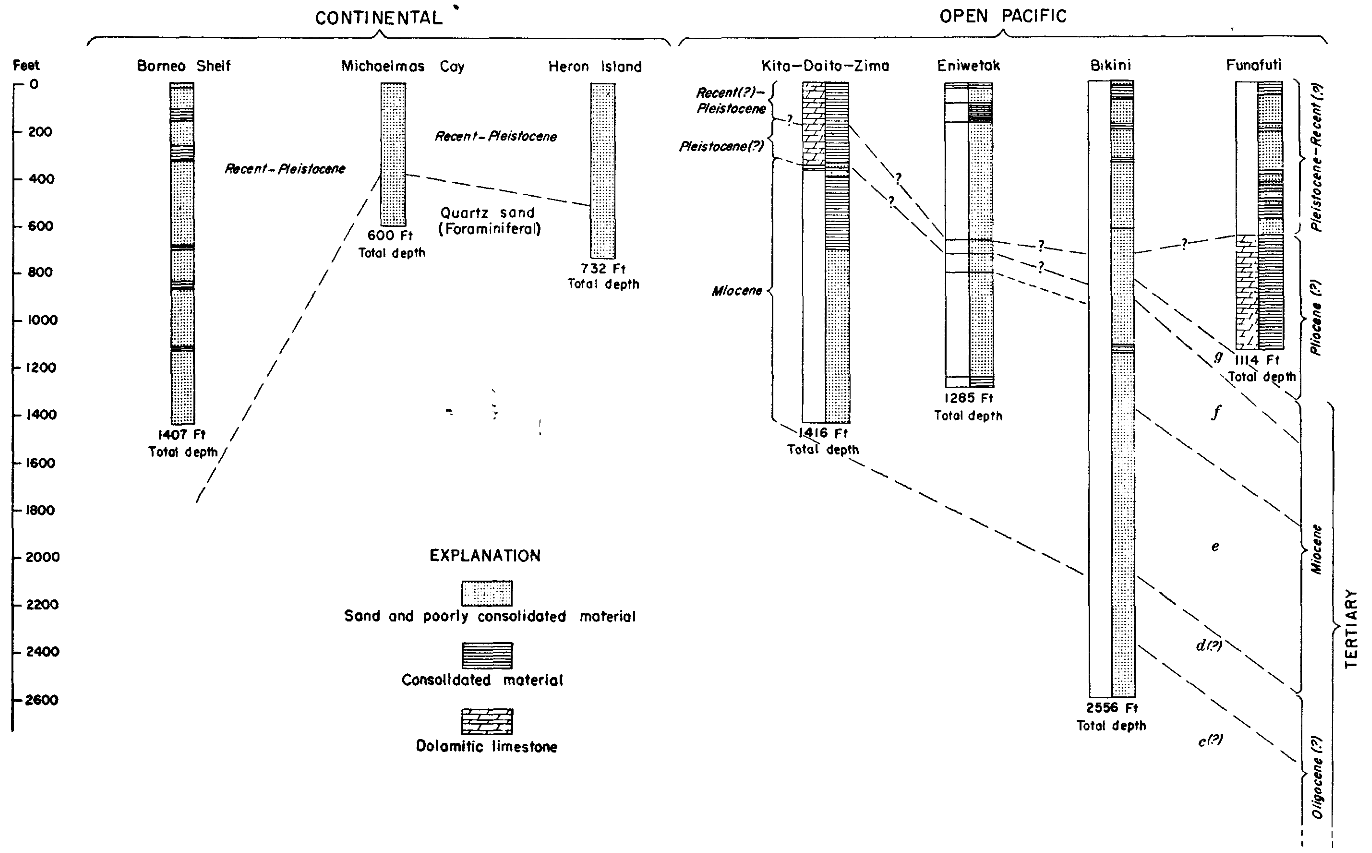

FIGURE 66.—Summary of results of deep drilling on Pacific reefs. Single letters in italics on right are stages of the Tertiaiy as recognized in Indonesia. Age of quartz-foraminiferal sand in Michaelmas Cay and Heron Island noles is unknown. In the Kita-Daito-Zima hole, "Pleistocene (?)" should be "Pliocene (?)."

a calcium carbonate content of 83-98 percent. The age of the sediments penetrated is not stated. The section, except for the greenish marl reported in the first hole, is similar to that found under Bikini island. As Kuenen pointed out, had the hole been carried 100 meters deeper, the Borneo platform would probably have been encountered and the maximum thickness of "coral growth" in that area would thus have been established.

Great Barrier Reef.—In connection with the comprehensive study of the Great Barrier Reef of Australia, two holes were put down, one on Michaelmas Cay, the other on Heron Island. These sites are 700 miles apart, Michaelmas Cay being at about the central point in the length of the reef and Heron Island at the southern end. The Michaelmas Cay hole, lying 14 miles from the seaward margin of the barrier, was carried to a depth of 600 feet; the Heron Island hole, 10 miles from the reef edge, was drilled to 732 feet. For practically the entire depth of each hole the material encountered was loosely coherent, and none of it was dolomitized. The northern hole passed through 378 feet of coralliferous limestone into quartz-foraminiferal sand; in the southern hole the calcareous material extended to 506 feet before entering the sand. Neither hole reached the basement rock. Core recovery was poor, a small fraction of 1 percent being recovered below 20 feet. It was concluded that the limestone section was accumulated at depths never greater than 25 or 30 fathoms. Mollusks were found in the Heron Island hole to depths of 696 feet, all apparently littoral species. Some of the foraminiferal assemblages, however, both in the calcareous section and in the sands below, consisted of large worn and broken shallow-water species mixed with smaller well-preserved, deeper-water species. No extinct species were found, and it was concluded that the entire section is Recent in age.

Three of the 4 holes drilled in the smaller Pacific islands penetrated Tertiary beds; in one hole the upper 340 feet was dolomite, in another the last 477 feet was dolomite.

Funafuti Atoll, Ellice Islands.—In 1896–98 the Royal Society and Government of New South Wales sponsored expeditions to Funafuti Atoll that in spite of many difficulties cored a hole to a depth of 1,114 feet on the seaward margin of Funafuti Island 500 feet from the reef edge. They obtained an over-all core recovery of 34 percent. The section from 0 to 637 feet consisted of porous, friable limestone containing corals, calcareous algae, mollusks, and foraminifers. From 637 to 748 feet was a white, soft and earthy dolomitic limestone with fossil remains less conspicuous. From 748 to 1,114 feet the rock was a hard and compact dolomitic limestone, 85 percent of which was recovered as a solid rock core. All of the fossils were shallow-water forms and all are referable to still-living species, though the section undoubtedly includes Pleistocene and possibly Pliocene deposits.

Magnesium carbonate was generally 1 to 5 percent to a depth of 637 feet, with the exception of a maximum of 16 percent between 15 and 25 feet. Below 637 feet, in the white, earthy limestone, the magnesium carbonate rose rapidly to a maximum of 40 percent, this percentage being maintained to the bottom of the hole with the exception of 2 intervals, from 819 to 875 feet and from 1,050 to 1,097 feet where dolomitization was less.

Kita-daitō-jima (North Borodino Island).—In 1934–36 the Japanese cored a hole to a depth of 431.67 meters (1,416 feet) on Kita-daitō-jima, a small island lying south of Japan and to the east of Okinawa. According to figures given by Endo (1935), a core recovery of about 28 percent was obtained above 240 meters; in the lower part of the hole Sugiyama (1936) states that recovery was lower but averaged above 10 percent. Study of the cores by Hanzawa (1940) revealed that down to a depth of 103.49 meters (340 feet) there was cavernous, indurated, dolomitic limestone, containing reef-building corals, calcareous algae, and Foraminifera; from 103.49 to 116.41 meters (340 to 382 feet), grayish-blue calcareous mud with some limestone; from 116.41 to 209.26 meters (382 to 687 feet), white granular limestone; from 209.26 to 394.98 meters (687 to 1,296 feet), coarse-grained calcareous sand; and from 394.98 meters (1,296 feet) to the bottom of the hole at 431.67 meters (1,416 feet), fine-grained calcareous sand. On the basis of the Foraminifera, Hanzawa (1940) refers the material above 103.49 meters to the "Plio-Pleistocene," the interval 103.49 to 394.98 meters to the Aquitanian (lower Miocene), and the lowest zone (below 394.98 meters) to the Chattian (upper Oligocene). W. Storrs Cole reviewed the Kita-daitō material generously loaned for study by Dr. Hanzawa and concluded that the hole ended on Aquitanian, Tertiary *e*. (See chapter O.) Dolomitization was high in the upper levels, ranging from 78.87 to 90.45 percent dolomite for the interval 0 to 103.49 meters. Below this the dolomite content dropped abruptly to 1.07–6 percent, with a few intervals having a much higher percentage (41.31–87.56 percent.)

The dolomitic limestones of the upper part of the section in the Kita-daitō-jima hole have no counterpart in Bikini Atoll, but the section below 209.26 meters is much like that of Bikini, both sections being unconsolidated, nonmagnesian, foraminiferal sands.

Information about the thickness of reefs in the Pacific has also been obtained from structures now elevated above the sea. Tertiary and Quaternary limestones of this sort are widely exposed in parts of Polynesia and Melanesia to the south (Hoffmeister, 1932; Ladd, 1934, Ladd and Hoffmeister, 1945). On many islands the volcanic foundation on which the limestones rest has been exposed by erosion. The volcanic rocks are predominantly pyroclastics and a zone of tuffaceous limestone separates the volcanic base from the overlying limestone. Some of the limestone sections are as much as 1,000 feet thick and are similar in all essential features to those penetrated by the drill in Micronesia.

RATES OF GROWTH

A number of methods are available for estimating the rate of deposition of sediments on the tops of atolls as well as in the very deep areas of the ocean. As pointed out by Sverdrup, Johnson, and Fleming (1942), all such estimates can be classed under either stratigraphic or supply methods. The stratigraphic method involves the measurement of increments or of thickness of sediments deposited within a known length of time. The supply method is based on a computation of the total quantity supplied divided by the probable area in which deposition occurs. When sediment is first deposited it may have a porosity in excess of 90 percent by volume, but as shown by Athy (1930) the porosity gradually decreases with depth of burial so that at a depth of 6,800 feet the sediments of the coast of the Gulf of Mexico have porosities of only 2 percent; this change gives rise to an increase in bulk density from slightly more than 1.0 when the sediments are first deposited to 2.63 at 6,800 feet. In order to place all of the rate estimates on the same basis for easy comparison they are herein expressed as the number of millimeters of pore-free compacted sediment deposited per year. Most of the cores of unconsolidated sediment used in the stratigraphic methods have a water content so high that only one-third of the core consists of solid material. A correction in the opposite direction is also necessary because the length of core is usually only two-thirds the distance of penetration of the corer although it contains material from all depths penetrated (Emery and Dietz, 1941). When both corrections are applied, we find that an approximation of the true thickness of solid material penetrated by the corer is one-half the length of the core of loose sediment.

The most complete summary of the rates of deposition of deep-sea sediments is that provided by Kuenen (1946), who reviewed and compared the available literature on the subject and added some methods of his own. The best methods for red clay and *Globigerina* ooze, the kind of deep-sea sediments surrounding the Marshall Islands, are based on: (1) the thickness of post glacial sediments found in deep-sea cores in the equatorial Atlantic Ocean and in the Indian Ocean, (2) variation of radioactivity with depth in cores, (3) the thickness of sediments deposited in the East Indies since the formation of a layer of volcanic ash in 1899, (4) estimates of the rate of infall of meteorites and their percentage abundance in the sediments, (5) estimates of the rate of growth and deposition of coccoliths and their percentage abundance in the sediments, (6) Kuenen's correction of Clarke's estimate of the total amount of sediments derived from weathering of igneous rocks—based on the amount of sodium now present in the ocean, and (7) a method based on the difference between the ratios of limestone, shales, and sandstones observed on land and the ratio computed from geochemical considerations. The resulting rates corrected to a pore-free basis as well as for core-shortening are summarized in table 27, but the interested reader should refer to Kuenen's excellent paper and thence to the original papers for details of methods and results. Also included in the table are three additional estimates based on organic growth and other processes observed on atolls, as described later.

TABLE 27.—*Rate of deposition (millimeters per year) of solid material*

Method	Red clay	*Globigerina* ooze	Ocean (general)	Atoll	
				Reef	Lagoon
Postglacial sediments (Atlantic and Indian Oceans)	0.0037	0.004			
Radioactivity	.002	.0023			
Postvolcanic		.012			
Meteorites	.0013	.013			
Coccoliths		.003			
Sodium in ocean			0.00082		
Ratio of sedimentary rocks			.0014		
Coral growth				<14.0	
Ten-fathom terrace				0.91–1.33	
Carbon isotope					>3.8

Measured annual growth of coral.—A number of direct measurements of the rate of growth of a coral have been made. Among these the work of Vaughan and Mayor are most notable. Vaughan (1915; 1919) made thousands of measurements of growth of 25 species of corals both naturally growing and artificially planted in the West Indies and found that the commonest coral, *Orbicella annularis*, has a growth rate averaging about 6 mm. per year, while a branching type, *Acropora palmata*, the fastest grower measured, increased in height between 40 to 45 mm. per year. Mayor (1924*c*) measured the growth rates of corals at Samoa and summarized previous literature on the subject. He, like Vaughan, found that massive types grow more slowly than branching ones both in height and in weight. He realized that the growth rate of individual colonies is not the same as the rate of an addition of limestone to the reef surface, and so he estimated the percentage of the reef area covered by various species and that which was barren, and concluded that coral limestone having a specific gravity of 1.8 is added at a rate of 8 mm. per year over the entire Samoan reef. He also (Mayor, 1924*b*) estimated for the year in which he made measurements that 2 mm. was lost by solution in sea water, 0.2 mm. was dissolved by digestive processes of holothurians, and 0.1 mm. was carried away into deeper water by storms. In summary, Mayor's results indicate that 8 mm. (5.3 mm. on a pore-free basis) are available annually for reef building, that this is roughly the maximum quantity, and that the amount actually retained is smaller—being that amount which is necessary to maintain the reef depth with respect to tide level.

A refinement of Mayor's method of estimating the amount of coral living on the reef was made during Operation Crossroads by Sargent and Austin (1949) at Rongelap Atoll. During the night when algae could not photosynthesize and influence the results, they found an oxygen consumption of 25 milliliters per square meter per hour. Using accepted and their own independently measured values of the rate of coral respiration, they found that this oxygen consumption would be caused by a population of 5×10^4 grams of living coral per square meter of reef area. Mayor and others reported that the average rate of coral growth is 0.75 grams of new coral per gram of coral per year. Thus, Sargent and Austin's data indicate an increase of reef coral amounting to 3.8×10^4 grams per square meter per year. On a pore-free basis this would correspond to a maximum possible growth of the reef amounting to 14 millimeters per year, if no solution by water and organisms or removal by storms occurred. This rate is about 2½ times that found by Mayor at Samoa, and though it may hold true for reef zones in which there is a prolific growth of corals it certainly is excessive for the reef as a whole. As Sargent and Austin pointed out (1949, p. 248–249) their method is based on the assumption that the total respiration of the reef is identical with the respiration of the lime-depositing organisms. There are many other types of organisms on a reef and some, like bacteria, have respiratory rates many times larger than that of corals. No similar data seem to be available for *Halimeda* which comprises an even greater percentage of the lagoon sediments than coral, making it impossible to apply the method to the lagoon area.

Terrace depth.—An estimate of the rate of growth of reef material is provided by physiography. Around the inside edge of the reef at Bikini, Eniwetok, and Rongelap Atolls is a terrace whose edge is at a depth of 10 fathoms. A similar terrace occurs seaward of the reef, where the depth is slightly shallower. As mentioned elsewhere, the terrace may be a former reef surface formed when sea level was lower than now. As sea level rose when the ice sheets melted after the last glacial advance, the present reef kept pace and grew above the old reef level. If the time that sea level rose above the 10-fathom terrace be taken as 20,000 years ago the reef material would have been deposited at a rate of 18,200/20,000 or 0.91 millimeters per year. The assumption of 20,000 years duration of postglacial time is the chief source of error (Flint, 1947) and the assumption of steady growth is not provable; also it should be noted that the computed rate cannot be applied to the main area of the lagoon. Still another possibility should be taken into consideration: during the climatic optimum estimated to have occurred 4–6 thousand years ago the ocean level stood 6 feet above the present level and the reef may have grown correspondingly higher. This would give deposition at the rate of about 20,000/15,000 or 1.33 millimeters per year.

Carbon Isotope.—Work in nuclear physics since 1947 by Harold Urey and associates at the University of Chicago and Laurence Kulp and associates at Columbia University has led to the establishment of a geological time scale based on the ratio of $Carbon_{12}$ and its isotope, $Carbon_{14}$. Analyses of a core of *Halimeda* debris from Bikini Lagoon (Bik 224, lat. 11°35.6′; long. 165°30.1′; depth 23 fathoms) were kindly made by Kulp. He found that the material at depths of 2 to 6 inches, 6 to 10 inches, and 10 to 15 inches all gave ages of less than 100 years, which is the present lower limit of measurement by this method. Thus, a rate of deposition of $>$3.8 millimeters per year is indicated. The chief nonanalytical source of error is the possible mixing of younger surface sediment with the older deeper sediment by the burrowing activity of organisms. This would indicate a too recent age for material at depth.

Summary.—The rate of growth or deposition obtained for the top of the atolls are as follows: (1) coral growth on reef—$<$14 mm per year, (2) postglacial growth of reef surface—0.91 to 1.33 mm per year, (3) organic production—14 mm per year, and (4) carbon isotope—$>$3.8 mm per year. Although each method is open to one or more objections it is believed that at least the correct order of magnitude is indicated. In contrast, the most probable rate of deposition of red clay and *Globigerina* ooze in the vicinity is only 0.002 and 0.007 mm per year, respectively. Thus, it appears that the shallow sediments are deposited atop the atoll about 1000 times as fast as those of the surrounding deep water. It is interesting also to note that the rate of deposition of the atoll sediments is probably greater than the present rate of rise of sea level due to addition of glacier melt water, 0.6 mm per year (Flint, 1947, p. 407–500).

RELATION TO EXPOSURE

Even the most casual examination of the charts of the Marshall Islands indicates a prevalent orientation of various features of the atolls in relation to exposure, or direction of the prevailing winds. Nearly 150 years ago most of these relations were recognized and reported by Chamisso (1821) and later observations of this sort were recorded by Darwin (1842). In an article lauding the accomplishments of Chamisso as a naturalist Du Bois-Reymond pointed out (1890, p. 259) that Darwin and those who followed erroneously credited Chamisso with a fundamental observation on reefs to the effect that since corals are fixed they need a stirring sea to bring food, oxygen, and lime, and hence they thrive on edges favored by wave and current. The remark in question appears at the end of Kotzebue's third volume in an "Appendix by other authors" (Chamisso, 1821b, p. 331.) and probably should be credited to Frederick Eschscholtz, who was the physician on the ship.

In the northern Marshalls the prevailing winds are the trades that blow very steadily with an average velocity of about 18 miles per hour from a general east-northeasterly direction throughout most of the year. During the late summer and early fall a northward shift of the climatic zones results in periods of doldrums or even southeast trade winds of low velocity. Infrequent storms also arrive from various directions. The northeast trade wind appears to be one of the chief underlying, though indirect, factors that controls the general shapes and distribution of features of the atolls. Because of friction against the water surface, the wind produces a water current and a swell which also move in a westerly direction, except where modified by shallow water. The swell and current, aided perhaps by the wind acting directly, are the immediate shaping factors, though the exact manner in which they operate is not always clear.

Of the five atolls studied all except one, Ailinginae, have practically all of their islands distributed over the eastern reef, with no islands or only very small islands on the western reef. Ailinginae, the exception, may be different because its eastern and northeastern reef is somewhat sheltered by Rongelap Atoll (pl. 73). A second factor that controls the position of the islands is the shape of the reef edge, for wherever the reef projects seaward, within the projection one is likely to find an island. Some of the islands on the western reef are within such projections. It should also be noted from plate 73 that the windward part of the main reef itself is different from the leeward part. On the windward side, the reef is continuous and unbroken and usually it extends from the southeast corner around the entire east and north sides to about the middle of the west side without a break of much size. On the other hand, the reef of the leeward side is commonly broken and penetrated by wide passes, some of which are fairly deep. Rongelap Atoll might appear to be an exception to this generalization, but the passes through the eastern reef in reality face southward, a leeward direction.

Surge channels and grooves also are characterized by a preference for the windward side. Actually, the term should be swellward side, because the swell, unlike the wind, is refracted by shallow water so that it may strike part of the south and the north reef edge even though the general direction of propagation is westerly. Reference to plate 73 indicates that the typical surge channels, shown by narrow serrations, have exactly the distribution to be expected if they are controlled by strong steady swell. They are most common on reef edges having an easterly exposure and they extend a short distance around the ends of reef projections but are absent on the leeward side of those projections. This relationship is discussed more fully elsewhere by Munk and Sargent (chapter C of the present report).

The exceptionally steep slopes off the leeward reef may indicate unstable seaward reef growth into the generally quiet water. At times of storms, however, the edges of the reef might be expected to be broken away on the leeward side because of its instability, but the windward reef might not be affected because it is built directly against large swells which probably are able to break away unstable growths before they become very large. Examination of plates 37 and 73 shows that areas in which the outer reef edge has broken away are present on the leeward sides of three atolls and the windward sides of none.

Relationship to wind and swell direction is not confined to large reef features. Locally, on the outer third of the reef are many reef blocks (plate 20; fig. 78). These appear to be blocks of reef material torn from the edge of the reef by storms. Although the storms might come from any direction, those from the leeward side are most apt to break off blocks because those storms attack the most unstable part of the reef. Thus, the reef blocks are commonest on the leeward reef though not restricted to it.

Scattered along the center of the reef, particularly on the windward side, are many small discontinuous sand bars. Nearly all of these bars have curved ends, which on the windward reef point toward the lagoon (pl. 32, fig. 1). Similarly the sand spits at the ends of the windward islands also are curved and point toward the lagoon. On the leeward side also the reef has a few sand bars, but the tips of these show a less definite preferred direction. Current measurements show that the current flows lagoonward over the windward reef. These measurements also show that the indefinite character of the sand bars of the leeward reef is undoubtedly due to reversals of current direction over that reef throughout the tidal cycle.

A summary of the relationship of islands, passes, and surge channels to wind direction is given in figure 70. The diagram for wind was based on data supplied by Humphrey (1947) from 19-year records at Ujelang. The length of the radial spokes indicates the percentages of time during the year that the wind blows from the various directions. The three other diagrams show what is called the azimuth of islands, passes, and surge channels, that is, the direction in which each of these features is concentrated. The data for these diagrams of reef features were compiled from measurements of all five atolls shown in plate 73. Each spoke in the diagram for islands represents conditions over a 15° arc. The direction of the spoke is at right angles to the trend of the reef in the 15° of arc. The length of each spoke is a measure of the number of statute miles of islands in the segment, the island length being measured parallel to the reef front. The same system is followed in the diagrams showing the distribution of passes and of reefs with surge channels.

The diagram showing islands exhibits a marked development of islands in the northeast and southeast quadrants, which are directly or nearly upwind. The one for passes shows that large reef openings occur most commonly on the south side of the atolls, neither directly upwind nor downwind. The surge-channel distribution bears the closest relationship to the wind diagram, although the two are not identical in pattern, there being a marked abundance of surge channels on the north side. Some of the irregularities of the diagrams are due to the refraction of swell, and some probably are dependent on the general shapes of the atolls. The relationships that are present are in accordance with the suggestion that the growth of *Lithothamnion* is most rapid in the zone of violent surf on the swellward side, thereby producing surge channels on that side. Similarly, where the growth is most rapid, comminution is most rapid, producing debris which is carried across the reef and deposited as islands, which also are approximately on the swellward side. The slow growth of *Lithothamnion* on the south leeward side may result in failure to close up reef gaps, leaving them as passes.

WIDTH OF THE REEFS

It is apparent from a casual inspection of the atoll charts (Nos. 2, 5, 7, 8, 9) that most of the north and west reefs are wider than south and east ones, and also that the southern islands are much closer than northern islands to the seaward margin of the reef. This relationship, for the three large atolls is shown in figures 67, 68, and 69. In preparing these diagrams, the reef

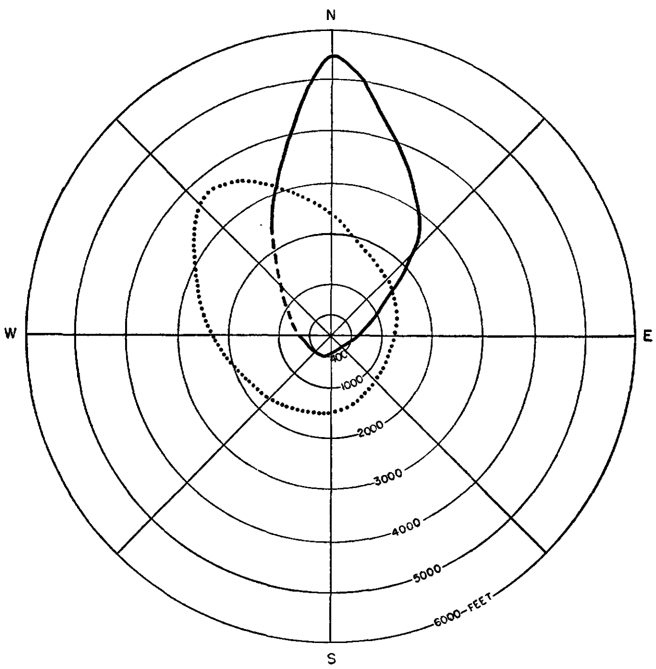

FIGURE 67.—Average width of reefs around Bikini Atoll. Width between islands shown by dotted line. Width from margin of reef to seaward coast of islands shown by solid line. Dashed line used where islands are absent. Northerly islands lie on broad arcuate reefs structures much wider than the normal reef between islands.

width was measured on aerial photographs at intervals around each atoll. The approximate average width for all segments of the reef facing in one direction was plotted as a point in the radial graph. Points were plotted around the graph for each compass direction that was faced by a significant length of reef. Ignoring minor irregularities, a smooth curve was drawn through these points. Distances from reef margin to islands were plotted in the same way and a second curve was drawn. The procedure is of course an approximation, for averages were obtained by inspection. More accuracy was not attempted because of the considerable irregularities in the reefs, and because it is extremely difficult in many places to determine the lagoon edge of a reef either from aerial photographs or in the field. In some places the reef flat terminates at the lagoon in a ledge, whereas in others it shelves off gradually, and either it is bounded by an irregular front of coral heads at depth of 10 to 20 feet, or it has no well-defined boundary.

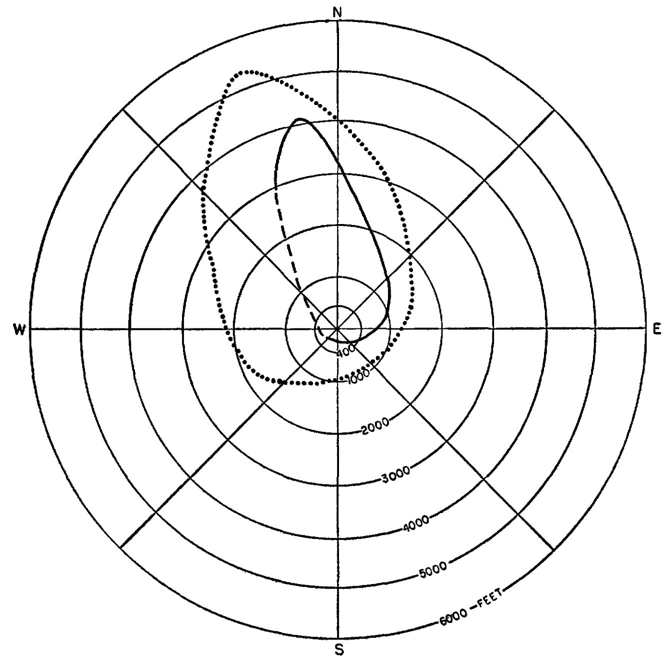

FIGURE 68.—Average width of reefs around Eniwetok Atoll. Width between islands shown by dotted line. Width from margin of reef to seaward coast of islands shown by solid line. Dashed line used where islands are absent.

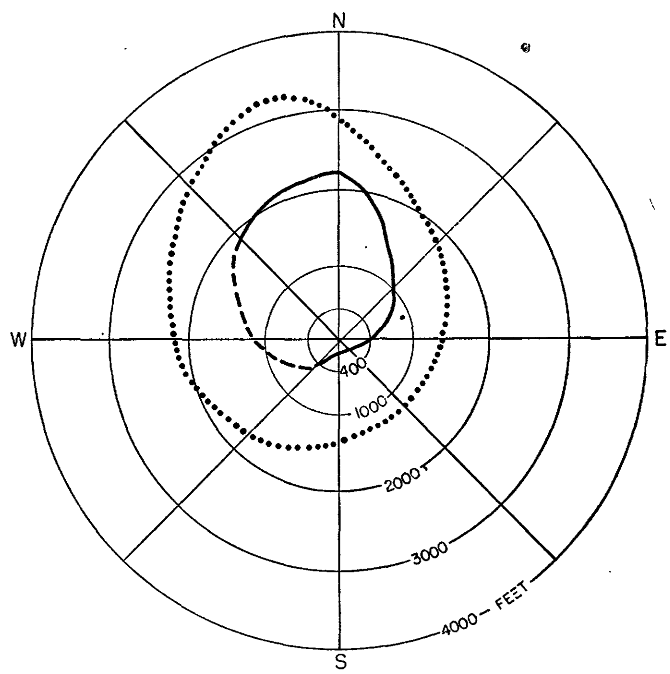

FIGURE 69.—Average width of reefs around Rongelap Atoll. Width between islands shown by dotted line. Width from margin of reef to seaward coast of islands shown by solid line. Dashed line used where islands are absent.

Average reef widths of all three atolls show similar patterns relative to compass direction as can be seen from figures 67, 68, and 69. Southerly reefs average 1,000 to 1,500 feet, easterly reefs 1,200 to 1,500 feet, westerly reefs 2,000 to 2,300 feet, northerly or northwesterly reefs, 3,000 to 5,000 feet. A similar pattern of

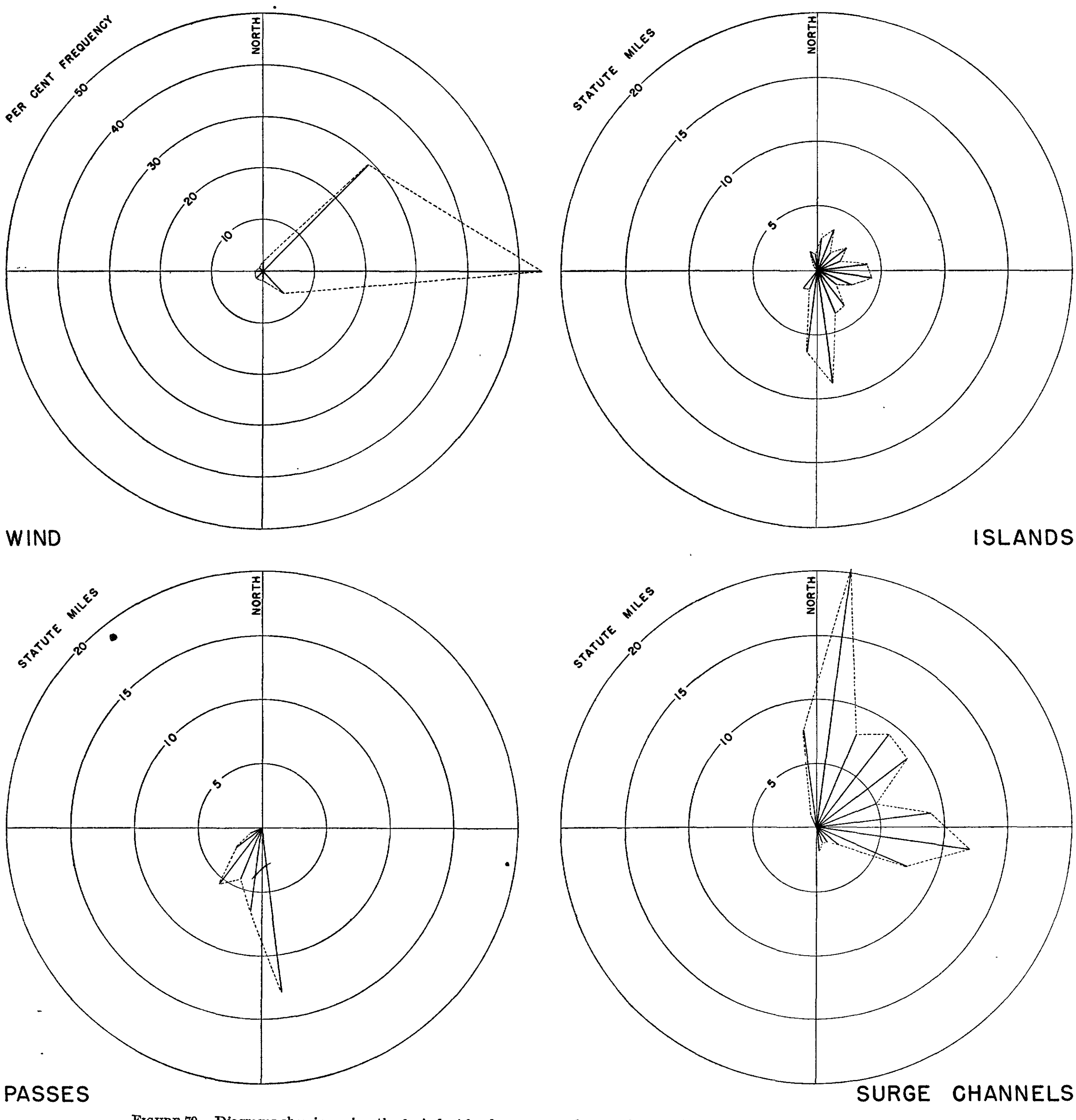

FIGURE 70.—Diagrams showing azimuth of winds, islands, passes, and surge channels in parts of the northern Marshall Islands.

distance from island beach to reef margin relative to compass direction is evident. Southern islands lie 200 to 300 feet from the reef edge, eastern islands average 500 to 700 feet, and northern islands average 2,000 to 4,000 feet from the seaward margin of the reef. The anomalous pattern in the graph for Bikini atoll, wherein the distance from reef margin to northern islands exceeds the average reef width, is due to the fact that all northerly islands lie in three convex arcs or bows of the reef, formed at intersections of the long concave-seaward reefs between islands. Reef widths in the graph were averaged over the long concave stretches of reef; island to reef-margin distances were averaged over the convex arcs where the reef is excessively wide. On Eniwetok and Rongelap, islands are more regularly distributed and not so distinctly grouped.

The curves shown in figures 67, 68, and 69 are all roughly elliptical in shape, and are elongate to the north or northwest, approximately at right angles to the prevailing direction of wind and current.

Although it is possible that reef widths are determined by the configurations of submerged reefs of an earlier stage, during which wind and current directions may have been altogether different, or in part by landslides (p. 70) it appears more reasonable that the present reefs are controlled by present conditions. Seaward reef margins on the east and north sectors show the most flourishing growth, those on the west and south the least. Seaward margins are most eroded on the southern reefs. Lagoon reef margins, on the other hand, show most flourishing growth on the west and north sides and most sedimentation on the west. The resultant reefs are therefore widest on the northwest and narrowest on the south.

ORIGIN AND DEVELOPMENT OF REEF FEATURES

The wave-resisting qualities of the existing reefs are due partly to organic growth and partly to inorganic cementation. The *Lithothamnion* ridge of the reef margin that successfully withstands the attacks of all ordinary waves is constructed of imbricate and interlocking colonies of corals and algae and conceivably a narrow structure of this kind extends downward to the volcanic foundation of the atoll.

Inside the *Lithothamnion* ridge, at or near intertidal levels the reef sediments are firmly cemented to form a rigid plate that also gives the reef stability. Rock of this sort was drilled under the main reef flat and beneath a rock groin off Engebi Island at Eniwetok Atoll. Layers of solid rock as much as 14 feet thick were found but its distribution is not known nor are the processes of its formation well understood.

SUBMARINE GROOVES AND SURGE CHANNELS

The submarine grooves that form the "toothed edges" of exposed reefs are so situated that close examination and sampling are difficult or impossible. In some areas on calm days it was possible to swim off the reef and to examine the grooves and intervening ridges through a face mask. Our clearest impressions of the nature of the grooves and ridges were obtained in this way. Off islands, where some of the grooves are continued through the *Lithothamnion* ridge as surge channels, it was possible to examine the landward parts and to sample the material of the walls.

The ridges between the submarine grooves appear to be growth forms whose development is controlled by the circulation of the water off the reef edge, these waters carrying food, oxygen, and nutrients. The grooves are interpreted as areas where adverse circulation, erosion, and sedimentation have retarded growth. The bottoms of the grooves are covered by sand and boulders derived from the reef but it is doubtful if erosion is effective except during periods of storm.

The surge channels that pierce the *Lithothamnion* ridge off islands serve to drain the reef flat of water piled up by the breakers. When the surf is high the rush of water seaward through the channels may be very great.

In some areas off islands the *Lithothamnion* ridge is very irregular, and the algal ridges or buttresses on the seaward slope stand up as separate bosses 10 to 25 feet in diameter. Locally the reef may be built on these pillarlike structures, for the algae by lateral growth shelve over the intervening channels, thus forming an algal platform at low-tide level underlain by connecting caverns. Stages in the formation of the caverns are shown in figure 71. The separate bosses (fig. 71, *A*) grow vertically until they reach the surf

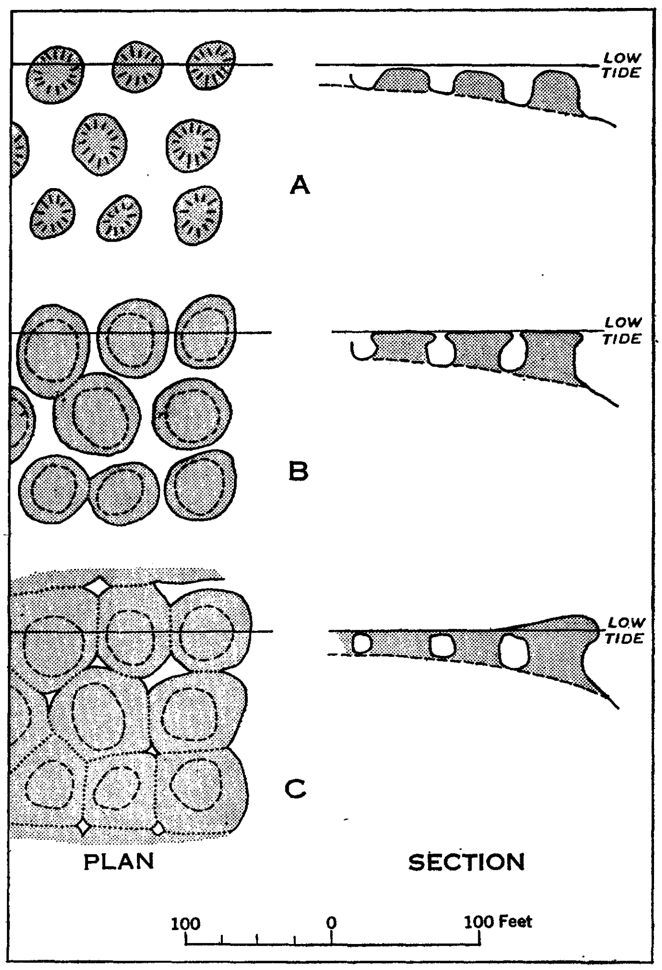

FIGURE 71.—Diagrams illustrating the development of room-and-pillar structure. A, Algal bosses at reef margin. B, Shelving of the bosses and lateral growth in the surf zone. C, Coalescense of shelves to form reef floor underlain by room-and-pillar structure.

zone, a foot or so below low-tide level. Here algal growth is much more vigorous for several reasons, probably including more intense sunlight, more vigorous movement of the water past the algae, and the churning of the water into a foam with each advancing wave, with a resultant effect upon the dissolved oxygen, carbon dioxide and minerals. As growth continues in the surf zone the bosses develop overhanging walls that shelve outward until some of them coalesce (fig. 71, *B*). Growth continues until the surge channels are mere cracks on the reef surface with occasional pools where development of the roof is incomplete (fig. 71, *C*). During the development the algae on the reef surface remain alive and healthy near the cracks through which water wells with each advancing wave. Once the crack heals completely, however, the *Lithothamnion* on the surface dies, and the reef surface becomes a barren algal limestone. All stages of the process may be recognized. The rounded bosses at the reef edge give way shoreward to shelving bosses that in turn are replaced by an area where cracks and pools exist. Finally, behind the pools a honeycomb pattern may be seen where the process has been completed. Even in this area some small openings a few feet in diameter still remain at the intersection of the roofed channels. By diving in these pools underneath the reef one can see caverns 5 to 10 feet wide and 10 to 15 feet deep, brilliantly lighted at intervals of 50 feet or so by sunlight through small cracks and openings in the roof (reef floor). The structures resemble underground mine workings developed by the room-and-pillar type of mining. Areas underlain by caverns are generally smaller than areas occupied by pillars, although they are equal when conditions are favorable.

Surge channels comparable to those seen on Bikini and on nearby atolls have been described by a number of workers from other parts of the Pacific. Those described by Gardiner (1898) and by David and Sweet (1904) from Funafuti appear to be very similar to those present off Bikini island. Kuenen (1933, pp. 79–82) and Hanzawa (1942) writing about the East Indies and the Marshall Islands respectively, also expressed the opinion that the grooves and ridges were due primarily to organic growth rather than to mechanical erosion or solution.

Newell, Rigby, Whiteman, and Bradley (1951, p. 24–25) have briefly described some closely spaced, straight, parallel grooves in the rock floor of the platform off Andros Island, Bahamas. They state that the Andros grooves are similar to those described from Bikini (Ladd and others, 1950, p. 412) and Australia (Fairbridge, 1950, p. 338) except that some of the Andros grooves occur over areas where corals and coralline algae are inconsequential. Some are cut in oolitic country rock and Newell and others suggest that the grooves are cut by currents that return spent water seaward in response to gravity. The description of the Andros grooves indicates clearly that they and the intervening ridges are not due to organic growth. The grooves shown in a sketch (Newell and others, 1951, fig. 3, p. 24) do not resemble the Bikini grooves very closely but neither the writers nor Newell's group is in a position to make direct comparisons. The Andros grooves may be due to erosion as the authors of the paper suggest—or they may conceivably be due to solution at a time when the sea stood lower.

BLOWHOLES

In areas where the surge channels are narrow and 50 to 75 feet long, the pavement algae on the back slope of the *Lithothamnion* ridge may by lateral growth encroach upon and eventually roof over the landward 25 to 50 feet of the channels. This process may continue until the openings are very small at the inner end of the tunnel so formed, and "blowholes" result. At times of low water these holes may spout water 5 to 20 feet or more into the air after each wave. Because of the continual supply of water, prominent mounds made of living algae may develop around the opening or spout. These attain diameters of 10 to 30 feet and rise 1 to 3 feet above the reef flat. On Bikini Atoll, blowholes occur off the south end of Enyu island, but the most striking examples seen were at Eniwetok Atoll, on the reefs along Eniwetok island. All stages of development are found there, from open surge channels at the northeast end of the island, progressing southwestward through partly roofed channels and incipient landward mounds, to completely sealed tunnels and blowholes having beautifully developed mounds. Along one segment of the reef, nearly half a mile long, every surge channel is roofed over, and the majority form active blowholes.

LAGOON DEPOSITS

The lagoon sediments of the four atolls that were studied follow a fairly consistent pattern. Below 34 fathoms in sufficiently deep lagoons there is an area of abundant Foraminifera which, probably because of the low intensity of light, can accumulate unmasked by *Halimeda*. In somewhat shallower water of brighter light the sediment is composed dominantly of *Halimeda* debris. Still nearer to shore the *Halimeda* debris itself is masked by an influx of fine debris produced and transported by the waves and currents. Some of this fine sandy debris is of broken *Halimeda* segments but most of it is derived from the reefs and beaches. The beaches comprise still another sediment zone, one consisting chiefly of Foraminifera of reef-types, an assemblage that differs from that found in the deepest parts of the lagoons. Scattered throughout all of these zones are small patches of coral, largely in the form of coral knolls. The seaward beach, like the one bordering the lagoon, is a zone of abundant Foraminifera. Beyond the beach is the reef flat, the zone of most abundant coral and the chief source of the Foraminifera of the beaches.

Very little sediment escapes from the lagoon, and its floor is slowly being raised (1) by sand from the marginal reefs and the coral knolls, (2) by debris from the large areas of living *Halimeda*, and (3) by the skeletons of the corals that form the *Acropora* thickets.

Halimeda debris was also abundant in many short cores obtained in the lagoon. The British who drilled 2 holes in the lagoon floor at Funafuti (Halligan, 1904) found a section of *Halimeda* with fragments of mollusk shells to depths of 180 to 190 feet. In the drill holes put down on Bikini island *Halimeda* was a relatively unimportant constituent though the sediments have been interpreted as largely lagoonal, probably comparable to the fine debris zone of the existing lagoon.

CORAL KNOLLS

It is not known if the knolls are recent features of the lagoon bottoms, or if they are deep-rooted growths that have developed over long periods of time on a lagoon floor being slowly buried in sediment. The larger knolls may extend to appreciable depths below the present lagoon bottom. Those with bases a mile or more in diameter are most likely to have deep roots but it is possible to explain the growth of most of these structures without assuming any considerable depth of their roots, and this may be done by considering that all varieties observed, from the small low mounds to the large coral peaks, represent stages in a logical growth sequence.

The luxuriant growth of corals and other organisms on the tops of the knolls indicates clearly that these structures are growing upward under existing conditions, the tops being raised by corals and algae in place, the intervening areas filled in by organic debris. The sides of the knolls are probably being slowly extended as sand and coarser debris are added to their slopes. The age, origin, and internal constitution of the knolls are not known, because no structure of this kind has ever been drilled. They may represent sporadic growth that was initiated during a part of the Pleistocene when sea level was much lower than now.

The lagoon floor is covered with a debris of *Halimeda* fragments and medium to coarse calcareous detritus. Calcareous silts and muds have been reported from other localities, but at Bikini and the other atolls studied, very little fine material was found. Corals occur in thickets of staghorn *Acropora* in shallower water, and sporadically over the entire bottom. Any colony, or cluster of colonies, provides a foundation for the development of additional colonies. These, growing on older forms, are raised somewhat above the floor and are less subject to burial by sediments. Water circulation is freer a little above the bottom, and new growths of corals are, therefore, more favorably placed to obtain food from the lagoon currents. Once initiated, a small mound of corals becomes the home of many forms of life and a biologic community is established. The growth of this community continues, dominantly in an upward direction toward the zone of more light and freer currents. At the same time, debris from the top of the knoll builds up a detrital slope or talus apron around the sides of the community.

It is noteworthy that only one coral knoll in any of the atolls studied is above water at low tide. Small coral patches in shallow water near the main reef in many places are awash at low tide but these are not classed as coral knolls, but as parts of the lagoon reef.

REEF ROCK AND BEACH ROCK

COMPOSITION

The proportions of constituents that make up the reef and beach rocks are determined by the location of the rocks with respect to the sources of sediments on the reef, and their relation to the prevailing winds and currents that transport and concentrate the sediments. Proportions of constituents in the lagoon are discussed in the section on lagoon sediments. Overall composition of the reefs and islands is hard to evaluate because most specimens are found to be characteristic of only small areas. In some samples of detrital reef rock, two thin sections made from the same specimen are markedly different in proportions of constituents and grain size. Careful estimates of percentages of organic remains would, therefore, be misleading unless averages were computed from a large number of thin sections from each area studied.

It is likewise difficult to estimate proportions of constituents by measuring the relative areas of reef covered by major living and contributing organisms, for the organisms differ in their rates of growth. They also differ in their ability to withstand erosion. Some are easily broken down to fine material, and consequently, may contribute large amounts of fine sediment that lodges on the flat, on island beaches, or is swept into the lagoon. For example, living *Lithothamnion* forms 90 to 100 percent of the marginal zone, but it covers only 5 to 10 percent of the whole reef surface, and it probably does not form more than 20 percent of the living, calcareous-secreting organisms of the reef. Yet samples of rock from lagoon beaches may contain 30 to 50 percent of fine to coarse grains derived from *Lithothamnion* because of the rapid rate of growth of the alga, and because of its rapid comminution to coarse material by the surf and to fine material by the scraping of animals, and by the abundant boring organisms that infest the living alga.

Another factor that adds to the difficulty of evaluating constituents over the entire reef is the large variation in relative proportions of each group depending on the location of the reef with respect to prevailing winds. Corals, for instance, that form probably no more than 10 percent of material on the wide windward reefs, form possibly 25–50 percent of the detrital material on the leeward reefs. Boulder ramparts that make up a considerable part of the southern islands are formed almost wholly of coral. *Lithothamnion*, on the other hand, is not nearly so widespread on leeward as on windward reefs and it forms a relatively small proportion of the reef detritus.

INTERSTITIAL PASTE

The finely detrital limy mud or paste that fills cavities and intergranular pore spaces in reef limestone commonly forms 5 to 30 percent and averages more than 10 percent of the reef rock. Individual thin sections may contain 70 percent or more of paste. Beach sandstone contains much less paste, generally only a few percent near the exposed surface of the rock although individual sections may contain 10 percent or more.

The limy mud consists partly of fine detrital grains in a microgranular matrix. In some thin sections the grains are sparsely scattered in the brown impalpable paste, whereas in others the fine-grained detritus comprises most of the silt or mud, with only a small amount of microgranular paste as a matrix. Most grains, even small ones 0.01 millimeters or less in size are recognizably of organic origin. Some particles, however, show no structure under high magnification but consist of brown microgranular material similar to the matrix paste. Under high magnification the paste shows a mat of minute bright lines probably representing birefringent needles or granules about a micron in size. The finely detrital grains of organic origin probably form more than half of the limy mud. The microgranular paste forms the other part, or 5 percent of the reef rock as a whole. It is not known whether this impalpable paste is of organic or inorganic origin.

Sorby (1897, p. 70) stated that some calcareous skeletons such as shells or corals disintegrate to minute plates, fibers, or granules that may give rise to a calcareous mud composed of extremely minute particles, and that aragonite particles may change to granules of calcite that show no relation to the original organic structure.

Thorp (1935) reviewed evidence for the origin of shallow fine calcareous sediments of Florida and the Bahamas, and concluded that most of the sediments studied are of organic origin, and that only 4 percent is definitely inorganic. Evidence for inorganic origin is the presence of oolites, or of minute needles of aragonite (figured by Vaughan, 1917, pl. 47, fig. 6) which are present over most of the area studied although they probably formed in one or two local regions such as mangrove swamps, and have been washed into other areas. Thorp reviewed the physico-chemical conditions of saturation and supersaturation of sea water by carbonate, and concluded that the conditions necessary for the formation of the needles are unusual in the ocean and occur in only a few restricted, relatively stagnant shallow water areas of the tropics and subtropics. He believed most of the precipitated carbonate was due to the physico-chemical conditions of the sea water, but a part may be precipitated by the action of denitrifying bacteria.

Wood (1941) suggested that the amorphous limy mud may be the result of precipitation by the photosynthetic action of marine algae. He stated that the material, seemingly almost cryptocrystalline in thin section, is composed of minute calcite grains whose boundaries are obscured by high birefringence and internal reflection of the calcite, and that the fine bright lines or needles reported from thin sections by many geologists are actually the Becke lines of the boundaries of the calcite grains.

There is no direct evidence for the presence of inorganic carbonates in the limy mud of Bikini Atoll. No oolites were found in any of the thin sections, and no minute aragonite needles were found whose crystal habit could be identified. The fine bright lines or carbonate needles noted in many thin sections in the microgranular paste may be precipitated needles of aragonite, or precipitated grains of calcite or aragonite, but there is no proof. The small radial spherulites common in the paste may be a precipitate. Their presence on the surface of living *Lithothamnion* in the surf zone suggests that they are organic and the regularity of their shapes suggests that they are probably spherulites of ascidians. The only materials definitely known to be inorganic are the fine acicular aragonite and calcite that coat cavities and pores in the limestone, especially in the beach sandstone.

CEMENT

Well developed acicular carbonate that coats grains and fills cavities is for the most part limited to porous rock in the intertidal zone. It is especially abundant in beach sandstone, but it is also found on the reef groins in coarse detrital rock that is exposed to the air at low tide. The needles normally range from 0.01 to 0.1 millimeters in length.

Staining tests using dilute cobalt nitrate indicate that the carbonate that coats and cements grains is aragonite. Samples of beach rock having a high polish were tested and the surface layer was found to show little or no staining. The cement of the surface layer is largely composed of finely granular to microgranular paste which presumably contains much calcite. The surface polish is a late characteristic that is acquired by the rock after cementation and during abrasion by waves, therefore the primary cement of the beach rock is acicular aragonite.

The origin of the aragonitic cement has been discussed by geologists from many areas in the tropical Atlantic and Pacific. Gardiner (1931, p. 43) suggested that freshwater from the island meeting the salt water at the beach precipitated calcium carbonate to partly consolidate the beach sand, and that subsequent precipitation by evaporation of seawater caused a further consolidation to hard sandstone. He pointed out that the induration is greatest at the top, the rock being more friable below.

Daly (1924, p. 139) proposed that the local concentration of beach rock was due to the piling up of shelf sand from shallow water by major storms. The shelf sand contains more organic material (roughly 5 percent) than normal beach sand, and decay of the organic material on the beach, he said, would cause enough precipitation of calcium carbonate to bind or fix the sand, so that other causes of precipitation might have time to do their work.

The present study serves to emphasize that the sand is most consolidated near the surface, and that the hardest rocks are those which are actually exposed to wave attack. The carbonate cement may result from precipitation during wave action, by evaporation, by release of CO_2 in the wave surge, or by release of CO_2 due to increase in temperature at the shore.

Cementation in reef limestone, at or below low-tide level, is probably due largely to consolidation of the limy interstitial paste that forms the rock matrix. The consolidation is considered to result from precipitation of microgranular carbonate within the paste, or from crystallization of the paste probably during daytime periods of low tide when the water flowing over the reef is warm, and when algal activity on the reef flat utilizes much of the CO_2.

The alteration of brown paste to clear crystalline or microcrystalline calcite seen in thin section, as tiny clear spots or as veinlets, is probably a further effect of the consolidating action. Whether the activity of boring invertebrates or boring algae in dissolving the surficial layers would cause precipitation at a little distance is not known. The activity of bacteria in the upper few inches of reef rock is also a possible cause of the cementation.

The strong consolidation of loose detritus on the reef at or just below low-tide level, and the marked cementation on the shore line in the intertidal zone do not appear to be present in other parts of the atoll. In depths of 5 feet or even more, the reef surface was found to be hard beneath a thin veneer of sand, but the bottom of the lagoon does not appear to be consolidated even at shallow depths.

In conclusion, the processes that consolidate detritus on an atoll appear to be most effective at low-tide level and in the intertidal zone; they are probably effective for a few feet below sea level, but available evidence from lagoon cores and bottom samples indicates that they are ineffective at lower levels.

FEATURES OF THE LAGOON AND PASSES

Much of the Pleistocene history of the atolls may be inferred from the physiography of the lagoons. First of all, each of the lagoons has a flat floor. This floor is covered by Recent sediments and from it rise the coral knolls and the annular reef. Bikini, Eniwetok, and Rongelap Atolls each has also an extensive, shallow (8- to 10-fathom) terrace. The terrace fringes parts of the reef on both the lagoonward and the seaward sides and it forms the threshold beneath some of the passes, such as the pass west of Enyu at Bikini Atoll and South Channel at Eniwetok Atoll. At Rongerik the terrace is shallower. The reef of each atoll is pierced by a single deep channel which can be traced seaward to depths of 35 to 40 fathoms before it becomes indistinguishable on the steep outer slopes. The shallowest depth along the channel occurs in the lagoon and at Eniwetok and Bikini Atolls this depth is about 25 fathoms.

The flat lagoon floors were explained long ago by Daly (1910) as resulting from truncation by wave erosion during the glacial epochs when sea level was lower than now and the colder water prevented reef-building organisms from forming a protective ring. According to Flint (1947, p. 437) sea level was lowered about 120 meters. Solution of the exposed basin-shaped island was doubtless important, too. The subsequent rise of sea level and warming of the water during interglacial epochs produced a reef around the margin of the platform. This reef is now marked by the 10-fathom terrace, whose width is much greater than that of the present reef. During glacial low stands of the sea, sinkholes developed on the terraces and solution cavities formed in the limestone. Such cavities were penetrated by the drill between 60 and 200 feet. The post-glacial rise of the sea level resulted in the development of a new reef standing above the former one. At some places the new reef is at the seaward side of the old one and at others nearer the lagoonward side. Much of the present irregularity of the atolls' plan can be ascribed to position of the new reef relative to the interglacial one. On the leeward side of the atoll, the interglacial reef did not completely enclose the original platform, and the gaps remained unfilled by the present reef, constituting the present deep pass. Elsewhere, the present reef has left gaps atop the interglacial reef, forming the shallower passes, in particular the wide channels. Coral knolls within the lagoon rise to all depths, there being no marked concentration at 10 fathoms, suggesting that much of the growth of the existing knolls has taken place in post-glacial time.

This version of the history of the atolls is a combination of certain features of Darwin's subsistence theory, which most satisfactorily explains the great bulk of the calcareous mass, and Daly's glacial-control theory, which explains the accordant flat floors of the lagoons. A similar combination of the two theories was first proposed by Kuenen (1950) but Kuenen's synthesis has been further augmented by data from the detailed survey of lagoonal topography.

The relationship of depth and diameter of atoll lagoons was investigated by B. L. Conrey, University of Southern California, in a study of published charts. The maximum lagoonal depth was taken as the greatest depth represented by three or more soundings; the diameter was the width between outer reef edges. Measurements made for about 110 atolls showed a

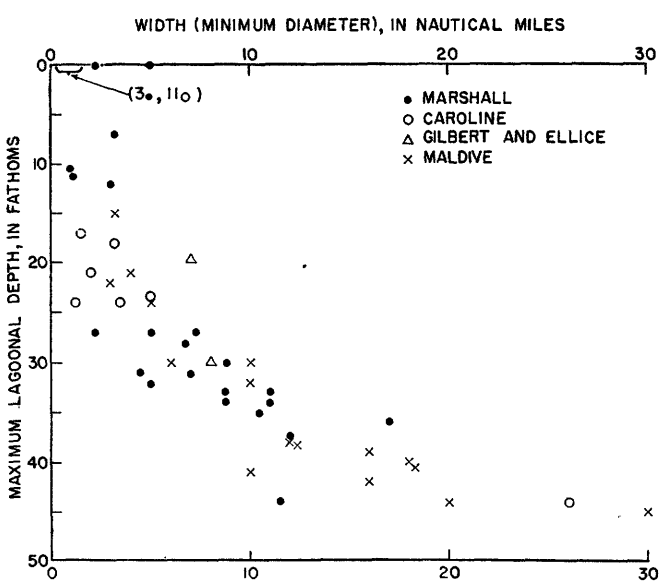

FIGURE 72.—Plot of 61 well-sounded oceanic atolls showing relationship of depth and diameter for atoll lagoons.

general trend of increasing depth for wider atolls. The relationship was much improved by omitting atolls from inside the andesite line and atolls which were poorly sounded, having fewer than one sounding per square mile or soundings only near the main entrance. The resulting plot, based on 61 well-sounded oceanic atolls reveals a much closer dependence of depth upon width (fig. 72). For very small atolls, less than 5 miles wide, the depth shoals rapidly from 25 to 0 fathoms as the width decreases. For greater widths, between 15 and 30 miles the depth appears to be fairly constant at about 45 fathoms. This relationship is attributed to relatively fast deposition of sandy debris from the reef where the radius of the atoll is less than the distance to which the sandy debris can be carried lagoonward from the reef.

RECENT NEGATIVE SHIFT IN STRANDLINE

The shores of many Pacific islands and of certain of the bordering lands exhibit benches, nips, and related features that indicate a negative shift of the strandline of about 6 feet. These features are so widely distributed and the amount of displacement is so uniform that the shift is presumed to have been eustatic. Evidence is best preserved on high islands where in protected places nips, sea caves, and beach deposits may be preserved. On low islands such as the atolls of the northern Marshalls the evidence is obscure or wanting entirely.

At Bikini Atoll on a few islands there are remnants of a platform of reef rock somewhat above the present reef level. It is possible that this slightly upraised reef platform underlies many of the islands even though it is not exposed through the cover of coral rubble, beach sand and rock, and inland gravel and sand. The best exposure seen at Bikini Atoll is between Eninman and Reere islands, on a broad rocky flat on the seaward side of the islands. The flat is largely a truncated boulder conglomerate, much of which is covered by loose coral rubble. The rock platform, in places, rises 2 feet or more above the reef level. Part of the seaward half of the platform is a truncated surface about 6 or 8 inches above the present reef level, showing *Heliopora* in place. The elongate, radial fingers of the blue *Heliopora* are more resistant than the matrix rock, and stand out 1 to 3 inches in bold relief. In one place a large mass of *Heliopora* stands nearly 8 inches above the level of the truncated platform, proof that the former level of the reef at this locality was at least 16 inches higher than the present level. The elevations of these truncated colonies of the former reef were estimated, not measured, but it is reasonably certain that the stated heights above the present reef are not in error by more than a few inches. The colony could well have been truncated several feet below its original top and the older reef level could therefore have been as much as 3 or 4 feet above the present stage.

Evidence of an older, truncated reef surface slightly higher than the present one was also found along the seaward coast of Aomoen (p. 214).

Off the south west side of Chieerete Island (Detailed reef traverses, traverse 11, p. 168–169) a stack of beach conglomerate rises 6 feet above high-tide level. The stack is 7 feet in diameter. Although it may be an unusually large reef block, its size suggests that it is a leeward remnant of a beach deposit laid down when the sea stood about 6 feet higher than now.

The above evidence suggesting a higher stand of the sea at Bikini Atoll is not very convincing but there is reason to believe that with a slight lowering of the sea, reefs are widely and quickly truncated by wave action and solution. MacNeil (1950) found strong evidence to indicate that the present flats surrounding Okinawa have been truncated during very recent times—that several feet of reef rock have been removed from flats that in some places exceed 1,000 feet in width. He 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 shore. The blocks of limestone have broken from shoreline cliffs and appear 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 now. Since that time they have been isolated by erosion. Where such blocks are absent the wide reef flats are as bare as those of Bikini.

FORMATION OF ISLANDS

The large islands of Bikini Atoll are located on wide crescentic sections of the reef and appear to be fairly stable under existing conditions. Over a period of years they may in some places—through the action of waves and winds—be slowly growing. The islands of the windward side appear to be migrating across the reef toward the lagoon. This process is most clearly discernible in the case of the smaller islands. The seaward sides of such islands are being eroded whereas their lagoon beaches are constantly augmented by foraminiferal sand. On the seaward coasts of Eniairo and Rochikarai, for example, there are exposures showing consolidated seaward-dipping layers of coarse material overlying an earlier series of beds that dip lagoonward. The sandstones exposed beneath the center of the bar extending northwest from Bikini dip lagoonward and clearly suggest bar migration in that direction.

In some instances there apparently has been a loss of land area. Thus, the beach rock beds at the south end of Bikini island on the seaward side strike south toward Bokonfuaaku Island at a considerable angle to the existing shoreline, suggesting that the two islands formerly were connected. Similarly on the south side of the atoll, as noted in Description of islands (p. 206–207), there is some evidence suggesting that Airukiiji was once connected with Airukiraru, Reere with Eninman.

Namu, largest of the northern islands was probably larger in past times than now as suggested by a somewhat complicated series of changes in the strike and dip of the beachrock beds exposed along the north and eastern shores. In at least two other places evidence suggests that in past times the land areas were more extensive. One of these is the area north of the bar that connects Yurochi and Uorikku. In this area there is a broad belt of eroded bedded rock that probably represents the foundation of an island that no longer exists, possibly a separate island or an extension of one of the islands on either side. Likewise, the bar of beachrock and loose sand that extends west from Romurikki toward Uorikku suggests that these two were at one time connected. Seasonal changes in the shoreline such as those observed on Ourukaen may also occur in other places and add to the difficulties of interpreting island history.

Wood-Jones (1912, pp. 259–261) who spent more than 15 months on Cocos Keeling in the Indian Ocean concluded that island building there had not proceeded regularly and gradually over a long series of years but by fits and starts—periods of rapid land growth being followed by quiescent periods.

Many who have studied Pacific atolls have stressed the importance of changes in sea level in the formation of islands. David and Sweet (1904, p. 83–88) in their report on the geology of Funafuti suggested several small oscillatory movements of the shore, the last being a negative shift of the strandline. These movements, in their opinion, stimulated reef erosion to form linear islands from which the existing islands were evolved. Gardiner (1931, p. 35–36) referred to the widespread negative shift in sea level as the dominant cause of the formation of the islets of atolls. He stated that on such islets losses nearly always exceeded gains in their rocky areas, adding that they "* * * can scarcely be conceived as having come into existence without such a relative movement of land and sea." Sewell (1932, p. 457–458) held similar views. He also noted the widespread evidence of recent erosion and the evidence for migration of the islands across the reef flat toward the lagoon. Kuenen (1933, p. 70) pointed out that in the protected East Indian area many sand cays have been built at existing sea level over reefs of living coral but he agreed that many, probably most, islands were formed as a result of the emergence of their flats.

In examining the islands of Bikini and nearby atolls the writers found no evidence to indicate that extensive island building was in progress. There are seasonal changes that temporarily enlarge the areas of certain islands and other islands in their migration across the reef may become appreciably enlarged but such cases appear to be exceptional. Most of the changes that are detectable appear to involve a reduction in land area. Under these conditions and because of the evidence for a recent eustatic shift in sea level in other parts of the Pacific the writers are inclined to agree with the authors previously cited and to state that probably no habitable islands would exist in the Bikini area if there had not been a recent negative shift in sea level that permitted the erosion of reefs that had grown up close to low-tide level.

If the islands now present on the rims of atolls such as Bikini were formed originally by wave action following the Recent 6-foot lowering of sea level and if these islands are now being reduced or even destroyed by wave action, particularly by storm waves, these atolls as they exist today are indeed ephemeral structures. This conclusion, however, applies only to the islands themselves, those small fractions of the atoll's mass that project above sea level. The submarine mass—the broad cone of volcanics with its thick cap of sediments—that rises from the deep sea is far more permanent. In the northern Marshall Islands these structures have been in existence at least since early Tertiary and probably since late Mesozoic times. These masses, protected by the sea, will probably not be radically altered or destroyed in the foreseeable geologic future.

REGIONAL RELATIONS

Darwin was the first to express the opinion that large areas of the Pacific were characterized by submergence, others by stability or emergence. He published a map (1842) on which these areas were delineated. His evidence for subsidence, as explained later, was the widespread occurrence of sea-level atolls and barrier reefs, the evidence for stability or emergence was the presence of fringing reefs and elevated reefs. Many later workers have drawn boundaries of several sorts in the Pacific in attempting to determine its structural history (Bridge, 1948). Marshall (1911, p. 5, fig. 3) showed the "andesite line, suggested margin of Pacific basin." Born (1933) drew the andesite line essentially in the position shown in figure 64. Sibinga (1943) published a map showing the andesite line as an unbroken boundary continuing northward from Palau, past the Japanese and Aleutian Islands, to the west coast of America. The broad irregular Pacific Basin is thus completely enclosed except on the south. Inside the basin are the basalt and coral islands of the open Pacific. Outside the basin and across the line are the island arcs and their foredeeps, the islands with andesites and other "continental" rocks. The relations of New Guinea to the islands of the southwest Pacific are shown by Glaessner's map (1950, p. 850–861) and the Marshalls are seen to lie far to the east of the major synclinal belt that is enclosed by the "Pacific border (andesite line)."

In 1946 in attempting to integrate coral-reef hypotheses, Stearns called for great subsidence in the central Pacific in Pliocene time and for great shifts in sea level in Pliocene and Pleistocene time (1946, p. 248, 251). At the time that Stearns wrote, few Tertiary rocks had been reported east of the andesite line. Replin (1919) had reported briefly on mollusks and other fossils from Makatea in the Tuamotu (Paumotu) Islands that seemed to him to have an Eocene aspect. Since Makatea lies more than 1,800 miles east of the nearest known rocks of Eocene age their occurrence should be checked. Actually there are elements even in the living fauna of parts of the Pacific that are suggestive of the Tertiary. A more definite fossil occurrence was noted by Yabe and Aoki (1922) who described middle Tertiary foraminifers from Jaluit Atoll in the Marshall Islands. The fossils, however, occurred in pebbles in blocks of coral conglomerate thrown up on the reef flat by waves. Owens in 1923 reported the occurrence of a single tooth of *Carcharodon megalodon* in the terraced limestones of Ocean Island to the west of the main line of the Gilbert Islands. This species has been widely reported from upper Tertiary rocks. In 1927 Marshall described the occurrence of Miocene Foraminifera from a 200-foot limestone section in the Cook Islands.

Since Stearns' 1946 paper appeared we have drilled into thick Tertiary sections on two atolls in the Marshalls and late Cretaceous fossils have been recovered by dredging a number of isolated guyots that rise from the deep sea (Revelle, 1951). It now appears probable that Tertiary and possibly upper Mesozoic sections comparable to those elevated above the sea in Melanesia exist beneath the sea in the parts of Micronesia and Polynesia that lie to the east of the andesite line. These areas and the andesite line are shown on the map (fig. 64). The andesite line has apparently been a structural boundary of real importance that has separated two major provinces since late Tertiary or early Quaternary (Pleistocene) time. In general, elevation occurred to the west and south, subsidence to the east and north.

The total subsidence at Bikini is probably about 4,000–5,000 feet. The exact nature of this subsidence is not known—whether, for example, it was uniform, periodic, or if any tilting was involved. It is known that the overall rate of at least the upper 2,500 feet was slower than that of reef growth, for the reef organisms were able to keep pace with the sinking. In areas like the northern Marshall Islands, reefs developed in Tertiary and later times under conditions of subsidence as postulated by Darwin, though it is not known if the present atoll stage was preceded by barrier and fringing reef stages. Across the andesite line, however, conditions, apparently, were more complicated. Darwin recognized the widespread development of barrier reefs and the presence of one atoll in Fiji. Actually, fringing reefs are also widely developed there along with atolls comparable in size to those of the northern Marshall Islands. Some of the existing fringing reefs border elevated Tertiary reefs and many of the barrier reefs encircle islands that are partly or entirely made up of Tertiary limestones comparable to those now found beneath the sea in the Marshalls. No deep drilling has been done in the existing reefs of Fiji and their thickness is not known. It does appear, however, that barriers and large atolls have developed in areas where elevation seems to have been the rule since the close of the Tertiary.

It is possible to generalize broadly that elevation has been the rule in Melanesia, subsidence the rule in most of Micronesia and Polynesia. This generalization is significant because it eliminates eustatic shifts in sea level as the controlling factor. In many parts of Melanesia where elevation was widespread the movements seem to have been periodic, and islands in the Trade Wind belt that now stand high above the sea are terraced. The terraces appear to be mainly wavecut, for they are broader to windward than to leeward. Furthermore, it would seem that many of the movements that elevated the terraces were local, for terraces on islands only a few miles apart cannot be correlated accurately. Some of the high terraced islands west of the andesite line, such as those of Tonga, are clearly related to major structural features such as ocean deeps but in none of these little known island groups has the detailed structural history been worked out.

In Micronesia northeast of the andesite line it is even more difficult to obtain information on earth movements because most of the areas that were once land or were covered only by shallow waters now lie beneath the sea. Some inferences may be obtained by study of the geographic distribution of islands and the submarine topography, but most of our conceptions of island structure and island history in this area are based on geophysical surveys and drilling operations.

Theoretically, at least 3 types of movement may have contributed to the subsidence that has been demonstrated for Micronesia. These may be enumerated though it is not possible to determine accurately the relative importance of each.

(1) Subsidence due to compaction of sediments. Russell Raitt's work on the mid-Pacific expedition in 1950 has shown that seismic velocities increase irregularly with depth but most of the changes recorded are interpreted as changes in the nature of material rather than as increases due to compaction and the squeezing out of connate waters. In studying the drilling records it was found that the chief intervals of consolidation occurred in the layers of sediments above 725 feet, especially above 450 feet except for a thin zone from 1,125 to 1,155 feet. The material below 1,155 feet seemed to have lost no porosity because of compaction—in fact, the sediments appeared more porous with depth, especially below 2,080 feet, judging from the rate of loss of drilling mud. The loss occurred whenever the bit was cutting into fresh rock, but if drilling were halted for a few minutes so that mud could seal the freshly-cut interval, the mud loss would stop. It seemed beyond question that the rock was unconsolidated, porous, and fine-grained from 1,155 to the bottom of the hole at 2,556. At greater depths compaction may be much greater but supporting evidence is lacking at present.

(2) Regional subsidence. On the basis of present information it is difficult to evaluate the possible importance of this type of movement in the Marshall Islands and in other "low island areas" such as the Gilbert and Ellice Island groups that adjoin the Marshall Islands on the south. It is clear, however, that the groups mentioned have not felt the effects of the regional elevation that has lifted the many island groups lying to the south and west across the andesite line. It seems equally clear that there has been no subsidence in the Marshall Islands that is directly comparable to subsidence such as has occurred in connection with the well-developed island arcs that lie to the west. The Marshall area has no trenchlike foredeeps though most of the atolls and many of the guyots are arranged in irregular but roughly parallel lines. These lines are interpreted as fissures or lines of weakness in the sea floor along and near which volcanic materials were ejected at irregular spacings.

(3) Isostatic sinking of the piles of volcanic material heaped upon the sea floor. This may be the major factor though Russell Raitt's work seems to show clearly that a deep layer lying 7 to 8 kilometers below the surface at Bikini Atoll is not appreciably depressed by the pile of volcanic rocks and limestones that lie above it.

The Tertiary sections on the two sides of the andesite line actually have much in common both lithologically and faunally and this reflects fairly uniform conditions

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of sedimentation and growth over wide areas of the Pacific during most if not all of Tertiary time.

As shown by Cole (chapter O, table 1, of the present report), many of the Foraminifera that he identified from the Tertiary section under Bikini have been described earlier from one or more of a dozen localities in other parts of the Pacific area—from Australia and the East Indies to island groups in the more open Pacific such as Fiji, Marianas, Ryukyu and Kita-daitō-jima. In like manner, J. Harlan Johnson (chapter M of present report) has identified algae in the Bikini section that had previously been described from the Tertiary of Java and Fiji, and Wells (chapter P of the present report) found that the fossil coral fauna of Bikini was most closely related to the Miocene fauna of Borneo.

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DETAILED REEF TRAVERSES

As mentioned briefly in the Introduction, detailed observations across the reefs of Bikini, Eniwetok, and Rongelap Atolls were made along measured traverses. Generalizations written into the text are based largely on these traverses supplemented in the case of Bikini Atoll by observations made on trips by an amphibious truck (DUKW) over the reefs between islands and by scattered observations on a number of areas lying between the measured traverses. The locations of all traverses are shown in figures 6, 37, 46, 54. Observations made at the times the traverses were run are reproduced below in full as they constitute the source of basic data on which many interpretations of the text are based.

At Bikini a total of 30 traverses were measured. These are shown in figure 6 where they are numbered starting with a particularly detailed traverse off the east coast of Bikini island and extending around the atoll in a clockwise direction. All but 2 of the traverses extend entirely across the reef; 23 cross seaward reefs to an island or to the lagoon; 7 cross lagoon reefs to islands. All but 5 of the traverses are tied to islands, and the reefs adjacent to islands thus received a disproportionately large amount of attention. One reason for this, of course, was the fact that the reefs close to the islands were more easily accessible than the long stretches of reef between islands. The windward reefs of Bikini were fairly well exposed by the more favorable low tides and at such times it was possible to drive over them in a DUKW, stopping at intervals for detailed examinations. Trips of this sort were made over the windward reefs from Enyu island to a point on the reef 4 miles northwest of Bikini island and added much data to that obtained on the traverses. It was unfortunate that limitations of time and facilities did not permit similar trips along other sections of the inter-island reefs.

On traverses across the reef measurements were made by the compass-and-pace method and observations were recorded along a strip approximately 20 feet in width. In many instances the observations on the exposed reef were supplemented by others obtained while swimming with a face mask in the marginal pools and channels and off the seaward edge.

BIKINI ATOLL

1. TRAVERSE ACROSS SEAWARD REEF ABOUT 1 MILE NORTH OF SOUTH END OF BIKINI ISLAND

	Width (feet)	Cumulative width (feet)
1. Marginal zone:		
a. Submarine spurs and channels (not measured).		
b. *Lithothamnion* ridge:		
b_1. Buttress and surge-channel zone	120	120
b_2. Algal pavement	120	240
2. Coral-algal zone	210	450
3. Outer *Heliopora* zone	525	975
4. Main reef flat	1, 070	2, 045
5. Inner *Heliopora* zone	115	2, 160
6. Beach	105	2, 265

1. Marginal zone. The spurs and channels that form the submarine slope from the reef to the seaward terrace are included in the marginal zone because they are a part of the living reef and are closely related to the *Lithothamnion* ridge.

1a. Submarine spurs and channels. From the outer edge of the reef large algal spurs or ridges 25 to 50 feet wide extend seaward in gentle slopes. At distances more than 100 feet from the reef edge the slopes become steeper and more regular. The spurs are separated by canyonlike channels 10 to 20 feet wide. The overall slopes of the spurs though gentle are not uniform, for a few subcircular masses of algae rise nearly to sea level at points located from 25 to as much as 75 feet beyond the reef edge. Where present these growths constrict the channelways. The channels are about 20 feet deep at the reef edge, sloping to a depth of 35 feet at a distance of 100 feet from the reef edge. The channel walls are steep to vertical, the bottoms are irregularly flattened. As much as 10 percent of the sides and tops of the subcircular algal masses are covered by living coral. Shallow depressions in the channels contain debris in the form of rounded heads of corals and algae with gravel and coarse sand.

1b. *Lithothamnion* ridge. At the seaward edge of the reef a rich growth of calcareous algae forms a cuestalike structure whose steeper side faces the sea. The ridge is cut by the landward extensions of the submarine channels that lie beyond the reef edge. These extensions are called surge channels, and they divide the ridge into massive algal buttresses that rise steeply from the sea but have a gentle flattened slope to landward. The steep, seaward sides are completely covered by spongelike, globular colonies of lithothamnia (mostly *Porolithon gardineri*), and this area of rich growth is continued into the surge channels around the edges of each buttress. These algae are dark red to purplish red, their color contrasting with the blue water and white foam as the ridge is uncovered between waves. The highest parts of the ridge rise 3 feet above the reef flat.

The gentle backslope of the ridge is made up mainly of flattened botryoidal crusts of the "pavement type" algae chiefly *Porolithon onkodes*, with a few knobby or globular colonies. Parts of the pavement are scored by echinoid borings. The color of the backslope is a brownish red as compared with the dark red of the seaward slope. Near the landward edge of the backslope there are scattered remnants of an older reef rock that rise 2 to 3 feet above the general level (pl. 39). The rock is composed mainly of dead *Lithothamnion* of the types now forming the ridge, most if not all of them in position of growth. Spaces between the branches of the algae are almost completely filled by unsorted detritus in a finely granular matrix. The rock remnants are dense and hard but their sharply sculptured forms strongly suggest that they are now being eaten away by solution aided by boring organisms. In this zone there are also a few reef blocks or negroheads as much as 5 feet in diameter.

The surge channels that cut the ridge have vertical to greatly overhanging walls. The structure of the ridge and the caverns underlying it was examined by diving in the pools and swimming below the reef with a face mask. In this area the seaward edge of the reef appears to have developed from large pillarlike masses of algae 20 to 50 feet across and 2 to 25 feet apart that grow up to tide level from a floor 15 to 25 feet deep at the reef edge and 2 to 5 feet deep several hundred feet back from the edge. When these pillars have grown up to the surf zone, a foot or more below low-tide level, conditions apparently are particularly favorable for algal growth and the pillars mushroom or shelve out at this level. Most of the algae forming the upper 2 feet of the walls are *Lithothamnion* of the globular type. Growth in a horizontal plane is continued until the algal shelves partially roof over the channels and thus extend the marginal zone seaward. Algal growth appears to be most rapid along the edges of the channels and as the shelves continue to grow they coalesce leaving irregular openings at intervals—openings 5 to 10 feet across where 2 or more channels may intersect.

Below reef level the roofed channels extend under the reef in branching caverns, lit by sunlight through the reef openings at intervals of about 50 feet (pl. 16, fig. 2). The water in the channels is slightly murky near the seaward edge of the reef and near the top visibility is poor part of the time owing to bubbles in the rapidly moving surface layer of water. Below a depth of 1 foot, water movement is much less and visibility greater. The caverns are similar to those developed artificially in a mine by the "room and pillar" method. The ratio of the area of reef underlain by "rooms" to that supported by "pillars" is locally as high as 1:1 but in most areas it is considerably less.

The larger caverns are 10 to 25 feet deep and 5 to 15 feet wide. The walls are nearly vertical below and arch to the top. In most places the depth of the channels greatly exceeds the width and they resemble narrow canyons. The shelf forming the ceiling may be less than a foot thick for more than 6 feet across the cavern, but more typically it is 6 inches to a foot at the center of the arch and thickens rapidly to the sides.

The caverns and channels extend under the reef flat for distances of as much as 350 feet. In addition to the large openings that are alined with the open surge channels there are scores of smaller openings through which the water rises with each advancing surge. In one area, 30 feet in diameter, holes are almost as numerous as in a honeycomb. None of these openings suck air between surges nor is there any blowhole effect. The water rises through the small openings to form contiguous mounds. These mounds mark the progress of the wave beneath the surface, holes to landward continuing to discharge water after those next to seaward have subsided. This action is so regular that a sheetlike opening beneath the reef surface is suggested.

The walls of the caverns are formed of lumpy, irregular pink to purple *Lithothamnion*, including colonies of the globular type, on which many *Turbinaria* and other corals including *Heliopora* grow. Locally the corals cover half of the walls below a level of 2 feet from the top. The flattish floors are of pink to white algal limestone; they may be bare or carpeted with a veneer of sand and coarser material. In one channel at a point close to the edge of the reef two large masses of reef rock each measuring approximately 15 by 10 by 10 feet have slipped to the bottom where they now rest on the channel floor. There is some coral growth on masses such as these that lie above the channel floor.

2. Coral-algal zone. A flat area about half of which is covered by a few inches of water at low tide. Algal masses of pavement and nodular types and flat-lying colonies of a variety of corals cover the surface in about equal proportions. Lines of pools marking the landward continuations of the surge channels extend into this zone. Each pool has a thickened margin of pink algae but these margins are less well developed than they are seaward on the backslope of the *Lithothamnion* ridge. The encrusting pavement type alga is *Porolithon onkodes*. A specimen (B–107) is concave below, thin, and full of cavities that are encrusted by the dark-red foraminifer *Mineacina* and by a few coiled tubes. The outer surface of the specimen shows several thin growth sheets. Numerous parallel scars are the result of gnawing or scrapings of parrot fish. Such scars are widespread and may be a source of considerable fine sediment.

3. Outer *Heliopora* zone. In this area the general surface of the reef flat is distinctly lower than the zones to seaward and is covered by 1 to 4 feet of water at low tide. From the floor large subcircular microatolls, 3 to 25 feet or more in diameter, consisting largely of the blue alcyonarian, *Heliopora coerulea*, rise close to low-tide level. In the outer parts of this zone the microatolls are formed mainly by the scleractinian coral, *Acropora palifera*. In each microatoll there is a concentration of living forms around the periphery though live colonies, particularly *Heliopora* and algae, may be growing sporadically all over the structure. The *Acropora*, which apparently is not quite so hardy a form as the *Heliopora*, is concentrated around the edge of the microatoll and most of the colonies are at a somewhat lower level than the Helioporas; at low tide the tips of many *Heliopora* colonies break water and further upward growth appears to be limited. The rich growth around the edges of the structures suggests very definitely that the masses are expanding laterally in all directions. Many of the dead Helioporas in the central areas are covered by a film of sand rich in living Foraminifera. In a sample of the sand (B–106) about one-half of the material is coarse, ranging from 0.5 to 4 mm, and most of the grains are close to 1 mm in size. It consists of tests of Foraminifera and large grains (approximately 30 percent unworn *Calcarina spengleri*, 15 percent *Marginopora* 0.1 to 4 mm, 5 percent fragments of echinoid spines, algal tubelets, and less common Foraminifera). The other half of the sample consists of fine grains 0.02 to 0.5 mm in size.

4. Main reef flat. The landward edge of the Outer *Heliopora* zone is irregular and the reef floor from which the microatolls rise continues landward as a fairly level rock surface divided by what appears to be the marginal zone of an older reef, a zone 110 feet in width. At the present time this old reef line is a hummocky surface of limestone cut by wide transverse gaps and narrow longitudinal fissures. It is practically bare of organic growth and parts of it that dry at low tide appear to be undergoing erosion by solution. A sample of the rock (B–317)

is coral, one fragment of which is believed by J. W. Wells to be *Pocillopora*. The surface of the specimen is bluish gray in color, smoothly cuspate and pitted, and bottoms of the small pits or depressions are coated with a buff calcareous crust. A few specimens of *Marginopora*, two burrowing bivalves, and a number of small coiled worm tubes are on the surface of the specimen.

n thin section the coral is apparently unaltered aragonite with a small amount of crystalline carbonate lining some of the pore spaces. Near the surface of the rock, some pores are seen to be filled with a yellowish-brown microgranular paste that has a faint greenish tinge. The greenish cast may be due to microscopic algae, but no clear evidence was seen.

Sand (B–105) scraped from the hummocky surface of the old reef consists about 50 percent or more of Foraminifera; 20 percent of matted filamentous algae with a thin, tubelike, calcareous coating; 20 percent fine material, most of which is formed of broken spines of *Calcarina spengleri*; and less than 10 percent fragments of *Lithothamnion*, and mollusk shells. The proportions of Foraminifera in the whole sample are approximately 40 percent unworn and spiny *Calcarina spengleri*, 7 percent brown and white *Marginopora* discs 1 to 5 millimeters in size, and 3 percent *Amphistegina*, as well as a few tests of *Tretomphalus*, *Textularia*, and miliolids.

On the main reef flat there is no great development of reef building corals or algae; much of its surface is veneered with a mat of living smaller Foraminifera held together by fibrous algae.

5. Inner *Heliopora* zone. In this zone the microatolls are more widely scattered and in most places are smaller than in the outer zone. *Heliopora* is the dominant form but nearer shore colonies of *Porites lutea* become increasingly numerous and in some structures almost completely replace the *Heliopora*. Nodules of living coralline algae 1 to 2 inches in diameter are abundant.

6. Beach. A strip of coarse sand and gravel at the landward side of the inner *Heliopora* zone above which lies the cream-colored sand of the beach proper. The sand grains are mostly the shells of the smaller Foraminifera such as *Calcarina* and *Marginopora* that veneer the areas to seaward.

2. TRAVERSE ACROSS SEAWARD REEF ABOUT ONE-FOURTH MILE NORTH OF SOUTH END OF BIKINI ISLAND

	Width (feet)	Cumulative width (feet)
1. *Lithothamnion* ridge:		
a. Buttress and surge-channel zone	50	50
b. Algal pavement	35	85
2. Coral-algal zone	30	115
3. Reef-patch zone	160	275
4. Reef flat	225	500
5. Hummock zone	25	525
6. Beach rock	115	640
7. Beach	70	710

1. *Lithothamnion* ridge. Structure similar in major features to that found on traverse 1 but more irregular. Deep surge channels extend entirely across the ridge and into the coral-algal zone for total distances of 100 feet or more; these channels connect with shorter lateral fissures and the ridge is divided into a mosaic of irregular patches. The higher parts of the ridge rise 2½ feet above the reef flat and possibly as much as 4 feet above extreme low-water level. Large parts of the algal pavement are riddled by the borings of a small echinoid but the older parts of the borings are veneered with living *Lithothamnion*.

The underside of a specimen (B–314) of the encrusting alga (*Porolithon onkodes*) of the backslope contains many pink to red encrusting *Miniacina*. The bristly "whiskers" of this foraminifer that appear to grow from the bumps or tubercles on its surface are brittle and splintery. In oil of index 1.68 they are seen to have a low index and low birefringence. They are insoluble in HCL, and appear to be tubes or spicules of silica. Hickson (1911) states that they are stuck in the test of the foraminifer by the organism itself. They are pointed at the base where they are imbedded in the calcite of the test.

2. Coral-algal zone. Rich growth of living corals cover 40 to 50 percent of the surface of this zone, the balance is a pavement of living algae. Locally the corals appear to be growing over the algae, in other places the reverse is true. Some of the coral colonies are very large—irregular tide pools as much as 5 feet in diameter are carpeted with a brown species of *Acropora*, the sheet being formed by one continuous colony; other depressions are lined by *Favia*.

Close to the line of traverse at the inner margin of the coral-algal zone there are solution-sculptured rock masses that rise 1½ feet above low-tide level. The largest is irregular in outline and 20 feet in maximum diameter. A specimen from this mass (B–315) is a firmly consolidated algal-coral rock. *Lithothamnion* appears to be detrital. Coral pieces are seen to be fragments. *Gypsina* and *Carpenteria* are common throughout. The rock is well-lithified and compact, but it is riddled in the uppermost 1 to 2 centimeters by borings. The surface is smoothly cuspate and pitted. Under the binocular microscope the surface is seen to have a thin veneer of fine chalky detritus matted by fine soft algal fibers.

A thin section shows that the rock is formed of unsorted detrital material consisting of foraminiferal tests mostly of *Calcarina*, fine to coarse grains of *Lithothamnion*, *Halimeda*, coral and mollusk fragments in a gravish-brown microgranular matrix that forms about 70 percent of the area of the slide (pl. 42, fig. 4).

The microgranular paste appears to be stippled because areas of brown material are separated by areas of clear microgranular material that seems to have recrystallized from the brown. Larger grains in the slide are coated and many pores are filled by a crust of crystalline carbonate that is probably calcite.

3. Reef-patch zone. A rock flat thinly veneered with sand and covered by 3 to 18 inches of water at low tide. The deeper pools are irregular in outline and support a variety of living corals.

4. Reef flat. Similar to zone 3 but without the pools containing coral patches; covered by 6 inches of water at low tide. Near the line of traverse there are cracks in the reef flat that parallel the trend of the reef for distances of several hundred feet (pl. 38). These may be tension cracks resulting from the compaction of reef detritus. Similar features were noted at Funafuti (Sollas, 1904 p. 26).

5. Hummock zone. Rock flat with low rounded mounds of firm sand that are exposed at low tide. A sample of the rock (B–313) consists almost entirely of compact coral with a pitted surface containing minute rounded cusps. The surface is covered by a thin layer of fine detrital material and by much lichenlike soft algae. Holothurians and serpent stars (brittle stars) are abundant locally (pl. 40).

In thin section the structure of coral is seen to be formed of fine compact aragonite, but some pores are filled with clear acicular carbonate that appears to be optically continuous with the yellow fibrous aragonite of the coral. Other pores are filled with gray fine-grained to microgranular paste that in some places is altered to clear calcite ranging from a fine mosaic to almost microgranular material. Some cavities are lined with clear calcite that appears to be different from the acicular needles seen in some of the pores.

6. Beach rock. Belt of well cemented conglomerate extending out over the flat or a rock groin. Parts of the rock are pitted by solution, the rims of the pits having a glazed or polished surface. The rim of such a small solution pit is shown in plate 41, fig. 5 and plate 43, fig. 1. About half the rock consists of tests of *Calcarina spengleri* and other foraminifers, the rest is unsorted fragments of *Halimeda*, *Lithothamnion*, mollusks, and angular to rounded grains 1 to 3 mm in size. Most of the specimen is porous but well consolidated. The surface layer, 1 to 2 mm in thickness, is almost completely filled by porcelaneous white carbonate both in pores within fragments and in the intergranular areas. The surface of the rock is dark grayish-brown, finely pitted and rough like coarse sandpaper. Individual grains and tests stand in relief but are worn and some are polished. The hollows between grains are coated with a fine fuzzy growth that can be seen only under the binocular microscope—probably an algal growth. Minute cubes of halite are scattered over the surface. The solution pit, of which this specimen formed a part of the rim, was about 12 cm in diameter and 4 to 5 cm deep. The rim of the pit is smooth white laminated crust about 1 cm wide and 1 mm thick. It has a finely crackled or crazed appearance but under the binocular microscope the surface is seen to be smooth and polished. (Similar basins with polished rims were seen on Rongerik; pl. 43, fig. 2.)

In thin section the laminae of the rim crust resemble *Lithothamnion* laminae, but have no cell structure (pl. 43, fig. 1). In immersion oil most of the material seems to be calcite although some with an index greater than 1.66 is apparently aragonite. When the specimen was boiled in dilute cobalt nitrate, the thin outer laminae were unstained but the innermost ones were stained. The crust is apparently a mixture of calcite and aragonite. The porcelaneous white paste that fills pores and cements grains beneath the laminated crust is unstained and probably calcite, but most or all of the chalky material coating grains in the porous part of the specimen is stained and is aragonite. No reason was found for the distribution of the aragonite and calcite in the cementing or encrusting material. The laminae probably result either from physicochemical precipitation of carbonate from the water in the small pit, or from biochemical precipitation of carbonate due to the film of microscopic algae that coats the bottom and sides of the pit.

7. Beach. Composed of cream-colored sand, the chief constituent being the tests of Foraminifera (*Calcarina* and *Marginopora*) that live on the reef flat.

3. TRAVERSE ACROSS LAGOON REEF NEAR MID-POINT OF BIKINI ISLAND

In the lee of Bikini Island there is a discontinuous series of irregular reef patches that extends into the lagoon from near the edges of the beaches. The patches tend to be wider (into the lagoon) than long (parallel to shore) and they show concentric zoning rather than zoning parallel to the shore. Three fairly distinct zones may be recognized.

1. Outer zone. This zone has an irregular, lobate margin formed of discrete heads of coral and alcyonarians 4 to 20 feet in diameter. In the outer part where the sandy bottom lies 8 feet below low-tide level there are large areas covered by hydrocorals (*Millepora*) with a few small colonies of true corals. Inside this living margin there are large subcircular areas that uncover a few inches at lowest tide. The rounded outlines of many of these masses have been determined by the

alcyonarian, *Heliopora*, and the scleractinian, *Porites andrewsi* (ramose growth form), but most of the colonies are dead and veneered with a film of brownish algae. The bottom of the lagoon is covered by sand and broken coral on which there are widely scattered clumps of living *Halimeda*.

2. Middle zone. The floor of this zone lies 4 feet below low water. Colonies of *Heliopora* as much as 6 feet in diameter rise 2 feet above the sand-covered floor but, like those in the adjoining outer zone, many are dead and are partly encrusted with small branching corals. The sands of the deeper areas are bound by living *Halimeda*.

3. Inner zone. This zone is covered by only 2 to 3 feet of water at low tide. It supports a considerable variety of living corals but they cover only a small percentage of the bottom, the remainder being sand. The inner zone abuts against eroded beach rock where such is developed, elsewhere against the unconsolidated sands of the beach.

A sample of the sandstone (B-42) collected from the lagoon beach near traverse 3 is shown in plate 22, figure 2. The rock is polished, well-consolidated, well-bedded, beach sandstone. Beds are 2 to 10 millimeters wide and consist of moderately sorted fine sand and poorly sorted coarse sand. The fine material is composed of angular to poorly rounded detrital grains; medium grains are largely foraminiferal tests, notably *Calcarina spengleri*, and coarse material is mostly rounded fragments of *Lithothamnion* and mollusk shells. The polish is best developed on beds of fine material that form highly polished ridges on a weathered surface.

In thin section the alternating layers of fine and coarse grains are less clearly apparent (pl. 22, fig. 3). Cement in the fine material appears no more abundant than in the coarse, but many small pores are filled. The cementing coat about each grain is seen in section to be formed of an acicular fringe of carbonate separated from the grain by a "dark line" of microgranular carbonate.

4. TRAVERSE ACROSS SEAWARD REEF TO SOUTH END OF ENIAIRO ISLAND

	Width (feet)	Cumulative width (feet)
1. *Lithothamnion* ridge:		
a. Buttress and surge-channel zone	50	50
b. Algal pavement	65	115
2. Coral-algal zone	120	235
3. Reef flat	665	900
4. Beach rock	35	935

1. *Lithothamnion ridge*. Algal buttresses are exceptionally well developed on the seaward side of the ridge. At the surf zone, where they are separated from each other by surge channels, they measure 20 feet in width and rise 2 feet above the level of the reef flat. The tops of the buttresses are composed of pink *Lithothamnion* of the pavement type; the margins and the sides that form the surge channels are covered by large globular colonies of *Lithothamnion*.

On the backslope of the ridge and for a distance of 100 feet into the adjoining coral-algal zone there are numerous irregularly sculptured masses of algal rock. They rise as much as 4 feet above the reef flat and appear to be isolated remnants of an older buttress zone. A specimen from one of these remnants (B-300) is shown in plate 42, figures 1, 2. The rock is a massive, hard algal reef limestone containing about 50 percent lithothamnia in position of growth, 25 percent detrital filling between algal branches, and 25 percent open cavities of boring organisms. The alga appears to be *Porolithon gardineri* which is growing on the present ridge. The detrital filling consists of fine to coarse grains and foraminiferal tests, cemented and compact. Borings are unfilled, and cut both the algae and the detrital matrix. The destruction marked by their activity and by solution on the reef flat, therefore, appears to be a later phase separated from the algal growth, the detrital filling, and the consolidation.

In a thin section (pl. 42, fig. 3) more than 75 percent of the slide area is seen to be lithothamnia. Most algal boundaries are well defined and are marked by a film of yellowish-brown isotropic material that is presumably carbonaceous. Cavities between algal branches are filled or partly filled by an unsorted detritus of tests of *Marginopora*, *Calcarina spengleri*, and delicate pelagic foraminifers, segments of *Halimeda*, and fragments of shells in a fine-grained matrix. Minute spherules are abundant in some cavities, and form an appreciable percentage of the paste. Some intergranular spaces as well as pores in tests are lined with minute acicular carbonate, but there is no crystalline lining in the open borings.

The open surge channels extend well into the *Lithothamnion* ridge, their overall lengths being 50 to 75 feet and further extensions, largely roofed over, continue back to points 330 feet from the reef edge. Along the line of these covered extensions water surges through holes and cracks in the reef with every wave. Pink pavement algae cover the surface for 5 to 10 feet on each side of the extensions and in effect form prominent projections of the algal pavement into the coral-algal zone.

The surge channels are 5 to 10 feet wide at the reef edge and gradually are narrowed by algal growth to landward. At points 50 to 100 feet from the reef edge the roofing over is complete except for a discontinuous crack. Beyond 100 feet the crack is completely healed except for open pools in the reef, 2 to 6 feet across, every 50 to 100 feet.

At 100 feet there is an irregular opening about 4 feet wide and 7 feet long. Underneath the shelf the pool broadens to a cavern 10 feet wide and 8 to 10 feet deep that extends to the reef edge. The bottom of this cavern, or covered surge channel, is pink to white algal limestone apparently very little eroded. It is quite irregular and hummocky. The sides range from perpendicular to rounded slopes of 60°, and generally seem to overhang at about 45° in the upper parts. The shelf or roof is typically a foot thick or less where the algae have coalesced, and in places is less than a foot in thickness for 6 feet or more across the roof of the cavern. Two hundred feet from the roof edge a second pool in the same surge channel was examined. This had an opening 2 feet wide, 4 feet long, and broadened inside to a cavern 6 feet deep, about 6 feet wide, and 10 feet long. It is connected to the surge channel but apparently almost walled off by coral and algal growth. There is a rich coral growth on the side, especially of brownish-yellow *Turbinaria*.

At 294 feet there is a very small pool in the reef, 4 feet deep, with a sandy bottom, and at 330 feet the last pool in the chain is about 2 feet deep with a sand bottom.

2. Coral-algal zone. In this zone the surface of the reef is depressed a few inches below the landward edge of the *Lithothamnion* ridge. There is a rich development of branching and encrusting corals forming 50 to 75 percent of the surface area; the remainder is dead algal limestone. The corals are most abundant near the seaward edge of the zone, but they extend landward along the roofed over channels beyond the extensions of the algal pavement and well into the reef flat. These extensions are controlled by the channel cracks and openings in the reef surface.

3. Reef flat. This area seems to be composed mainly of algal limestone almost completely covered by a veneer of foraminiferal and detrital sand bound by velvety algae; its seaward part is covered at low tide by 1 to 3 inches of water. At a distance of about 425 feet from the reef edge the flat rises above low-water level becoming a hummocky surface with small pools of shallow water between the sandy mounds. About half of this part of the zone is dry at low tide. At a distance of 570 feet from the reef edge the flat is 6 inches above low-water level, the hummocks broad and low; shallow pools occur, some of them containing colonies of living coral, mostly *Porites* (pl. 44, fig. 1).

4. Beach rock. Beach sandstone fringes Eniairo island forming a bench 35 feet in width that slopes seaward at an angle of about 7°.

5. TRAVERSE ACROSS REEF FROM SEA TO LAGOON ABOUT ONE-FOURTH MILE NORTH OF ENYU ISLAND

	Width (feet)	Cumulative width (feet)
1. Marginal zone:		
a. Submarine spurs and channels (not measured).		
b. Reef edge	11	11
c. Tide-pool zone	19	30
2. Coral-algal zone	17	47
3. Alcyonarian zone	13	60
4. Zoanthid zone	67	127
5. Rock flat	563	690
6. Coral zone	221	911
7. Gravel bar	33	944

1a. Submarine spurs and channels. Those beyond the exposed reef edge were examined by swimming with a face mask. Large fingerlike spurs extend seaward for 150 to 300 feet, separated by long canyonlike channels 5 to 10 feet wide. (See fig. 73.) The spurs are 10 to 40

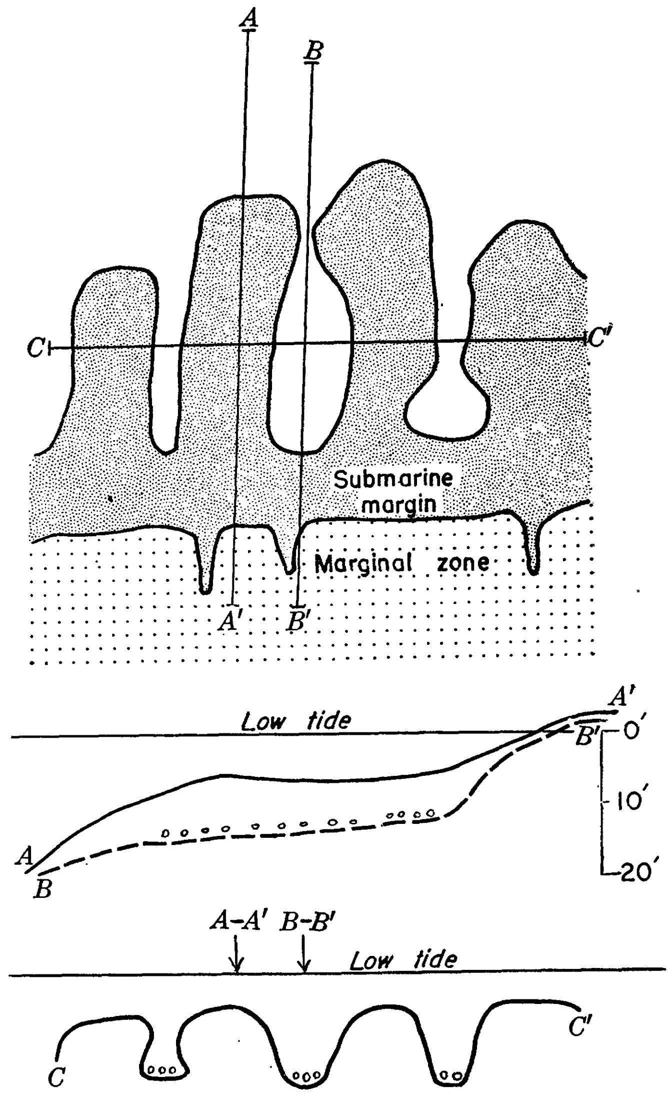

FIGURE 73.—Plan and sections through spurs and channels north of Enyu Island Elongate spurs separated by narrow channels are covered by 3 to 8 feet of water. Channels are 7 to 10 feet deeper.

feet across, averaging about 25 feet. They slope gently seaward and are covered by 3 to 8 feet of water at low tide. In some places there is a slight rise near their seaward ends. The seaward ends are blunted, sloping to greater depths at an angle of 45° or more. In cross section (parallel to the reef edge) the spurs are broadly crested or almost flat-topped, and consist of mammillary algal structures with abundant coral growth that forms about 20 percent of the surface.

The channels separating the spurs are about 8 feet deep near the exposed reef edge, and 15 to 18 feet deep near the outer margin where the channel walls are 7 to 10 feet high. In most places the walls are vertical, in some the angle is as low as 60°, in others overhanging. Coral growth is abundant on the channel walls; the floors are flat, rounded at the edges like the bottom of a bathtub, and in some places, hummocky. Parts of the floors are barren, white, eroded rock, other parts are covered by coral or algal gravel or boulders. Some of the channels are constricted to 2 feet or less at their seaward margin. A sample of gravel (B-70) was collected from a surge channel at the north end of Enyu island about 100 feet seaward of the edge of the reef in 15 to 20 feet of water. The material (pl. 44, fig. 2) consists mostly of worn pebbles and fragments of coral 0.5 to 3.0 centimeters in size. *Stylophora* and *Acropora* are present. Most pebbles are worn and polished, and a few have a reddish-orange surficial stain or tint. Most are pitted with tiny holes possibly caused by boring sponges. There are a few fragments of mollusk shells. Material finer than 0.5 centimeter, most of it larger than 1 millimeter, forms less than 5 percent of of the sample. It consists of a few *Calcarina spengleri*, worn, white, broken, thick *Halimeda* segments, some segments of crustacean appendages, and fragments of a small tubelike calcareous alga having a central organic thread. Fine material presumably is present in greater proportions but was washed out when the specimen was collected by diving.

1b. Reef edge. A narrow zone whose seaward boundary is made irregular by poorly defined surge channels. There is no *Lithothamnion* ridge and no well-developed buttresses, the areas between channels sloping very gently seaward. Surface covered by corals (including *Millepora*) and algae in about equal proportions. At lowest tide parts of the zone are uncovered between waves. Colonies of *Millepora* are irregular in outline and several feet in maximum diameter. *Pocillopora* is the commonest coral, many of the colonies reaching a foot in diameter; an encrusting *Acropora* also occurs in abundance. Algal areas are covered by encrusting and globular types of *Lithothamnion*; large masses of algae are encrusted by *Acropora* on their landward sides.

1c. Tide pool zone. A flattish area rising slightly above the reef edge; the surface is irregular in detail but has a maximum relief of only 1 foot (except for prominent steep-sided pools). *Lithothamnion* covers three-fourths of the surface, the remainder being occupied by corals.

Two subcircular pools close to the line of traverse measure 9 and 5 feet in diameter and 3 to 5 feet in depth; their walls are steep to overhanging, their rims encrusted with *Millepora*, *Acropora* and algae with some large colonies in the upper half of the walls. Superficially, at least, these pools resemble large potholes and heavy cobbles as much as 6 inches in diameter are scattered on their sand floors.

2. Coral-algal zone. At its surface is composed primarily of algae and is overgrown partially by colonies of encrusting *Acropora*. In areas near the line of traverse these colonies are very large, one single unbroken colony extending for a distance of 30 feet. Colonies of brownish *Pocillopora* are numerous, also purple algae that cover 30 percent of the surface; over large areas the corals cover an equal area.

3. Alcyonarian zone. Underlain by algal limestone with a maximum relief of 6 inches. More than half of the surface is veneered with a layer of soft olive-green Alcyonaria in reticulate pattern; scattered heads of *Pocillopora* and circular masses of encrusting *Acropora* cover 5 percent of the surface.

4. Zoanthid zone. Like zone 3 above is a flat of algal rock. From 5 to 70 percent of the surface is covered by soft zoanthids of the size and shape of silver dollars (pl. 45). F. M. Bayer has identified specimens of this form from Bikini Atoll as *Palythoa*, probably *P. tuberculosa* (Esper). There are, likewise, numerous colonies of *Pocillopora* 3 to 4 inches in diameter, most of them dead, and many small holothurians.

To the south of the line of traverse the zoanthids give way to a rich coral zone 50 feet wide; living corals (*Acropora, Favia, Pocillopora*) in this zone cover more than half the surface.

5. Rock flat. A wide level area slightly lower than reef to seaward; maximum relief less than 1 foot. Living corals mostly less than 1 foot in diameter cover 5 to 10 percent of the surface; a few small nodular pink algae are present; part of surface is covered with thin veneer of sand, and a few large blocks (maximum diameter 1 foot) are widely scattered. A sample of the sand (B-132; pl. 47, fig. 1) has the following composition: about one-third is branching fibers of soft green and brown algae, joints of *Halimeda*, fragments of *Lithothamnion*, corals and mollusk shells. Another third consists of Foraminifera, mostly exceptionally spiny forms of *Calcarina spengleri*, some *Marginopora*, and less common *Amphistegina;* the last third consists of

angular detrital grains less than 1 millimeter in size. Most grains are recognizably organic. Gorgonid spicules, and minute crab and shrimp claws are present.

6. Coral zone. Similar to the last but with the numbers of corals increasing lagoonward until they cover 20 percent of surface. Most colonies are less than 1 foot in diameter. The zone is covered by 1 to 2½ feet of water at low tide. Dead corals and coarse debris appear near lagoonward edge.

7. Gravel bar. Rises steeply from 2½ feet of water to 6 inches above; the gravel is poorly sorted and mixed with sand, the largest pieces not exceeding 6 inches. The edges of the bar are scalloped in plan and the deposit shelves off gradually into the lagoon.

6. TRAVERSE ACROSS SEAWARD REEF ON SOUTHEAST SIDE OF ENYU ISLAND

	Width (feet)	Cumulative width (feet)
1. *Lithothamnion* ridge:		
a. Buttress and surge-channel zone	45	45
b. Algal pavement	55	100
2. Coral zone	50	150
3. Reef flat	230	380
4. Beach	70	450

1. *Lithothamnion* ridge. Seaward edge of reef deeply scalloped into rounded buttresses separated by deep surge channels; lines of buttresses rise well above the general level of the reef, the highest points being on the seaward edge. Seaward slope of buttresses not accessible. Even at lowest tide the crests of the buttresses are covered momentarily by each wave. The buttresses which are composed almost entirely of *Lithothamnion*, form a cavernous structure and on the gently sloping leeward side there is an irregular series of blow holes that spout like geysers with each advancing wave (pl. 46, fig. 4). Surge-channels and pools lined with globular type of *Lithothamnion* that are purplish pink; these combine with the lighter, more brownish-colored nodular algae on the buttresses give the structure as a whole a pink color. Corals are exceedingly rare on the buttresses. Small masses of soft green seaweed occur and there are numerous large club-spined sea urchins in protected places; mollusks are rare, the commonest forms being a large *Turbo*, a small *Drupa*, a small *Trochus* and one or more species of limpets.

A fairly distinct strip about 50 feet wide forms the landward slope of the *Lithothamnion* ridge. The surface is smooth with broad and irregular shallow depressions. Most of the pavement appears to be a sheet of living algae, colored light shades of pink and tan. A few colonies of living corals grow in the shallow depressions but they cover less than 5 percent of the surface of the zone as a whole.

2. Coral zone. This zone is the seaward margin of the main reef flat and merges imperceptibly into it. It is covered by 6 inches to 1 foot of water at low tide. A considerable variety of reef corals occur but they are so irregularly distributed that it is difficult to estimate their importance—only locally do they cover more than 25 percent of the surface. Practically all of the corals are alive and apparently healthy. Corals are attached to a solid rock pavement that is only thinly veneered with sand.

3. Reef flat. A rock flat partly covered by thin layer of sand and covered by 6 to 8 inches of water at low tide. Small colonies of living corals are widely scattered over seaward half of flat. To the southwest of the line of traverse a large triangular area is covered by coral blocks and boulders as much as 2 feet in diameter; to the northeast an area of lithified beach conglomerate covers the landward part of the reef flat.

4. Beach. Cream-colored sand composed chiefly of the tests of *Calcarina*.

7. TRAVERSE NORTHWARD ACROSS SEAWARD REEF TO EAST END OF ENINMAN ISLAND

	Width (feet)	Cumulative width (feet)
1. *Lithothamnion* ridge:		
a. Buttress zone (approximately)	100	100
b. Algal pavement	40	140
2. Coral zone	20	160
3. Reef flat	100	260
4. Old reef	480	740
5. Boulder zone	60	800
6. Beach rock (not measured).		

1. *Lithothamnion* ridge. The seaward margin of the ridge, a zone approximately 100 feet in width, is composed of lobate algal buttresses that slope gently seaward declining 6 feet in 100 feet. The buttresses are formed mainly of yellowish *Lithothamnion* that, at the time of examination, appeared dead in contrast to small amounts of pink algae. Globular colonies of *Lithothamnion* are rare but the columnar type of colonies (*Porolithon craspedium*) is common. *Pocillopora* and other corals are present and *Millepora* covers large patches but the total area covered by the corals is less than 10 percent of the zone.

The backslope of the ridge is a rock floor composed of knotted and nodular algae that dips gently shoreward. Globular types of *Lithothamnion* are common and the columnar type is rare. Many small branching colonies of coral cover only a small percentage of the area.

The numerous channels that separate the buttresses of the *Lithothamnion* ridge extend landward into or even through the coral zone—a distance, in some cases, of 90 feet from the crest of the ridge. The channel edges are zones of algal growth and stand up as ridges 6 inches above their surroundings. At the ends of some channels in the coral zone there are mounds 10 to 20 feet across that rise a foot or more above the general surface. In old mounds that have been eroded the channels are still observable though completely coalesced. The channels are 10 to 12 feet deep at the ridge crest but are only 4 to 6 feet deep at points 50 to 80 feet landward. Their floors are covered by coral sand. They form an anastomosing network through the ridge, many of them now being completely roofed over.

2. Coral zone. This zone lying in back of the ridge has an irregular but relatively sharp boundary on its seaward side. Its surface is covered by several inches of water at low tide. Massive and encrusting corals of all types grow in great abundance on the algal floor and cover 50 to 75 percent of the surface. At the line of traverse the zone is only 20 feet wide but it broadens to 100 feet or more both east and west of the traverse. Shoreward the corals decrease in numbers and the change to the reef flat is gradual.

3. Reef flat. Hummocky pavement of algal limestone with a patchy veneer of sand; corals rare.

4. Old reef. A rough and pitted rock flat that dries at low tide. The inner edge rises to 1½ to 2 feet above the reef flat. Colonies of *Heliopora* up to 6 feet in diameter are weathered out of the rock in radial ridges. These colonies all appear to be in positions of growth; the matrix is sandstone or algal limestone.

5. Boulder zone. Large boulders of all types, most of them well rounded, resting on a rock surface like that in (4).

6. Beach rock. One to 2 feet of bedded sandstone and conglomerate resting on 1 foot of conglomerate that in turn lies on a truncated surface that appears to be old reef rock.

West of the line of traverse there are blocks of beach rock 2 feet across and 1 foot in thickness that have been recently quarried by the sea.

8. TRAVERSE NORTHEAST ACROSS SEAWARD REEF NEAR MIDDLE OF ENIRIK ISLAND

	Width (feet)	Cumulative width (feet)
1. *Lithothamnion* ridge	70	70
2. Coral zone	80	150
3. Reef flat	450	600
4. Rock platform (not measured).		

1. *Lithothamnion* ridge. Seaward part of ridge consists of rounded, well-defined lobes that slope gently seaward from a crest 1 foot above low tide to a margin that is about 2 feet below low-tide level. Beyond the outer edge of the ridge proper isolated masses of algae and corals rise almost to the level of the reef. The crest of the ridge and the seaward slope are covered predominantly with pink to orange-yellow algae but with corals very abundant; on the walls of the channels that separate the lobes corals cover about one-half the surface. The seaward edges and the sides of the lobes are partly roofed over at the surface by algal growth, forming projecting shelves 2 to 6 feet wide. They are exceedingly cavernous and efficiently absorb the force of the waves.

2. Coral zone. An area of rich coral growth, most of the colonies being low branching types that rise 3 to 6 inches above the flat. Corals decrease in abundance landward, and the zone merges into the reef flat.

3. Reef flat. In the outer 150 feet colonies of living coral are scattered over a rough pavement of algal rock covered by 6 inches to 1 foot of water at low tide; beyond this line for a distance of 130 feet there are numerous colonies of *Heliopora* and other corals in circular, flat-topped colonies 2 to 4 feet in diameter and 6 inches to 1 foot high. These forms cover 10 percent of the surface. Reef blocks are abundant on this part of the flat, many rising 6 to 8 feet above the flat. One such erratic, lying 50 feet west of the line of traverse, measures approximately 25 x 25 feet and is 12 feet high (pl. 46, fig. 3).

The inner part of the reef flat (430–600 feet from the reef edge) is largely bare rock with only sparse coral growth in small pits and pools.

4. Rock platform. The surface of the platform lies 2 to 3 feet above low tide. It may be an old reef but there is no clear evidence to indicate that such is the case.

9. TRAVERSE ACROSS SEAWARD REEF AT THE WESTERN END OF ENIRIK ISLAND

	Width (feet)	Cumulative width (feet)
1. Marginal zone:		
a. Eroded submarine edge (not measured).		
b. *Lithothamnion* ridge:		
b_1. Seaward slope	35	35
b_2. Landward slope	20	55
2. Reef flat	360	415
3. Beach rock (not measured).		

1. Marginal zone. The seaward edge of the reef in this area is made irregular by a series of reentrants formed apparently by the collapse of large overhanging sections of the reef under wave attack. The sides of these indentations are steep; their depth on the landward side is about 20 feet, at the outer edge about 30 feet. The flat gently-sloping floors of the reentrants are covered with sand and coarser debris, including large sections of the undermined reef edge. About 50 percent of the sides of the reentrants are covered with living coral; there is a considerable variety, *Pocillopora* being the most abundant. Where no reentrants are present the reef edge is lobate in plan and it drops to the depths with a ragged near-vertical profile, showing no suggestion of a terrace. On this outer edge there is a rich growth of coral extending to a depth of about 20 feet, below this level the colonies are more widely scattered. In the indentations the reef edge from which the blocks have been torn is still somewhat overhung.

The *Lithothamnion* ridge is a broad low structure, the outer part of which slopes seaward at an angle of about 8°. Orange-yellow nodular *Lithothamnion* forms about half of the surface, corals including *Acropora*, *Millepora* and *Heliopora* cover most of the remaining surface of the seaward part of the ridge. Some of the encrusting *Acropora* colonies exceed 10 feet in diameter. Over large areas *Millepora* occupies three-fourths of the coral area; its ridges 1 to 6 inches high are oriented parallel to the reef edge, i. e., at right angles to the direction of greatest water motion. The algal areas are pierced by a series of irregular holes; most of these are only an inch in diameter but some reach a diameter of 6 inches.

The comparatively narrow back slope of the *Lithothamnion* ridge is a flat area almost entirely covered by living corals. An encrusting species of *Acropora* with short stubby projections covers about 40 percent of the slope, *Millepora* covers an approximately equal area and other corals, including *Pocillopora*, cover the remaining 20 percent.

2. Reef flat. This area lies less than a foot below the crest of the *Lithothamnion* ridge. It is composed of algal limestone thinly veneered by sand bound together by soft fibrous algae. Short-branched corals are numerous near the seaward margin of the zone where they cover half of the surface. At extreme low tide the outer part of the flat is nearly dry, with only 2 or 3 inches of water partially covering the coral colonies.

In the inner part of the zone about 25 percent of the flat is covered by living corals, about half of these being *Heliopora*. The water over the inner part is 6 inches deep at lowest tide.

Near the line of traverse a long channel that may represent a roofed-over surge channel passes entirely through the marginal zone.

3. Beach rock. Well-bedded sandstones dipping seaward at an angle of about 10°.

10. TRAVERSE ACROSS LAGOON REEF OFF NORTHWEST SIDE OF RUKOJI ISLAND

	Width (feet)	Cumulative width (feet)
1. Algal ridge	10	10
2. Sand flat	50	60
3. Zone of eroded beach rock	50	110
4. Zone of uneroded beach rock	30	140
5. Boulder rampart	40+	180+

1. Algal ridge. An elevated area, broadly convex upward, rising at least 2 feet above the flat adjoining it to landward; very irregular in outline. The edge facing the lagoon drops off sharply for a few feet to a zone of light-blue water. Surface cavernous and fragile, consisting mainly of algae many of which appear to be encrusting masses of dead coral. Calcareous algae themselves coated with soft algae that make the surface very slippery. Living corals rare on the crest of the ridge but fairly numerous on the lagoonward slope.

2. Sand flat. Rock flat veneered with sand and covered by 2 to 3 feet of water at low tide; small heads of living coral widely scattered.

3. Zone of eroded beach rock. Beach conglomerate in masses 4 to 5 feet in diameter that are pitted and appear to be remnants of a once more extensive deposit. Lithified area partly covered by loose coral boulders.

4. Zone of uneroded beach rock. Conglomeratic beds showing little evidence of erosion.

5. Boulder rampart. Coarse boulder deposit consisting of worn coral heads, *Tridacna* shells, etc. Deposit continues landward as an area of gray weathered boulders lying above high tide.

11. TRAVERSE ACROSS SEAWARD REEF ON SOUTHWEST SIDE OF CHIEERETE ISLAND.

	Width (feet)	Cumulative width (feet)
1. Marginal zone	30	30
2. Reef flat	325	355
3. Beach rock	45	400
4. Boulder rampart	40	440

1. Marginal zone. An irregular, deeply-scalloped zone the higher parts of which are in the seaward third and are uncovered between waves at time of low tide; seaward edge vertical or overhanging. On the seaward side the surface is covered by living corals and algae in roughly equal proportions; in most places the algae surround the corals closely and appear to be encroaching on them but in other places the reverse is true. The largest coral colonies near the seaward edge are 5 feet across and this part of the zone has a relief of less than 1 foot. The landward two-thirds of the zone slopes to the reef flat at a very low angle and is covered by 4 to 6 inches of water at time of low tide. Corals occupy about one-third of this surface, the remainder being composed of algae.

2. Reef flat. A rock flat whose general surface lies 4 feet below low tide near its seaward margin and 3 feet below that level near the beach; irregular depressions supporting a variety of large coral colonies extend 2 to 3 feet below the general level; some of these are so large that it is not possible to reach the seaward edge of the reef without swimming.

Along the line of traverse at about the mid-point of the flat there is a large stack of beach conglomerate that measures 7 feet in diameter and rises 6 feet above high-tide level. This mass may possibly be a reef block; the upper part is deeply pitted by solution but consists of coral heads that lie at various angles; spines of sea urchins are mixed with the corals; they still preserve their original color.

The rock forming the stack is white coral-algal limestone with a dark-gray weathered surface containing small solution pits and cusps. Most cavities are filled with white, powdery to poorly cemented calcareous detritus. A sample (B–8) contains roughly 20 percent *Lithothamnion*, 50 percent coral, 5 percent echinoid spines, mollusk shells, etc., and 25 percent detrital material including foraminifers. When stained with Meigen solution, small patches or fragments of *Lithothamnion* were unstained, but both corals and detrital material were deeply stained, indicating that the detritus is dominantly aragonitic.

A thin section of the rock (pl. 47, figs. 2, 3) appears to be mostly coral. Pores and cavities in the coral are filled by a fine brown detrital mud or paste containing angular grains less than 0.01 to more than 0.1 millimeter in largest diameter. Under high magnification (pl. 47, fig. 3) the fine grains appear to have rather diffuse borders and the brown paste is cloudy. Some open pores in the coral are encrusted with fine needles, probably of aragonite. *Carpenteria* and *Lithothamnion* encrust portions of the coral surface. The detrital paste contains some recognizable fragments of *Calcarina spengleri* and *Halimeda* with diffuse borders. Small, clear radial spherulites of carbonate are rather common and have possibly grown in the paste, although more probably they are ascidian spicules. A few small globular forms may be sections of globigerinids. There is no apparent alteration of coral in the section although some small carbonate crystals have cemented the paste and coated tiny pores.

3. Beach rock. A belt of conglomerate.

4. Boulder rampart. Well developed; nearly as wide as belt of beach rock.

12. TRAVERSE ACROSS SEAWARD REEF ON SOUTH SIDE OF OURUKAEN ISLAND

	Width (feet)	Cumulative width (feet)
1. *Lithothamnion* ridge:		
a. Buttress and surge-channel zone	50	50
b. Coral-algal zone	25	75
2. Reef flat	295	370
3. Beach rock	40	410
4. Beach	30	440

1. *Lithothamnion* ridge. Buttresses and surge channels well developed, the buttresses as wide or twice as wide as the intervening channels. Channels deep, some extending entirely across the *Lithothamnion* ridge. Columnar-type colonies of algae (*Porolithon craspedium*) form all of the high points on the ridge, 5 or 6 colonies being found to the square yard; the algal masses measure as much as 8 inches in height and 4 to 5 inches in diameter. The landward sides of many of the algae are partly encrusted with thin films of living *Millepora*, the hydrocoral assuming the growth form characteristic of the alga. The spreading film of *Millepora* kills the part of the alga that is covered but a sectioned specimen (B–116) shows that the alga may in turn overwhelm the coral and such reversals may occur more than once. Corals (*Pocillopora* and *Acropora* in addition to the *Millepora*) are subordinate to algae on the buttresses but become more numerous landward. Surge channels are lined with globular colonies of algae (*Porolithon gardineri*).

The back slope of the ridge is an algal pavement with a rich development of corals—*Acropora* (4 species), *Pocillopora, Favites.* Also present are colonies of the alcyonarian *Lobophytum* with thick stubby processes. At the seaward edge of the coral-algal zone the corals cover only a quarter of the surface but at the landward edge they occupy three-quarters. The coral-algal zone is a sinuous strip that advances seaward over the buttress areas and retreats landward around the ends of the surge channels. Colonies of *Halimeda* live in crevices and cavities of the coral-algal zone.

2. Reef flat. A fairly solid pavement covered by 6 inches to 1½ feet of water at low tide; a variety of living corals grow on the flat and in irregular and discontinuous pools. Also occurring are large colonies of soft corals (*Sinularia*). Many corals, though fresh and unbroken, are dead and veneered with a film of soft algae. At the landward edge of the flat living corals cover 25 percent of the surface; small knobs of pink algae cover 15 percent and the remainder is rock pavement.

Some of the larger and deeper pools along the line of traverse connect with fissure-like openings to the west where a large pool 6 to 12 feet deep covers much of the seaward part of the reef flat. This pool was examined with the aid of face masks. It has a profuse growth of corals in great variety—an assemblage comparable to that found on the coral knolls in the lagoon. Many of the colonies of coral are several feet in diameter; Tridacnas, Turbos and thin-spined sea urchins occur with the corals. Two openings through the *Lithothamnion* ridge permit waves and currents in the pool. The currents probably winnow out fine material and carry it to sea. Sand in the bottom is unsorted and coarse. About half ranges from 1 to 2 millimeters, but the other half consists of shells and fragments from 2 millimeters to 2 centimeters or more in size. Grains are worn, roughened, and finely pitted as if by solution. They are not polished.

3. Beach rock. A belt of thick layers of well-bedded sandstone. The rock (B–118) is coarse sand and coral conglomerate. Coral fragments are worn, moderately rounded, and are scattered through the coarse sand.

Under the binocular microscope most rounded grains are seen to be fragments of *Lithothamnion* and *Halimeda*, although some worm shell fragments and disc-like *Marginopora* are present. Most grains are polished and are coated thinly with a chalky powder that acts as a cement. The rock is well consolidated, and the surface layer is so hard that it rings under a hammer blow. The surface of the specimen is finely pitted and etched, and small pits and hollows are blackened, possibly by microscopic algal growth.

About two-thirds of the area of a thin section is seen to be formed of two rounded coral pebbles. The rest is formed of angular to rounded grains of *Lithothamnion*, 25 percent; coral, 50 percent; mollusk shells and Foraminifera, 25 percent. The grains range from 0.2 to 1 millimeter in size. All are coated with a microcrystalline brown layer 0.05 millimeter thick that appears to be the cementing material. The brown coat, lining open spaces between grains, is covered with rows of minute acicular carbonate crystals a few hundredths of a millimeter in length. The internal crystal structure of coral fragments appears to be unaltered, although a few open spaces are lined with carbonate needles that seem to be in optical continuity with the aragonite of the coral.

13. TRAVERSE ACROSS LAGOON REEF TO NORTHEAST TIP OF OURUKAEN ISLAND

	Width (feet)	Cumulative width (feet)
1. *Lithothamnion* ridge:		
a. Buttress zone	25	25
b. Algal pavement	15	40
2. Algal-coral zone	45	85
3. Reef flat	80	165
4. Boulder zone	245	410
5. Boulder-sand zone	30	440

1. *Lithothamnion* ridge. The margin of the reef facing the lagoon is very irregular in plan, consisting of well defined buttresses separated by shallow channels. On the buttresses colonies of the columnar type of *Lithothamnion* are very numerous, rising 8 inches to 1 foot above the general surface (pl. 46, fig. 1). Globular and pavement types of *Lithothamnion* also occur and on the parts of the buttresses that uncover between waves at low tide the algae cover fully 85 percent of the surface. The remainder is occupied by a fair variety of reef corals. Corals, especially *Millepora*, cover large areas in the shallow channels between buttresses and in deeper areas lagoonward, particularly on isolated subcircular reef patches 5 to 10 feet in diameter that lie beyond each of the buttresses. Except for scattered patches, the reef shelves off gradually into the lagoon for a distance of several hundred feet.

The landward slope of the buttresses is a pavement whose surface is rough in detail; algae cover three-fourths of the area, the remainder being occupied by living corals. The algal pavement merges landward into the algal-coral zone.

2. Algal-coral zone. This is an uneven surface covered by several inches of water even at lowest tide. Coral colonies are numerous and varied but they rarely exceed 8 inches in diameter.

3. Reef flat. A rock pavement covered by 8 inches of water at low tide. Living corals are rare and most of these are small colonies of *Porites*. Dead colonies in the form of boulders and cobbles become abundant landward.

4. Boulder zone. This is a wide area that is completely exposed at low tide. The surface is covered by large boulders and irregular blocks some of which exceed a foot in diameter.

5. Boulder-sand zone. The size of the boulders decreases landward in this zone which on the line of traverse ends at the base of a sand and gravel bank that forms the northeast tip of the island.

14. TRAVERSE ACROSS SEAWARD REEF OFF SOUTHEAST END OF BOKORORYURU ISLAND

	Width (feet)	Cumulative width (feet)
1. *Lithothamnion* ridge	25	25
2. Coral zone	90	115
3. Zone of blocks	110	225
4. Reef flat	315	540

1. *Lithothamnion* ridge. A low flattish area whose higher parts are uncovered between surges at low tide; cut by closely spaced surge channels some of which extend through the ridge into the coral zone to landward. Inaccessible seaward side of the ridge continues seaward below low water level for a distance of at least 35 feet before the slope steepens.

Three-fourths of the surface of the ridge is covered by algae, the globular type of *Lithothamnion* being especially abundant along the seaward edge. The pavement *Lithothamnion* on the landward slope of the ridge forms a pitted surface many of whose pits house large club-spined sea urchins and thick-shelled Turbos. Reef corals, including *Millepora*, cover roughly one quarter of the ridge surface; particularly numerous are small colonies of *Pocillopora*, an *Acropora* with short stubby branches, and colonies of *Heliopora*.

The landward parts of several of the surge channels were examined with the aid of a face mask. On the seaward side of the ridge the depth of the channels is 6 feet and the surging current is strong at low tide even though the surf is light. Near the middle of the ridge the channels have a depth of 4 feet and vary in width from 3 to 6 feet. The bottoms of the channels are broadly rounded and covered with sand and coarser debris including algal nodules. The pebbles (B-111) are of coral, worn, rounded, and coated in part with small dark-red encrusting *Mineacina*, pink and white *Homotrema*, and a few small patches of *Lithothamnion*. In a few places low transverse partitions of *Lithothamnion* divide the channels into elongated tublike cavities. The walls of the channels are nearly vertical and are covered with a growth of living algae and corals in about equal proportions. One colony of *Millepora* on a vertical wall measured more than 8 feet. In some places the algae are encroaching on the corals, in others the reverse is true. Colonies of reef corals exceeding 1 foot in diameter are, except for *Millepora*, confined to the heads of the channels. Mollusks are rare in the channels—a few Turbos, an occasional *Trochus* or *Cypraea;* club-spined sea urchins occur in crevices near the surface but none were seen in the deeper parts of the channels.

2. Coral zone. The general surface is flat and fully two-thirds of it is covered by living corals; depressions between the colonies have a depth of 2 feet. The corals are covered by a few inches of water at low tide.

3. Zone of blocks. A flat surface covered by a foot of water at low tide. Blocks of rock are widely scattered, the larger ones projecting above water; small heads of living coral cover 15 percent of the surface.

4. Reef flat. A rock flat completely exposed at low tide; no living coral, very little sand or other debris.

15. TRAVERSE ACROSS LAGOON REEF FROM BOKORORYURU PASS TO BOKORORYURU ISLAND

	Width (feet)	Cumulative width (feet)
1. Algal ridge	20	20
2. Algal-coral zone	25	45
3. Tide-pool zone	50	95
4. Reef flat	100	195
5. Boulder zone	65	260

1. Algal ridge. A low irregular strip, the higher parts of which are uncovered between waves at low tide. The edge of the reef that faces the pass is irregular but there is no well developed series of buttresses or channels; beyond the ridge the slope to the pass is gentle. Algae cover an estimated 85 percent of part of the ridge that is exposed between waves. Most of the algae are globular colonies with an occasional columnar mass (*Porolithon craspedium*) rising 10 inches above the general surface. Corals, except for scattered small colonies of pink *Pocillopora*, are rare. Near the reef edge large colonies of *Millepora* are developed into long ridges parallel to the reef edge. In this area *Millepora* covers larger areas of the reef than do the combined algae. In some places algae have grown completely over large masses of *Millepora* but *Millepora* of another generation is now being extended over the algae. Colonies of *Halimeda* occur in protected niches even on the higher parts of the algal ridge.

2. Algal-coral zone. This zone is covered by a foot of water at low tide. It is estimated that living algae cover 50 percent of the surface, and living corals 30 percent, the remainder being dead pavement.

3. Tide-pool zone. This zone has fewer living corals and a larger amount of dead coral and loose blocks than the coral-algal zone. The deeper pools contain 1½ feet of water at low tide.

4. Reef flat. A rock flat with no living coral; coarse debris abundant on the lagoonward half. Two species of *Turbo* are abundant in this zone and the same strip a little to the south of the line of traverse yielded the richest and most varied gastropod fauna seen on the atoll. Large species such as *Cypraea mauritiana* were found alive—as many as eight in one protected cavity.

5. Boulder zone. A surface completely covered by worn coral boulders, many over a foot in diameter; rises to a rampart at high-tide level.

16. TRAVERSE (PARTIAL) ACROSS SEA REEF ON WEST SIDE OF ATOLL

The reef forming the westernmost segment of the atoll was examined at two points. In both places detailed examination was limited to the marginal zones and the seaward part of the main reef flat, but the visible part of the seaward slope was examined with the aid of a face mask.

	Width (feet)	Cumulative width (feet)
1. Seaward slope	55	55
2. Marginal zone	50	105
3. Reef flat (from air photograph)	1, 750	1, 855

1. Seaward slope. A profile, figure 51, was measured with a sounding lead from a skiff anchored to the edge of the reef. The seaward slope drops off to a depth of at least 180 feet as a vertical cliff. This is an impressive sight through the water glass. The slope appears massive but has a rough lumpy surface. Some of the rounded masses on its surface may be old coral heads now overgrown with algae. The globular type of *Lithothamnion* in colonies 4 to 6 inches across occurs down to depths of 20 to 25 feet, but colonies of coral appear to be rare below the surface; such colonies as could be seen were less than a foot in diameter, and taken altogether they cover less than 5 percent, locally 10 percent, of the seaward slope (pl. 46, fig. 2). Many of the algal masses appear to be small colonies of coral completely encrusted by pink *Lithothamnion*. The slope appears to be mainly algal, large areas being green in color; small patches of *Halimeda* are widely scattered. The slope appears to be a favorite gathering ground for fishes, and a great variety of forms are present in large numbers; no mollusks were seen. At about 20 to 25 feet there are light-colored patches on a shelflike projection that may represent sand.

2. Marginal zone. A flattish area covered by 1 to 2 feet of water at low tide and rising 1 to 2 feet above the main reef flat. There are no buttresses or surge channels, no indications of the development of a *Lithothamnion* ridge. Living algae, however, cover approximately one-half of the reef surface and the remaining half is covered by a rich growth of corals and their relatives. *Millepora* is particularly abundant near the seaward edge, spreading over algae and other organisms as a thin enveloping crust to form colonies several feet in diameter and rising, under favorable conditions, into vertical plates. Over large areas it covers 20 percent of the surface. Small pink colonies of *Pocillopora* are numerous and there are a few large colonies of purple encrusting *Montipora*, a few large heads of *Lobophyllia*. Mollusks are few except for small nested Tridacnas.

3. Reef flat. A rough surface with large heads of living and dead coral or groups of colonies—rising 2 to 3 feet above the general surface. At low tide the water is about 2 feet deep over the higher coral masses, the intervening pools having a depth of 4 to 5 feet. Masses of living coral measure 6 feet or more in diameter. Present also are colonies of the soft coral *Sinularia*, a carpetlike form with low rounded lobes. Pools between coral areas are floored with coral sand, much of which is coarse. Sand in most pools is only a thin veneer one-quarter to one half inch thick over a hard rock surface but in a few places it reaches 2 inches in thickness. The material (B–110) is coarse, unsorted organic detritus; about halt consists of fragments of *Halimeda*, coral and *Lithothamnion*, tests of *Marginopora*, small echinoid spines and mollusk shells ranging in size from 2 to 5 mm. The other half ranges from 0.1 to 2 mm, and most of the material is 0.5 to 1 mm in size. It consists of angular fragments and tests of *Calcarina spengleri* and *Amphistegina;* small bryozoans are also present. Near the edge of the marginal zone sand layers as deep as 4 inches were measured. A fair variety of corals occurs along with a few colonies of *Heliopora*.

17. TRAVERSE (PARTIAL) ACROSS THE NORTHWEST REEF 3 MILES SOUTHWEST OF BOKOBYAADAA ISLAND

At this locality along nearly half a mile of the reef front there is a small seaward projection or bulge that extends a maximum of 300 feet beyond the normal line of the reef. Fringing this bulge, there is an apronlike submarine terrace 100 to 200 feet wide and about 10 fathoms in depth at the outer break in slope. This is one of very few places on the leeward reef where such a terrace exists.

This part of the reef was examined in some detail for about 500 feet back of the reef edge, but a measured traverse was not completed. The seaward slope and the terrace were examined both from a small skiff and by swimming with a face mask. A number of lead line soundings were taken on the terrace, but the wind was too strong to obtain a line profile across the terrace.

	Width (feet)	*Cumulative width (feet)*
1. Submarine terrace	50–200	-----
2. Marginal zone	50	50
3. Coral zone	100	150
4. Reef flat	250	400
5. Zone of microatolls and reef blocks	[1] 3, 350	3, 750

[1] Measured from air photo.

1. Submarine terrace. The terrace slopes outward from a depth of 15 feet at the inner edge where it meets the sloping edge of the reef margin, to a depth of about 70 feet at the outer edge where the steeper slope of the atoll begins. The outer lip was sounded accurately enough to determine a break in slope at 70 feet or approximately 12 fathoms.

The terrace bank and the marginal slope of the reef are completely covered with a profuse growth of corals in great variety. Even large fan-like growths of delicate branching *Acropora* are present, an unusual occurrence on a seaward slope, and good evidence for the rarity of large swells on this segment of the reef. *Lithothamnion* was not apparent although it may be present as a cementing material at the bases of the corals.

There is apparently little detritus on the terrace shelf, either large blocks of reef material, or cobbles, gravel, or sand. There could, of course, be detrital material present beneath the spreading corals.

The sloping margin of the reef is partly covered with coral, but much *Lithothamnion* is present—about half the surface area is covered by calcareous algae. The marginal zone slopes at an angle of 30° to 45° from the surface to the terrace at a depth of 15 or 20 feet; beyond this the terrace slope is more gentle and more irregular to a depth of about 70 feet at the outer edge. From this the outer slope drops at about 70° to a depth of at least 126 feet.

Near the surface the reef edge is cut by widely spaced fissures that occur at bulges on the northwest reef front, but only rarely along the intervening straight stretches. The fissures are from 50 to 100 feet long, from 2 to 5 feet wide, and as much as 10 feet deep. They do not cut the exposed part of the reef more than a few feet. The jagged and irregular walls suggest erosional forms. The walls in particular, but also the bottoms of the fissures, are covered with coral growth.

2. Marginal zone. The *Lithothamnion* margin is not crested but rises gradually to the level of the reef flat. Corals are abundant, especially flattened forms of *Pocillopora*, and cover from 10 to 20 percent of the surface

of this zone. The rest is yellowish to pink encrusting *Lithothamnion.*

3. Coral zone. Covered with closely packed coral colonies 6 inches to 1 foot in diameter. *Acropora* is most abundant. Zone grades into reef flat

4. Reef flat. A zone in which coral colonies grow from a whitened limestone surface, covered at low tide by 6 inches of water at the seaward edge of the zone, increasing to about 2 feet of water 100 feet across the zone. The depth of the floor gradually increases lagoonward. The coral colonies are small and closely packed at the seaward edge of the zone, but the limestone floor of the reef shows through at intervals.

The boundary with the preceding zone has been placed where these spaces first occur with some regularity. As one proceeds lagoonward, the spaces first increase in number as the coral colonies are more separated, then they increase in size.

5. Zone of microatolls and reef blocks. The coral colonies grade lagoonwards into tablelike microatolls 2 or 3 feet across, separated by an interval somewhat less. Further lagoonward, as the reef floor drops to a depth of 2 feet or more, the microatolls increase in size until they are 3 to 10 feet across and are separated by roughly equal intervals from the neighboring tables.

It is in this zone that reef boulders measuring 2 or 3 feet high and 4 to 6 feet across occur. The few examined all resembled microatolls torn from the reef flat and overturned. The reef boulders were at intervals of 100 to 300 feet or more, and seemed to occur as a group near the bulge in the reef. They were absent for a distance of ½ to 1 mile to the southwest, and for ¼ mile to the northwest where occurred the next groups of scattered boulders. To an observer on a ship at some distance, however, they appear to be closely and rather evenly spaced along most of the northwest reef.

18. TRAVERSE ACROSS SEAWARD REEF AT WEST END OF NAMU ISLAND

	Width (feet)	Cumulative width (feet)
1. Seaward slope	150	-----
2. Marginal zone	50	50
3. Submarginal zone	25	75
4. Coral-algal zone	150	225
5. Reef flat	850	1, 075
6. Boulder zone	200	1, 275
7. Zone of microatolls	1, 300	2, 575
8. Zone of coral bars	2, 000	4, 575
9. Beach	85	4, 660

1. Seaward slope. The reef slopes gently for a horizontal distance of about 150 feet, then descends abruptly. It was not possible to examine the seaward slope by swimming or by boat, so that the depth of the break in slope was not determined.

2. Marginal zone. This zone is of pink *Lithothamnion* with abundant coral colonies, mostly *Pocillopora* making up 5 to 10 percent of the surface. The zone slopes gently seaward. It does not have a distinct crest but merges with the submarginal zone. Cracks or fissures are small and widely spaced. This is essentially a smooth, lee-type marginal reef.

3. Submarginal zone. This is a belt of whitened and eroded algal limestone between the living marginal zone and the coral-algal zone. A few corals are growing in small hollows. The zone is depressed a few inches below the level of the coral-algal zone, and appears to be a belt formerly of the marginal zone that has been killed and somewhat eroded. This is similar to the submarginal zones on the windward reefs southeast of Aomoen island, traverses 25 and 26.

4. Coral-algal zone. This part of the reef flat is exposed at low tide. It is a limestone flat partly encrusted at the seaward edge of the zone with much living pink *Lithothamnion.* The first 20 feet of the zone are covered with soft corals. Beyond this, encrusting hard corals are common.

5. Reef flat. This zone is gradational from the last, but a boundary can be drawn along the line where the reef blocks make their appearance. The floor of the reef flat is coral-algal limestone, with a veneer of soft algae. Corals are chiefly scattered small colonies of *Acropora* and *Favia* is common in the shoreward part of the zone.

The reef blocks, 1 to 6 feet high, are largely coral, alined in each block but at various orientations. None of the blocks examined consisted dominantly of *Lithothamnion.* It is probable, however, that many if not all were brought onto the reef from the outer slopes by storm waves. At the seaward end of the traverse is a large block of living *Lithothamnion* torn from the outer slopes and resting in inverted position in about 2 feet of water a few feet from the reef edge. The block is about 10 by 10 by 4 feet, and on it are several colonies of *Pocillopora* upside down and encrusted with *Lithothamnion.*

6. Boulder zone. A zigzag boulder "bar" 30 to 100 feet wide, trends parallel to the reef front. The overall width of the zone is about 200 feet. It is formed of unconsolidated coral gravel and boulders, piled about a foot above the reef level. Airphotos indicate the presence of similar belts at an equivalent distance from the reef edge on the wide northern reef off Romurikku island. No similar structure is known on other reefs on Bikini Atoll.

7. Zone of microatolls. This zone reaches from the boulder belt halfway to shore. It differs from the outer reef flat in that it is covered by one to two feet of water, the floor is sandy, and a variety of corals grow in separate microatolls 2 to 20 feet or more across. Small

microatolls are most numerous and occupy as much as one-half the area.

8. Zone of coral bars. This zone reaches to the shore and is similar in most respects to the zone of microatolls, but the reef floor is generally deeper, from 2 to 4 feet, and the coral tables are greatly elongated normal to the trend of the reef. Some of them are a thousand feet long and a hundred feet wide, they appear in part at least to be large gravel bars encrusted with living coral. *Heliopora* is dominant on the nearly vertical walls of the bars, while *Favia* and *Porites* are most abundant on the gravelly tops. The greatest variety of corals is at the edges. Several groups of *Fungia scutaria* were found in all stages of development. Numerous *Hippopus* and *Tridacna* up to 1½ feet long were living on the reef.

The trend of the bars appears to parallel the current of water across the broad reef flat and around the lee end of Namu Island.

19. TRAVERSE ACROSS SEAWARD REEF AT NORTHEAST CORNER OF NAMU ISLAND

	Width (feet)	Cumulative width (feet)
1. *Lithothamnion* ridge:		
a. Buttress and surge-channel zone	50	50
b. Algal pavement	55	105
2. Reef flat	1, 165	1, 270
3. Zone of beach sandstone	100	1, 370

1. *Lithothamnion* ridge. The seaward half of the ridge consists of rounded buttresses whose lumpy irregular surfaces rise about 1 foot above low tide level and 2 to 3 feet above the wave troughs at low tide. Globular colonies of purplish-pink to red colonies of *Lithothamnion* cover much of the surface but corals are practically absent. The buttresses are separated by surge channels 5 to 15 feet across, 15 to 25 feet long, and 10 to 15 feet deep at their inner edge. Fairly regular ridgelike concentrations of algae line the upper 6 feet of the channels.

The landward half of the ridge is a level platform about 1 foot above low tide level covered between waves at low tide by a few inches of water. Half to three-fourths of the platform is composed of pink *Lithothamnion* of the pavement type; corals, chiefly encrusting types, cover 25 to 50 percent of the area and club-spined sea urchins are abundant averaging about 1 per square yard. The echinoids with their spines measure 6 to 10 inches across but average smaller than those in the buttress zone.

2. Reef flat. This area is distinctly lower than the *Lithothamnion* ridge and is covered by 6 inches to 1 foot of water at lowest tide. Its flat surface is a barren algal pavement containing small, shallow depressions floored with a veneer of sand. Sparse colonies of coral from 1 inch to 3 feet in diameter stand less than 6 inches above the flat.

20. TRAVERSE ACROSS LAGOON REEF OFF SOUTH SIDE OF NAMU ISLAND NEAR WEST END

	Width (feet)	Cumulative width (feet)
1. Marginal zone	25	25
2. Coral zone	120	145
3. Reef flat	300	445
4. Old reef-rock zone	90	535
5. Beach rock	50	585

1. Marginal zone. At the lagoon edge small buttresslike structures slope steeply to about 10 feet of water; they rise to a crest near low tide level so that small patches are exposed between waves. The edge of the zone is composed mostly of *Millepora* and yellow *Lithothamnion*. Coral, mostly *Acropora*, covers about 15 percent of the surface. Buttresslike areas are separated by shallow channels 2 to 6 feet across and 10 to 15 feet long. Behind the reef edge the marginal zone is a flat pavement composed of pink to yellow algae (75 percent) and small colonies of encrusting corals (25 percent). Most of the algae forms botryoidal crusts; globular colonies are rare.

2. Coral zone. A flat area on which corals in colonies 2 to 6 feet across and from 6 inches to a foot high cover half of the surface; the rest is a limestone pavement partly covered by sand.

3. Reef flat. An irregular rock pavement exposed at lowest tide. Much of the surface is composed of spongy, yellow-orange *Lithothamnion* with a rich and varied growth of small colonies of coral; low areas are covered by coarse debris and sand.

4. Old reef rock zone. An exposed rock flat, the higher parts of which appear to be truncated by erosion to form broad low hummocks enclosing tide pools containing numerous holothurians.

21. TRAVERSE ACROSS LAGOON REEF OFF SOUTH SIDE OF NAMU ISLAND AT EAST END

	Width (feet)	Cumulative width (feet)
1. Marginal zone	10	10
2. Coral zone	90	100
3. Reef flat:		
a. Coral-algal zone	380	480
b. Eroded pavement	820	1, 300

1. Marginal zone. A moderately developed *Lithothamnion* ridge 5 to 15 feet wide that rises fairly steeply from a sand bottom under 6 to 10 feet of water. The crest is cut by scattered, poorly developed surge channels 6 feet deep, 5 to 10 feet wide, and 5 to 15 feet long. Channels are partially roofed over on the inner side of the ridge leaving surge cracks 6 inches to a foot in width. The scalloped edge of the ridge has a bench-

like rim a few feet in width immediately below low water level. Corals cover as much as 50 percent of this irregular bench. The lobes of the ridge are composed entirely of algae of several types—pink nodular forms, flat colonies of the pavement type and pink, gray, and purple globular colonies; about 10 percent of the surfaces of the buttresses is covered by living corals. The ridge is made cavernous by holes left by several sorts of burrowing organisms, especially above the low tide level. The crest rises 1 foot above low tide and more than 2 feet above swell troughs. Small club-spined sea urchins are numerous on the outer edge of the ridge.

2. Coral zone. This zone is lower than the marginal zone, lying under 4 inches to 1 foot of water at low tide. It is a pavement covered by a rich growth of living corals of encrusting, branching and nodular types. The corals cover from 50 to 100 percent of the surface. Landward the colonies become more sparse and the growth pattern more patchy as the zone grades into the reef flat.

3. Reef flat. A boundary between this zone and the last was drawn where the coral-algal clusters cover only half of the surface. Between the colonies the limestone of the flat is thinly veneered with sand.

3a. Coral-algal zone. Consists of clusters on a sand veneered flat as noted above. The clusters are formed mostly of coral and rise 6 inches to 1 foot above the flat. The flat tops of the colonies lie just below low tide level. Scattered small reef blocks stand 6 inches to 2 feet above low tide in the seaward third of the zone.

3b. Eroded pavement. This is a wide tidal flat formed of eroded limestone with a patchy veneer of sand. The bare limestone areas stand out as low hummocks 2 to 3 inches high and as much as 10 feet across. Most of this flat is out of water at extreme low tide. Corals are rare but the shallow pools between hummocks support numerous holothurians. Two hundred feet to the east of the line of traverse, a gravel bar several hundred feet wide extends most of the way across the pavement from the beach to the lagoon.

22. TRAVERSE ACROSS SEAWARD REEF ON NORTHWEST SIDE OF YUROCHI ISLAND

	Width (feet)	*Cumulative width (feet)*
1. Marginal zone	80	80
2. Coral zone	250	330
3. Reef flat	1, 685	2, 015
4. Zone of beach rock	75	2, 090

1. Marginal zone. The seaward third of this zone is a flat platform sloping gently seaward, the remainder is a flat sloping gently landward; the crest rises about 1 foot above low tide and surge channels are poorly developed. The seaward slope is formed dominantly of pink to rose *Lithothamnion* with scattered rounded colonies of coral. Most of the corals are about 6 inches in diameter, a few reaching a foot. At low tide there is a steady seaward flow over the reef, although successive swells break over the seaward platform. On the backslope, pink to orange *Lithothamnion* covers half of the surface, the other half being occupied by closely packed corals—small branching forms, rounded heads and encrusting types.

2. Coral zone. This area is covered by 2 to 3 feet of water at low tide and colonies of coral 1½ to 2 feet high and 3 to 6 feet in diameter cover from 25 to 50 percent of the surface. Between the corals the surface is covered by sand that is bound by algal growth. Numerous reef blocks several feet in diameter rise 1 to 3 feet above low tide level. To landward the water at low tide stands 1 to 2 feet deep over large coral masses 3 to 12 feet across that rise a foot above the reef flat.

3. Reef flat. A sandy area covered by 6 inches to 1 foot of water at low tide. Small rounded heads of coral and clusters up to 4 feet in diameter rise about 6 inches above the floor and occupy 10 to 25 percent of the area.

4. Zone of beach rock. The sandstone layers dip gently seaward.

The reef on the northwest side of Yurochi is adapted to transverse winds and currents. A strong cross current is generated by northeasterly wind across the wide reef to the east and at flood tide the current near shore exceeds 2 knots. This cross current appears to be partly responsible for the poor transverse zoning of the reef flats.

23. TRAVERSE SOUTHWEST ACROSS SEAWARD REEF TO EAST END OF ROMURIKKU ISLAND

	Width (feet)	*Cumulative width (feet)*
1. *Lithothamnion* ridge	50	50
2. Coral-algal zone:		
a. Coral pavement	20	70
b. Coral-algal flat	30	100
c. Algal pavement	40	140
3. Reef flat	3, 260	3, 400
4. Zone of beach rock	30	3, 430

REEF ZONES

1. *Lithothamnion* ridge. The edge of the reef is a pronounced ridge that rises above the main reef flat and the level of low tide. Behind the ridge there is a distinct but gentle backslope. The ridge is cut by short, broad channels that are V-shaped below with upper walls vertical.

Globular and encrusting algae cover most of the outer part of the ridge; large club-spined sea urchins grow profusely on the ridge and the backslope—in a band 100 feet or more in width that stretches along the reef as far as the eye can see, these animals occur in such abundance that they average 1 for every 1 or 2 square yards.

2. Coral-algal zone. Immediately behind the ridge in a band approximately 20 feet in width encrusting corals grow on an eroded surface of dead *Lithothamnion*. Locally the corals cover the entire surface, individual colonies exceeding 20 feet in maximum diameter.

In a second band that averages 30 feet in width living corals cover about half of the surface, the remainder being algal limestone. Most of the algal rock is white and pitted but some is pink, living *Lithothamnion*.

The last 40 feet of the coral-algal zone is an eroded pavement of white to yellow dead algal rock on which corals, mostly encrusting varieties, cover less than 10 percent of the surface.

3. Reef flat. This is a surface of algal limestone covered by 6 inches of water (at low tide) at the outer edge and by 2½ to 3 feet near shore. Much of the flat surface is veneered with a mixture of fine detrital sand and the shells of Foraminifera bound by soft, noncalcareous algae. Corals are present including branching colonies of *Acropora* 1 to 2 feet and heads of *Porites* as large as 8 feet in diameter and 2½ feet high but they are not an important contributor to the reef. Heads of *Heliopora* are common. The flat is somewhat sandier and more barren near shore.

NEARBY BAR

About 200 yards west of the line of traverse is a rock bar 1,500 feet long, 100 to 200 feet wide, and 3 feet or more above the reef flat, trending northeast at right angles to the reef front and gently arcuate with the convex side to the west. The rock forming this bar appears to be all sandstone or conglomerate although some at the north end may be reef rock. It is rudely bedded, deeply eroded by solution pans and cusps 1 foot or more high. Large, straight furrows following joints are more than 2 feet across, 1 foot deep, and 50 or more feet long.

West of the rock bar the reef flat widens to nearly a mile, and much of this flat has 4 to 6 feet or more of water covering it. One pool adjoining the bar is 6 feet deep at low tide, and along the side of this pool has grown a large *Porites* 6 feet high and 10 feet across.

North of the sandbar joining Uorikku and Yurochi islands, an area of bedded, eroded beach sandstone marking the site of a former small island is surrounded by a deep, crescent-shaped pool in the reef flat. The pool is 2,500 feet in maximum length and 1,000 feet in width. The west end of the pool, examined by swimming, is 20 to 30 feet deep, steepsided and has a sand-covered floor. One coral knoll 12 feet high rises in 17 feet of water. The pool may represent the lagoon margin of the reef at a time before the present island chain was formed. The pool is similar to the closed depressions on the 10-fathom lagoon terrace near Bikini island.

24. TRAVERSE ACROSS SEAWARD REEF TO NORTHEAST BULGE OF AOMOEN ISLAND

	Width (feet)	Cumulative width (feet)
1. *Lithothamnion* ridge:		
a. Buttress zone	75	75
b. Algal pavement	75	150
2. Reef flat	1, 100	1, 250
3. Zone of beach rock	70	1, 320

1. *Lithothamnion* ridge. The seaward slope of the ridge is composed of massive, rounded buttresses separated by short, broad channels. The outer surfaces of the buttresses dip gently seaward for about 100 feet so that the structures become spurs 50 to 100 feet wide, composed of *Lithothamnion* with a few small corals and green algae in protected places. The crest of the ridge is broadly arched. It rises several feet above low-tide level but is completely covered by advancing waves even at time of low tide. A few encrusting corals are found on the crest with the algae.

The backslope of the ridge is a flat algal pavement formed of pitted *Lithothamnion* with a washed, dull orange color and a few corals. Large club-spined sea urchins are abundant everywhere on the pavement, the average in rich patches being one in every 4 square feet.

2. Reef flat. The pavement of living algae that forms the backslope of the ridge ends rather abruptly at the edge of the main reef flat. This surface of the flat lies about 6 inches lower than the landward edge of the ridge and is formed of algal limestone with a thin veneer of living and dead Foraminifera and detrital sand bound by soft algae. Living corals occur on the flat but the colonies are widely scattered and most of them are small. The commonest species belong to *Favia* and *Astreopora* but *Porites* of the massive type is fairly common; less abundant are *Acropora, Pocillopora* and *Favites*. There are a few fairly large colonies of *Heliopora*. Over large areas in the seaward part of the flat holothurians are abundant—20 to as many as 35 being counted in 1 square yard. Sea urchins with long thin spines are numerous on the landward part of the flat.

3. Zone of beach rock. Well-bedded layers of conglomeratic sandstone dip gently seaward in this zone. The seaward edge of the belt is sharply truncated by solution and wave action, the rock rising 3 to 4 feet above the reef flat.

25. TRAVERSE ACROSS REEF FROM SEA TO LAGOON ABOUT THREE-FOURTHS MILE SOUTHEAST OF AOMOEN ISLAND

	Width (feet)	Cumulative width (feet)
1. Marginal zone	125	125
2. Reef flat	1, 460	1, 585
3. Gravel bar	50	1, 635

1. Marginal zone. A broad zone of rich organic growth that borders the reef on the seaward side. It rises a few inches above the reef flat but as a low arch that has little resemblance to the cuesta-like ridge that borders the seaward islands. There are no buttresses or well-developed surge channels, the zone being at least briefly covered by each advancing wave at lowest tide. The reef surface is a *Lithothamnion* pavement but considerable areas are covered by large mat-like colonies of encrusting *Acropora*; in other areas there is a mat of soft olive-green algae with a reticulate growth pattern. In some places areas of *Millepora* have been covered by *Lithothamnion* which, in turn, is being covered by encrusting *Acropora*. Large club-spined sea urchins are very numerous, occupying the lower and slightly more irregular areas of the marginal zone. Patches of soft zoanthids appear on the backslope of the zone. Vertical platelike structures that tend to parallel the reef front are encrusted with pink *Lithothamnion* on the sea side and with *Acropora* on the lagoon side.

2. Reef flat. A broad area poorly exposed at low tide. Surface mostly algal limestone with some living algae and scattered colonies of living coral. Colonies of *Porites* become increasingly numerous as the lagoon is approached and occupy 15 to 25 percent of the surface where the water over the flat deepens to 3 feet. Some of the largest colonies of *Porites* have a diameter of 10 feet.

3. Gravel bar. Composed of coral and algal cobbles up to 6 inches in diameter; rises above low-tide level.

26. TRAVERSE ACROSS REEF FROM SEA TO LAGOON APPROXIMATELY MIDWAY BETWEEN BIKINI AND AOMOEN ISLANDS

	Width (feet)	Cumulative width (feet)
1. Submarine spurs and grooves (below low tide)	150–300	-----
2. Marginal zone	50	50
3. Submarginal zone	25	75
4. Zoanthid zone	80	155
5. Tide-pool flat	820	975
6. Sand flat	320	1, 295
7. Rock flat	800	2, 095
8. Zone of coral patches	830	2, 925

1. Submarine spurs and grooves. Fingerlike spurs extend seaward 150 to 300 feet beyond the exposed reef edge at intervals of 25 to 50 feet. They lie under 10 to 15 feet of water at low tide and slope gently seaward, dipping downward abruptly at the edge of the terrace. The spurs are separated by narrow deep fissures that are similar to those noted in traverse 5.

2. Marginal zone. A flattish zone exposed between waves at low tide and sloping gently to the submarine spurs that border the reef. About half of the surface is covered by globular colonies of *Lithothamnion* but they do not form a distinct ridge or buttress zone. Reef corals (*Pocillopora*, *Acropora*, *Favia*) cover about 30 percent of the surface and hydrocorals (*Millepora*) 20 percent. A few of the fissures of the submarine margin are continued into the marginal zone.

3. Submarginal zone. This is an irregular area that ranges in width from 25 to 100 feet. Much of the surface is rough and appears to be eroded by solution. Living algae form the knobby, higher parts of the surface and corals of encrusting types line many of the lower areas that intervene. A pool measuring 5 by 14 feet is elongated parallel to the line of traverse. It is 5 feet in depth with steep to overhanging walls, its bottom covered by coarse debris.

Club-spined sea urchins are very abundant in the lagoonward part of the zone where the average is one to every 5 square feet. These organisms may be largely responsible for the erosion of the surface.

The lagoonward edge of the submarginal zone is separated from the flats beyond by a bench or step that rises 3 to 6 inches above the surface of the submarginal zone (fig. 74).

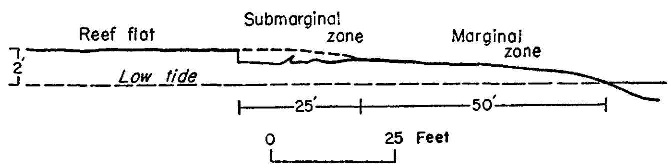

FIGURE 74.—Section through seaward margin of reef between Bikini and Aomoen islands. Sketch shows the gently sloping *Lithothamnion* ridge of the marginal zone, the eroded area of the submarginal zone, and the reef flat an estimated 2 feet above low tide.

4. Zoanthid zone. A rock pavement covered irregularly with flat-lying leathery zoanthid colonies, about the size of silver dollars. In the seaward third of the zone, which is almost completely exposed at low tide, the zoanthids cover 75 percent of the surface, the remainder being occupied by algae. Lagoonward the zoanthids are less numerous over the reef as a whole but are very abundant in large irregular patches. Pools 3 to 6 inches in depth contain small amounts of sand.

5. Tide-pool flat. A platform of limestone, algal at least on the seaward part, coated with a brownish-green algal scum. The embayments cutting into the zone from the seaward side, and a few isolated pools in back of these embayments, 6 inches deep, are floored

with algal rock bare of this soft algal coating. From one-third to one-half the area is above water at low tide, the rest being covered by pools 1 to 2 inches deep. Corals in heads as much as 8 inches in diameter occur in the pools. To seaward *Favia* is the commonest form but it is replaced lagoonward by *Porites; Acropora, Pocillopora* and *Astreopora* also occur.

The sand that veneers the low areas is rich in Foraminifera, both larger and smaller types. Three-quarters of the material consists of foraminiferal tests, of which over 75 percent are *Calcarina spengleri,* 20 percent *Marginopora,* and less than 5 percent are other types. The remaining quarter of the sand is a mixture of worn fragments of shells, *Lithothamnion* and *Halimeda;* fine angular grains, and matted soft algal fibers.

The tests of Foraminifera are unworn. Those of *Calcarina spengleri* are exceptionally spiny, indicating that they grew in or close to the shallow pool on the flat where they were collected. The proportions of constituents are almost identical to those of many foraminiferal beach sands. The only difference is in the spines of *Calcarina spengleri.*

A sample rock (B–72) from the edge of a shallow pothole about 150 feet inside the zone is a well-cemented limestone containing numerous algae, and spiny as well as worn tests of *Calcarina spengleri.* In a thin section, more than half of the slide is occupied by *Lithothamnion* that appears to be unworn and nodular rather than fragmental. The rest of the slide consists of detrital grains, tests of Foraminifera, and fragments of corals and mollusks scattered in a gray granular to microgranular paste. The paste contains some small round masses formed of radiating clear crystals. These spherulitic growths may have formed in small centers of crystallization of carbonate although it is possible that they are ascidian spicules. The pores and small cavities in organisms are partly filled with crystalline carbonate that also permeates the paste. Some larger cavities in corals and mollusks are partly filled with a finely granular mud or paste.

The lagoonward part of the zone is comparatively barren with many shallow basins and depressions that resemble potholes.

6. Sand flat. Sand several inches deep veneers a rock floor. Well-developed sand bars present on both sides of line of traverse. Area completely exposed at low tide.

7. Rock flat. An area of compact clastic limestones; surface cut by irregular transverse channels and partly covered by boulders and sand. Zone under thin sheet of water at low tide.

A sample of the rock (B–315A) is moderately to well lithified, formed mainly of detrital grains and containing numerous fragments of a species of *Acropora.* Many coral fragments are worn, well rounded and even polished, but some appear to be unworn and may be in position of growth. These are partly encrusted by *Lithothamnion* or by *Mineacina.* Tests of *Calcarina spengleri* are abundant. The rock near the reef surface is completely riddled by borings. The surface is a thin veneer of finely divided grains of carbonate poorly cemented to the rock and covered by a mat of fibrous soft algae. Many tests of *Amphistegina* and a few of delicate *Tretomphalus* adhere to the surface. The fine intergranular detritus between larger grains was stained by Meigen solution and the cementing material is therefore probably aragonite.

8. Zone of coral patches. Irregularly shaped patches of coral, three-fourths of it *Porites,* measuring 12 feet or more in diameter with a few areas of *Heliopora* and a few algae. Colonies growing on a rock floor which is almost free of debris.

Near the lagoon margin the reef flat is ribbed or fluted normal to the trend of the reef rather like the fluting on some beach rock. A specimen from the surface (B–71) is well-cemented coarse detrital limestone (pl. 48, fig. 1) consisting of about 15 percent fragments of coral, 10 percent fragments of *Lithothamnion,* 20 percent tests of Foraminifera, 5 percent encrusting Foraminifera coating coral fragments, and 50 percent fine reef detritus. The encrusting Foraminifera are mostly pink *Mineacina,* and the others are both worn and spiny *Calcarina spengleri,* thin *Marginopora,* and *Amphistegina.*

The common types of Foraminifera cover the surface of the specimen to which they are bound by velvety filamentous algae. Most of the rock, including interstitial material, was stained pink in Meigen solution and therefore contains much aragonite.

A coral fragment occupies about 10 percent of the thin section (pl. 48, fig. 2). The fragment is coated with pink *Homotrema* and with white encrusting *Lithothamnion.* Bore holes are empty, but labyrinthlike cells of the coral are filled with gray microgranular paste. A few spots within the paste, or lining pores, are made of clear crystalline material. The detrital material throughout the slide is mostly fine grained, and it is in a matrix of gray microgranular paste. Fragments in the detrital material and paste are angular and unsorted. Some grains are cemented by clear carbonate, and spots or areas within the paste are seen to contain clear fibrous carbonate.

27. TRAVERSE ACROSS SEAWARD REEF TO NORTHWEST END OF BIKINI ISLAND

	Width (feet)	Cumulative width (feet)
1. Submarine margin (not measured).		
2. *Lithothamnion* ridge	360	360
3. Reef flat	980	1, 340
4. *Heliopora* zone	760	2, 100

1. Submarine margin. Beyond the reef edge narrow straight grooves alternate with spurs. The grooves are 3 to 4 feet wide near the reef edge but become narrower to seaward; the walls are vertical, the bottom covered by sand some of which is ripple marked. The surfaces of the spurs are very rough and covered by algae and corals and show a sag in the middle.

As may be seen by swimming off the reef with a face mask, there is a fairly well developed terrace that lies 15 feet below the surface at the reef edge, sloping off at about 15°. About 25 percent of the shelf area is covered with gravel and debris, the rest is algal growth with some corals.

2. *Lithothamnion* ridge. Buttresses and surge channels well developed. The buttresses are about 10 feet across, the intervening channels measure 15 to 20 feet; some of the channels continue into the reef flat for total distances of 200 to 250 feet and are partially roofed over by algae leaving small open pools. The sides and ends of the buttresses are vertical to overhanging and a rim of living globular colonies of *Lithothamnion* 1½ feet thick is exposed between waves at time of low tide.

Remnants of an older *Lithothamnion* ridge are found on the landward side of the present structure; these are deeply pitted, apparently by solution.

3. Reef flat. Broad area; seaward part mostly covered by algae, landward part bare rock.

4. *Heliopora* zone. Microatolls as much as 20 feet in diameter, alined roughly in a direction at right angles to the reef front.

28. TRAVERSE ACROSS SEAWARD REEF NEAR NORTHWEST END OF BIKINI ISLAND

	Width (feet)	Cumulative width (feet)
1. *Lithothamnion* ridge	25+	25
2. Reef flat	2, 100	2, 125
3. Beach rock	55	2, 180
4. Sand	45	2, 225

1. *Lithothamnion* ridge. Well-developed cuestalike structure with steep slope to sea; composed of pink to red and purple algae. Ridge cut at fairly regular intervals by surge channels that are lined near the surface with globular colonies of algae; backslope covered largely by botryoidal crusts of pavement type algae. Details of ridge not observable at time of visit owing to heavy surf (poor tide).

2. Reef flat. A level rock flat covered by 1½ to 2½ feet of water. Globular colonies of *Lithothamnion* eroded from the ridge are scattered over the seaward edge of the flat and much of its surface is veneered with sand. Sand composed mainly of Foraminifera, chiefly the small *Calcarina* with some of large types such as *Marginopora* along with coral and shell fragments. Small heads of living corals occur over the entire flat but they are widely separated and probably do not cover 1 percent of the surface; at no place do the corals form a rich zone or even a rich patch. Large reef blocks are scattered over the seaward half of the flat.

3. Beach rock. Layers partly covered by foraminiferal sand.

4. Sand. The sand (specimen B–22) is composed of about 70 percent foraminiferal tests and 30 percent fine broken grains. The tests are about 60 percent *Calcarina spengleri;* most of them worn but not polished, and about 10 percent of them unworn with spines; the remaining 40 percent of the Foraminifera consist of *Marginopora,* most of them from 1 to 2 millimeters in diameter, but some of them 3 millimeters in size. This sand, derived from a wide reef flat, differs from lagoon beach samples in the high proportion of reef type foraminifers, the lack of polish on grains, the presence of 10 percent relatively unworn tests, and the presence of about 30 percent of fine angular grains. The beach sandstone, collected next to the sand, is a foraminiferal sandstone containing roughly 70 percent tests of Foraminifera, mostly *Calcarina spengleri.* They are solidly cemented by a porcelaneous white carbonate that completely fills all intergranular spaces.

29. TRAVERSE ACROSS SEAWARD REEF OBLIQUELY ABOUT 1 MILE FROM NORTHWEST END OF BIKINI ISLAND

	Width (feet)	Cumulative width (feet)
1. *Lithothamnion* ridge	195	195
2. Reef flat:		
a. Reef-block zone	665	860
b. Coral-algal zone	2, 620	3, 480
c. *Heliopora* zone	470	3, 950
d. Rock flat	115	4, 065
3. Beach:		
a. Coarse rubble	16	4, 081
b. Sand	102	4, 183

1. *Lithothamnion* ridge. Consists of cuestalike buttresses whose steeper slopes face the sea, separated at varying intervals by surge channels, a few of which extend entirely across the ridge. Globular types of *Lithothamnion* cover the higher parts of the ridge to seaward and line the surge channels to landward. A few living corals occur on the buttresses as do examples of a heavy-shelled *Turbo* and large club-spined sea urchins.

The gently sloping back of the ridge is a knobby surface made up almost entirely of algae. Numerous dark-spined boring echinoids are present and veneering corals become numerous to landward; locally they may cover half of the surface of the ridge. The landward part of the pavement has a relief of less than 6 inches.

2a. Zone of reef blocks. A rock flat thinly veneered with sand and covered by a few inches of water at lowest tide; not sharply separated from algal pavement to seaward; average relief to seaward only 6 to 8 inches. In this area living corals cover 20 to 25 percent of the surface. Many of the coral colonies are 3 to 6 feet across with living polyps limited to the edges of the masses. Reef blocks are abundant. To landward the colonies of living corals decrease in numbers; larger areas tend to be elongated at right angles to the reef front. At the landward edge of the zone algal nodules are rare and living corals cover only about 5 percent of the surface.

The rock of the flat near the landward edge of the zone is exposed at low tide. It is an algal limestone. A specimen (B–308) consists mostly of clusters or branches probably of *Porolithon gardineri* in a compact, hard detrital matrix. It is riddled, especially near the surface, by borings. These cut both algal branches and detrital filling. The surface of the rock is pitted by solution, and is matted with fibrous soft algae that encrust a thin veneer of fine detrital grains including some small tests of foraminifers.

In a thin section, the rock is seen to consist of about 70 percent *Porolithon* appearing as sections of round branches several millimeters in diameter, 20 percent fine to microgranular detritus between branches, and 10 percent round open bore holes. The detritus contains tests of small Foraminifera such as miliolids, encrusting *Carpenteria*, small angular grains of *Lithothamnion*, and scattered minute spherules, probably ascidian spicules. The tests and grains form 10 percent or more of the detritus. The matrix of the detritus is microcrystalline clear carbonate to nearly cryptocrystalline brown paste. The paste appears in small spots or patches that at first glance seem to be grains, but they occupy the centers of areas between recognizable grains. The paste is apparently a primary filling between grains that has become altered near grain borders to clear crystalline material.

2b. Coral-algal zone. A rock flat veneered with sand and covered by 1 to 1½ feet of water at low tide. Living corals and algae are growing on masses of dead coral 3 to 5 feet in diameter that rise to low water level from the rock flat. Locally living corals cover 25 percent of the reef surface—as much as the calcareous algae and soft algae combined.

A sample (B–301) of the rock floor near the inner edge of the zone is a dense limestone with conchoidal fracture containing much *Lithothamnion* and some coral. There is little sandy detritus although hollows and cavities in the rocks contain a few tests of *Amphistegina* and encrusting *Mineacina*. A few small cavities in the rock are packed with worn tests of *Calcarina spengleri* that are thinly encrusted by a chalky carbonate that firmly cements them to the rock.

Another sample of the rock floor (B–303) from a point 800 feet nearer shore and close to the margin of a rock groin is a compact, well-lithified detrital reef rock containing about 40 percent *Lithothamnion*, 20 percent foraminiferal tests, 15 percent corals, 5 percent fragments of mollusk shells and echinoid spines and 20 percent detrital grains. The rough and pitted surface layer is riddled for 2 to 3 millimeters by small borings. Small pits are filled with tests of foraminifers, fine angular detritus, and fibrous green algae.

Much of the hard surface appears to be a veneer of partly cemented fine detrital grains. It is conceivable that this represents a method of rock formation on the reef flat by precipitation of calcium carbonate during diurnal periods of low CO_2 content.

Numerous chips of hard rock (B–304) were collected from the groin. About half of them are coral, the other half are formed of well-consolidated detrital grains and algal fragments and contain many tests of foraminifers, especially *Calcarina spengleri*. Fine-grained detritus fills the spaces between larger grains. The surface of the rock is irregular and pitted as if by solution. The pits contain matted fibrous algae that hold numerous foraminiferal tests of *Amphistegina*, *Calcarina spengleri* and *Marginopora*. Tests of *Calcarina spengleri* on the surface are smaller and spinier than those cemented within the rock. The larger pits shelter living mollusks, small cowries and cones being particularly common; large chamas are cemented to the bare surface of the rock between pits.

A thin section of one of the detrital chips shows it to be formed of foraminiferal-algal sand. Over half the section consists of coarse material about 1 millimeter in size; the rest is finer grained and poorly sorted. Some cavities between larger grains are filled by a very fine detrital sand. The constituents are estimated to be 20 percent tests of *Calcarina spengleri*, 10 percent *Amphistegina* and other Foraminifera; 10 percent *Lithothamnion*, 60 percent shells and unsorted fine detritus. The material is cemented by a thin veneer of acicular carbonate about the grains, consisting of needles about 0.03 millimeter in length. Many cavities are empty, but are lined with the crystalline carbonate. Several patches in the slide are formed of gray finely granular detritus and small foraminiferal tests. Some of the detritus is so fine grained that it appears under low magnification (x20) to be a gray microgranular paste. A photomicrograph of a sample (B–306) from the top of the groin is shown in plate 48, figure 3.

2c. *Heliopora* zone. Area composed of subcircular microatolls of *Heliopora* as much as 10 to 15 feet across, the flattened tips rising close to low tide level; living polyps limited almost entirely to margins of colonies. Between the *Heliopora* masses the water varies in depth from 1½ to 3 feet.

2d. Rock flat. A sand-veneered surface with few small nodular colonies of living *Porites*. A sample of the sand (R4902a) scraped from the surface of the rock consists of tests of Foraminifera and fine matted filaments of algae. Tests of *Calcarina spengleri* are abundant, *Marginopora* is common. A few ostracodes are present. About 30 percent of the sand is less than 0.1 millimeter in size, and contains some silt size particles. The specimen dried in the sample sack to form a hardened "mud ball." This is unusual, and is probably due to the abnormal amount of fine material in the sample.

3a. Coarse rubble. A narrow strip of light gray sand and gravel.

3b. Sand. Cream-colored foraminiferal sand extending to edge of vegetation; maximum slope 10°.

30. TRAVERSE ACROSS SEAWARD REEF TO MIDDLE OF BIKINI ISLAND

	Width (feet)	Cumulative width (feet)
1. *Lithothamnion* ridge	90	90
2. Coral-algal zone	285	375
3. Reef-block zone	415	790
4. Zone of microatolls	495	1, 285
5. Sand zone	885	2, 170
6. Coral zone	690	2, 860
7. *Heliopora* zone	370	3, 230
8. Beach	95	3, 325

1. *Lithothamnion* ridge. A cuestalike structure composed of moderately well developed buttresses separated by broad, shallow surge channels that make the seaward margin very irregular (pl. 49). Seaward parts of buttresses are cavernous and irregular, their upper surface formed of knobby, pavement-type algae. Highest parts of buttresses rise 2 to 3 feet above low tide, the tops being wet only by an occasional wave at low tide. Lower parts of buttresses are (up to about 1 foot above low tide) covered by the globular type *Lithothamnion*. These algae form a hummocky surface, the largest masses reaching a diameter of nearly 2 feet.

In a zone lying 35 to 50 feet from the seaward edge there are small, scattered remnants of older reef rock, now deeply pitted as though by solution, that rise as much as 1 foot above the present algal pavement. A typical specimen (B–54) shows slender branches of *Lithophyllum* filled by fine detrital sand. The rock is compact and well consolidated. About half is formed of slender algal branches, alined and in place. The rest consists of angular fragments of mollusks and forminiferal tests in a fine sandy matrix. Several large worm tubes penetrate the rock.

In a thin section (pl. 48, fig. 4) the rock is seen to be about 60 percent *Lithothamnion*. The rest is foraminiferal tests and fine detrital grains in a brown paste filling spaces between algal branches. An acicular carbonate coats the surfaces of grains and cavities, and intergrowths of clear acicular carbonate fill small areas within the paste which in places is almost wholly converted to crystalline carbonate, so that only small, irregular areas of brown, microgranular paste remain. The process is one of alteration rather than leaching and filling, and it appears to be an alteration of paste to clear crystalline material rather than of crystalline to microcrystalline carbonate. The section is typical of reef material, and the brown paste is similar to that seen in many core sections of both reef and lagoonal origin, but it is different from beach and island material.

The gentle backslope of the ridge is an algal pavement; the seaward part is riddled by echinoid borings; the landward part is covered with increasing numbers of living corals. A few of the surge channels continue entirely across the ridge as deep caverns partially roofed over above, widening out below.

To the south of the line of traverse, the backslope of the ridge widens and there is a series of shallow pools 3 feet or more in length that are elongated at right angles to the reef front. The average width of the pools is 1 foot and they contain 3 to 4 inches of water at low tide.

2. Coral-algal zone. An undulating flat about 20 percent of which is covered by colonies of living coral, 5 percent by living algae and the remainder a rock flat veneered with sand. Large colonies of *Acropora*, and small heads of *Favia* (as much as 8 inches) are numerous along with a few colonies of *Heliopora*. The algae consist of globular and pavement type *Lithothamnion* and *Halimeda* with some soft algae.

One-quarter mile north of the line of traverse the coral-algal zone is better developed and more luxuriant than similar zones seen elsewhere in the area. The zone is 500 feet wide, extending along the reef for several hundred yards in either direction although it disappears a few hundred feet north of traverse 30. The outer 150 feet of this zone is composed of 50 to 100 percent of corals on an eroded algal pavement with some live *Lithothamnion*, particularly on the seaward margin. Shoreward the patches of coral standing up 6 inches or more from the floor become more discrete, until at the shoreward margin of the zone the patches form some 25 percent of the total surface. The zone grades into the next zone. More different types of corals were seen here than in any other single locality. *Pocillopora* and many varieties of *Acropora* were the most common. *Stylophora*, *Seriatopora*, found most commonly in the lagoon, were present as were large growths of *Lobophyllia*, and *Symphyllia*. Several large *Hippopus* were on the reef entirely out of water.

3. Reef block zone. An irregular rock surface with widely scattered blocks of reef rock. Living corals cover 5 to 10 percent of the surface and with them are

small nodules of *Lithothamnion* and a few colonies of *Heliopora*. Many of the worn reef blocks have been in place long enough to permit the growth of small colonies of corals (*Acropora*, the commonest) and nodules of algae. Sand appears in increasing amounts to landward.

The line of traverse was made through the largest reef block found on Bikini Atoll. This erratic measures 33 feet in greatest diameter yet is clearly made up in large part of reef rock. There are two distinct parts to the mass that are not cemented together at the present time but may have been connected at one time. Most of the larger of the two parts consists of coral colonies (*Heliopora*, etc.) whose orientation can be easily determined. In several places colonies of globular *Lithothamnion* lie above the corals. The orientation of the colonies in the smaller of the two masses is less perfect than in the larger but is clearly at an entirely different angle. The top of the mass rises 8 feet above high tide (as measured above the nip formed at that level). At the base of the coral colonies there is a conglomerate layer about a foot thick containing smooth, flattened, well-rounded coral pebbles 1 to 3 inches in diameter.

4. Zone of microatolls. Tablelike masses measure 2 to 10 feet across and are roughly elongated at right angles to the reef front and cover 40 percent of the zone. Corals (chiefly *Acropora palifera* and *Stylophora*) now growing around the edges of the microatolls together with nodules of algae. Sand veneers the lower areas.

5. Sand zone. In the seaward part of this zone the rock masses cover only 20 per cent of the surface and they disappear almost entirely about one-third of the way across the zone. Many of the rock masses that do occur are well covered by pink, nodular algae, the low areas between them are covered by sand and coarser debris. The landward two-thirds of the zone is a sand-veneered rock flat supporting scattered small nodules of *Porites* and an occasional *Acropora*.

6. Coral zone. A zone in which scattered coral heads grow on a rock flat veneered with sand and coarser debris. Most of the corals are small but there are a few large masses, also many small nodules of *Lithothamnion*. To landward the veneer of sand and coarser debris is several inches in thickness.

7. *Heliopora* zone. Scattered masses of *Heliopora* rising from a flat veneered with sand and coarse debris.

ENIWETOK ATOLL

1. TRAVERSE ACROSS SEAWARD REEF NEAR NORTHEAST END OF ENIWETOK ISLAND

	Width (feet)	Cumulative width (feet)
1. *Lithothamnion* ridge	50+	50
2. Outer reef flat	130	180
3. Inner reef flat	70	250
4. Boulder rampart	250	500

1. *Lithothamnion* ridge: Buttresses small, moderately well developed; ridge relatively low with crest about 1 foot above reef level; surge channels are small, relatively straight and regular.

Practically all the calcareous algae on the ridge and 70 to 90 percent of the corals, which form some 10 percent of the inner edge of the ridge, are dead and covered with a thick growth of fuzzy brown algae. Though the ridge has been dead for only a few years the *Lithothamnion* has a corroded look; solution and worm borings have destroyed much of the original algal surface leaving the rock so deeply pitted that it crumbles easily under a hammer blow.

2. Outer reef flat. Covered by 3 inches to 1 foot of water at low tide. A barren, flat of algal limestone covered with a soft velvety algal veneer and pitted with small depressions a few inches deep and a foot or two in diameter. A few small hummocks are present.

3. Inner reef flat. Exposed at low tide, rising gradually to about a foot above water level at the bench line. The shoreward part of this zone is covered with loose scattered cobbles.

4. Boulder rampart. A very steep beach of cobbles. This probably is in large part artificial from construction work on the island, but the island outline has been changed very little.

The close similarity of this reef to the southeastern reefs on other atolls, particularly Rongelap, should be noted. It is narrower and not as well developed as the reef off the southeast end of Enyu island, Bikini Atoll, and Eniwetak island, Rongerik Atoll. The reef off Kwajalein island, though not examined closely, appears similar. On Eniwetok, Kwajalein, and Rongelap Atolls, the southeastern islands for which the atolls are named are long and narrow; the associated reefs are exceptionally narrow, the reef flat is barren and the boundary between *Lithothamnion* ridge and reef flat is sharp, with the ridge rising rather abruptly from the flat.

Stearns (1945a) studied the reef fringing Eniwetok island in 1944 shortly after it had been subjected to heavy bombardment and coated by fuel oil from damaged ships. It is felt that the features of decadence described by Stearns were caused by battle damage rather than by a local change in the strandline as suggested by Stearns.

2. TRAVERSE (LATERAL) ON SEA REEF TO SOUTHWEST OF TRAVERSE 1, ENIWETOK ISLAND

All along the traverse the reef has been killed, in part by oil from a wrecked tanker to the northeast. The *Lithothamnion* is almost completely killed off; the algal pavement is pitted, eroded and riddled with borings. About 80 percent of the corals have been killed. Most all those still alive do not look healthy but there are some small areas of new growth. A thick slimy growth of stringy hairlike algae one to three inches long covers most of the dead calcareous algal surface, and the dead coral surfaces.

The most interesting feature of this traverse is the presence from northeast to southwest, of successive stages in the development of blow holes. On the northeast there are small, poorly developed open surge channels; to the southwest the channels show increasing amounts of roofing over and at the southwest end of the island fully developed blow holes occur.

DISCUSSION OF ZONES

The reef ranges in width from 200 to 300 feet, and consists of three well-defined units: (1) A *Lithothamnion* ridge 50 to 75 feet in width, well developed in most places; broader and more massive to the southwest; (2) an outer reef flat 100 to 150 feet in width depressed a foot or more below the *Lithothamnion* ridge, pockmarked with small basins or solution pits; and (3) an inner reef flat 50 to 100 feet wide covered with a scattered cobble or boulder shingle near the beach line.

At the northeast end of the traverse the *Lithothamnion* ridge is relatively low, about 1 foot or more above low-tide level. There is no massive algal development; surge channels are small, about 5 feet wide, 6 to 10 feet deep and 25 to 50 feet long. The reef flat is exceedingly level and the solution pits or basins are small, shallow and scattered.

Proceeding to the southwest along the reef the *Lithothamnion* ridge becomes more massive, higher, and the surge channels lengthen and deepen until they are 50 to 75 feet or more long and 15 to 20 feet or more deep at the reef edge. Near traverse 1, the surge channels are well developed, narrow and straight. The walls are vertical and fairly regular, and a pronounced algal shelf has developed at reef level over the channels, partially closing the channelways. (See fig. 75.)

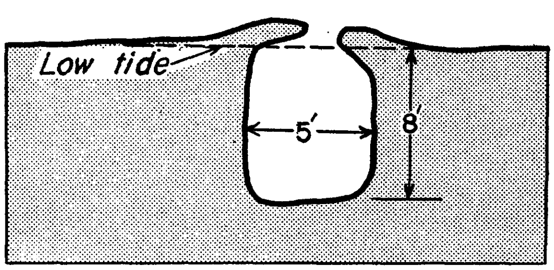

FIGURE 75.—Section through surge channel of Eniwetok Island. Growing algal shelf has nearly closed the top of the channel.

Farther southwestward the development of ridge and channels continues, until the *Lithothamnion* ridge is quite massive and 2 to 3 feet above low-tide level. The shelving over of the channels continues until the reef opening is but a crack along the channel's length, through which every wave surges to refresh the algal growth along the crack. By this means the lips of the channel, of living algae, grow an inch to a foot or more above the reef flat.

Farther to the southwest the algal shelves coalesce and seal the crack more or less completely. The channels are roofed for 25 to 50 feet or more except for the extreme shoreward end where an opening remains. Water surges out of this opening after every wave, and if the openings are small blowholes may result. Along the southwest part of this traverse nearly every surge channel has developed into a blowhole, and these may be seen spouting—some as high as 20 feet into the air—for a distance of half a mile down the reef.

When the channel has been roofed over, new water no longer pours over the algae at low tide and no further growth results except around the blowhole where algal mounds similar to geyser cones are developed. These are commonly 2 feet and occasionally 3 feet above the reef level (pl. 50, fig. 1). They are 10 to 30 feet in diameter.

The blowholes are 20 to 50 feet behind the *Lithothamnion* ridge, and the series of blowholes cuts the reef flat into re-entrants 25 to 50 feet across. The reef flat also changes in character from northeast to southwest, for the small, shallow pits increase in size, depth, and number as the *Lithothamnion* ridge increases in height. In the blowhole area these basins become 2 to 4 feet broad, 4 to 10 feet long, transverse to the reef edge, and as much as 2½ feet deep with rounded bottoms, much like bathtubs. Some contain sand, gravel or boulders and appear to be excavated by wave erosion but others contain no sand or boulders.

3. TRAVERSE NORTHWARD ACROSS SEAWARD REEF TO POINT 100 YARDS EAST OF WEST END OF IGURIN ISLAND

In its prolific coral growth and marginal algal development the reef resembles the reefs of Eninman and Enirik islands, Bikini. It is a lee reef. At the time the reef was visited swells from the prevailing winds were striking it diagonally so that there was much vertical motion of the water at the reef edge, but little surf.

Six main zones characterize the reef:

	Width (feet)	*Cumulative width (feet)*
1. Marginal zone	50	50
2. Submarginal zone	35	85
3. Coral flat	125	210
4. Reef flat	150	360
5. Boulder flat	90	450
6. Boulder rampart (not measured).		

1. Marginal zone. Rises rather abruptly on the seaward side from a submarine zone of algae that slopes gently to a depth of 20 feet. The edge of the marginal zone is formed of large algal growths 20 to 50 feet

across. These are flat and like fungi they shelve outward and overhang several feet; the marginal zone rises 3 to nearly 5 feet from the shelving edge to the crest of the reef. The crest, the inner edge of the marginal zone, is 1 to 2 feet above lowest low-tide level. The zone is made almost entirely of encrusting *Lithothamnion*, but they were yellow, slick, and appeared dead or dying. The zone is honeycombed with small borings 1 to 3 millimeters across and crumbles easily. No algae of the globular type were seen. The coral *Pocillopora*, is common but forms only a small percentage of the surface. Sea urchins both large and small are abundant, and their borings, particularly on the shelving edge, give the reef a spongelike structure which effectively breaks up the force of the waves.

2. Submarginal zone. From the crest of the marginal zone the reef slopes very gently shoreward to the level of the reef flat, where it is covered by about 6 inches of water at a normal low tide. Much of the algal surface is thickly covered by branching *Acropora* and *Pocillopora*. The ratio of corals to algae ranges from 1:1 to 3:1.

3. Coral flat. Structurally this zone is part of the reef flat, as it has the same bare algal limestone floor. The floor is covered with branching corals; on the seaward edge of the zone the ratio of corals to barren algal rock is 3:1; on the inner edge the corals are more scattered but even in this area cover 50 percent of the surface. In the central part of this zone, the corals cover almost all of the reef surface.

4. Reef flat. An algal rock floor, covered with a thin veneer of foraminiferal sand. Branching corals decrease in numbers, becoming rare at the shoreward side of the zone.

5. Boulder flat. Similar to reef flat above; floor rises gradually to tide level and above, but is completely covered to shoreline by a shingle of coarse gravel and boulders.

6. Beach and boulder rampart. A layer of beach sand occurs above mean-tide level on top of the shingle. The sand wedge gives way at high-tide level or lower to a boulder rampart rising about 6 feet above high-tide level.

4.—TRAVERSE ON SEA REEF SOUTH OF BUGANEGAN (MUTI) ISLAND, FROM SEAWARD REEF EDGE NORTHWARD ACROSS THE END OF ISLAND TO THE LAGOON REEF FLAT

	Width (feet)	*Cumulative width (feet)*
1. Marginal zone	100	100
2. Submarginal zone	30	130
3. Secondary algal ridge	36	166
4. Reef flat	198	364
5. Coral conglomerate	162	526
6. Beach sandstone	126	652
7. Sand flat	270	922
8. Lee slope of dunes	36	958
9. Windward slope of dune sand	30	988
10. Beach sandstone	12	1,000
11. Lagoon reef flat (not measured).		

1. Marginal zone. The reef edge is 50 to 100 feet on the seaward side of the crest exposed at low tide, and is covered by about 5 feet of water. The marginal zone slopes gently seaward, and the crest is a foot or more above low tide level. The margin is cut by deep clefts or crevices rather than by long channelways. This zone is almost wholly porous algal material, is of a dull orange color, and does not appear to be in a healthy condition.

2. Submarginal zone. Behind the reef crest this zone is covered by 6 inches to 1½ feet of water. The floor is eroded, hummocky algal limestone. Corals are rare.

3. Secondary algal ridge. This feature, only 36 feet wide and somewhat more than 100 yards long, is of eroded algal limestone. It rises about 1 foot above water level on the reef, and is cut by numerous parallel scoop-shaped channels transverse to the reef front. The bottoms are about at the level of the reef flat.

4. Reef flat. A barren flat of eroded algal limestone covered by 9 inches to 1 foot of water at low tide. Corals are rare.

West of the secondary algal ridge the submarginal zone broadens and corals, particularly encrusting types, become more abundant until 100 yards west of the end of the secondary ridge they form as much as 50 percent of the submarginal zone. In the reef flat branching corals also are abundant west of the secondary ridge.

5. Beach sandstone. Well-bedded medium-grained foraminiferal sand; E–W, 10° S.

6. Sand flat. The flat at about mean-tide to high-tide level covers the truncated sandstones of the bar.

7. Lee slope of dunes. Back slope of windblown sand. Crest of sand is about 4 feet above high-tide level.

9. Beach sandstone. Well bedded, dipping 10° N.

10. Lagoon reef. Wide reef flat covered by 1 foot of water at low tide. Flat is formed of coarse sand on cobbles rather firmly bound together, probably by a surficial algal growth. Corals are fairly common in scattered growths.

5.—TRAVERSE ACROSS SEA REEF OFF GRINEM (GIRIINIEN) ISLAND

At the time the reef was visited the prevailing swells were traveling nearly parallel to the reef front so that they struck the reef diagonally. Normal swells at low tide merely rose and fell over the reef edge, but large swells every 12 to 15 minutes carried a tremendous surge of water onto the reef that washed all the way to the shore; then for 3 to 5 minutes afterwards there was a strong current off the reef flat and over the reef edge.

There is normally a strong current at the headward end of the channels that cut into the reef. This is true both at low tide and at middle ebb tide. The reef was not examined at other times but it is probably true throughout the tidal cycle.

	Width (feet)	*Cumulative width (feet)*
1. Submarine margin (not measured).		
2. Marginal zone	120	120
3. Submarginal zone	80	200
4. Reef flat	50	250
5. Secondary reef and flat (not measured).		
6. Beach rock (not measured).		

1. Submarine margin. Examined by swimming; slopes seaward for 100 to 300 feet where, at an apparent depth of 10 or 15 fathoms it drops off more steeply. Irregularly lobate algal spurs separated by wide, deep, canyon-like channels extend below sea level. These are about 30 feet deep at the reef edge and continue seaward to the edge of the 15-fathom terrace. The spurs are dominantly made of rounded *Lithothamnion* with abundant large branching corals and *Heliopora* very abundant on the nearly vertical channel walls. The bottoms of the channels widen to 50 feet or more, are rather flat, eroded, and covered with coral and algal cobbles and boulders; isolated coral heads grow on this floor.

2. Marginal zone. The edge of the marginal zone is quite irregularly lobate, the spurs being 50 to 75 feet across, separated by channels 10 to 30 feet wide that may be erosional in part. In the marginal zone the spurs slope gently seaward.

The marginal zone does not rise to a well defined crest. Instead there are scattered hummocks or mounds of *Lithothamnion* 20 to 60 feet across that rise to a maximum of 1 foot above low-tide level. The zone is composed of approximately 75 percent *Lithothamnion* yellow and cavernous, and 25 percent corals, dominantly *Pocillopora* around the canyon edges.

3. Submarginal zone. An irregular algal floor covered by 6 inches of water at low tide. The floor is dominantly eroded algal limestone though some yellow *Lithothamnion* lives on the surfaces. Corals, particularly *Acropora* and *Porites* are abundant. In this zone are some irregular pools 6 to 10 feet or more in diameter and 2 to 5 feet deep. The structure of the submarginal floor is exposed in these pools. It is formed of coalesced *Heliopora* heads with a surficial algal veneer. The pools are merely spaces between uncoalesced heads of *Heliopora*.

4. Reef flat. Covered by about 1 foot of water. The floor is of algal limestone, irregular and hummocky, with sandy patches in the hollows. *Porites* are abundant, small *Heliopora* are common. Corals grow scarce shoreward.

5. Secondary reef and flat. What appears to be a second reef edge is exposed on the shoreward edge of the reef flat. It forms a ridge of coral limestone 1 foot above low-tide level truncated to cusplike forms. The corals in the rock seem to be in place. Scoop-shaped pans are cut into this ridge. To shoreward there is another reef flat, slightly below this ridge but above low-tide level. On this platform lie the boulders and bedded sandstone of the island shore.

6.—TRAVERSE (UNMEASURED), RIGILI ISLAND, GENERAL DESCRIPTION OF REEFS

The reef is on the southwest side of the atoll. Northwest of Rigili island is the lee reef, the seaward margin of which forms a low pink ridge awash at low tide. As seen from the air, the reef edge is regular, gently crested, with a steep seaward slope; it resembles the reef northwest of Bokororyuru island, Bikini Atoll.

Southwest of Rigili as the reef approaches the wide shallow channel, the marginal zone becomes very irregular and a narrow submarine terrace, probably erosional in part, is present.

Southeast of the island, along the side of the shoal channel the reef has no well-defined margin. It is rather an indistinct zone of irregular coral heads rising in 8 to 15 feet of water and partly coalescing. The channel itself appears to be a wide submerged reef on which is an abundant growth of elongate coral masses about 50 or 100 feet wide and several hundred yards long, parallel and transverse to the reef. They are separated by narrow channel-like passageways that seem as already noted, to be sandy, and relatively free of bare coral or algal rock.

The long coral structures further southeast, tend to coalesce on the lagoon and sea margins of the submerged reef, forming a poorly developed surface reef margin.

The gradual development of a well-defined crest on the sea side, actually awash at low tide, is seen to striking advantage from the air as one flies southeastward from Rigili toward Grinem.

The margin of the seaward reef off Rigili island is irregular with well developed buttresses separated by indentations that are floored with sand. The buttresses are 10–12 feet wide and 25–30 feet long; their surfaces show a relief of a foot or more, some of the low points being steep-sided cavities 8 inches or more across. Living pink lithothamnia of the pavement type that encrusts coral colonies covers about 40 percent of the surface (no globular colonies were seen); the remainder of the area is occupied by living corals. There are

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veneering Acroporas 2 to 3 feet across, irregular colonies of *Millepora* up to 12 feet in maximum diameter and scattered small colonies of *Pocillopora;* large club-spined sea urchins are also abundant.

At the landward edge of the buttress zone there are irregular pools with living corals but the growth is not as profuse as on the seaward parts of the buttresses. The marginal zone averages 50 feet in width and is widely exposed at extreme low tide.

The surface of the reef behind the marginal zone is covered by water up to 2 feet deep at low tide. To seaward a variety of corals cover 75 percent of the surface but only about one-fourth of the colonies are alive; many of the dead colonies are veneered with lithothamnia most of which appear to be dead; irregular pools are floored to a depth of several inches by coarse sand.

The lagoon reef northeast and east of Rigili is divided into 4 fairly well defined zones.

1. Submarine margin. This is a zone about 350 feet wide, extending from the marginal zone where it is covered by about 4 feet of water to a break in slope where the water is about 50 feet deep. This zone was not examined closely. In structure it is similar to the marginal zone with abundant coral heads growing on a rock surface.

2. Marginal zone. This poorly defined zone is actually the break in slope between the submarine margin and the coral flat. It is approximately 50 feet wide and consists of scattered large coral heads 2 to 4 feet high and 5 to 15 feet in diameter growing on a limestone floor covered by about 4 feet of water. The heads are not awash at low tide. Heads form about one-quarter to one-third of the total area. A wide variety of corals is present. Large heads of *Platygyra* and *Symphyllia* are common but *Heliopora* is even more abundant. The lagoon reef faces the prevailing wind, and the water under ordinary conditions is rough and choppy.

3. Coral flat. This zone, 100 to 200 feet wide, is a reef flat covered at low tide by 2 to 3 feet of water on which large scattered coral heads cover about 20 percent of the surface. The floor is algal rock, white and eroded. Shoreward the floor rises, the coral heads become smaller and much more scattered.

4. Reef flat. The central part of the reef, 200 to 400 feet wide, covered by 1 to 2½ feet of water at extreme low tide. The floor is fine to coarse detrital and foraminiferal sand, with abundant scattered coral colonies. *Porites* colonies as much as 1 foot thick and several feet across are most abundant.

From a small island northeast of Rigili a gravel bar has been built westward onto the reef flat. Below lowest tide level the bar is rimmed by a peripheral band of gravel that is partially covered by numerous disc-like colonies of *Porites* 1 to 3 inches thick and 6 inches to 4 feet in diameter. These are alive only at the edges, but they are so numerous that they tend to hold the gravel down, and in places they are coalescing to form a rock veneer over the gravel floor. This appears to be an unusual method of forming a limestone pavement on reef flats. It may be more common than realized, although not seen in the other islands visited.

The small island is formed of beach conglomerate on which are piled coral gravel and boulders. A marked boulder rampart encircles the whole.

7.—TRAVERSE FROM EDGE OF LAGOON REEF NORTHWEST TO WEST END OF LIDILBUT (TEITEIRIPUCCHI) ISLAND

In this area, the lagoon reef is well developed and extends almost continuously for several miles. It is not, however, so uniform nor so well developed as the comparable lagoon reef off Namu in the Bikini Atoll.

	Width (feet)	*Cumulative width (feet)*
1. Marginal zone	20±	20±
2. Submarginal zone	55	75
3. Algal pavement	50	125
4. Reef flat	320	445
5. Sand flat	180	625
6. Sand bar	975	1, 600
7. Beach sandstone	50	1, 650
8. Sand beach and dunes	100	1, 750

1. Marginal zone. From a lagoon floor that is only 4 to 8 feet deep at the line of traverse, the marginal zone rises abruptly to the surface as a series of narrow, crescent-shaped ridges, a maximum of 1 foot above extreme low tide and only 5 to 10 feet wide. Algae and corals are about equal except on the crest which is 75 to 90 percent yellow to brown dead *Lithothamnion.* The calcareous algae are partly covered by slimy brown algae.

2. Submarginal zone. Branching corals of many varieties form about 50 percent of the area of this zone. They grow from a limestone floor that may be dominantly algal. It is covered by 6 inches to 1 foot of water at low tide. Behind the channelways formed by the crescent-shaped ridges are pools 10 to 25 feet across and 4 to 5 feet deep. These appear to be areas where the reef structure has not completely developed. The sides of the pools are lined with corals, and the bottoms are covered with sand and gravel.

3. Algal pavement. Small colonies of corals cover 10 to 50 percent of the area. The pavement is covered by 1 to 2 feet of water.

4. Reef flat. Irregular rock floor with a veneer of sand, covered by 2 to 3 feet of water at low tide. Large heads of living coral 5 to 20 feet across and 1 to 2 feet high are present.

5. Sand bar. The bar is building south from the

west end of the island. East of the line of traverse the corresponding area is similar to the reef flat described above, though it is shallower, more regular, with abundant scattered coral colonies and is partly covered by sand and gravel.

6. Beach sandstone. Well-bedded rock of Foraminifera and detrital sand, dipping parallel to the present beach.

8.—TRAVERSE FROM SEAWARD EDGE OF REEF SOUTH-SOUTHWEST TO NORTHWEST CORNER OF BOGON ISLAND

The reef is very wide in this area; it may be divided into the following zones:

	Width (feet)	Cumulative width (feet)
1. Submarine margin (not measured).		
2. Marginal zone (crest only)	15	15
3. Submarginal zone	42	57
4. Coral zone	893	950
5. *Heliopora* zone	1, 820	2, 770
6. Reef flat	2, 350	5, 120

1. Submarine margin. The seaward slope dips quite gently, estimated at 10°, for about 50 feet. It was impossible to see beyond this in the heavy surf, but from the air the *Lithothamnion* ridge along this section of reef seemed to have three distinct crests. The innermost ridge is covered by water and lies about 100 feet beyond the reef edge exposed at low water. The three ridges are parallel and successively deeper offshore; the outermost one is covered by an estimated 20 or 30 feet of water.

2. Marginal zone. The exposed reef crest is long, narrow and is very gently arched. It is very regular and not grooved or channeled except for very small, short and narrow cracks only 6 inches to 2 feet deep that occur at intervals of about a hundred feet. The *Lithothamnion* forms about 50 percent of the crest, and is exceedingly rugose. *Pocillopora* is the most abundant coral and encrusting types are also common.

3. Submarginal zone. There are two distinct parts to this belt. The first, about 18 feet wide, consists of encrusting corals and some blunt branching forms on a bare, dead algal rock that lies slightly below the reef crest. The second subzone, about 24 feet wide, is a strip of soft, spongy corals covered by 0 to 3 inches of water. This carpet extends along the reef edge as far as can be seen in either direction. *Cypraea caput-serpentis* is very common in this zone.

4. Coral zone. The outer subzone is about 53 feet in width, and consists of about 30 percent encrusting and branching corals on an eroded algal pavement covered by 2 to 5 inches of water.

The coral flat is a dead algal limestone pavement about half covered with a very luxuriant and varied growth of coral. The colonies grow in great profusion in bunches separated by equal areas of pavement. Shoreward the corals diminish in numbers until in the next subzone they form only 25 percent of the total area. The floor is covered by 6 inches of water or less at the outer edge of the subzone, by 1 foot of water at the inner edge. The corals stand several inches above water. *Acropora* is the most common form, but the variety of types of coral within this zone is greater than seen anywhere except on the northeast part of Bikini reef (400 yards northwest of Bikini traverse 3). Some *Tridacna* and *Hippopus* 1 foot to 18 inches in length are fully exposed at low tide. The coral flat is about 600 feet across. The inner boundary at the next subzone is very gradational.

The inner subzone is about 240 feet wide with poorly marked boundaries. This subzone is transitional between the coral zone and the main reef flat. The reef floor is covered by debris, the coral clusters grow more separated, and the depth of water increases. *Heliopora* is common and increases in abundance shoreward until it is the dominant form.

5. *Heliopora* zone. The reef floor, covered with a rather patchy veneer of coral debris and foraminiferal sand is under 3 to 4 feet of water at the outer edge of the zone and shoals gradually. *Heliopora* heads are dominant and occupy about 20 percent of the floor. The colonies are 3 to 20 feet across, averaging 10 feet in diameter, and are uncovered a few inches at low tide. Fragile, branching *Seriatopora*, generally found only by dredging in the deeper waters of the lagoon, is very common in small colonies between the branching radial fins of *Heliopora*. The floor of the shoreward 500 feet of this zone is covered by a layer of debris from a few inches to a foot or more thick. One to two feet of water cover the floor, and *Heliopora* heads are smaller. Around the *Heliopora* colonies are thick tangles of long branching white *Acropora* with blue tips. This coral makes up most of the debris on the reef floor. It is a form seen only rarely on the reef.

6. Reef flat. The outer 250 feet of this zone is a transition from the previous one. *Heliopora* is not common; instead *Porites* and other flat corals grow in abundance and serve to consolidate the debris-covered floor. Some crusty pink *Lithothamnion* is common also. The reef flat is here covered by about 6 inches of water. The next 500 feet of the zone is a barren algal pavement with a thin and patchy sand veneer covered by only 2 or 3 inches of water. *Porites* heads and other debris are piled up by waves in places a few inches above low tide level. Inside this area is a subzone 800 feet wide, consisting of a crusty pavement of algal limestone with abundant large slabby *Porites*, covered by 2 inches of water. The next 300 feet form a barren algal limestone flat with a thin patchy veneer of sand and coral gravel and the innermost 500 feet consists of the same algal

limestone covered by a sand veneer. Corals are common but have all been washed in from the outer parts of the reef. Holothurians are very abundant; one per square foot is not uncommon over fairly large areas.

9.—TRAVERSE ACROSS REEF FROM SEA TO LAGOON NORTHWEST OF ENGEBI ISLAND

	Width (feet)	*Cumulative width (feet)*
1. Marginal zone (not measured).		
2. Coral zone	180	180
3. Rock flat	275	455
4. *Porites* zone	195	650
5. Boulder zone	140	790

1. Marginal zone. A broad belt, elevated a few inches above the adjoining flats and sloping gently to the sea. At low tide a strip 25 feet in width is exposed between waves; this strip is completely covered by living organisms, about 85 percent being algae and the balance corals. In many places large colonies of *Pocillopora* are more or less completely covered by *Lithothamnion,* in a few places flat colonies of *Acropora* are encroaching over the algae. The algae are mostly of the pavement type with some small colonies of the globular type. In addition to the algae and corals there are a few club-spined sea urchins and small Tridacnas.

Large, well-developed surge channels cut the zone at intervals ranging from 100 to 165 feet.

2. Coral zone. A comparatively smooth rock pavement covered by 4 to 6 inches of water at low tide. Corals cover about 80 percent of the surface and most of them are alive. Colonies of *Acropora* with short stumpy branches are as much as 3 feet in diameter and rise close to low-water level; other matlike colonies reach a diameter of 6 feet. The surge channels of the marginal zone extend half way across the coral zone, their rims raised several inches above the general level by algal growth. Thin-spined sea urchins are abundant on the lagoon side of the zone and on the rock flat that adjoins it.

3. Rock flat. A fairly flat pavement similar to last but with corals decreasing in numbers lagoonward with broad shallow potholelike depressions. Surface along line of traverse a little lower than adjoining areas and covered by a few inches of water even at lowest tide, the water moving steadily across the reef at all times. Much of rock surface is thinly veneered with algae and sand. Black holothurians become abundant lagoonward until there are, on the average, 3 or 4 per square yard and as many as 16 per square yard locally. Living *Conus* abundant.

4. *Porites* zone. A flat on which 80 percent of the surface is covered by colonies of *Porites,* most of which are alive. On the seaward side of the zone the colonies are truncated and the largest measure 6 feet across; on the lagoon side the *Porites* are smaller, but more numerous and are accompanied by a few other corals as well as large examples of the "strawberry clam," *Hippopus.* Sand and coarser debris occurs between the corals, the patches becoming thicker toward the lagoon.

5. Boulder zone. Similar to last but with larger amounts of loose boulders. Living *Porites* widely scattered. The larger heads contain numerous small Tridacnas embedded in their dead central areas—as many as 9 clams being noted in 1 coral head; *Hippopus* present in abundance.

10.—TRAVERSE ACROSS SEAWARD REEF OFF ENGEBI ISLAND

	Width (feet)	*Cumulative width (feet)*
1. *Lithothamnion* ridge	60+	60
2. Coral zone	140	200
3. Rock flat	910	1, 110
4. Beach (not measured).		

1. *Lithothamnion* ridge. A zone of buttresses and surge channels comparable in general form to the ridge found off Bikini island. The buttresses off Engebi are lower and less accessible than those off Bikini but the rich covering of living pink to purple globular colonies of *Porolithon* that characterizes Bikini's reef is completely lacking at Engebi. No colonies of this type are present on the surface of the buttresses or on the sides of the surge channels below low tide level. The ridge as a whole is dark brown; there are a few pink to light brown areas but the darker parts of the ridge are almost black. Much of the algal limestone that forms the surface of the ridge is soft and crumbly, partially covered with a film of soft algae. There are scattered colonies of living *Pocillopora* on the ridge surface, a few sea urchins, both large club-spined forms and the short-spined boring type and small mollusks (*Drupa*). Near the surge channels the surface is made up of pavement-type *Lithothamnion* that has a pink color and appears alive but elsewhere the surface of the ridge is pitted and appears to be eroded.

Surge channels and potholelike depressions are floored with sand and well-rounded coral pebbles and boulders, but none of the larger pieces are moved by heavy waves even at low tide; the water at such times appears fairly clear. The smooth walls of the surge channels are made of tan to pinkish algae and bear numerous scratches that apparently are the tooth marks left by the large numbers of fish. Colonies of living corals are rare.

2. Coral zone. A rough rock flat with a relief of a foot or more. Living corals, chiefly *Acropora* and *Pocillopora* are very numerous near the ends of the surge channels but over the zone as a whole they probably do not

cover more than 15 percent of the surface. Areas between the corals are veneered with pink algae much of which appears to be alive.

Near the landward edge of the zone are scattered remnants of an older algal limestone that rise from 6 inches to a foot above low-tide level. The rock is not as sharply pitted as were the similar remnants seen at Bikini.

3. Rock flat. A barren surface with many pools in pits and irregular depressions. Surface rough near seaward edge becoming smoother lagoonward with thin patches of sand. Some of rock areas show the outlines of coral colonies that appear to have been truncated by erosion.

4. Beach. Fine ripple-marked sand at the edge of the flat, coarser at higher levels with largest worn coral heads exceeding a foot in diameter.

11.—TRAVERSE ACROSS REEF FROM SEA TO LAGOON MIDWAY BETWEEN ENGEBI AND MUJINKARIKKU (MUZINBAARIKKU) ISLANDS

	Width (feet)	*Cumulative width (feet)*
1. Marginal zone	30+	30+
2. Outer coral zone	140	170
3. Rock flat	65	235
4. Sand flat	100	335
5. Inner coral zone	495	830
6. Boulder zone	140	970

1. Marginal zone. Poorly exposed at time of visit. Central area raised a few inches above the adjoining flats with a gentle slope to sea. Zone composed almost entirely of *Lithothamnion* but drab in appearance with about 25 percent of the surface dead. Surge channels shorter and broader than those seen northwest of Engebi (traverse 9), their algal rims less well developed.

2. Outer coral zone. Colonies of *Acropora*, some veneering films, others with short stubby branches, completely cover the surface around the inner ends of the surge channels but the colonies become progressively smaller and more scattered lagoonward and near the inner edge of the zone cover only 5 percent of the surface. The largest coral colonies are subcircular veneers as much as 9 feet in diameter. Zone covered by 4 to 6 inches of water at time of low tide.

3. Rock flat. Has shallow potholes measuring as much as 1 foot in diameter. Colonies of living coral small and widely scattered.

4. Sand flat. A rock surface thinly veneered with sand and small amounts of coarser debris. Potholes more numerous than on the rock flat, most of them being partly filled with sand. Holothurians abundant, especially in the lagoonward part.

5. Inner coral zone. Similar to last but with scattered heads of *Favia*, *Porites* and other corals. Large numbers of long-spined sea urchins in seaward part of zone.

6. Boulder zone (with sand). A barren area covered by several inches of water at low tide.

12.—TRAVERSE FROM POINT ON REEF S. 30° W. ACROSS CENTRAL GROIN TO RUJIYORU (RUJORU) ISLAND

This is a windward sea reef, and the reef flat is characterized by the extensive development of lines of groins or rock bars transverse to the reef edge. The reef may be divided into the following zones:

	Width (feet)	*Cumulative width (feet)*
1. Marginal zone	50	50
2. Submarginal zone	30	80
3. Algal pavement	66	146
4. Reef flat	444	590
5. Rock bar or groin	1, 300	1, 890
6. Channel	60	1, 950
7. Sand beach (not measured).		

1. Marginal zone. The reef front slopes gently seaward with no buttresses apparent. The zone is composed of about 15 percent encrusting corals and 85 percent *Lithothamnion*. There are surge channels in the form of widely spaced cracks 1 to 4 feet wide and 1 to 5 feet deep, that extend 50 feet or more beyond the ridge crest (submarginal zone). They may broaden and deepen somewhat seaward, but this was not observed because of the surf.

The channel walls are straight sided and smooth composed of living *Lithothamnion* with 25 to 50 percent coral growth. The floor is eroded algal limestone, its surface wavy and bare except for sparse gravel and boulder nodules in shallow potholes. The inner ends of the channels, where they are merely cracks 1 foot across, are filled with boulders, and coral and algal growth appears to be sealing the cracks and cementing the boulders.

2. Submarginal zone. The crest of the *Lithothamnion* ridge is gently rounded and lies a foot or more above low water. This zone is composed of 50 to 75 percent of corals, and 50 percent or less *Lithothamnion*. *Millepora* and *Acropora* are most common; some *Pocillopora* is present; the *Lithothamnion* is all the flat encrusting type.

3. Algal pavement. A flat pavement of *Lithothamnion* mostly yellow and dying or dead, under 1 foot of water. Colonies of *Favia* are numerous but scattered.

4. Reef flat. A barren flat of orange-yellow algal limestone veneered by a thin film of foraminiferal sand and soft algae. The flat surface, covered with 2 to 6 inches of water, is pitted with holes as much as 6 inches deep and 1 to 3 feet across; steep on the sea side and gently sloping on the shore side. Corals are rare or entirely absent except in these small pools.

The shoreward 270 feet of this zone is quite hummocky, and the last 100 feet particularly is ribbed by rounded, irregular ridges about 1 foot apart, and 2 inches high. The larger hummocks are 2 to 3 inches out of water at low tide.

5. Rock bar or groin. Approximately 150 feet of the outer part of the rock bar is a lithified conglomerate, truncated by erosion and solution to a rough platform about 3 inches above low-water level on the reef flat. To landward the base of the bar is lithified and on it is piled a mass of loose boulders of coral and algal limestone that stands 1 to 2 feet above low water Farther shoreward the rubble grows finer, and the last 500 feet of the groin is a gravel and sand bar

6. Channel. The narrow channel separating the groin from the island beach is gravel-covered. The water is 1 to 1½ feet deep at low tide and in an early flood tide the current through this channel is about 2 knots.

There are several other groins along the length of Rujiyoru, all elongate at right angles to the reef trend, separated from each other by channels narrower than the groins, and separated from the island by narrow channels.

The groin examined (pl. 30, fig. 1) was 1,300 feet long and 200 to 400 feet wide, and was separated from groins on either side by channels 100 to 200 feet wide and from the island by a channel 60 feet wide. The channels between groins, 1 to 3 feet deep, were floored by rock on the outer part, and by boulders and gravel on the inner part. The gravelly channel floor was largely covered by a growth of slabby *Porites*. A current of 2 to 3 knots swept shorewards at late ebb and early flood stages of the tide.

The groins may be the same width throughout, or they may flare at either the seaward or landward end. All of those examined, both on Eniwetok and on Rongelap, were being eroded on the seaward end and built up on the landward end.

13.—TRAVERSE ACROSS CHANNEL REEF N. 30 W. TO SOUTHEASTERN END OF BOGEN (JIERORU) ISLAND

Bogen island lies on an extension of the reef that has developed lagoonward along the main channel leading into Eniwetok's lagoon. Swells through the channel wash the reef, and during the low tide period when the reef was examined, a current estimated at one-half knot swept northwest along the channel edge of the reef.

The reef is divided into the following zones:

	Width (feet)	Cumulative width (feet)
1. Submarine margin	50	50
2. Marginal zone	40	90
3. Coral flat	126	216
4. Algal flat	36	252
5. Rock flat	148	400

1. Submarine margin. The reef rises from a sandy bottom in 8 to 20 feet of water, and is similar in aspect to some lagoon reefs, for example that off Namu island, Bikini Atoll. The bottom slopes gently for some little distance, and from this slope isolated coral heads rise. The reef margin itself is convex and slopes from 20° to 45°. It is composed of equal parts of *Lithothamnion* and corals. Below lowest tide level the algae are yellow in color, though apparently alive, but from low tide to the reef crest the *Lithothamnion* is all dead and covered with a slimy coating of brownish soft algae. Below lowest tide, corals make up about a third of the growing reef. Above this level, corals form about half the crest with *Pocillopora* dominant, encrusting types common: the rest is a slimy brown algal growth on what was formerly living *Lithothamnion.* The floor from which the reef rises is mainly coarse sand with some coral cobbles.

2. Marginal zone. Flat, sloping very gently shoreward; about 75 percent of the area is covered by encrusting types of corals. Branching forms, *Pocillopora* and *Acropora,* are common but form a small percentage of the reef area.

3. Coral flat. This zone, under 1½ feet of water at low tide, is covered with a prolific growth of branching corals that cover 75 percent of the surface. The corals grow on an eroded flat rock bottom, presumably algal limestone.

4. Algal flat. Actually a margin of the previous zone. Branching corals in small colonies form 25 percent of the area of this zone that is floored by eroded limestone.

5. Rock flat. Similar to the reef flat of most reefs, but because of the narrowness of this reef and presumably because of channel waves and currents, this zone is almost completely covered by cobbles and boulders of rock rising somewhat above low tide level.

The island of Muti (Japtan) on the main reef immediately north of the East Channel is bordered by a broad and prominent boulder rampart. The reef on the seaward side is narrow and when examined in 1952 appeared dead. Its blackened surface was partly covered by soft algae but the structure of the marginal zone indicated clearly that it has been a flourishing structure in the not too distant past.

RONGELAP ATOLL

Between Rongelap and Bokujarito islands on the southeast corner of Rongelap Atoll the reef trends north-south. The inter-island section is concave to the sea but bends markedly in a convex bulge at Rongelap island and becomes slightly convex at Bokujarito. Traverse 1 was measured midway between the two islands. There are striking differences between the reef off the islands and the reef between the islands. In the one-half-mile expanse of reef between the islands, as noted in traverse 1, the seaward margin is low, crested, and slopes gently seaward. There is no well developed buttress formation or true *Lithothamnion* ridge. Off both Rongelap and Bokujarito islands, however, a *Lithothamnion* ridge is high and narrow and the surge channels are large and prominent between the algal buttresses of the seaward edge. The reef flat is narrow and very barren, with no coral zone, whereas between the islands a large and prolific coral zone is present. The rich coral growth between islands is probably the result of continuous passage of waters over the reef flat except during low tides on calm days, whereas off Rongelap and Bokujarito the land forms a barrier that prevents continuous flow. Also when the surf is high the sediments of the reef and shore line are stirred up and carried about by the waters on the reef, whereas between islands clear sea water flows continuously over the reef.

1.—TRAVERSE ACROSS REEF MIDWAY BETWEEN RONGELAP AND BOKUJARITO ISLANDS

This traverse was made in conjunction with biochemical studies by Marston Sargent and T. S. Austin, and meteorological and oceanographic measurements by Charles Bates. In addition to the measured traverse, the reef front was examined by swimming at the line of traverse and at the north end of Rongelap island; the lagoon edge was examined by swimming, and the whole reef from Rongelap to Bokujarito island was inspected. This is a windward sea reef, and may be divided into the following zones:

	Width (feet)	*Cumulative width (feet)*
1. Submarine margin (not measured).		
2. Marginal zone (approximately)	50	50
3. Coral platform	540	590
4. Reef flat	540	1, 130

1. Submarine margin. A terrace 15 to 20 feet below low-tide level slopes gently seaward and apparently forms a base on which the exposed reef has developed. On this terrace long, blunt ridges or spurs extend seaward for 100 feet or more, separated by long narrow channels most of which do not reach the exposed part of the reef (see fig. 76). The ridges are 20 to 50 feet broad, are covered by a few feet of water at the exposed reef edge, and by 6 feet or more of water at their outer margin where they slope steeply to the 15- to 20-foot terrace.

The channels are 2 to 4 feet wide and from 4 to 6 feet deep at the inner ends, and 4 to 10 feet wide and 10 feet deep at the outer ends. The walls are vertical, and are covered with living *Lithothamnion* and corals. The floors are flat with rounded edges, eroded in the

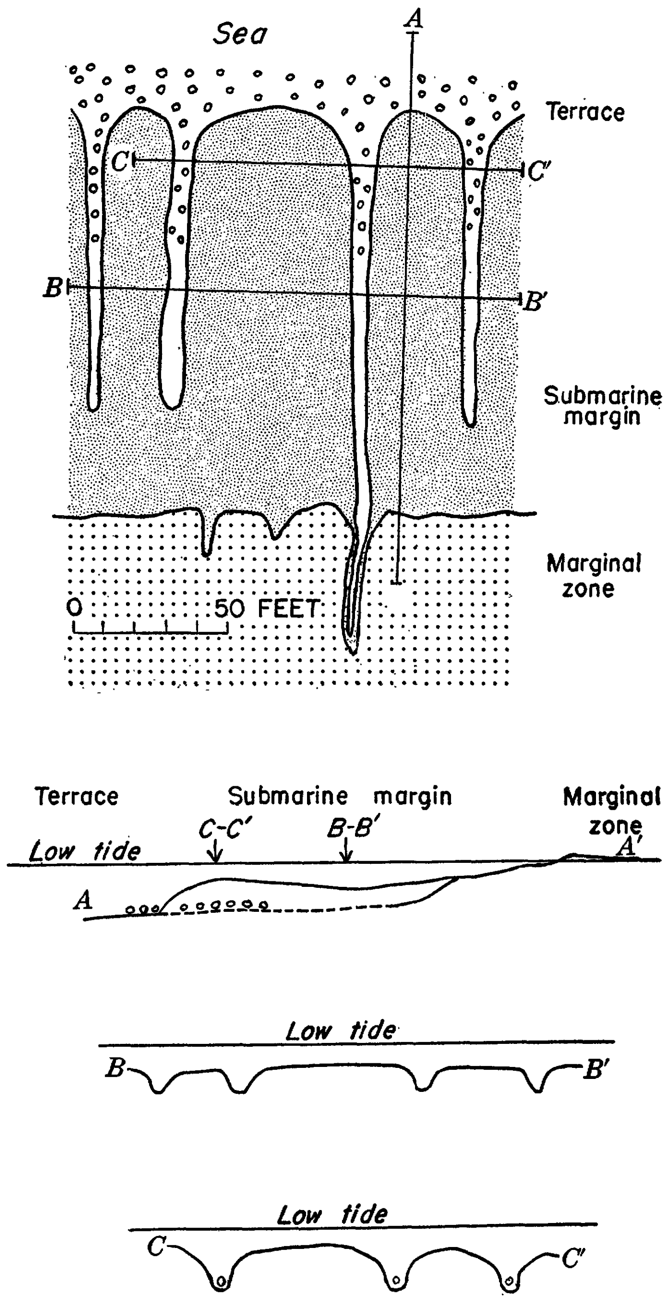

FIGURE 76.—Margin of reef between Rongelap and Bokujarito islands, Rongelap Atoll. Elongate spurs growing on a sloping submarine terrace merge into the *Lithothamnion* ridge at the reef crest (marginal zone). The broad spurs bound straight narrow grooves or channels.

bare inner part and covered with a gravel and boulder veneer on the outer part.

The terrace is almost barren of coral growth and is covered with boulders as much as 2 feet or more in diameter. The crests of the submerged ridges, from channel to channel, are a very rugose algal and coral growth, with *Lithothamnion* forming at least three-fourths of the surface. Toward the marginal zone the ridges merge and form a gentle regular surface that rises to the reef crest. Most of the channels end where the ridges merge, but some continue through the reef crest as narrow, shallow cracks.

2. Marginal zone. The front of the reef rises regularly to a level about 1½ feet above low water, but it stands no more than 6 inches above the wave troughs when the surf is moderate because of the piling up of the water on the gently sloping margin. Large globular heads of *Lithothamnion* are most common on the seaward side of the crest.

Colonies of *Pocillopora* are abundant though they cover a relatively small percentage of the area—no more than 10 or 20 percent on the line of traverse, and less in most places. Most of the channels across the crest are narrow and shallow, but some are 5 or 6 feet across and 6 to 8 feet deep on the seaward edge of the marginal zone.

3. Coral zone. On the seaward margin of this zone corals are very abundant and locally in the first 100 feet cover 75 to 100 percent of the total area. Encrusting forms dominate, and in the first 35 feet a green spongelike Alcyonarian is very common. *Lithothamnion* is poorly developed but soft velvety algae cover the rock floor where corals are absent. Station 1 of Sargent and Austin (1949) is at 86 feet from the seaward end of this traverse, or 36 feet inside the coral zone. About 3 to 7 inches of water covers this part of the reef at low tide (pl. 46, fig. 4). Beyond 95 feet branching corals dominate and occur in patches 2 to 6 feet across and 2 to 20 feet long separated by approximately equal areas of reef floor covered with tan velvety algae and encrusting foraminiferal sand. The floor is under 6 to 8 inches of water at low tide, and the patches of coral rise to low water level. The tops of the patches appear to be almost entirely composed of corals, but a careful inspection shows much dead coral rock and soft algal growth between the bases of the coral colonies. In fact, less than half of the area of many of the patches is composed of living coral, and the percentage of coral on the patches decreases lagoonward until at the inner part of this zone the living corals are more or less confined to the rims of the patches which in this area are much smaller and more widely separated. At station 2 (Sargent and Austin, 1949), 330 feet inside this zone, or 380 feet from the seaward end of the traverse, the area of the floor approximately equals the raised area of the patches, and on the platformlike patches the ratio of corals to soft algae is about 1:1, so that corals make up about 25 percent of the total floor. Branching corals outnumber encrusting types by about 3:2. At 450 feet corals are fewer though their patchy areas still equal the floor areas; at 550 feet the patches form less than 25 percent of the total and living corals are much more sparse, forming only about 10 percent of the total area.

4. Reef flat. The floor is a ribbed and slightly hummocky limestone covered with a thin veneer of Foraminifera and fine detrital sand, bound by a velvety tan algal growth. Corals are sparse, in small colonies less than 1 foot across, and occupy only about 1 percent of the area on the seaward quarter of the zone. Lagoonward they become very rare. The floor is covered by 3 to 4 inches of water at low tide, deepening lagoonward to about 8 inches. The lagoon edge of the reef forms a shelf or ledge, the base of which is covered by the sand and debris of the lagoon floor.

A specimen (B–75) from the edge of the lagoon margin of the reef in approximately 2 feet of water is a massive algal-foraminiferal limestone similar in appearance to coarse beach sandstone. The rock is coarse grained, unsorted, well consolidated, and consists of about equal parts of foraminiferal tests and of *Lithothamnion* grains and fragments. The exposed surface appears to be corroded by solution. It is covered with a fine mat of dried green algal filaments and by numerous small coiled worm tubes. On a sawed face, the outer 1 centimeter is seen to be riddled by a network of borings leaving a spongy rock skeleton. Many of the borings are filled with loosely packed fine detritus. The inner parts of the rock are compact and firmly consolidated.

In a thin section the rock is seen to consist of small rounded grains or pellets of *Lithothamnion,* some of which appear to be nodular growths rather than worn fragments; tests of *Calcarina spengleri, Amphistegina, Marginopora,* and small miliolids; and uncommon fragments of coral and *Halimeda.* These recognizable organic remains are in a matrix of finely granular detritus cemented by microgranular carbonate. Large intergranular pores and spaces within tests and grains are filled by acicular carbonate. The proportion of acicular carbonate appears to be greater than that in most specimens of beach rock, many grains being coated with a layer from 0.1 to 0.3 millimeter in thickness. In another thin section of the same specimen, the proportions of constituents were estimated as 30 percent large fragments of *Lithothamnion,* 10 percent coral, 5 percent *Halimeda,* 15 percent foraminiferal tests, 30 percent finely granular detritus, and 10 percent finely crystalline cement. The finely granular detritus consists of roughly equal parts of fine angular grains and microgranular brown to gray paste.

A second specimen from the top of the reef, a few feet from B–75 is similar but contains a larger percentage of coral fragments.

The lagoon floor is 3 to 6 feet deep at the reef edge and in 50 feet deepens to 10 or 15 feet. The shelving edge of the reef (see fig. 77) is undercut and large blocks, some of them 15 feet across and 2 to 4 feet thick, have been broken off and now lie on the lagoon floor. A rather sparse growth of *Porites* occurs on the shelving edge of the reef.

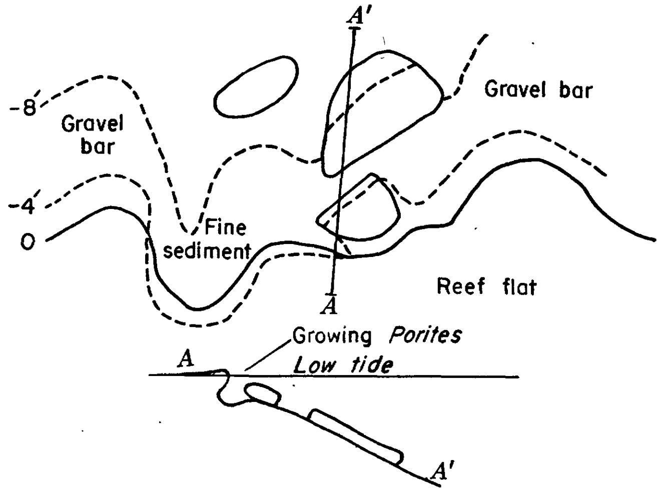

FIGURE 77.—Margin of lagoon reef between Rongelap and Bokujarito islands, Rongelap Atoll. Sketch plan and section show slabs broken from lagoon reef margin resting on sloping sand and gravel of lagoon bottom.

2.—TRAVERSE ACROSS SEAWARD REEF OFF SOUTH SIDE OF RONGELAP ISLAND

The traverse was made on a day of high surf, and it was not possible to examine the reef in detail.

	Width (feet)	*Cumulative width (feet)*
1. Marginal zone (not measured).		
2. Submarginal zone	30	30
3. Reef flat:		
a. Outer subzone	70	100
b. Inner subzone	30	130
4. Beach conglomerate (not measured).		

1. Marginal zone. A fairly well developed *Lithothamnion* ridge slopes gently seaward. The ridge is cut by deep channels 50 feet or more in length, which drain the rush of water from the reef after each wave. Large globular colonies of *Lithothamnion* are very abundant.

2. Submarginal zone. The surface is rough and pitted with basins several feet across and up to 2 feet deep. The basins are eroded. The top of the zone is covered with living pink *Lithothamnion,* smooth or nodular. Corals are abundant but do not occupy more than 20 percent of the area.

3a. Outer subzone of reef flat. Approximately 3 to 6 inches below the previous zone. A smooth hard limestone is coated with fuzzy pink algae binding a thin scum of living Foraminifera and fine-grained sand. Film is about ⅛ inch thick.

3b. Inner subzone of reef flat. Similar to the last but with many pits 3 inches to 1 foot deep and 2 to 6 feet across, usually elongated at right angles to the reef front.

Blocks of rock are common, those near shore measuring 10 feet in length and 1 to 3 feet in thickness. These may be remnants of reef conglomerate broken from the shore.

On the lagoon side of Rongelap island beach sandstones are exposed in the concave area where the trend of the island changes from south to west. A sample (B–60) was collected in a depression at about high tide level 100 feet from the lagoon beach. The beds dip gently lagoonward.

The rock is a light-brown, porous, medium-coarse beach sandstone composed mostly of foraminiferal tests of *Calcarina spengleri, Marginopora, Amphistegina* and a few miliolids, with some grains of coral, mollusk shells, *Lithothamnion* and *Halimeda.* The rock has a leached appearance and contains numerous horizontally elongate cavities 1 to 5 millimeters in size. The cavities are lined with a thin crust of yellowish carbonate. Horizontal zones or porous bands of abundant cavities and pores a few millimeters wide are separated by compact layers of approximately the same thickness (pl. 50, fig. 2).

A specimen was boiled in Meigen solution. Foraminiferal tests were unstained, but the chalky interstitial cement was deeply stained. The specimen had a very irregularly stained appearance in which the staining seemed to be proportional to the porosity of the bands, although the yellowish carbonate lining small cavities was unstained. The cement is apparently mostly aragonite, but some calcite is present.

In thin section the rock is seen to be moderately well sorted, and most grains range from 0.1 to 1 millimeter in size (pl. 50, fig. 3). The grains are closely packed, and are cemented by a coating of acicular carbonate that fills some pore spaces and lines open cavities. Many grains have cloudy, brownish areas that seem to indicate a partial disintegration from crystalline to microcrystalline carbonate. Some grains show slight recrystallization, for crystal growths of carbonate cross the boundary between the grain and the fringing coat of carbonate.

3.—TRAVERSE FROM REEF EDGE NORTH TO EAST SIDE OF THE BARE, NARROW WAIST OF TUFA ISLAND

The reef faces directly south and transverse swells from the prevailing northeast winds break over the margin at low tide (pl. 48). The submarine margin was examined by swimming.

	Width (feet)	*Cumulative width (feet)*
1. Submarine margin (not measured).		
2. Marginal zone	12	12
3. Coral pavement	36	48
4. Reef flat	126	174

1. Submarine margin. A flat, sand and debris-covered terrace 100 to 200 feet wide, 10 to 12 feet deep

at the marginal zone and increasing in depth seaward to 25 feet. The outer lip of the terrace is a luxuriantly growing reef edge that rises 10 to 15 feet or more above the terrace (see fig. 78). Beyond this outer ridge the

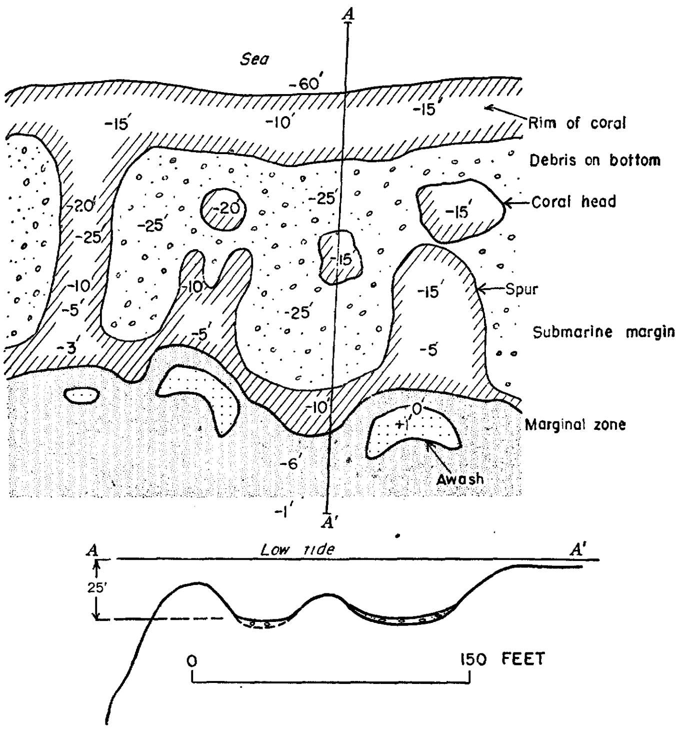

FIGURE 78.—Seaward reef off Tufa island, Rongelap Atoll. A submerged terrace fringes the exposed marginal zone of the reef. The edge of the terrace is a growing rim of coral. Depths below low tide on plan indicated by numbers.

reef plunges steeply (45° to 60° or more) to the depths. The troughlike terrace contains some scattered large coral heads, some of which may be blocks torn from the marginal zone and now entirely covered with coral growth. The wide terrace may have been formed by erosion; certainly the exposed marginal edge of the reef is being eroded to some extent.

2. Marginal zone. This zone is very irregular and rudely scalloped. Spurs extend from the arcuate areas of the reef front, 20 to 50 feet or more over the submarine terrace, while the embayments in the reef front drop off steeply to the terrace 10 feet below (see fig. 78). A few of the spurs extend out to the rim. The *Lithothamnion* ridge is very poorly developed, and only a few arcuate patches at the heads of the spurs rise above lowest tide level. These are separated by shallow, wide channels over the re-entrant parts of the reef. The submerged reef front is covered by a luxuriant coral growth, while 60 to 70 percent of the flat top of the marginal zone is covered by pale pink *Lithothamnion*, mostly of the encrusting type but with some columnar masses. *Millepora* is abundant in extensive incrustations, and small colonies of *Pocillopora* are numerous.

3. Coral pavement. Corals, especially *Acropora* and *Pocillopora* form 60 to 80 percent of the surface areas in this zone. They grow from a yellow, irregular *Lithothamnion* floor. The algae do not look healthy, but the surface is not pitted or eroded. The floor is covered by 6 inches to 1 foot of water, and the corals rise to the surface in places. Soft corals of 2 or 3 types are common.

4. Reef flat. Much as above, but the floor is eroded rock on which there are patches of *Lithothamnion* and corals up to 50 feet across. The floor is covered by 1 to 2 feet of water, and the corals are covered by 3 to 9 inches of water. The innermost part of the reef is a bare hummocky limestone flat, exposed at low tide with large tide pools.

4.—TRAVERSE ACROSS THE CHANNEL-LAGOON REEF ON THE NORTHEAST SIDE OF TUFA ISLAND

The reef faces the prevailing wind, and the choppy waves across the lagoon are 2 to 5 feet high over the reef. Walking or swimming is difficult because of the constant ebb-and-flow of water. No measured traverse was made. This reef is similar to lagoon reefs at Rigili island, Eniwetok Atoll, and Bokororyuru island, Bikini Atoll, although not nearly so large or so rich in organisms.

1. Marginal zone. Approximately 100 feet across. This zone slopes off gently from a 3 foot depth at the inner or shoreward edge to 8 feet or more at the lagoonward edge. Neither boundary is well defined and there is no marginal ridge.

The floor is an irregular, rough pavement or mosaic of dead white limestone. Sand, cobbles and boulders are lodged in cracks and cavities in the floor. Twenty-five to 40 percent of the floor is occupied by coral heads 3 to 20 feet across, separated by distances of 3 to 30 feet. The heads rise almost to low-tide level and are exposed in the troughs of waves. *Acropora* is most abundant, especially in large fanning forms some of them 10 feet long. Some large subspherical *Porites* are 3 feet or more in diameter. Algal development is poor, although a few of the heads are dominantly of yellowish pink *Lithothamnion;* the algae do not look healthy.

2. Reef flat. About 150 feet across. This zone is floored with rough white limestone covered by a few inches to more than a foot of sand and gravel, bound together by greenish soft algae in strands 2 to 3 inches long. There are some coral heads but they cover only a small part of the area. The floor is under 3 feet of water at the outer edge where it joins the marginal zone but becomes progressively shallower toward the land.

5.—TRAVERSE ACROSS SEAWARD REEF OFF THE WEST SIDE OF BUROK ISLAND

This is a lee reef completely protected from the prevailing winds, and the surf on the reef at low tide is normally negligible. Because it lies in the lee of the island, there is normally no wind current across this part of the reef but when the winds shift to the south, particularly during storms, great damage may result to the reef edge. The submarine margin was examined by swimming for a distance of 300 yards along the reef edge. The marginal zone was also examined for this distance, and the reef flat for about 200 yards.

	Width (feet)	Cumulative width (feet)
1. Submarine margin (not measured).		
2. Marginal zone	35	35
3. Reef flat	185	220
4. Beach rock (not measured).		

1. Submarine margin. Drops off steeply with a pronounced ledge at 60 to 100 feet. To the north-northwest, the reef drops off more steeply and the shelf or ledge becomes less pronounced and disappears. Where the shelf exists, the reef edge is deeply embayed by re-entrants up to 100 feet in width that extend 50 feet or more into the reef. The shelf flooring these re-entrants rises to a 20- or 30-foot depth at the inner edge (see fig. 79).

In 5 of the 7 re-entrants examined there were large blocks, 10 to 30 feet or more across, resting on the ledge. Some of these may have been coral heads growing in place, but most of the masses are angular and flat on one side. They appeared to be large sections broken from the reef at the surf zone, which have moved 10 to 50 feet down the shelf. In several places the outline of the broken segment matches jagged notches in the reef edge. The sloping floor of the shelf is covered with light-colored debris and no living growth is visible. The steep sides of the growing reef are composed of coral and algae in about equal proportions. The algae are pale pink or rose in color; many of the corals of varied colors, many of the colonies large.

Opposite the northwest tip of Burok island where no erosion was apparent, the coral growth was prolific and healthy as far down as could be seen—at least to 70 feet. The reef edge could be seen down to 100 feet or more but not distinctly.

Along the margin of the reef there were other evidences of a breaking-up of the reef edge. Large scallops or buttresses of the reef 50 feet across are completely separated from the remainder of the reef proper by a curved narrow fissure 1 foot wide or less. One such fissure, examined by swimming, was open to a depth of about 5 feet. Below that level some evidence of the crack in the reef could be seen, but it was largely healed by fresh growths of algae and corals. Another such fissure, however, widened with depth until the buttress was separated from the reef by more than 3 feet at the level of the shelf, under about 20 feet of water.

2. Marginal zone. The flat top of the reef edge is awash at low tide. Corals, including encrusting and branching forms, are very prolific and cover about 50 percent of the surface. *Pocillopora* and *Acropora* are most abundant; the rest of the surface is pink encrusting *Lithothamnion.* No surge channels are present but there are several small deep pools connected with the sea by underwater openings. The marginal zone grades laterally to the outer reef flat. The floor of the gradational zone is a very rough and irregular pink *Lithothamnion,* with abundant large coral colonies.

3. Reef flat. For a distance of 60 feet the surface of the flat is a rough tan to whitish limestone covered with a veneer of fine sand bound by soft algae. Coral colonies are abundant but make up only 20 percent of surface. There is a rich variety, *Acropora* and *Favia* being most common; pink algae are absent. For the next 35 feet (95–130 feet from reef edge) the floor is flatter and corals are less abundant though they occur in larger heads or patches. *Heliopora* is common, and *Favia* is more abundant than *Acropora.* Some *Pocillopora* occurs here, and two specimens of *Fungia* were found.

On the inner part of the reef flat (130–220 feet from the reef edge) *Porites* is most common while other genera are relatively rare. Corals form a very small proportion of the surface except at the shoreward margin where *Porites* is very abundant. Reef blocks are very common on the reef flat, especially off the northwest end of the island where several large angular blocks 15 feet long occur. The whole of the reef flat is covered by 6 inches to 2 feet of water at extreme low tide, and the coral colonies grow up to low-water level.

Along the reef flat to the northwest, the corals are more numerous and varied. Beyond the northwest tip of the island the outer reef flat becomes a distinct coral zone.

4. Beach rock. A strip of beach rock lies between the reef flat and the beach of the island. In the outer part of the zone the beds are truncated and show large shallow basins that apparently have been formed by solution.

6.—TRAVERSE (UNMEASURED) ACROSS LAGOON REEF NEAR MIDDLE OF BUROK ISLAND.

1. Marginal zone. A zone 25 to 50 feet wide where the reef floor drops from 3 or 4 feet at the inner edge to 8 feet or more at the outer edge. At the outer edge the sands of the lagoon floor cover the marginal zone.

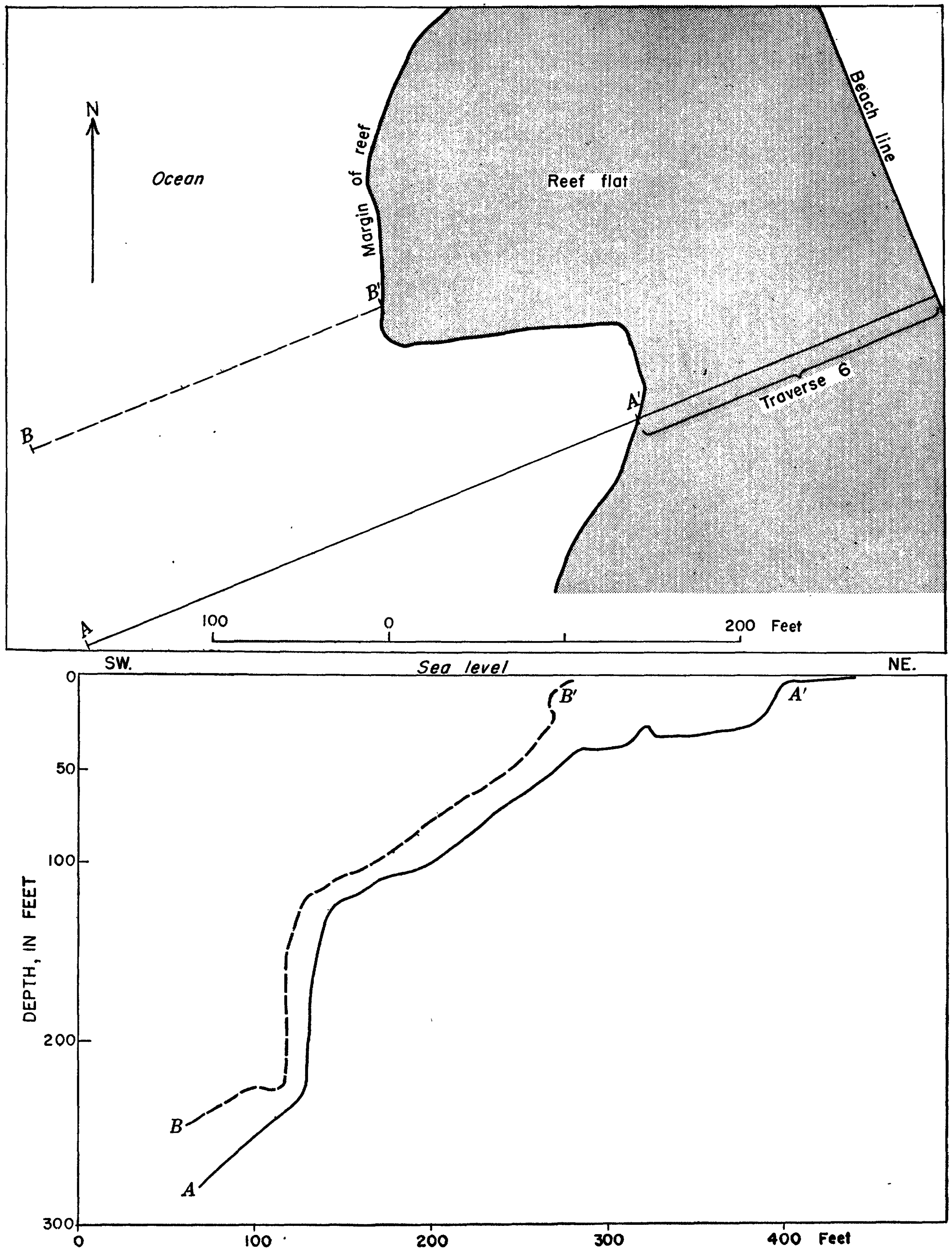

FIGURE 79.—Seaward margin of reef off Burok island, Rongelap Atoll. Eroded reentrant of reef is floored by a shelf 30–50 feet deep. Profiles *A-A'* and *B-B'* were sounded, using a lead line from a rowboat.

Heliopora colonies in great abundance, 10 to 50 feet long and 6 to 10 feet wide, grow upward nearly to low-tide level. These colonies are elongated at right angles to the edge of the reef and parallel to the prevailing wind and choppy waves across the lagoon.

2. Submarginal zone. Several hundred feet wide; colonies of *Heliopora* on a flat floor covered by 3 to 4 feet of water. The colonies are smaller and more scattered than on the marginal zone.

3. Reef flat. A broad area covered by 3 feet of water at outer edge and 1 foot of water near shore; area probably partly exposed by extremely low tides. Much of the inner part of the reef-flat floor appears to be formed in large part of coalesced *Porites* heads. Between the coral colonies there are pools about 1 foot deep, and 10 to 50 feet across. The sides of these pools are formed of *Porites*, both living and dead colonies, and the floors are covered with medium-grained ripple-marked sand. The floor of the reef flat is covered by ¼ to ½ inch of fine clastic and foraminiferal sand bound by a fine fuzzy alga. Corals are fairly numerous near the submarginal zone but are very rare near shore save for the *Porites* on the pool edges.

4. Beach rock zone. A wide belt of beach rock fringes the shore, the beds dipping conformably with present-day beach. The surface of the sandstone is polished. The rock consists mostly of tests of *Calcarina spengleri* and *Amphistegina*, with some worn fragments of corals and mollusks. It is poorly cemented, but well cemented on the white, polished surface. A sample (B–73) contains a worn piece of green glass embedded in the exposed polished surface. The glass, a broken fragment about 3 centimeters long, apparently from a Japanese fish-net float, is worn and dull on both exposed and buried sides. Under the binocular microscope the buried side of the glass appears finely etched, but the surface is clear and vitreous. The exposed side is etched or frosted and dull in appearance, and it contains minute pits or spalls possibly due to concussion of sand or gravel fragments. A thin white film cementing the glass to the sand grains looks chalky rather than crystalline or granular under the microscope.

7.—TRAVERSE (UNMEASURED) SOUTH FROM REEF EDGE TO NORTH END OF PIGANIYAROYARO ISLAND

1. Submarine margin. About 200 feet wide, examined by swimming. A flat debris-covered terrace borders the marginal zone at a depth of 15 feet. On the seaward side of this terrace, 100 feet from the marginal zone is an outer *Lithothamnion* ridge 100 feet wide. It appears to be superposed on the terrace. Its surface rises regularly from the terrace level at the inside, to within 6 feet of low-tide level at the outer edge. It is broadly crested but to seaward it appears to drop off quite steeply, although the seaward slope was not closely inspected.

This submarine *Lithothamnion* ridge is cut every 25 to 50 feet by straight canyonlike transverse channels 3 to 4 feet wide and 8 to 10 feet deep at the crest of the ridge. The vertical walls appear to be covered with living algae and corals. The flat floors of the channels are covered with debris and are at the level of the terrace. The terrace floor is veneered with gravel on the innermost 50 feet, and with boulders and slabs as much as 2 feet across in the outer zone. The channel floors are covered with cobbles. The terrace and channel floors appeared flat and at about the same depth, but presumably there was a gentle dip seaward so that the reef material could be transported over the edge, as there was only a thin veneer of debris and apparently no accumulation. (See fig. 80.)

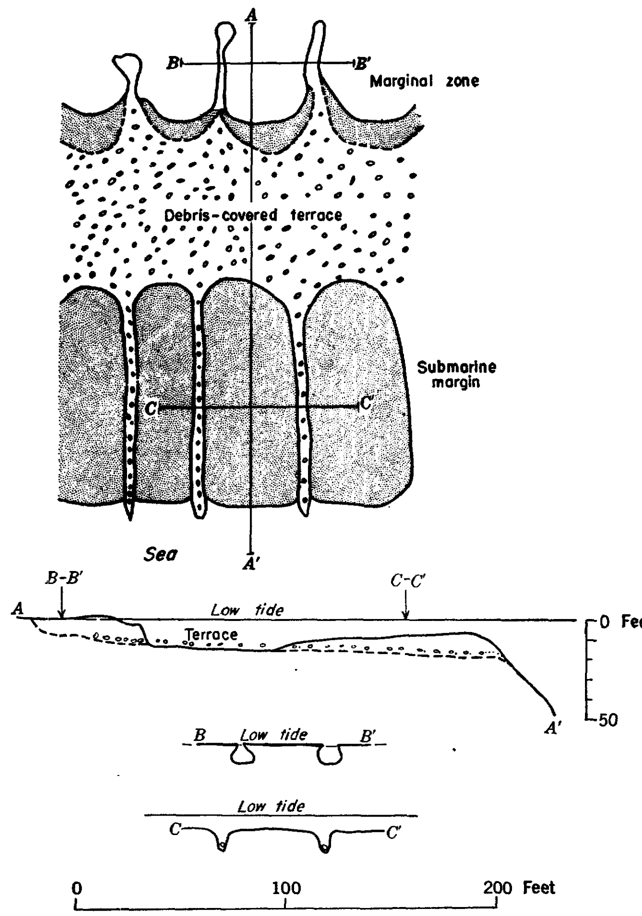

FIGURE 80.—Double *Lithothamnion* ridge, Piganiyaroyaro island, Rongelap Atoll. Algal spurs grow on debris-covered terrace about 100 feet from marginal zone of reef. Channels between spurs appear to be continuations of terrace.

2. Marginal zone. About 50 feet wide. There is a well-developed *Lithothamnion* ridge formed of very spongy algal heads. Most of the surge channels are narrow and deep, steep-walled with much shelving

at the surf zone. They are straight and regular, and extend back from the sea edge 50 to 75 feet. They suggest undeveloped blow holes, as algal growth is vigorous along the sides and particularly on the inner end where algal mounds rise a foot or more above the reef flat. The channels are only a few feet wide on the reef, although they widen below the reef to 6 feet or more and at the seaward edge of the marginal zone the mouths are 10 to 15 feet wide. Some of the channelways are aligned with those farther out on the submarine margin, but the majority seem to have no definite relationship. Corals are abundant on the flat crest of the ridge but they cover only a small percent of the surface. *Pocillopora* and *Acropora* are most common. The growth of globular colonies of *Lithothamnion* is vigorous along the channel and reef edges.

3. Submarginal zone. About 100 feet wide. A deeply pitted limestone flat that is depressed 6 inches to 1 foot below the flourishing marginal zone.

4. Reef flat. About 400 feet wide. A hummocky limestone surface with many solution basins and pits, both small and large, generally 2 to 6 inches deep. The flat is exposed at low tide and basins occupy about half the area.

8.—TRAVERSE THROUGH REEF IN "SMALL BOAT PASSAGE" BETWEEN AERIK AND YUGUI ISLANDS

The passage is about 200 to 350 feet wide and has a maximum depth of 50 or 60 feet at a point opposite the north ends of the islands on either side. Across the marginal zone of the sea reef the passage shoals to at least 30 feet and in places 10 feet, over a well-developed lip or sill formed by a coral-algal ridge. The coral growth, as seen from a small landing craft, is very prolific. Behind the sill (lagoonward) the deep channel is 50 to 60 feet deep, covered with sand and coarser debris with scattered coral heads 5 to 10 feet in diameter and of about the same height. Farther lagoonward opposite the southern tips of the channel islands the passage gradually shoals across the lagoon reef to 20 feet or less. The bottom is sand and gravel, and on this floor elongate *Heliopora* patches grow to within a few feet of low tide level. These structures are about 400 to 700 feet long, 50 to 100 feet wide, and elongated along the axis of the passage. They are separated by small channelways or barren spots about 50 feet wide.

The banks or sides of the passage were examined by a circuit of the passage in a small boat and were examined locally on the east bank by swimming. The steep banks to the deep part of the passage vary roughly in slope from 30° for minor spurs extending into the channel, to 45° or even 60°. A profuse coral growth covers the walls. Along much of the passage a terrace 10 to 50 feet wide has been formed on top of the banks, varying in depth from about 3 feet near the exposed reef to 8 feet near the steep bank. Separate small coral heads and colonies grow on this shelf.

Currents in the passage are strong, and the general flow seemed inward to the lagoon through the late-ebb and early-flood tidal stages. A spiralling of the current, downwelling on the west and upwelling on the east, results in a patch of water on the eastern side 50 to 100 feet wide and 1,000 feet long that is slick, with boils, while the western half of the channel is choppy and turbulent.

9.—TRAVERSE ACROSS SEAWARD REEF, YUGUI ISLAND

The traverse from sea reef edge was made at a point 150 yards east of small boat passage separating Yugui and Aerik islands.

The submarine margin was not examined by swimming but appears to be an algal surface sloping gently seaward for at least 100 feet. It is cut by channelways but these were not closely inspected.

	Width (feet)	Cumulative width (feet)
1. Marginal zone	50	50
2. Coral-algal zone (approx.)	200	250
3. Reef flat (extends from zone 2 to shore).		

1. Marginal zone. A gently crested belt cut by channels about 100 feet apart. Half of the surface is covered by *Lithothamnion*, the balance by corals.

2. Coral-algal zone. Pink algae, corals and a light-blue encrusting sponge are abundant, each occupying about one-third of this zone.

3. Reef flat. Coral and algal patches on a sandy bottom. The sand is a thin veneer over a hard pavement. Outer part of zone formed of large, closely packed patches with small sand areas. Shoreward the patches become more widely scattered and smaller and the sand areas increase. Reef blocks of coral and algae are abundant on the outer part of this zone. To the east they become so abundant that from a distance they resemble a rock bar stretching along the reef. Near the shore corals are present in great variety though they occupy only a small part of the area.

10.—TRAVERSE, LOMUILAL ISLAND

The sea reef, a wide flat, was not traversed. As seen from the shore, reef blocks are so profuse near the seaward edge that they appear to form a nearly continuous boulder pile; actually they probably are scattered as at Yugui.

To the west of the island a *Heliopora* zone is developed with the deepest pools about half way between the sea and the lagoon margins of the reef.

Seaward the reef flat rises nearly to low-tide level, and lagoonward it rises to a level 4 or 5 feet below low tide, but in the area of the pools the sandy floor is 20 feet or more below low tide. The "pools" are actually semicontinuous channelways in which large *Heliopora* heads are growing and coalescing. These occurrences differ from other *Heliopora* zones in that the heads are growing in 6 to 20 feet of water. The sides of the heads are generally steeply rounded, although vertical and even overhanging walls occur. Growth forms of the *Heliopora* are numerous and range from large radiating green plates, ½ inch thick, 1 to 2 feet high, several feet in length, and vertically corrugated, to long, slender spines, 1 to 2 feet long, less than an inch in diameter at the base, and growing in parallel series from radiating stalks.

The current from the reef around the end of the island is fairly strong, particularly in constricted areas between heads. Movement of the sand grains on the bottom was noted, and ripple marks are common. In some places sand is piled in the lee of the heads.

On the island's beach solution-sculptured detrital sandstone crops out at about mid-tide level. A sample (B–64, pl. 53, figs. 1, 2) was collected at the bottom of a pothole more than 2 feet in diameter. The top of the specimen formed the eroded, pitted bottom surface of the pothole. Small pits on the surface are from 5 millimeters to 2 centimeters across, and the surface is covered with a thin light-blue substance that appears to be an algal coating. The rock is a coarse well-lithified sandstone containing abundant Foraminifera (*Calcarina spengleri*, *Marginopora*, and *Amphistegina*), coral and mollusk fragments, grains or fragments of *Lithothamnion* 1 to 5 millimeters in size, and of *Halimeda*.

In thin section cavities between larger grains are seen to be filled with gray, finely detrital to microgranular paste. The grains are coated and cemented thickly by a layer of acicular carbonate. The dark-gray mud is altered to clear crystalline carbonate next to the grains (pl. 53, figs. 1, 2). In some places the clear carbonate forms a uniform zone, in others it penetrates the gray paste in tiny apophyses and veinlets, and in still other places the gray seems to be permeated with clear carbonate that appears under the microscope as minute clear areas or patches in the gray paste. The gray microgranular paste as well as brownish-gray finely detrital material is not confined to a limited zone 1 millimeter thick near the surface of the specimen, but it is found throughout, and in part it has been altered to clear carbonate that cements and coats grains. The gray paste seems to be originally deposited material rather than material deposited during precipitation or solution in the weathering of the exposed rock.

The abundance of the gray paste makes it a possibility that the sandstone was formed as a detrital reef rock. If so, the rock has now emerged more than 3 feet above low-tide level.

A specimen (B–65) from the rim of the same pothole is dark greenish brown to dark gray, rough and pitted with sharp cusps on a weathered surface (pl. 53, figs. 1, 2, 3). The pits are larger and deeper than those on the surface of specimen B–64, and the cusps are longer and sharper, some of them more than a centimeter in length. The standstone is coarse-grained, although finer than specimen B–64, hard, and cavities are filled by carbonate.

In thin section it appears to be a typical medium-coarse beach sandstone composed principally of Foraminifera but with abundant grains of *Lithothamnion* and coral, cemented by a well-developed coat of acicular aragonite that fills some of the intergranular spaces to form a compact rock (Pl. 52, fig. 3). No gray microgranular paste was noticed. The grain borders are dark, probably because of microgranular calcite at the boundary between the grain and the acicular aragonite. There is a possibility that this rock is a true beach sandstone overlying detrital reef rock represented by specimen B–64. Another more likely possibility is that the open texture in B–65 results from the position of the rock near the top of the large solution pit, whereas the pasty matrix in specimen B–64 results from its location at the bottom of the pit.

11.—TRAVERSE (GENERAL DESCRIPTION) OF REEF BETWEEN LABAREDJ, AIJIKAN, AND BOKOEN ISLANDS

The surf was extremely high when the reef was examined. It was not possible to inspect the marginal zone, and currents and depth of the water on the reef were such that not much could be observed on the reef flat. However the half-mile of open reef between Aijikan and Bokoen Islands was covered and the large groins north of Bokoen were carefully examined.

The high surf piled water upon the narrow reef fringing the island. At approximately 10-minute intervals a series of several larger waves, some 15 feet high, struck the reef and within a few seconds the water level over the entire reef increased from 1 foot to as much as 3 feet. For several minutes the water level slowly decreased to a depth of about a foot, where it was maintained until the next large series of waves struck. Lateral currents along the island were strong and irregular, their direction depending upon the location of the highest waves. At each end of the island the current set uniformly around the end of the island to the lagoon.

Over the open reef between the islands, there was no piling up of water, but there was a marked increase in current across the reef with each large wave series. Over the more level parts of the flat where the water was about 1 foot deep the current was estimated at 2 to 3 knots, but lagoonward where the flow was somewhat constricted in shallow channels in the reef 2 to 3 feet deep the current was estimated at 5 to 6 knots and "standing waves" developed similar to those in swiftly flowing shallow streams.

The reef flat close to land was barren limestone thinly veneered with Foraminifera bound by soft algae. Pits and basins were common, though they did not seem to be as abundant as on Busch Island reef to the south.

The reef between islands was divided into three zones, excluding the marginal zones. Because of the high surf it was not possible to go within 100 yards of the reef edge. These zones are:

1. Reef flat. A barren limestone surface, about 500 feet wide, not so pitted with basins as the flat fringing the island, corals rare. The water over this zone was uniformly about 1 foot deep.

2. Zone of groins and channels. About 750 feet wide. The north half of this zone, near Aijikan island is much the same as the reef flat in the preceding zone, with but one broad shallow channel about a foot deeper than the reef level, into which the water is constricted. The south half of this zone near Bokoen island is divided into approximately equal areas of groins or rock bars and channelways, the latter about 100 feet wide. The groins were similar in all respects noted to those seen on Rujiyoru reef, Eniwetok Atoll. They consist of a seaward margin, 50 feet wide or more, of coral conglomerate truncated to low-tide level. They were under water when seen, but they lie a few inches higher than the reef flat and are probably dry at low tide on calm days. Behind this margin there is a wider zone of the same rock in various stages of erosion rising as much as a foot above the marginal zone. Lagoonward are, successively: zones of loose boulders and cobbles, 2 to 3 feet above the reef flat; gravel, and finally sand at the lagoonward end of the groin. Deposition is active on the lagoon side, erosion on the seaward edge. The channels are bare at the seaward end, and gravelly at the lagoonward end although there was very little debris when examined, because of the swift current.

In the middle of the reef flat, near the 3 large groins off Bokoen island, are 2 groins that appear to have been almost completely truncated at low tide level. Only a few cusps of conglomerate stand 6 inches to 1 foot above low-tide level, near the lagoonward end. These relict groins have very little gravel or sand on their leeward ends.

3. Zone of reef corals. Not examined but appear from air photograph to be 500 to 1000 feet wide. The inner or lagoonward margin consists of a floor apparently similar to the reef flat but sloping gently lagoonward, and covered by 2 to 4 feet of water or more. On this floor are extensive coral patches that have a rough alignment parallel to the current trend. They are 50 to 100 feet wide and 200 to 500 feet long. From the airphotos it appears that some deposition of sand occurs outside these patches but inside the reef margin.

Conclusion: A partial traverse of this reef and subsequent inspection of airphotos indicate that deposition and coral growth are developing the lagoonward margin of the reef, laterally and particularly vertically to high-tide level, whereas erosion is dominant on the seaward margin of the rock structures that are already built. This will result in (1) disappearance of present groins or their translation lagoonward, (2) migration of the islands lagoonward and widening of the seaward reefs.

12.—TRAVERSE ACROSS SEAWARD REEF ALONG LINE 100 YARDS NORTH OF SOUTH END OF BUSCH ISLAND

The reef was visited on a day of very high surf, and the marginal zone could not be closely examined.

	Width (feet)	Cumulative width (feet)
1. Marginal zone (about 50 feet).		
2. Submarginal zone (about 25 feet).		
3. Reef flat	360	360
4. Rock flat	130	490
5. Eroded beach rock (not measured).		

1. Marginal zone. A moderately well developed *Lithothamnion* ridge scalloped by deep, though not very long, surge channels that extend through the marginal zone. When examined, extremely high waves poured over the ridge onto the reef. A series of several large waves raised the water level of the whole reef flat as much as a foot for several minutes. The surge channels provided an outlet for the impounded waters, and after several large waves there was a noticeably depressed cone on the water surface, about 50 feet in radius, about each surge channel. The rush of water was so great during these periods that it was impossible to stand within 25 feet of the surge channels though the water was not more than 2 feet deep. Under such conditions the floors of the surge channels may be actively eroded.

2. Submarginal zone. This is actually the irregular margin of the reef flat where it abuts against the inner edge of the *Lithothamnion* ridge. It is a floor of limestone covered by Foraminifera and a very thin soft algal veneer that lies at low-tide level. The *Lithothamnion* ridge rises abruptly a foot or more above this level. Between surge channels this limestone floor is pitted, the pits measuring 6 to 8 inches in depth. There are also tublike basins 2 to 5 feet across and 5 to 10 feet long normal to the reef front. Some corals grow in these basins, but they are otherwise rather barren of life and those examined contained little debris. Behind this zone the reef flat extends as a limestone floor veneered with a thin layer of algae and Foraminifera. It is pitted with small and widely

spaced basins. Small depressions are particularly abundant on the reef flat in the lee of obstacles such as small boulders.

On the shoreward margin of the reef flat large basins, 2 to 8 feet wide, 10 to 20 feet long, and 6 inches to 1½ feet deep are common. Most of them have very little debris and their origin is uncertain.

RONGERIK ATOLL

At Rongerik Atoll, the reefs of three islands were examined. The locations of unmeasured traverses are shown in figure 54 and observations are summarized below.

From Bock Pass at the southwest end of Bock island, to the bend in the reef northwest of the island, the sea reef is covered by 3 to 6 feet of water or more at low tide. The floor is sandy, and abundant coral heads grow nearly to low-tide level. The seaward margin of the reef is not exposed at low tide. To the northeast the reef flat becomes shallow until at the bulge in the reef (approximately at the line of traverse) the reef flat is covered by 1 to 2 feet of water, and the marginal zone is just awash at low tide. The reef to the northeast rises from a 10- to 15-fathom terrace that extends 1000 to 2000 feet offshore (estimated from aerial photographs).

1.—TRAVERSE FROM REEF EDGE APPROXIMATELY S. 60° E. TO NORTHWEST BULGE OF BOCK ISLAND

Traverse not measured in the field but air photographs indicate that the distance from marginal zone to shore is about 1,250 feet.

1. Submarine margin. Light-blue water is visible for 50 to 100 yards off the reef edge, caused by a shallow terrace that rises to within about 20 feet of the surface at the marginal zone. The terrace is flat and gently sloping; many small coral heads grow on its surface which is partly covered with debris.

2. Marginal zone. An irregular *Lithothamnion* ridge from which exceedingly irregular algal-coral spurs extend out over the terrace. These are about 100 feet in length, 50 feet or less in breadth, and are separated by somewhat narrower channels. The floors of the channels are flat and composed of a bare white limestone from 4 to 10 or 15 feet below the reef edge. The spurs are awash at the edge of the ridge, and slope gently underwater to a depth of 4 or 5 feet at their outer ends, where they plunge sharply to the terrace floor in 20 to 30 feet of water. The sides of the spurs are steep, and both the sidewalls and the upper surface of the spurs are covered by about equal parts of algae and corals.

3. Reef flat. Covered by 1 to 2½ feet of water at lowest tide. On the rough and irregular limestone surface a large variety of coral colonies grow upward close to low-water level. They cover nearly 50 percent of the flat at its outer margin, but decrease shoreward and on the inner margin cover only 20 percent of the surface.

2.—TRAVERSE OFF LATOBACH ISLAND ON THE WINDWARD SIDE OF RONGERIK ATOLL

1. Marginal zone. This zone of the sea reef consists of a regular *Lithothamnion* ridge cut by rather short shallow channels. Offshore the reef front slopes gently a short distance seaward then plunges abruptly. On the reef opposite the island the coral development is poor, but westward beyond the island, coral areas 50 to 100 feet wide cover much of the reef. These areas lie immediately behind the *Lithothamnion* ridge. Off the island there are large patches of soft corals or spongy soft green algae.

2. Reef flat. Very level and very barren. *Porites* is common locally in solution basins and on the rocky flats but the main growth on the reef floor is a brown to green algae in small clusters resembling wet puffs of cotton batting.

On the lagoon side of Latobach a considerable growth of coral occurs along the south beach. The sandy bottom of the lagoon slopes regularly to a depth of 12 or 15 feet about 150 feet from shore. On this bottom, coalescing heads of coral grow from 1 to 5 feet below low tide level. Where examined the reef was about 100 feet wide, and formed a very irregular surface on which it was almost impossible to walk. The reef margin was examined by swimming. *Acropora* was common in numbers of colonies but the dominant coral in forming large heads was *Porites andrewsi;* large colonies of *Symphyllia* and *Platygyra* also were noted.

3.—TRAVERSE, ENIWETAK ISLAND

1. Marginal zone. Shows a very well developed *Lithothamnion* ridge with a healthy growth of *Lithothamnion* of the globular type. The reef edge is cut by channels 5 to 10 feet wide that are 8 feet deep at the crest of the ridge. Some of these become narrow and lead to blowhole mounds, others widen behind the algal ridge to pools 5 to 8 feet deep with vertical or overhanging walls covered by a rich coral growth. The channels widen and deepen off the submarine margin of the reef, and the areas between channels form submerged spurs or buttresses extending 50 feet or more over a debris-covered terrace that slopes moderately seaward. The crest of the *Lithothamnion* ridge is flat, 10 to 50 feet wide, and encrusted with pink algae and about 20 percent of coral growth. The edges of the reef and channels are formed of very luxuriantly growing rose to red *Lithothamnion.*

2. Reef flat. An irregular limestone floor veneered with fuzzy, soft tan algae binding a thin (⅛ inch maximum) layer of Foraminifera and detrital sand. On this floor coral colonies are abundant, covering as much as 50 percent of the reef surface. The boundary between marginal zone and reef flat is sharp although very irregular in trend, and the reef flat, covered by a few inches to a foot of water at low tide, lies about 2 feet below the crest of the *Lithothamnion* ridge.

DESCRIPTIONS OF ISLANDS—BIKINI ATOLL

BIKINI

Bikini island lies on a major bend or arc of the reef on the northeast corner of the atoll. It is about 2.5 miles long, 0.5 miles wide, and has a dry land area of 540 acres, excluding beaches and sandbars. The island is roughly crescent-shaped and is extended in a northwest-southeast direction, with its convex side to the sea. The reef on the seaward side is nearly 3,000 feet wide on the northeast but narrows to 300 feet off the southern end of the island. The general relations of the island to the reef and the lagoon floor are shown in figure 81.

northeast bend of the island, and a long but discontinuous strip parallels the shoreline for half a mile along the northwest end of the island. A sandbar extends northwestward from the northwest end of the island. No beach rock is exposed on the seaward side of this bar but layers of coarse sandstone occur on the lagoon side and in a deep cut through the bar—a cut that was opened overnight during the time of our visit to Bikini Atoll in 1946. In this cut layers of well-sorted beach rock are exposed dipping lagoonward at angles as much as 20°. The sands making up these beds probably were deposited on the lagoon side of the then-existing sandbar. Their present position under the middle of the bar and beneath 7 feet of loose sand and fine gravel suggests that a lagoonward migration of the bar has occurred.

At the south end of the island there is an eroded platform of conglomerate 1 or 2 feet above the level of the reef flat and 50 to 250 feet wide. The platform appears to be similar in most respects to the groins seen on nearby atolls especially on the east side of Rongelap and Eniwetok. On Bikini island the platform is nearly continuous along half a mile of shoreline and it probably underlies part of the south end of the island.

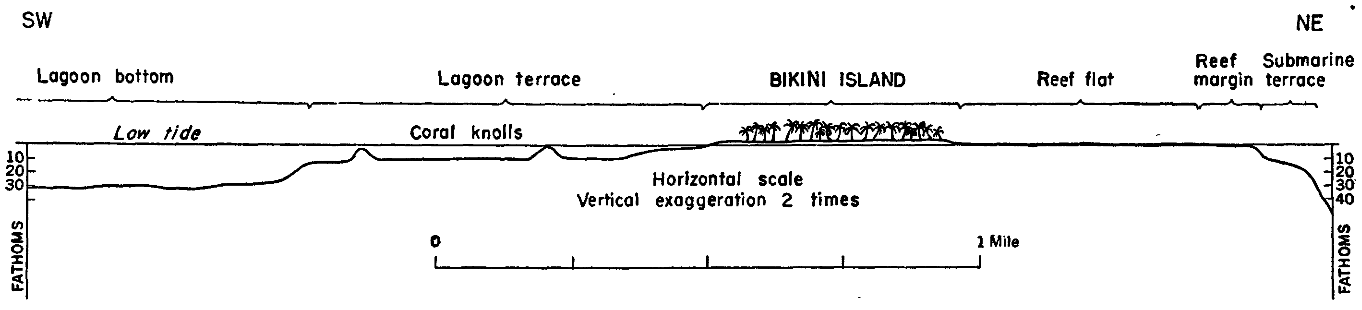

FIGURE 81.—Generalized cross section through the windward reef of Bikini island. Figure shows profile of island and reef, seaward and lagoon terraces, and lagoon bottom.

COASTS

Seaward.—A sand beach, 75 to 100 feet wide, bounds almost all the seaward coast of the island. The beach consists of well-sorted to poorly sorted coarse sand, containing scattered worn pebbles of coral and *Lithothamnion*. Locally there are concentrations of gravel, but as a whole the long shore contains less gravel than most beaches on the atoll. From the reef flat to a height of about 6 feet the beach slopes uniformly about 8° to 10°; above this the slope decreases and in places forms a nearly flat berm of fine wind-blown sand. Along most of the coast vegetation covers the beach crest 10 to 12 feet above the reef flat. Scattered dunes and mounds, generally less than 6 feet high, are inside the line of vegetation behind the beach crest. Eroded outcrops of beach sandstone are found in two localities—a small strip less than 500 feet long lines the beach at the

A part of the rock platform consists of bedded, eroded beach rock but most of it shows no trace of bedding. The beach rock beds strike south in the direction of Bokonfuaaku island and at a considerable angle to the shoreline. It is possible that the two islands were formerly connected.

Lagoon.—The lagoon beach, like the seaward beach, is mainly of sand. Small areas of broken beach rock are found in several places along the southeast half of the coast and long stretches of beach sandstone and fine conglomerate are found on the northwest half. Much of the beach sandstone consists of large slabs—some 3 to as much as 12 feet in maximum diameter—loosened by waves and piled on top of other layers still in place. Some of the blocks have a high polish.

The lower part of the beach-rock belt—near the ebb tide mark—measures about 10 feet in width and its surface is roughened by narrow ridges that appear to be remnants left by solution. The upper part of the beach rock belt is about 12 feet in width and in many places is worn into a curious pattern of furrows and pits. The pits average 3 to 4 inches in diameter and usually have a low point on the down-beach side leading into a furrow which may be short and straight or long and twisted but which leads in each case to another pit (fig. 82). The pits are 1½ to 2½ inches deep on

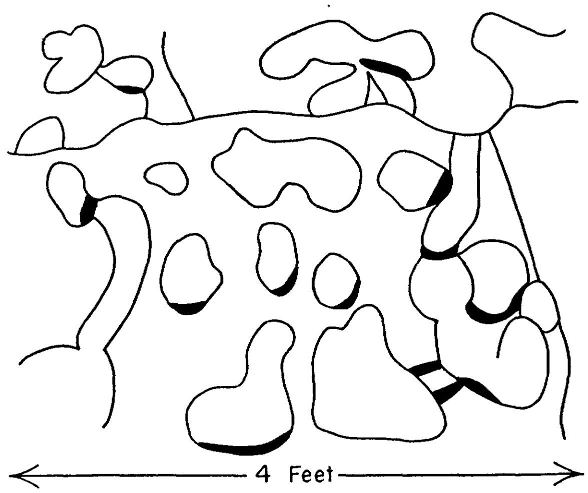

FIGURE 82.—Pits and furrows in the beach-rock belt; black areas are low parts of rims; lagoon coast, Bikini island.

the average and their bottoms are relatively flat. Irregular cracks that tend to parallel the water line extend through both parts of the beach rock belt and a second set of irregularly spaced cracks trends roughly at right angles to the first set.

ISLAND INTERIOR

The surface of the island consists almost entirely of coarse to fine calcareous sand containing scattered pebbles of coral gravel. No gravel surfaces were seen by the writers. The elevation of the general island surface ranges from about 8 feet above low-tide level to a maximum recorded elevation of 19 feet, the site of drill hole 2B, at about the center of the island and 220 feet from the lagoon beach crest. It is of course possible that some dunes on the island are higher.

A considerable part of the island, especially in the broad central part, is uniformly flat at an elevation of 12 to 15 feet. A transit-pace traverse was run along a well-marked, straight native trail that crosses the center of the island in a direction about N. 60° E. The resulting profile (fig. 83) shows the extreme flatness of much of the island. The prominent trench in the

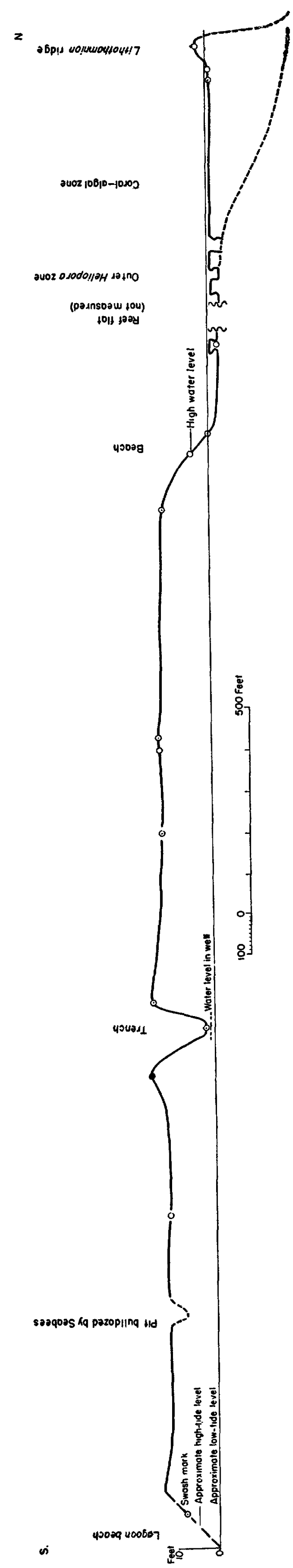

FIGURE 83.—Level-pace traverse across Bikini island. Central flat of island is 12 to 15 feet high. The *Lithothamnion* ridge of the reef margin is 3 feet higher than the reef flat (approximate mean low-tide level).

center of the island is of especial interest. It trends N. 22° W. from a point 450 feet southeast of the trail to a point about 200 feet northwest of the trail, at which point its direction changes to N. 35° W. for another 250 feet. It is 13 feet deep, and about 180 feet from crest to crest. The flattish bottom is 30 feet wide. The trench is obscured on aerial photographs, stereoscopically, because of the heavy cover of coconut palms. A shallow pit dug by natives lies a few feet south of the trail. The pit was filled with soggy vegetation, but contained a little water 1.1 feet lower than the flat bottom of the trench, or about 1 foot higher than the reef flat which is probably 1.5 feet above lowest tide level. The water in the pool smelled of hydrogen sulfide, from the decaying vegetation, and had a brackish taste, possibly due more to acidity than salinity. The trench appears to be a natural feature and may represent a former lagoonal margin of the island. The sand flats to the southwest may have accumulated in a later phase of island growth.

Pits excavated by bulldozer during preparations of Operation Crossroads showed excellent vertical sections of the island sediments. The following 5-foot section was measured on the vertical walls of one of the pits located 1000 feet south of the transit-pace traverse, and approximately 150 yards east of the lagoon beach. The pit was about about 40 feet square.

Pit section on Bikini island

[Section measured on vertical east wall, near midpoint of Bikini island about 150 yards inland from lagoon beach, on a sandy flat about 16 feet above low-tide level.]

	Depth (feet)
Grass roots and black leaf mold mixed with fine sand, grading to unit below in bottom 0.1 feet	0. 3
Dark-brown to black coarse carbonaceous sand, grading to medium-brown coarse sand, average grain size about 1 mm. Much fine carbonaceous dust included	. 6
Brown to tan dusty coarse sand, average grain size about 1 mm	1. 0
Bedded white coarse sand and gravel. The beds range in thickness from 0.05 to 0.5 feet. Sand beds consist of carbonate grains dominantly 1 mm in diameter, but range from fine angular clastic grains about 0.1 mm, to worn spherical tests of *Calcarina* 2 mm in diameter. Pebble gravel lenses are relatively well sorted. They alternate with sand beds, and in each gravel lens the grain size is progressively coarser downwards. The pebbles range from small granules 3 to 5 mm in diameter to large well-rounded coral pebbles 2 to 3 cm long. Almost all grains larger than 2 mm are well rounded, grains 2 to 0.5 mm are subangular, and grains less than 0.5 mm are angular	5. 0

The alternating sand and gravel beds of the 1- to 5-foot interval may be subdivided into smaller units. Most gravel lenses are less than 0.1 foot in thickness; thicker ones are separated by thin sand beds.

Detailed section of the 1- to 5-foot interval

[Depth measured from 1-foot level]

	Depth (feet)
Dominantly sand, with several thin granule gravel beds about 0.05 feet thick	2
Dominantly gravel beds 0.05 to 0.2 feet thick separated by thin coarse sand beds	3. 5
Foraminiferal sand consisting mostly of worn tan tests of *Calcarina* less than 1 mm in diameter	4
Dominantly gravel beds. The bottom half is a granule gravel containing some pebbles in the basal 0.1 foot, which is slightly indurated. The unit overlies coarse (2 mm) sand forming the bottom of the pit	5

A sample (B-31) from the bottom of the section above was a poorly indurated, white sandy gravel layer about 2 cm in thickness, in unconsolidated bedded gravelly sand. About half of the constituents are rounded, worn pebbles of coral and *Lithothamnion*, 0.5 to 2.0 cm in size, riddled by boring organisms. The rest are unsorted rounded sand grains containing abundant worn tests of *Calcarina spengleri* and *Marginopora* and segments of *Halimeda*.

The sample shows small pockets and pores coated or filled by a white loose mat that resembles a spider web. Under the petrographic microscope it is seen to consist of fine fibers or needles about 0.5 μ in diameter and 0.01 to 0.2 mm long. The needles are straight sided but so thin that their shape in cross section could not be determined. They effervesce in hydrochloric acid but do not dissolve in water; have a high birefringence and in most cases an inclined extinction of about 35°, but some seem positive whereas others are negative. A mat of closely packed needles under high magnification resembles the gray microgranular paste seen in some surface rocks, but probably is not the same. The weblike material is common throughout the interior of the specimen, and is not restricted to the outer surface as would be expected if it were an organic mold formed after the specimen was collected.

Bedding in the north-trending walls of the pit showed no dip, but it was not possible to correlate beds on the two vertical walls.

The thin zone of leaf mold and carbonaceous dusty sand appears to be typical of the large central-lagoonal area of the island. Along the seaward side of the island most of the white sand is free of leaf mold, although thin gray crusts of algae (Myxophyceae) bind the sand in places. The northwest end of the island is dominated on the seaward side by a dense growth of *Suriana*. Most of the eastern margin is covered by less dense *Scaevola* and *Tournefortia*. Thick woodlands of *Cordia* cover some large areas inland, with infrequent *Pisonia* trees. The central part and lagoon shores are covered mostly by coconut palms, with some *Pandanus* and areas of open grassland.

A more complete description of the vegetation on this and other islands is given by Taylor (1950, p. 28).

BOKONFUAAKU

Bokonfuaaku is an islet about 1,700 feet south of the sandbar at the southern tip of Bikini island. It is a barren flat of parallel rock ledges partly covered by sand (pl. 54) with but a minor amount of scrub vegetation. The islet is 1,200 feet long not including sandbars at the ends, 500 feet wide, and covers about 14 acres.

Seaward side.—Gray to brownish-black belt of eroded conglomerate 50 to 300 feet wide. The seaward edge merges with the barren reef flat; to landward the rock is 1 or 2 feet above the reef level and is much eroded into pits and cusps. Parts of the rock belt consist of eroded, poorly bedded sandstone, most of which dips lagoonward even on the east side of the island.

Lagoon coast.—Sand lagoon beach rising from a flat platform just below low-tide level to heights of about 8 feet. The crest is covered with *Scaevola* and other shrubs.

Island interior.—The island behind the sand beach crest is a low flat of sand and beach rock. The beach rock forms a belt of truncated beds that strike north and dip west at about 10°. They rarely protrude more than a foot higher than the sand flat. The belt of uniformly dipping beds more than 500 feet wide suggests that the island has grown lagoonward by westward migration of sand owing to the trade winds. The migrating sand forms a beach at the lagoon where it is held by lagoon swells through Enyu Channel. In this way layers of beach rock are formed on the lagoon beach, and are later uncovered by lagoonward migration of the beach.

YOMYARAN

Yomyaran, an islet even smaller than Bokonfuaaku, is only 700 feet long and 500 feet wide, and covers about 7 acres. It is similar in most respects to Bokonfuaaku, except that the scrub vegetation is thicker.

The lagoon shore is a sand beach, the seaward coast is eroded conglomerate and bedded rock that strikes for the most part north and south, and dips lagoonward. The inland flat consists of a series of eroded beach-rock beds nearly covered with sand.

ENIAIRO-ROCHIKARAI

Eniairo-Rochikarai are two green islands that form a doublet connected by sand and a beach rock flat. The smaller of them, at the north end, is Eniairo, and the larger at the south end is Rochikarai Island. When combined the two are about 3500 feet long and 700 feet wide, having a dry land area of about 40 acres. The vegetation covered area of Eniairo Island is about 2 acres in size, and that of Rochikarai, 1400 feet long by 650 feet wide, is about 18.5 acres.

Seaward coast.—The shore facing the reef is an eroded rock surface 25 to 100 feet wide, merging into the reef flat at the outer edge, and 3 or 4 feet above the flat at the inner edge where the sand cover begins. The structure of the rocky shore can be seen in several places where it is cut by inlets having nearly vertical walls. The rock consists of poorly bedded coarse sand and gravel dipping to the west (lagoonward) and overlain by a thin veneer of nearly flat coarse conglomerate. In a few places the conglomerate dips to the east (seaward), and it is therefore a consolidated layer of coarse material piled upon a previously existing shoreline cut into lagoon-dipping beach rock. This suggests that early stages of the island were formed on the reef flat (east) of the present seaward coast. The same relationship may hold for many islands, but rarely are good sections discernible in the eroded and solution-pitted rocks of the shore.

On both the north and the south ends of the island, the beach-rock beds strike north and dip toward the lagoon, at a considerable angle to the trend of the coast. They may once have extended a considerable distance north and south on the now-barren reef flat. Indeed, it is possible that the whole eastern reef of the atoll was once covered by island sediments and rocks.

Lagoon coast.—The entire coast for 3,500 feet is a broad sand beach. Beach sandstone appears in a few places at the north and south ends of the island. The beach rises from a submerged lagoonal flat that is covered by only a foot or two of water at low tide, but landings can be made in a few places even at low tide.

Island interior.—The sand and rock flat between Eniairo and Rochikarai islands is 300 to 500 feet wide and 1500 feet long. The area is low, only a few feet above the reef level and parts may be covered by highest tides. The flats are formed of beds of beach sandstone that dip about 10° E. (lagoonward). These have been truncated and sand covered, but individual beds may be traced nearly the length of the island.

The areas covered by vegetation are of windblown sand, a little higher than the open flats. Near the lagoon beach sand dunes covered by *Scaevola* and other shrubs are 10 feet or more above sea level.

IONCHEBI

Ionchebi island, a small islet 1300 feet long and 350 feet wide, covers about 7 acres. It differs from the other eastern islets in that it has no open sand and beach rock flats. Instead, the interior of the island is of sand, covered by a moderately dense low scrub growth dominantly of *Scaevola* and *Tournefortia*. The seaward coast is a wide, eroded platform probably of conglomerate; the lagoon side of the island is bordered by a sandy beach.

ENYU

Enyu, the second largest island of the atoll, is about 8,400 feet long by 1,800 feet wide, and 290 acres in area. It is the only island other than Bikini that was inhabited by natives prior to Operation Crossroads. The island is crescent shaped, concave side toward the lagoon, and elongate in a north-south direction.

Seaward coast.—A long curved sand beach faces the seaward reef and, as on Bikini island, the beach slopes uniformly at about 10°, and flattens to a moderately wide berm of wind-blown sand rising to a crest that is held stable by bushes of *Scaevola* and *Tournefortia*. Small dunes inside the beach crest are parallel to the shore line and are covered by sparse vegetation.

Beach sandstone is exposed in small areas near the center of the beach and at the north end of the island. Conglomeratic rock groins are well developed at several places near the middle of the coast, and at both north and south ends. Some extend from the shore line onto the reef as much as 500 feet, and near shore the broad eroded surfaces are 2 to 3 feet higher than the reef flat.

Lagoon coast.—Unlike the corresponding coast of Bikini island, the lagoon shore at Enyu is in most places an eroded ledge of rock exposed at low tide. Thick growths of *Halimeda* are found in pools and rock crevices near low-tide level. In back of the ledge the intertidal beach is also formed of rock. In some places it is bedded beach sandstone, furrowed and fluted by wave erosion but sloping like a former sand beach at angles of 6° to 10°; in other places the beach is a jumble of rectangular blocks of broken beach sandstone, and in still other places the beach is formed of rock so intricately sculptured by solution, that it shows little resemblance to beach sandstone. Sand is found in a zone 10 to 15 feet wide between high-tide level and the island vegetation at the beach crest.

Southern (Enyu Channel) coast.—The south end of Enyu island borders on Enyu Channel, and the coastline is distinctive. The reef fringing the coast is narrow, the margin is poorly developed. The shore around the southern end of the island is a well-developed boulder rampart 8 to 10 feet higher than the reef flat, formed of coral boulders and large cobbles that grade at either end to gravel and sand where the rampart merges with the seaward and lagoon shores. The rampart crest is 2 to 5 feet higher than the inland boulder flat back of the crest.

Island interior.—Most of the island is a sand flat 10 to 12 feet above low-tide level. Dunes rise several feet above this level along the seaward coast. The sand is white and loose, covered mostly by *Scaevola* and *Tournefortia* along the seaward edge, and it is bound in places by a thin gray algal crust. Inland, the sand is brown and dusty, and covered by leaf mold. Palm groves are thickest along the lagoon part of the island.

The southern tip of the island is a boulder, cobble, and gravel flat 5 to 8 feet above low-tide level, covered by sparse patches of vegetation. A small depression behind the boulder rampart forms a shallow pool during high-water spring tides. The pool, about 200 feet long and 30 feet wide, is bounded by two small boulder ridges that probably marked former island shore lines.

AIRUKIIJI

Airukiiji is the easternmost of the string of five islands extending west of Enyu Channel. It is 2,400 feet long, 950 feet wide, and has a dry land area of about 45 acres. A well-developed boulder rampart forms the southern seaward shore and extends around a part of the eastern shore facing Enyu Channel. The lagoon coast on the north is irregular in outline, composed of eroded beach rock; a large bay on the west end of the island has a sand beach. The interior of the island was not examined. Vegetation consists mostly of low scrub growth although a small group of palms occupies the center of the island.

AIRUKIRARU

Airukiraru lies about 500 feet west of Airukiiji island. The reef flat near both islands is rough and eroded, and is dry at low tide. Aerial photographs suggest that the two islands were formerly continuous across the flat. Airukiraru is 2,700 feet long and 650 feet wide, and has an area of about 40 acres. The seaward coast at both east and west ends is an eroded rocky flat covered above high tide level by sand and gravel. The central part of the coast is a boulder rampart but not so well developed as that of Airukiiji island.

The lagoon coast is formed of eroded beach rock on the east, and of sand on the west.

BIGIREN

Bigiren island is 1,400 feet long, 800 feet wide, and about 15 acres in area, but only a small part is covered by vegetation. The rest consists of a low eroded rock surface and barren sand and gravel flats. A sand beach, the crest of which is covered by scattered bushes, forms the lagoon coast.

REERE

Reere island is 2,400 feet long, 900 feet wide, and covers about 30 acres. The seaward coast is a broad belt of eroded rock thinly veneered with loose cobbles and boulders above mean tide level. Above high-tide level the coast consists of gravel and sand. The eroded rock is apparently reef limestone, for one large truncated *Heliopora* colony is exposed at the west end of the island, about 18 inches above the reef flat. The lagoon coast consists mostly of eroded beach sandstone, with small areas of beach sand. Inland the island is formed of gravel and boulders of coral that form low, broad ridges parallel to the seaward shore. Most of the island is covered by thickets of *Tournefortia* and *Guettarda*, and the coasts are fringed by *Scaevola* shrubs.

ENINMAN

Eninman island is the western island of the group of five small islands west of Enyu Channel. It is 3,200 feet long, 900 feet wide, and covers approximatley 50 acres. It is separated from Reere by a broad flat 100 feet wide of greatly eroded rock, gravel, and sand. A large part of the flat is covered by water at low tide. The occurrence of rock between Eninman and Reere islands suggests that they were probably connected at one time.

The seaward cost is a broad belt of low, eroded rock on the east, partly covered by boulders and gravel. The west half of the coast is a sand beach. The lagoon shore is eroded beach sandstone on the east, and a broad sand beach on the west. The interior of the island is a gravel and cobble flat on the east end, merging into a sand beach on the lagoon. A stagnant pool near the lagoon beach contains 0.5 to 1 foot of brackish water at low tide. The west half of the island is a sand flat covered by thin low shrubs, but bearing a number of coconut palms.

ENIRIK

The third largest island on the atoll, Enirik, is 7,600 feet long, 1,800 feet wide, and covers about 210 acres. The island lies on a bend in the reef. The east part of the island faces a southeast reef, the western part faces a southwest reef. The east part of the island is long and narrow, and is cut by a broad sand and gravel flat covered by water during high tides.

Seaward coast.—The shore that borders the southeast reef is a long, well developed boulder rampart that in most places is 8 feet or more above the reef flat. Many boulders are 1 to 3 feet in maximum diameter. Along the southwest coast the shore is a broad, flat belt of bedded beach rock 50 to 300 feet wide.

Lagoon side.—The east part of the island has a shoreline of eroded beach sandstone and conglomerate. The west part has a broad, uniform sand beach, but bedded beach sandstone is exposed in a few places. Over large low flat areas the sands are blackened and case-hardened. Below the crust is a greenish layer that probably is algal. The west end of the island is a long blunt sand bar built by the waves and currents that converge around the island.

A sample (B–50) of the indurated crust of a sand flat at the southeast end of the island is poorly consolidated, 1 to 2 centimeters thick, formed by the partial cementing of the loose foraminiferal grains. The constituents are dominantly *Calcarina spengleri*, some of them spiny and unworn, *Marginopora* and *Amphistegina*; fragments of mollusk shells and echinoid spines are common and fragments of *Lithothamnion* and *Halimeda* are rather rare. The sample was boiled in dilute cobalt nitrate and surfaces of all grains were deeply stained; the cementing material is, therefore, probably aragonite.

In thin section the grains that form the slide are moderately coarse with few fines present. Cementing material is almost completely absent but some grains are seen to be coated by a thin, highly birefringent, microcrystalline film. Some grains show a thin dark rind that may be a carbonaceous coating. There is very little gray, microgranular paste such as is present in most beach rock, and is abundant in reef rock. The gray crust may be algal though no positive evidence of this was seen.

Island interior.—The south side of the island for some distance from the boulder rampart is a flat of cobbles and boulders of weathered coral. Most of the island interior, especially the western part, is a sand flat partly covered with abundant leaf mold.

Over large areas the sands are fine with few Foraminifera and are probably windblown in large part. Coconut palms are abundant in the central part of the island. Low sand dunes, covered by vegetation, form a narrow belt paralleling the west part of the lagoon shore.

RUKOJI

Rukoji island is located at the southeast end of a small reef segment bounded by Rukoji Pass on the southeast and Chieerete Pass on the northwest. Rukoji island covering about 40 acres is about 2,100 feet long in a north-south direction, and 1,000 feet wide. With the exception of a sand beach at the western side of the island, the whole coastline is marked by a boulder rampart that is best developed at the southeast end.

The coast of the island is in most places formed of three components: a smoothly truncated rock platform 50 to 100 feet wide, dry at low tide, containing many pools and pits 2 to 6 inches deep; a rough, eroded belt of limestone conglomerate, from low tide nearly to high tide level; and a well developed boulder rampart the crest of which is about 10 feet above the reef flat.

The smoothly beveled rock flat, merging with the reef flat, may represent either an old truncated reef, or a smoothly eroded extension of the conglomerate belt.

The conglomerate is formed of coral boulders solidly cemented in compact detrital limestone. The lower part of the conglomerate, between reef level and approximate mid-tide level, has a rough, deeply pitted surface. Pits left by the removal of boulders have been enlarged, apparently by solution, and some have partially coalesced resulting in sharp cusps. The upper part of the conglomerate from mid-tide nearly to high-tide level is smoothly worn. Boulders and cobbles are firmly cemented but they are rounded by erosion and stand out from the matrix. The overlying boulder rampart is formed of loose cobbles and boulders of rounded coral, many of them 1 to 3 feet in diameter. The lower slope of the rampart averages about 20°, the upper part is steeper in places where it has been eroded by storm waves.

Along the east coast facing Rukoji Pass the shoreward part of the beach rock belt is cut by a series of furrows each measuring 1½ feet across. The furrows cross the belt at right angles to the waterline and at irregular intervals potholelike expansions are developed. The lower part of the beach rock belt is conspicuously pitted.

Most of the island interior is a flat formed of gravel or weathered gray coral-head boulders. Along the south and east sides the island surface is formed of large rounded cobbles and boulders These decrease in size to the west and north, and the southwest part of the island is mainly formed of pebbles and gravel, whereas the northwest end is formed of sand. On the southeast end of the island a secondary ridge of boulders was observed about 100 feet inside the crest of the boulder rampart and parallel to it.

Near shore the island vegetation consists mostly of *Scaevola* and other beach shrubs. The island interior is dominantly open *Pisonia* forest. From the sea, the silhouette of the tree tops is rounded and symmetrical, rather like a drumlin. The crest of the tree tops is nearer the windward shore than the center of the island and the resultant curve is rather like the airfoil surface of an airplane wing. The shape is ideally suited to protect the brittle branches of the *Pisonia* trees from the strong trades, and some of the highest trees measure 70 feet.

CHIEERETE

Chieerete lies on the northwest end of the reef segment, one-quarter of a mile west of Rukoji island. It is 1,600 feet long and 1,000 feet wide, covering about 30 acres. The south coast of the island facing the ocean is a broad belt of eroded beach rock. Some beds are of coarse foraminiferal sand, whereas others are of conglomerate containing boulders as much as 2 feet in diameter. Some parts of the coast are broad belts of much-eroded rock, but in other parts the surface slopes smoothly about 10° controlled by the bedding planes. The beach rock is broken by rectangular joints that parallel both dip and strike of the beds. In many places the rock has been broken into large blocks, and the cracks between have been filled by detritus and sand that is now firmly consolidated. Between 500 and 1,000 feet inland from the south coast there are scattered coral boulders measuring as much as 3 or 4 feet in diameter.

The north coast consists of well-bedded but eroded beach rock on the west, and of loose sand forming a broad sloping beach on the east. The east end of the north coast is a spit built into the direction of the prevailing wind. Just south of this spit, at the east end of the south coast, is an older spit of beach sandstone, now truncated. The seemingly anomalous position and direction of the sand spit probably results from convergence of currents and waves in the lee of Rukoji island. No well defined boulder rampart is present on the island, although a veneer of cobbles and boulders covers parts of the eroded beach rock belt above high tide level. The interior of Chieerete is a flat that is formed mostly of sand on the east, of gravel and cobbles in the center, and of boulders in the west. The central part of the island is dominantly open *Pisonia* forest, the peripheral part is covered by low tangled beach shrubs. Inland from the west coast is a low, indistinct scarp trending northeast parallel to the shore, formed of massive blocks of conglomerate. The crest of the scarp was estimated to be about 12 feet above high-tide level. Large coral boulders are present also, the largest being a massive colony 4 feet in diameter. A sample of the limestone from one of the blocks in the scarp (B–9) is a compact and consolidated coarsely granular sandstone, composed of fragments of coral, *Lithothamnion*, and foraminifers in a matrix of porcelaneous limy paste. The surface of the rock is sharply pitted and has prominent small solution cusps. The weathered surface is dark gray to brown; the brownish surface is matted with small carbonaceous fibers and organic material.

In thin section the rock is seen to be composed of 5 percent *Calcarina spengleri*, 10 percent *Marginopora*, 10 percent *Lithothamnion* nodules, 25 percent *Halimeda*, 10 percent mollusk shells and fragments, and about 40 percent finely granular to microgranular brown paste. A few coral fragments and encrusting *Carpenteria* are present. *Halimeda* segments are light to dark brown with black, carbonaceous-appearing patches. Pores are solidly filled with finely crystalline carbonate some of which is acicular. There appears to be a moderate amount of finely recrystallized carbonate throughout the brown and black material of the *Halimeda*, and small cracks are filled with clear carbonate. Borders of the *Halimeda* are ragged and in places are obscure under high magnification. Sections of *Marginopora* are similar to those of *Halimeda*, but the brown material is light in color and is more nearly isotropic under crossed nicols. Some mollusk and coral fragments have ragged, dark-brown patches along their borders, as if some disintegration has taken place. The brown paste seems to be very finely granular under high magnification but the grains are diffuse and have no clear boundaries. The paste is permeated with microgranular clear carbonate, and some spherulites are present (pl. 58, fig. 1). One piece of the rock was boiled in dilute cobalt nitrate. Coral and mollusk fragments were stained, but the interstitial paste appeared stained only slightly to the naked eye, and under the binocular microscope it appeared to be unstained. Grains of *Lithothamnion* and foraminifers were unstained, but some of them were coated with a deeply stained thin crust. Some of the cement, therefore, is aragonite although much of the paste is apparently calcite. The deeply stained coating around grains indicates that some of the late finely crystalline carbonate is aragonite. The amount of interstitial paste and the texture of the rock seems to be more closely related to detrital reef limestone than to beach rock.

ARRIIKAN

Arriikan is the smallest islet of the atoll that has a cover of vegetation. It is only 600 feet long and 250 feet wide, with an area of about 2 acres. The part covered by vegetation trends roughly north and south: at the north end a sandbar extends both to the east and the west, forming a T. A boulder rampart extends along at least a part of the south half of the island, and an eroded platform of rock surrounds the rampart and merges with the reef flat. No landing was made on this island by the writers.

Arriikan island lies at the southeast end of a small segment of reef, next to Arriikan Pass. At the northwest end of the reef segment, by Ourukaen Pass, is a small sandbar measuring 150 feet by 200 feet, surrounded by a narrow belt of eroded rock. At high tide this bar is nearly awash. It appears to be a remnant of a former islet now nearly destroyed.

OURUKAEN

Ourukaen island lies on a small segment of reef bounded on the southeast by Ourukaen Pass, and on the northwest by Bokoaetokutoku Pass. The island is 1,100 feet long, 500 feet wide, and it covers about 12 acres.

Windward coast.—The windward shoreline forms a broad curve facing southeast. The north end faces east toward the lagoon, the south end faces south toward the sea, and the central part faces southeast toward Ourukaen Pass. The north and southwest ends of the coast are formed of well bedded beach sandstone and conglomerate dipping conformably to the coastline. The central part of the coast is formed by a massive and well-developed boulder rampart that extends both north and south above the beach rock. The rampart normally dips about 15° to 18° to the reef, and locally the dip is 25° (pl. 55, fig. 1). The crest is 8 to 10 feet above the narrow reef flat. The rampart is low but broad where it overlies beach sandstone, and near the north and southwest ends of the eastern coast a belt of sand overlies the boulders.

Leeward coast.—A sand beach forms most of the north-facing coast along Bokoaetokutoku Pass. Beds of beach sandstone are exposed in a few places, and large blocks of sandstone are scattered over much of the coast. The crest of the beach is a sand dune at the east end of the coast; the dune increases in height to nearly 10 feet above high-tide level at the west end of the coast.

Western spit.—The west end of the island is a broad tongue of sand formed by convergence of waves and currents around the island. The flat top of the spit is 5 to 7 feet above low-tide level, nearly 200 feet wide. Around the flat is a broad sand beach, 40 to 50 feet wide, that dips uniformly 10°. The sand spit or tongue apparently grows during winter and spring, for it can be measured in the aerial photographs flown in February 1946; it was found to be even larger when visited by Ladd and Tracey in May 1946. The island was revisited in August 1946 and August 1947, and on both these occasions the spit, as such, was destroyed and a broad belt of beach rock was exposed. The beach rock was well bedded and dipped radially, conformable to the former spit. Much sand had been stripped from the sand flat, exposing nearly flat bedded beach sandstone. Blocks of the beach rock had been quarried by the waves, and white scars left by blocks recently removed were conspicuous. The spit, adapted to prevailing northeast trades, is unstable under the variable southerly winds of the summer months. In this example of a spit periodically stripped of sand, it is noteworthy that only the broad tip of the spit was affected. The wide sand berm 100 feet back of the beach was untouched, and the western (leeward) side of the spit was still a broad sandy beach.

Island interior. Boulders form most of the surface near the east and south coast and through the central part of the island. A sample (B–316) from a sandstone block several feet square is a medium brown (tan on a fresh fracture) and has a dark brown organic crust in some patches. It is moderately cemented and porous

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and is formed of rounded, polished grains and fragments of mollusks, tests of *Calcarina spengleri* and *Marginopora*. Intergranular spaces and pores are coated with a thin brown material. Cement is aragonite, determined by staining tests with Meigen solution.

In a thin section the rock is seen to consist of coarse unsorted grains of coral, *Lithothamnion*, *Halimeda*, *Calcarina spengleri*, and broken but rounded shells of mollusks cemented by a thick well-developed rind of clear acicular aragonite that coats each grain. Individual crystals are mostly less than 0.2 millimeter in length. All organic grains have a yellow-brown stained color that seems to be carbonaceous.

Much of the interior supports an open *Pisonia* forest. Large colonies of sea birds nest in these trees and the soil is a brown mixture of leaf mold, bird droppings, and bits of rotting wood with sand and pitted coral. The layer measures from 1 to 6 inches or more in thickness. The north and west tips of the island are sand flats covered by scrub vegetation. The southwest limit of the *Pisonia* forest is approximately the boundary between the boulder flat and the western sand flat. The edge of the boulder flat here forms a low rise about 3 feet above the sand flat.

BOKOAETOKUTOKU

Bokoaetokutoku island lies on the west side of a small segment of reef between Bokoaetokutoku Pass and Bokororyuru Pass. It is 700 feet long, 400 feet wide, and covers about 5 acres. Most of the coastline is a broad sand beach. Bedded beach sandstone, more or less conformable to the sand beach, is exposed at intervals at mid-tide level. In places there are scattered broken blocks of sandstone 2 to 5 feet long. At the north end of the island such blocks form a massive rampart. The west end of the island is a sandspit comparable to that on Ourukaen island. The south part of the island interior is a sand and gravel flat with scattered low scrub growth. The north section is partly a boulder flat and is covered by a *Pisonia* forest.

BOKORORYURU

The southwesternmost island of the atoll, lying on the southeast tip of the long western reef, Bokororyuru is 1,000 feet long, 300 feet wide, nearly rectangular in outline, and covers almost 7 acres. A boulder rampart forms most of the north and the entire east coast. The south coast is a wide flat of eroded conglomerate 3 to 4 feet above the reef. Near the shore the surface of the flat is poorly bedded, and at the vegetation line it is covered by a few feet of gravel and sand.

The surface of the conglomerate flat is dark gray, pitted, cuspate, and indurated. In a sample (B–69) the constituents are approximately 50 percent broken fragments of coral, 20 percent segments of *Halimeda*, 10 percent tests of Foraminifera, mostly *Marginopora* and *Amphistegina* with a few *Calcarina*, and 20 percent fine-grained material, mollusk fragments, and indeterminate grains. On a fresh fracture of the specimen, possibly along a previous fracture, grains are coated with a thin white carbonate "frost."

Coral constitutes 75 percent of a thin section cut from the sample. The cellular structure of the coral is unaltered but some pores are lined with acicular crystals that seem to be continuous with the orientation of aragonite within the coral. Some pores are filled with these crystals, but others are filled with a brown finely granular to microgranular paste. A few globigerinids are present in the paste. The fibrous calcite of these thin-walled tests is partly broken down. Where the globigerinids are filled with brown paste, the wall margins are indistinct and the walls seem to be disintegrating. Some cavities in the section are filled partly by finely granular or detrital paste and partly by microgranular paste. Boundaries between the two kinds of paste are obscure, and it is possible that the granular is altering to microgranular paste. The relations are similar to some seen in thin sections of cores.

The north part of the west coast is a broad gravel flat exposed at low tide. A small sand beach is located at the center of the west coast, an area protected from waves and currents.

The island interior is almost entirely a cobble and boulder flat 2 to 3 feet lower than the top of the boulder rampart. Several depressions in the boulder flat are filled with water during spring high tides. The boulder flat merges into a coarse gravel flat to the west and south.

The island was revisited in August, 1946, at which time a Naval Construction Battalion detachment was at work there. During the course of their work, the writers logged 2 jackhammer holes through the conglomerate at the south end of the island and inspected a 6-foot trench opened by bulldozer on the south edge of the island interior. The first drill hole was located near the middle of the conglomerate platform, 4 feet higher than the reef. The jackhammer penetrated 5.3 feet of hard limestone conglomerate and ended in loose material at 5.7 feet. The break from hard to unconsolidated material was sharp. The hole was stopped in the unconsolidated material. A second hole was drilled in the beach conglomerate nearly in the middle of the western shore, 3 feet below the upper edge of the beach rock belt. The crust of the beach rock was indurated, but below the surface layer the drill penetrated 0.75 feet of poorly consolidated rock and the hole ended in loose material.

The trench dug by bulldozer was about 50 feet long, and 6 feet deep at the deepest part. The island surface, measured by hand level, was 6 feet higher than the reef flat. A few inches of water filled the bottom of the pit near mid-tide when 1.5 feet of water covered the reef 75 feet away. The vertical sidewalls of the pit showed several layers of sand, gravel, and cobbles, and two distinct layers of roots and brown carbonaceous sand that appear to mark former island surfaces. The upper zone is a brown sand 3 inches thick, covered by about 6 inches of fine surface gravel on which the present island vegetation grows. The lower zone is in the middle of the exposed section, 3 feet below the surface. Numerous roots are preserved in this zone, and are covered by a bed of cobbles and coarse gravel more than a foot thick. Possibly the surface of an earlier island was submerged by hurricane waves that deposited the coarse overlying material. The roots in the lower carbonaceous zone are rotted, but the material cannot have been buried for any considerable time.

BOKOBYAADAA

Bokobyaadaa island is the westernmost on the northern reef. It was not visited by the writers, and the following remarks are based on an examination of aerial photographs.

The island is about 1,600 feet long, 900 feet wide, and covers approximately 27 acres. The northwestern seaward coast, 2,500 feet from the seaward margin of the reef, is a convex shoreline formed mostly of eroded bedded beach rock, covered by sand between high-tide level and the vegetation line at the beach crest. The long straight lagoon coast extends beyond the island limits both southwest and northeast toward nearby Bokonejien. The lagoon shore appears to be a straight sand beach nearly 100 feet wide.

The interior of the island shows sparse low scrub vegetation. On the aerial photographs there are prominent narrow lines that are barren of vegetation. The lines are 25 to 75 feet apart and occur over most of the island. They parallel the edge of the lagoon beach and are recurved, parallel to the west coast, at their southwest ends. They probably represent former beach ridges similar to those described on the east end of Namu island. The interior flat of Bokobyaadaa island is therefore probably formed of sand and gravel. The structure of the ridges, paralleling the lagoon (southeast) coast and the west side of the island suggests that the island grew by accretion of beach material on the lagoon shore.

BOKONEJIEN

Bokonejien lies 2,000 feet northeast of Bokobyaadaa island, is 800 feet long and 400 feet wide, and covers about 7 acres. The lagoon coast is a broad sand beach that extends as a spit more than 500 feet beyond the island, both toward Namu to the northeast, and toward Bokobyaadaa to the southwest. The rest of the coastline, facing the reef flat in the east, north, and west, is a narrow sand beach in places overlying a bedded, eroded belt of beach rock. Northwest of the island and tangent to the northwest beach, is an elliptical belt of eroded, bedded beach rock. The belt is 25 to 100 feet wide; the ellipse formed by the belt is 600 feet long trending N. 45° E., and 250 feet wide. It is evidently the site of a former island, possibly distinct from Bokonejien but more probably a part of it. As Bokonejien was not visited, the composition of the inland surface is not known. The scrub vegetation, sparse over most of the island but thick in the center, suggests that the interior is a flat of sand or sand and gravel.

NAMU

Namu island is the largest of the northern islands. It is roughly triangular in shape, about 5,000 feet long and 2,000 feet wide, and covers about 144 acres.

Seaward coast.—The seaward coast, along both the long north shore and the recurved east shore, consists predominantly of bedded beach sandstone and bedded conglomerate, overlain above high tide level by sand. The west part of the north shore line and the south part of the east shore line are sand beaches. The belt of beach rock along most of the coast does not conform to the present beach line. In most places, and especially along the rounded northeast end of the island, the beds strike at right angles to the shore, and succeeding series dip in opposite directions. The strike of some beds forms an open S-curve. Near the middle of the east shore the beds strike parallel to the coast but dip landward. These irregularities strongly suggest that in earlier times the area of the island was greater than at present.

Lagoon coast.—The long, gently recurved lagoon shore consists along most of its length of well-bedded uneroded layers of beach sandstone dipping 10° toward the lagoon. The lower edge of the sandstone belt rests on the gravels that veneer the lagoon reef flat and the contact is exposed at extreme low tides. The upper edge of the sandstone belt lies about 4 feet above the lagoon reef flat. The rocks have a few irregular cracks but show no systematic jointing parallel to dip or strike. Above the sandstone loose sands slope to the beach crest. This sandstone belt on the lagoon shore of Namu is the longest one seen in any of the atolls visited.

Island interior.—The flat inland surface of Namu is formed of sand or gravelly sand along the west part of the lagoon side of the island. The east part is a broad gravel flat, containing low gravel ridges a few inches to a few feet high and 10 to 25 feet or more apart. Small palm groves are found on the west side, but the eastern flat is barren except for scattered low bushes. The low ridges are parallel to the lagoon shoreline in a belt at least 250 feet wide. Similar ridges may occur over much of the island interior under the dense cover of vegetation. The ridges probably mark former beach lines added as the island grew lagoonward by accretion of beach material, and later flattened by wind action to inconspicuous ridges. The floor of most of the central part of the island is sand or sandy gravel, covered over the southern part by a layer of leaf mold generally no more than an inch thick, but reaching 3 to 6 inches in a few places. The central part of the island is covered by a dense thicket of twisted *Cordia* trees, and in places, by *Pisonia*. Palms occur in small, scattered open groves. Near the north shore a broad boulder flat merges at the beach crest with sand and gravel but no rampart was seen. The boulder flat is covered with thick *Scaevola* and a nearly impenetrable tangle of *Cordia*.

Near the center of the island a well dug by natives occupies the center of an oval natural depression 75 feet in length, elongated east and west, and nearly 6 feet deep. The well is circular, 15 feet in diameter and 6 feet deep. When examined by Tracey it contained a few inches of brown water that smelled strongly of H_2S and tasted slightly brackish.

YUROCHI

Yurochi island is the westernmost of four islands that lie on the broad arc in the center of the northern reef and are tied to each other by long sand bars. Yurochi is about 1,700 feet long, 1,100 feet wide, and covers about 33 acres. The island is triangular in shape. The south side faces the lagoon, the northeast side faces the exceedingly broad flat of the reef arc, and the northwest side faces the northwest reef margin.

Seaward coast.—The northeast and northwest shores of the island are similar. Both consist of a belt of eroded, bedded beach rock overlain above high-tide level by a beach crest of windblown sand. The bedding of the beach rock is well marked, and the strike departs from the trend of the present beach by only a few degrees. The north tip of the island is a broad spit of well-bedded sandstone. The tip of the spit is 250 feet from the upper sand beach, and it extends along the shoreline for more than 500 feet. Along the axis of the sandstone spit the intertonguing beds slope conformably with the sides of the spit. The beds were probably deposited by waves and currents from the south that converged at the north end of the island. The Yurochi spit resembles the one seen on the west end of Ourukaen island on the opposite side of the atoll. That one was sand covered during the spring but stripped of sand during the summer. Possibly the Yurochi north spit, that is bare during the prevailing trade season, may be sand covered during periods of southerly winds in the summertime. The question cannot be decided as the spit was visited only once, in March. If the spit is periodically reburied by sand, it may be that the rock layers are forming intermittently at the present time; but on the other hand the spit may be a relic structure formed at some time in the past when the climatic cycle was different from today, and when southerly winds were more prevalent. This possibility does not appear to be a likely one, for if southerly winds were ever dominant there should be more evidence of it in other island structures and in the marginal reef structures that are now adapted to the northeast trades.

Lagoon coast.—Well-bedded layers of beach sandstone dipping 6° to the lagoon are widely exposed from near high-tide level to low-tide level. The upper edge of the belt is scalloped by erosion and the layers are cut by joints, one set parallel to the dip, another to the strike. The layers are irregularly fluted and furrowed parallel to the dip. A sample from this belt of beach rock (B–25) is a poorly consolidated foraminiferal beach sandstone consisting of about 40 percent tests of *Calcarina spengleri;* 5 to 10 percent other Foraminifera, especially *Amphistegina* and *Marginopora;* 20 percent *Halimeda* segments; 5 percent mollusk shells and fragments; and 25 to 30 percent rounded organic grains. The material is cemented by a thin frosty coating of calcium carbonate on each grain. Intergranular areas are unfilled and the rock is very porous.

A sample of sand (B–26) from the lagoon beach adjacent to B–25 has the same constituents in approximately the same proportions. Many grains are worn and some have a high polish but none has a coating of carbonate such as forms the cement in B–25.

Unconsolidated sands extend from the upper edge of the beach rock belt to the beach crest. The beach is extended westward as a sandbar for 500 feet and eastward for more than 3,000 feet to Uorikku.

Interior flat.—The interior of Yurochi island is a flat mostly of sand and gravelly sand, covered by tangled scrub vegetation.

SANDBAR JOINING YUROCHI AND UORIKKU

The long bar is actually a rock bar, 3,000 feet long and 200 feet wide of bedded sandstone covered by a high bank of windblown sand. Most of the sandstones on the north side dip irregularly seaward, but the inner part of the rock belt dips to the south (lagoonward). On the lagoon side of the bar the beach rock dips uniformly lagoonward conformable to the beach slope. The bar apparently is slowly migrating lagoonward.

A sample (B–58) from the beach rock on the lagoon side of the bar is poorly bedded, moderately sorted, well-polished foraminiferal-algal sand, coarse-grained and porous at the base, and fine-grained and less porous at the surface. The cement at the base of the specimen consists of a network of small ridges of aragonitic material (deeply stained in Meigen solution) on each grain. At the surface of the specimen, 3 to 5 mm of the rock is completely filled with a calcareous porcelaneous paste that appears to be aragonitic except for the top 0.5 mm which stain tests indicate is calcitic. Average grain size is 0.5 mm at the top, grading to 1 mm near the center and to 2 mm at the base of the specimen.

In thin section the rock is seen to be a coarse detrital sandstone containing small amounts of microgranular detrital paste near the surface of the specimen. Many grains are well rounded. Some are rounded *Lithothamnion* grains. The grains are rimmed with a dark-brown to nearly black, carbonaceous-appearing film 0.02 to 0.05 mm thick that appears to be an alteration surface rather than a coating on the grains (pl. 58, fig. 2). In places on the brown film is a coating of aragonite needles normal to the grain surface. The needles do not penetrate the brown film, nor does the film coat any of the needles. The total thickness of the brown film and the needles ranges from 0.02 to 0.1 mm. Some small pores in the grains or between grains are filled by the aragonite.

A few grains of coral and of *Lithothamnion* appear to be partly altered to brown microgranular material, and some grains of *Lithothamnion* contain large areas of clear fine-grained crystalline carbonate. The polished surface layer in thin section appears to be made of dark-brown microgranular paste containing fine detrital grains. The paste is white in reflected light.

North of the bar between the two islands is a broad belt of eroded bedded rock that is joined to the sandbar by a wide belt of bedded rock. The eroded rock probably is the foundation of a former island. The site of the island is of interest for it is surrounded on three sides by a deep arcuate pool on the reef flat. The pool is roughly crescent shaped, 2,500 feet in maximum length, 1,000 feet in maximum width, and 20 to 30 feet deep.

UORIKKU

Uorikku is an island about 1,000 feet long, 500 feet wide, and covers about 9 acres. The seaward coast is of eroded, bedded sandstone fringed by sand near the vegetation line. Along the northwest shore most of the beach rock dips north and strikes approximately east-west, forming an angle almost at 45° to the shoreline. The beach-rock layers have been eroded so that their line of outcrop parallels the present beach, and a layer of sandstone 2 to 4 inches thick covers parts of the truncated surface of the beds (pl. 55, fig. 2). The lagoon coast is a sand beach with some exposed layers of beach sandstone. The island interior is predominantly sand, brown and carbonaceous at the top and covered with an inch or less of leaf mold. Some palms grow on the island but most is covered with a dense thicket of *Scaevola* and other low scrub growth.

ROMURIKKU

Romurikku is joined by a narrow sand flat to Aomoen island to the southeast. Together the two islands form a long narrow arc 8,400 feet in length and 600 feet wide, covering about 82 acres. The vegetation-covered part of Romurikku is 4,600 feet long, 500 feet wide, and covers about 43 acres.

Seaward.—The long shoreline facing the broad northern reef is formed mostly of beach sandstone on the convex-seaward curves near either end of the island, and of unconsolidated sand in the concave-seaward beach between the two extremities. The beach sandstone is well bedded, more or less conformable to the present beach line, but much eroded. It is covered by sand above high-tide level. The sand beach is broad, uniform, and gentle in slope. When measured it sloped about 5° as a nearly plane surface 84 feet wide. A large dune covered by vegetation parallels the beach. The height of the dune, measured by hand level, was 17.5 feet above the highwater mark on the beach, or 23 feet above the reef flat. It is, therefore, probably the highest point on the atoll.

Lagoon coast.—The lagoon shore is composed partly of sand and partly of bedded sandstone. Along part of the coast much of the sandstone is broken into large blocks 2 to 5 feet long that form a massive rampart at high-tide level.

Island interior.—The island is a rather low sand flat. Next to the high dune along the seaward coast the interior flat was 17 feet lower than the crest of the dune, or about 6 feet higher than the reef flat. The humus layer in some places appeared to be several inches thick, and many palms grow on the island.

West sand bar.—A bar composed of beach rock and loose sand extends nearly 1,000 feet west of Romurikku toward Uorikku. The two were probably connected at an earlier time, for traces of bedded rock are found in the present gap in the bar. A channel nearly 400 feet wide now cuts the bar, and water that is piled on the broad reef flat by the prevailing winds, and dammed by the long chain of islands and bars, pours through the channel at all stages of the tide.

AOMOEN

The part of the Aomoen island that is covered by vegetation is 2,300 feet long, 500 feet wide, and covers about 23 acres. Beach rock forms a low arch over the island axis. Beds near the lagoon dip southwest, those near the reef dip northeast, and the rock over the central axis is flat lying.

Seaward coast.—Beach rock is widely exposed on the long nearly straight northeast coast. The rock is conglomeratic and poorly formed beds dip a few degrees to the reef. The inner edge of the reef flat forms a low arched pavement (A of figure 84) 20 to 40 feet wide rising 2 to 3 inches above the water level at low tide.

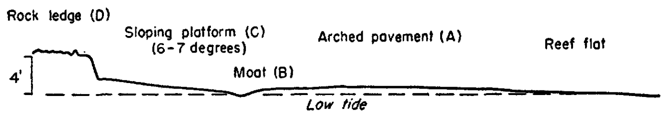

FIGURE 84.—Profile of coastal features, Aomoen island. The north coast facing the seaward reef. An arched pavement (A) rising only 2 to 3 inches above the reef flat, is separated from a sloping wave-cut platform (C) by a narrow "moat" or gutter (B). These features are evidently caused by long-shore currents at times of high surf.

The surface is generally flat but rough in detail due to the etching out of coral and shell fragments. The pavement meets the shore to form a shallow depression or moat (B of figure 93) 1 or 2 feet wide and 1 to 2 inches deep. From the moat the sloping wave-worn platform of the shore rises 6° to 7° (C of figure 93). It averages about 15 feet in width, and is a smoothly worn flat surface containing truncated *Heliopora* colonies (pl. 56, fig. 1), some of them nearly a foot higher than the present reef flat. Behind the sloping platform rises the massive ledge of sandstone and conglomerate (D fig. 93 or pl. 54) that rises 3 feet to a level 1 foot above high tide. At the base of this miniature cliff there are wave-cut caves 6 to 8 inches deep and 6 inches high; smaller nips are cut along bedding planes at higher levels. The upper surface of the ledge is 8 feet wide and is roughened by solution in a honeycomb of pits as much as 8 inches deep. Some of the walls of the pits are so thin they can be broken with the fingers.

Lagoon coast.—The lagoon shore of Aomoen is a broad sand beach. In a few places exposed beds of beach sandstone are conformable with the sand beach; in other places blocks have been dislodged and piled irregularly on the beach (pl. 54, fig. 2).

Island interior.—The island is a barren flat formed of truncated beds of beach rock half buried in gravel and windblown sand. According to officers of the Naval Construction Battalion who were making installations on the island, rock near the margins was well consolidated, and 3 to 5 feet thick; whereas that over the central part was soft and generally not more than 6 inches thick. Most of the sparse shrubs on the island are *Scaevola*. Sand on the flat areas between rock outcrops was found to be bound by a thin crust of algae (Myxophyceae). A specimen of the crust (B–67) from the northeast side of the island at about high-tide level is 5 to 13 mm thick. The sand consists mostly of tests of the common Foraminifera, unconsolidated below the crust. The material is porous and friable; about 1 mm of the upper surface is dark gray, and consists of a mat of sand grains bound by minute fibers probably of a blue-green alga. Grains throughout the crust are covered with a weblike mat of minute bristlelike fibers that are stiff like crystals, although many are slightly curved or bent. A small amount of chalky powder on some grains stains a deep lavender in Meigen solution. This is probably aragonitic and may account for a part of the cementation.

DESCRIPTION OF CORES AND CUTTINGS

Drill hole 1

[The drill rig was set up on the northeast side of Bikini island (fig. 31), on a sand flat adjacent to the beach and 13 feet above the level of the reef, or approximately 15 feet above lowest water level. The reef flat is unusually wide at this place, and the hole is located about 2,700 feet from the seaward margin; total depth 300 feet. A diagrammatic section is shown in figure 33]

	Method and recovery	*Depth (feet)*	*Thickness (feet)*
Unconsolidated, coarse foraminiferal sand containing several thin streaks of gravel. The cuttings consist of about 85 percent worn tests of *Calcarina spengleri*, about 5 percent *Marginopora*, and about 10 percent rounded pebbles of coral and *Lithothamnion*. The material is the same as that forming the present-day beach a few feet away.	Rock bit..	13	13
Consolidated white limestone. Cuttings consist about half of chips of compact porcelaneous white algal limestone, and half of well-cemented foraminiferal sand and coral fragments. Because of the proportion of algal limestone, and because the top of the rock is at nearly the same level as the reef flat, the material is probably reef rock continuous with the present-day reef.	Rock bit..	19	6

	Method and recovery	*Depth (feet)*	*Thickness (feet)*
Two core runs of 10.5 and 13.5 feet, respectively. From 19 to 21 feet the rock was drilled rapidly but it appeared firm and moderately consolidated, and probably is continuous with the 6 feet of reef rock just above. From 21 to 43 feet the material is loose, completely unconsolidated coarse sand formed mostly of unworn tests of *Calcarina spengleri* showing unbroken spines, some unworn tests of *Marginopora*, and a few broken fragments of coral and *Lithothamnion.* *Interpretation.*—The material apparently accumulated on or near the lagoon edge of a reef in a few feet of water, as indicated by the abundance of unworn *Calcarina* and the scarcity of other organisms.	Core run; 0 ft	43	24
The top of this unit was moderately consolidated and most of the core probably came from the hard layer. Below, the rock drilled like unconsolidated sand and gravel. The core from this run consists of broken pieces of coral and cemented detritus. The coral is a fresh and unworn specimen of *Acropora* cf. *palifera.* Some fragments are coated with a thin crust of *Lithothamnion.* The detritus consists of moderately well cemented tests of *Calcarina spengleri, Marginopora,* and segments of *Halimeda.* Cuttings of unconsolidated material at 50 feet consist mostly of unworn tests of *Calcarina,* abundant *Halimeda* segments, and abundant fragments of *Lithothamnion* and coral. Some of the *Halimeda* segments are fresh and unworn, but others are broken, worn, and encrusted with *Sagenina* and with minute coiled tubes, probably worms. *Interpretation.*—The material apparently accumulated in shallow water near a reef, as indicated by the abundant *Calcarina,* reef-type coral, and *Lithothamnion.* The appearance of abundant segments of *Halimeda* indicates that the deposition was on the lagoon edge of the reef or on a lagoon bottom near the reef. The consolidated unit 1 foot thick at 43 feet may possibly indicate the top of a former reef flat at that level.	Core run; 1 ft	53.5	10.5
About half of the recovered core consists of broken fragments of coral, mostly *Astreopora* and *Acropora.* The rest is fairly well cemented detritus of *Halimeda* segments, mollusk fragments, forminiferal tests, and rare echinoid spines. The corals are for the most part fresh in appearance and unworn, although some fragments are worn, rounded, and encrusted with a *Lithothamnion* determined by J. H. Johnson to be *Porolithon.* Worm tubes encrust some of the coral surfaces. *Interpretation.*—The material evidently accumulated in shallow water near a reef, apparently close to the edge of a lagoon.	Core run; 1.5 ft	64	10.5
Unsorted, moderately consolidated coralliferous detritus. Coral forms about half of the recovered material, and consists of fragments and core pieces of *Astreopora, Porites,* and *Acropora,* some of which are apparently in position of growth. Some of the coral is encrusted with Lithothamnion. The cemented detritus consists of *Halimeda* segments, mollusk shells, and echinoid spines and broken coral fragments in a matrix of detrital grains mostly 0.5 to 2 mm in size. The detrital matrix contains abundant unworn tests of *Calcarina spengleri.* Pore spaces are filled with a fine chalky powder, and some of the coral and *Halimeda* fragments are friable and chalky. A few cavities in corals are half filled with compact white fine-grained limestone, probably a hardened calcareous paste, and the top surface of the paste is flat and perpendicular to the axis of the core. Specimen 1–5–10[5] (4.5-cm core).—A branching coral, probably *Acropora,* in a cemented detrital matrix containing abundant unworn tests of *Calcarina spengleri* and segments of *Halimeda.* A rounded piece of *Lithothamnion* about 1 cm long is included. Chalky powder partly fills spaces between detrital grains and foraminiferal tests. In thin section the coral is seen to be composed of brown, finely fibrous aragonite. Some pores are filled with acicular carbonate, probably aragonite, that grows from the cellular walls of the coral apparently in optical continuity with the aragonite of the coral. Many pores are empty, and a few are partly filled with dark-gray finely granular paste. Distinct grains in the paste are cemented by gray microgranular carbonate. The outer surface of the coral in thin section is coated with loose, coarse detritus consisting of *Calcarina* tests, angular grains, and an encrusting foraminifer, probably *Carpenteria.* One *Halimeda* segment appears much disintegrated. Pore spaces between detrital grains are empty, but very fine grained calcite coats each grain or test and cements the material.	Core run; 1.8 ft	74.5	10.5

[5] Each piece of core has 3 numbers separated by dashes: first number is that of hole; second number that of core run; third number refers to specific piece of core in that run, the pieces being numbered from top downward.

	Method and recovery	Depth (feet)	Thickness (feet)
Interpretation.—The material of the interval 64–74.5 feet accumulated on or near a reef in a few feet of water. In the abundance of coral, unworn *Calcarina*, and *Lithothamnion* the material is similar to much of the rock that forms present-day reef flats near the lagoon margin. The acicular aragonite in pore spaces, and the microgranular carbonate cementing detrital grains suggests that the rock may have been cemented at low-tide level, as is the present lithified cap of the reef flat; but no conclusive evidence was found.			
Coarse, unsorted, poorly to moderately consolidated coralliferous detritus. About half of the material is coral, consisting of *Astreopora*, *Acropora*, and possibly *Pocillopora* and *Favia*. The rest is detritus of fine to coarse angular fragments 0.1 to 1 mm in diameter, abundant *Halimeda* segments and *Calcarina* tests. Encrusting *Lithothamnion* and encrusting foraminifers are common on coral surfaces. Echinoid spines and alcyonarian spicules are rare. The material is porous but cemented, and pore spaces are lined or filled with chalky powder. Some of the corals are chalky and are rather disintegrated. Specimen 1–7–12, (4.5-cm core).—Nodular white calcareous algae and cemented unsorted detritus. In thin section the material is seen to consist of *Lithothamnion*, encrusting foraminifers, *Calcarina spengleri* and *Halimeda* in a fine to coarse granular matrix. The grains of the matrix range from 0.01 to 1 mm in size and are angular to rounded fragments of *Lithothamnion*, coral, and *Halimeda*. Encrusting foraminifers include both *Carpenteria?* and *Homotrema?*. The material is cemented around each grain by acicular carbonate, probably aragonite, that fills some of the spaces between grains and lines the edges of other spaces. The acicular carbonate also fills internal pores of some shells and tests. The boundary of the cementing carbonate with most grains is sharp, but the boundaries of some *Halimeda* grains are gradational, suggesting a considerable alteration of *Halimeda*. *Interpretation.*—The abundance of *Halimeda* suggests that the material of the interval 74.5–85 feet probably accumulated in a lagoon. The presence of a number of corals of reef type and of *Lithothamnion*, the abundance of *Calcarina*, and the amount of detrital grains of *Halimeda* and *Lithothamnion* suggest that the material accumulated in very shallow water near the lagoon margin of a reef. The acicular cement that is seen in thin section is abundant enough to suggest that the material was at or above sea level for a short time. Whether the chalky nature of some of the coral is due to leaching, or is a natural alteration that might happen below sea level after burial is not known. The rock in this core run is similar to that in hole 2 from 74.5 to 95.5 feet both in its constituents and in the acicular cementing carbonate.	Core run; 2.5 ft	85	10. 5
Corals in a coarse, detrital matrix. *Stylophora pistillata*, *Porites*, *Pocillopora?* and *Favia?* are present. Many are worn, and some are coated with encrusting Foraminifera. Others are altered and have pores filled with powdery chalk. The detrital matrix is fine-grained in some specimens but is coarse in most of them, and it contains foraminiferal tests, mollusk shells and echinoid spines. The material is apparently similar to and continuous with that in the preceding unit (74–84.5 feet).	Core run; 0.5 ft	95. 5	10. 5
The interval drilled like loose unconsolidated sand. Cuttings taken at 100 feet show *Baculogypsina* and *Calcarina hispida*, neither of which were present above, according to Mrs. Post. These probably appear at about 95 feet where the formation is soft and unconsolidated, at about the same depth that *Calcarina hispida* was found in hole 2. *Interpretation.*—To judge from the drilling and from the foraminifers present, the material was probably deposited in a lagoon in 10 fathoms or more of water, which is the present minimum depth of abundant *Calcarina hispida*. Tests of *Calcarina spengleri* are also present in cuttings, but are probably contamination from higher parts of the hole.	Core run; 0 ft	127	31. 5
Chalky, poorly consolidated coralliferous detritus. The recovered core consists of one branching coral and a piece of detrital limestone. The detrital core piece consists of a white, friable but moderately consolidated fine-grained matrix containing casts of coral fragments. Worm tubes and hard, limy crusts of algae or encrusting foraminifers are abundant. Specimen 1–11–1, (5.5 cm core).—The coral, probably *Acropora*, is corroded on its surface by borings and possibly by solution, and it is partly coated with a thin limy crust of algae or foraminifers. Some minute worm tubes are on the coral. The larger pores within the coral are filled with fine chalky to compact carbonate.	Core run; 0.3 ft	137. 5	10. 5

	Method and recovery	*Depth (feet)*	*Thickness (feet)*

In thin section the coral is apparently unaltered but many pores are partly or completely filled by acicular carbonate that has grown from the pore walls. Some pores that are partly filled by acicular carbonate are empty in the centers, others are filled with gray microgranular paste which the carbonate needles penetrate with diffuse boundaries, as if they have grown at the expense of the paste. Still other pores are empty, or are filled with dark finely-granular to microgranular paste, but they contain no acicular carbonate.

The needles of carbonate are probably aragonite, although no test was made. The degree of crystallization or recrystallization in this specimen is about the same as that seen in specimen 1–6–12.

	Method and recovery	*Depth (feet)*	*Thickness (feet)*
Coralliferous detrital limestone. The recovered core consists largely of coral colonies, some of them in position of growth. *Acropora*, *Stylophora*, and *Astreopora* are the most common genera. Detrital material of the core is chalky and soft, and contains abundant *Halimeda* segments and gastropod shells. Surfaces of corals, or of cavities in the detritus, are coated with encrusting foraminifers, worm tubes, and with small, thin encrusting corals.	Core run; 2 ft	158. 5	21

Specimen 1–12–2 (14-cm core).—Branching coral in position of growth (pl. 58, fig. 3). Delicate cells in the central parts, and some on the outer parts of the coral are perfectly preserved and are unfilled, but much of the coral in between is dense, porcellaneous limestone that appears to be due to addition of carbonate. Several orange-brown streaks, that appear as dark areas in the photograph, color the border of parts of the coral.

Detrital material between branches of the coral (shown in the middle of the photograph) consists of *Halimeda* segments, some foraminiferal tests and encrusting organisms. On the outer surfaces of the coral are many tiny worm tubes and a few attached bivalves.

Interpretation.—The material of this interval accumulated in shallow water, probably close to the lagoon edge of a reef. It is similar to coralliferous material from hole 2 at approximately the same depth (158.5–169 feet).

	Method and recovery	*Depth (feet)*	*Thickness (feet)*
Unsorted, poorly-consolidated and friable to well-crystallized and compact, coralliferous detrital limestone. Colonies and fragments of coral, especially *Astreopora* and *Acropora*, form more than half the recovered core. The detrital material includes abundant *Halimeda* segments, tests of *Calcarina hispida* and *Marginopora*, mollusk molds and shells altered to chalky powder, and angular detrital grains. A well-preserved operculum of *Turbo* and a few large cross-sections of echinoid spines are visible.	Core run; 3.1 ft	169	10. 5

Some of the coral colonies are in position of growth and are apparently unaltered. Others are broken down to a chalky powder that preserves original cellular coral structure, or are recrystallized to compact, coarsely crystalline calcite that almost obliterates details of the coral structure.

The recrystallization of the detrital matrix is patchy and irregular. Small areas of core specimens are friable and chalky, but most of the recovered core is moderately to well crystallized. Most of the crystalline calcite is clear, but some that fills cracks or spaces is medium brown. Several cavities in corals are half filled with white, porcelaneous, calcareous paste. The top surfaces of the filling are normal to the core axis, and empty parts of the cavities are coated with minute crystals of calcite.

Interpretation.—The material of this core run, like that of the preceding one, is dominantly coral, some in positions of growth. Detritus consists largely of unworn organic remains. A near-reef environment in a lagoon is considered likely, at depths close to 10 fathoms—not much deeper because of the abundance of reef-type organisms, and not much shallower because of the abundance of *Calcarina hispida.*

The amount of crystalline calcite in the core is greater than in any limestone at higher levels. Partial disintegration of corals and gastropods, recrystallization of coral material, and filling and replacement by both clear and brown calcite have all occurred. The material of this core run apparently was raised above sea level for a period long enough for considerable leaching and deposition of calcite.

284244—54——16

	Method and recovery	Depth (feet)	Thickness (feet)
Irregularly consolidated and unsorted detritus, containing abundant coral, mollusk shells and molds, foraminifers and algae. The coral consists mostly of fragments of *Acropora* and *Astreopora*. Many pieces are altered to chalky powder in the centers, and are filled or replaced by crystalline calcite on the outer margins. Mollusk molds are common but original shells altered to chalky material are abundant in the lower part of the core. Abundant whole *Halimeda* segments and large *Marginopora* form a large proportion of the material, especially in the lower half of the core. Small tests of miliolids and other foraminifers, large echinoid spines, and fragments or encrustations of *Lithothamnion* are also present.	Core run; 1.9 ft	179. 5	10. 5

The upper part of the core is similar to the material of the preceding core run, except that it is more consolidated and recrystallized. Clear fine to coarse crystalline calcite cements grains and pervades many organic remains, especially coral, in irregular patches. The lower part of the core contains tan to brown crystalline calcite that fills most of the spaces between coarse grains and organic remains. Several large areas resemble brown pebbles, but all are apparently areas of calcite filling.

Specimen 1–14–2, (12 cm core).—Recrystallized coralliferous detrital limestone (pl. 58, fig. 4). Corals are altered and chalky in their centers, but are filled near their edges by clear crystalline calcite that also permeates the detrital matrix. The matrix is finely granular, and contains small foraminifers and angular fragments, but these are apparent only in chalky areas; in recrystallized areas the organic remains are for the most part obliterated.

The specimen was boiled in Meigen's solution, and most of it proved to be calcite, although small chalky patches in both coral and matrix were stained and are apparently aragonitic.

Under the ultra-violet lamp the compact calcite areas the specimen fluoresce a bright blue-white, and show a pale greenish phosphoresence that lasts nearly 3 seconds, whereas chalky, aragonitic patches are drab and do not fluoresce.

Specimen 1–14–13 (6.2-cm core).—Well-consolidated fossiliferous limestone. Coral fragments are common, but mollusk remains, *Halimeda*, and *Marginopora* are the most abundant constituents. Mollusk remains are molds lined with powdery disintegrated material of the original shell. *Halimeda* and *Marginopora* are somewhat chalky but are well preserved. The remains are more or less scattered in a tan to brown matrix of compact crystalline calcite.

Under the ultra-violet lamp the tan to brown calcite filling does not fluoresce, but small areas of clear calcite fluoresce a pale white color.

In two thin sections from this specimen the organic remains are seen to be in a mosaic of clear calcite. *Halimeda, Marginopora,* and most mollusk skeletons are not much altered under the microscope, although they are friable and powdery in the core. Some coral skeletons look like original fibrous aragonite, but others are formed of coarse crystals of calcite, and pore spaces are filled with gray microgranular paste. In a few places on the slide gray paste is present within the calcite mosaic, in small shreds and ragged patches. The gray paste apparently has recrystallized or altered to calcite mosiac, and may originally have formed the entire matrix.

Brown areas in the rock are seen under the microscope to be irregular cloudy brown microgranular material in which shreds can be seen that appear to be traces of former organic remains. The material is similar to that described under specimen 2–11–15 and 2–11–16 in hole 2, at 179–190 feet.

In one of the thin sections, one small whole specimen and several fragments of *Rotalia calcar* were seen. Miliolids and other small thin-walled types are common, but large forms such as *Marginopora* are most abundant.

Interpretation.—The material from this core run is very similar to the lower part of the eleventh core run from hole 2, at 179–190 feet. In types of organisms present, and in the amount of calcite recrystallization and pore filling, the two are similar. In both cores, *Rotalia calcar* first appears in the hole in the lower part of the core run. The material was probably deposited in a lagoon at a depth of 10 to 20 fathoms.

Whether the clear crystalline calcite of the upper part of the core, illustrated by specimen 1–14–2 (pl. 58, fig. 4), is different from the tan to brown calcite of the lower part of the core is not known. The fact that the one fluoresces brightly and the other not at all suggests that the two have a different origin, and may indicate that there were two periods of emergence in which there was strong recrystallization and addition of calcite.

	Method and recovery	*Depth (feet)*	*Thickness (feet)*
No description (no core recovery)	Core run	184.5	5
White to tan moderately consolidated detrital limestone. Altered coral fragments are present, some of them as molds. *Halimeda* is rare except in one core piece in which it is common, but *Marginopora* is abundant, *Rotalia calcar* is abundant, and mollusk molds are common. The organic remains form about half of the detrital material, and the other half consists of medium to fine angular grains probably of organic derivation. The material is irregularly pervaded by tan to medium-brown crystalline carbonate that forms a compact although patchy matrix. The rock from this interval differs from that at higher levels in a relative decrease in the amount of *Halimeda*, and in the relative abundance of *Marginopora*. In these respects it is similar to material in the bottom part of the twelfth core run, 192–200.5 feet, in hole 2A. The amount of tan carbonate cement suggests an uplift relative to sea level after deposition of the detritus.	Core run; 1 ft	200.5	16
White to light-buff coralliferous detritus. About half the recovered core consists of coral colonies, some of them in position of growth, and most of them encrusted by *Lithothamnion* or foraminifers. The rest of the core consists of medium to fine unsorted detritus, most of it moderately consolidated and filled with clear crystalline calcite, but some of it friable and porous.	Core run; 2 ft	211	10.5

Specimen 1–17–16 (8-cm core).—Altered and recrystallized coral in a matrix of medium to fine detritus. The coral structure is all but obliterated by compact recrystallized calcite. Distinct cavities 3 to 5 mm in diameter are partially filled by porcelaneous carbonate paste that shows a fine horizontal lamination. The top surface of the paste is also horizontal. The top parts of some cavities are empty, and surfaces are coated with fine crystals of calcite; others are completely filled by clear crystalline calcite.

In thin section the coral cell walls are seen to be formed of a mosaic of gray, rather dirty-appearing calcite in grains mostly 0.05 to 0.5 mm in size. Some pore spaces are filled by a clear mosaic of calcite, others are filled by dark-gray, fine-grained to microgranular paste containing a few minute foraminiferal tests. The paste is apparently finely granular under low magnification, but under high magnification the grains are seen to be formed of blurred, dark-gray microgranular carbonate that grades imperceptibly into lighter gray surrounding material. It appears that the paste was originally a fine detritus composed of grains 0.01 to 0.05 mm in size that have broken down to microgranular material. Some cavities 1 to 3 mm in diameter are nearly filled by the paste, but the tops of cavities are filled by a mosaic of calcite. One cavity contains horizontal laminae that are seen under low magnification to consist of alternate layers of relatively finer and coarser blurred grains. The matrix surrounding the coral is composed of scattered foraminifers and detrital grains in similar gray paste.

Interpretation.—The material of this core run contains a relatively large proportion of coral, and in this respect it differs from material of equivalent depth cored in hole 2A. The fine paste filling pores and cavities in the coral, and forming much of the detrital matrix, is practically identical, however, with that seen in this section in hole 2A from 200 to about 250 feet.

The recovered core is poorly consolidated, unsorted detrital limestone containing coral fragments, encrusting foraminifers, mollusk molds, and altered shells in a granular detrital matrix containing abundant *Rotalia calcar* and *Marginopora* and rare *Globigerina*. The material drilled rapidly starting just above this interval at 209 feet, apparently because the calcite cement, which was strongly crystallized above 209 feet, is minor in this core run.

The material is similar to that cored in hole 2A at an equivalent depth but it is somewhat coarser-grained and contains more coral and encrusting Foraminifera. The rock probably accumulated in lagoonal waters a little shallower and nearer a reef than the comparable material in hole 2A.

	Method and recovery	*Depth (feet)*	*Thickness (feet)*
Poorly consolidated, unsorted detrital limestone similar to that cored in the preceding run (211–232 feet). Specimen 1–19–3 (6.8-cm core).—Detrital limestone, moderately consolidated, containing abundant tests of foraminifers, mollusk molds, and altered coral fragments. The middle part of the piece is irregularly mottled and replaced by brown, porous but hard calcite. In thin section the brown material is seen to be cloudy brown microgranular paste that apparently has partially replaced and nearly obliterated some organic remains, although other shell fragments and *Halimeda* segments are seemingly unaltered. Small streaks or openings in the brown material are filled by a fine calcite mosaic, but it is impossible to tell which is replacing the other. The material is similar to brown calcite paste seen in other specimens at various depths, for example in specimens 2–2–10 and 2–11–15. Some larger grains in the slide are brown, microgranular, and almost opaque under crossed nicols. A second thin section from the same specimen is seen to consist of *Halimeda*, foraminiferal tests including *Marginopora, Amphistegina* and *Rotalia calcar;* mollusk shells and fragments; and dark-gray to dark-brown, rounded detrital grains in a light-brown microgranular paste. In parts of the slide the foraminiferal tests, which form 30 to 40 percent of the material, are altered and broken down to microgranular material. The brown paste is porous but many pore spaces are filled with fine-grained crystalline calcite. The thin section is very similar to the one made from specimen 2A–16–5, from 232–242.5 feet in hole 2A.	Core run; 0.8 ft	242.5	10.5
The recovered core is similar to that in the preceding run (232–242.5 feet) but is a little more consolidated and some cavities are lined with calcite crystals.	Core run; 0.5 ft	253	10.5
Moderately to well-consolidated, unsorted fossiliferous limestone. Coral fragments are common, some of them as chalk-filled molds. Mollusk molds lined with calcite crystals are common. Encrusting lithothamnia and *Lithophyllum*, nodular, identified by Mr. J. Harlan Johnson, are common in some specimens. Foraminiferal tests particularly of *Amphistegina* and *Marginopora* are abundant. The detrital material is coarse-grained. It is porous in a few places, but in most it is filled with hard and compact crystalline calcite. Specimen 1–21–7, (4.5-cm core).—Consolidated coarse foraminiferal detritus. In this section the material is seen to consist mostly of tests of *Marginopora and Amphistegina*, coral and other detrital fragments, and small nodules of Lithothamnion. Most grains are apparently well preserved but one coral fragment is completely altered to a coarse mosaic of calcite and only the coral outline is preserved. The detrital grains and tests are in a matrix of crystalline calcite that is very finely granular near the borders of fragments, but grades to a medium-grained mosaic of calcite between fragments.	Core run: 3 ft	263.5	10.5
Fine-grained, compact but cavernous detrital limestone. Corals are abundant both as empty molds and as casts of crystalline calcite. John W. Wells has identified *Galaxea* sp. Abundant mollusk molds are lined with crystals of calcite. Foraminiferal tests are almost unrecognizable in the compact recrystallized matrix. Specimen 1–22–8 (3.5 cm core).—Moderately consolidated, fine-grained detrital limestone. In thin section the material consists of about 20 percent organic remains more than 0.3 mm in length, including tests of *Marginopora, Amphistegina* and *Rotalia calcar*, rare echinoid spines and *Lithothamnion* fragments. The rest of the material consists of tests of small foraminifers and angular grains from 0.3 to 0.01 mm or less. In part of the slide the material is mostly larger than 0.3 mm in a coarsely crystalline mosaic of calcite; in the rest of the slide the material is mostly fine detrital grains in a gray microgranular to finely granular paste.	Core run; 2.5 ft	269	5.5
Moderately to well-cemented but cavernous, white, fine-grained detrital limestone. The material is similar to that in the preceding core run (263.5–269 feet). It consists of numerous molds of small mollusks, a number of altered, chalky coral fragments, and rare foraminiferal tests in a fine grained detrital matrix. Most of the rock is consolidated and compact, but small areas are porous and friable. Parts of the rock are permeated by clear, moderately to coarsely crystalline calcite. Specimen 1–23–7 (3.8 cm core).—Fine-grained white limestone containing a few molds of small mollusks. In thin section the rock is seen to consist of a few large coral fragments and rare whole *Marginopora* tests in a fine-grained gray detrital matrix. The matrix contains common tests of small foraminifers, but it is mostly made up of broken shells and angular grains in a brownish-gray microgranular paste. The microgranular paste surrounds the grains, but it grades away from the grains into a	Core run; 3.5 ft	284.5	15.5

	Method and recovery	Depth (feet)	Thickness (feet)
mosaic of clear calcite. The paste has apparently recrystallized to the calcite mosaic. Some of the foraminiferal tests are apparently formed of original fibrous calcite that has been very little altered, but most of them seem to have disintegrated to microgranular, almost cryptocrystalline, yellowish-brown material. The coral is seen to be completely recrystallized to finely granular calcite. Pores in the coral are filled with dark-gray microgranular paste containing scattered fine detrital grains.			
Compact, moderately to well-consolidated fine-grained detrital limestone containing molds of mollusks and corals. Both *Acropora* and *Seriatopora* molds can be recognized. The detrital material is mostly fine grained and well crystallized, although in some specimens grains 1 to 4 mm in size are scattered in a fine matrix. Several pieces of core are banded or veined by tan to brown, porous but hard carbonate. Specimen 1–24–2 (2.5 cm core).—Fine grained detrital limestone irregularly replaced by compact brown material that gives the specimen a mottled appearance. The brown material has fine light and dark bands that look like concretionary or weathering phenomena. In thin section the material is seen to be mostly brown microgranular paste containing a few rocognizable fossil fragments. The paste is very porous and many pores are filled with fine-grained clear calcite. Light and dark obscure zones in the paste form indistinct concentric rings and layers that appear similar to concretionary structures seen in thin sections of calcareous or bauxitic pisolites. The material is almost identical with that seen in 2–2–10, in pebbles in specimens 2–11–15 and 2–11–16; and, in this hole, in specimen 1–14–3. The material also resembles the brown paste seen in sections made from deeper cores in hole 2A; for example specimens 2A–35–1, 2A–37–7, and 2A–37–14. In those, however, the paste has not altered and obliterated the organic remains, nor is there the appearance of concretionary structures.	Core run; 3.3 ft	300	15.5

Interpretation.—The material from the lower part of hole 1, from 211 to 300 feet, is similar to that seen at equivalent depths in hole 2A. Fine-grained detritus is dominant, smaller foraminiferal tests are common to abundant, and mollusk molds are common. The material was apparently deposited in a lagoonal environment in less than 30 fathoms of water. The lagoon bottom was apparently formed of fine detrital sand, and coral growth was accordingly rather scarce. Material from this hole is somewhat coarser than that from hole 2A, probably because hole 1 was closer to the reef. The material from hole 1 seemed somewhat more consolidated than that from hole 2A, but accurate comparisons are impossible because core recovery was so low.

The amount of alteration and recrystallization of calcite in the lower part of hole 2 suggests that the rock at this depth stood at or above sea level for an appreciable period of time after deposition.

Drill hole 2

[The drill hole was located on a grassy sand flat 16 feet above low-tide level near the middle of the lagoon beachline of Bikini island, 63 feet from the vegetation line at the crest of lagoon beach (fig. 31). The elevation of the collar of the hole was approximately 17 feet above low-tide level. Total depth 190 feet. A diagrammatic section of the hole is shown in figure 34]

	Method and recovery	Depth (feet)	Thickness (feet)
Beach sand and gravel. Beach foraminifers, broken and worn coral and mollusk fragments. Hard rock struck at 14 feet.	Rock bit..	14	14
All core recovered came from 14 to 16.5 feet: beach sandstone. No recovery from 16.5 to 22 feet: loose sand and gravel. Well-cemented beach sandstone, showing poorly defined beds 5 mm to 10 cm thick. The beds range from thin, sandy layers consisting of closely packed rounded grains 0.1 to 1 mm in diameter, to coarse gravelly sand layers containing polished well-rounded pebbles 4 mm to 2 cm in diameter, in a matrix of fine sand. About half the material consists of pebbles of *Lithothamnion*, 60 percent, corals, 30 percent, and mollusk shells, 10 percent. The other half is unsorted detritus ranging from 0.1 to 4 mm in diameter, and averaging about 1 mm, of foraminifers—mostly *Calcarina*—and of angular to rounded fragments of *Lithothamnion*, coral, and mollusk shells, in order of abundance. The rock is well cemented and hard. It is less well cemented near the base of the recovered core, below which it grades to unconsolidated sand and gravel not recovered in coring. Under the ultra-violet lamp the rocks fluoresce—the *Lithothamnion*, coral, and mollusk fragments with a pale bluish-white color; the fine sand of the matrix with a light-yellowish-tan color. Rare specks in the core—probably mollusk fragments—fluoresce a bright red.	Core run; 2.5 ft	22	8

	Method and recovery	Depth (feet)	Thickness (feet)
Specimen 2–1–1 (13-cm core).—Light-tan beach sandstone (pl. 58, fig. 5). The top 7 cm consist of unsorted pebble gravel; pebbles as large as 1 cm in diameter are in a matrix of fine to coarse unsorted sand. Below is a layer 3 cm thick of comparatively well sorted sand that is fine at the top and coarser downwards. Grain size ranges from 0.1 to 1 mm with some scattered grains from 1 to 3 mm. The average grain size is about 0.5 mm. In thin section the grains are seen to consist dominantly of *Lithothamnion*, *Halimeda*, corals, foraminiferal tests, and mollusk shells. Small grains as little as 0.1 mm seem to be moderately rounded. The cementing material consists of needlelike crystals of aragonite normal to the grain surface. They form a fringe about each grain 0.1 mm or less in thickness and seem to be identical with the cementing material seen in all thin sections of present-day beach rock (pl. 59, fig. 1). Specimen 2–1–8 (9.5 cm core).—Light-tan conglomeratic beach sandstone. The rock is formed of subrounded to well-rounded, relatively coarse *Lithothamnion*, coral, and mollusk fragments in a fine-grained matrix. In thin section the distinction between coarse fragments and fine matrix is striking. The coarse rounded fragments range from 2 mm to 1 cm in diameter, and form about half the specimen. The fine matrix consists of rounded grains mostly between 0.15 and 0.3 mm in diameter, all of organic origin. About half are recognizably derived from foraminifers, corals, mollusks, or calcareous algae. The rest are indeterminate. The cement is not nearly so well developed as it was in specimen 2–1–1, at the top of the beach rock. It consists of ragged fringes of acicular carbonate about each grain, but the needles are only 0.01 to 0.02 mm long and they are not so well oriented as are the larger needles above.			
Judging from the manner of drilling and from the cuttings recovered the unit from 16.5 to 42 feet consists of gravelly sand below the lithified beach sand. Most of the grains and granules are worn, and a large proportion are polished. About 10 percent of the specimens of *Calcarina spengleri* are but little worn and the delicate spines that characterize the species are well-preserved. Below 27 feet the percentage of *Lithothamnion* fragments decreases, and that of *Halimeda* fragments increases. It is probable that most of the material was deposited along the margin of the lagoon near the reef or island beach, in a few feet of water. At 42 feet, hard rock was struck.	Rock bit__	43	21
Broken fragments and some core of coral, mostly porous *Astreopora*, in a friable, uncemented matrix of fine unsorted detritus, very little of which was recovered in coring. Some of the smaller fragments (2 to 3 cm) are worn in appearance and are partly coated with *Homotrema rubrum*, a red encrusting foraminifer, and with thin films of calcareous algae. Larger pieces are riddled with small holes (1 to 3 mm) of boring organisms. The original outer surface of the coral is covered with tiny coiled or irregular worm tubes, bryozoans, and small mollusk shells. Several of the corals are upright. About half of the detrital matrix consists of abundant foraminifers, mostly well-preserved *Marginopora* and *Calcarina spengleri* with some unbroken spines, of common *Halimeda* segments, and of less common gastropods 1 to 2 mm in length. The remaining half of the matrix consists of fine to medium, subangular to subrounded grains ranging from 0.05 to 1 mm in diameter. One specimen, 3.7 cm long, near the bottom of the recovered core, consists of medium-brown compact carbonate at the top grading downward to light brown extremely porous carbonate. The specimen is discussed in detail below. The bottom of the cored interval consists of chalky *Halimeda* and foraminiferal debris similar to the detrital matrix at the top of the core. Specimen 2–2–2, (7.5–cm core).—A large, thick branch of coral. It is compact and crystalline with a rather faint coral structure. Several long holes 2 to 3 mm wide pierce the coral; tiny holes riddle it near its edges, and these are filled with a fine limy paste. The surface of the coral is encrusted with minute coiled worm tubes. In thin section few of the pores seem to be nearly filled with long fibers of aragonite that are continuations of the original fibers in the coral. In small areas of the slide, fibrous aragonite of the original coral structure is broken up into a mosaic of very fine grains near carbonaceous "dust lines" that outline the coral structure. Under the ultra-violet lamp the specimen fluoresces a pale blue to pale yellow, much lighter than other corals (*Astreopora*) in this core run.	Core run; 1.5	53.5	10.5

Specimen 2–2–10 (3.7 cm core).—This specimen, near the bottom of the recovered interval, is unlike the rest of the material. It is medium brown and compact at the top, light brown and very porous at the bottom. On a sawed face the upper 1 cm is seen to be finely laminated with nearly horizontal but finely contorted light and dark-brown laminae. The dark laminae range from 0.1 to 0.5 mm in width and are compact, whereas the light-brown laminae are thicker and more porous. The lower part of the specimen is finely porous and has a leached appearance. A few thin medium-brown laminae are scattered and discontinuous. No fossils can be seen although under the binocular microscope there a few vague small forms that may be nearly obliterated foraminifers.

In thin section the constituents are very obscure. A few foraminifers, including encrusting types, are recognizable. Echinoid spines, apparently unaltered, remain as crystalline calcite. The matrix enveloping the rare organic remains is cloudy, microgranular, yellow to brown material. The contorted laminae mentioned above appear under low magnification to resemble concretionary structures such as are developed by weathering processes (pl. 59, fig. 3). Under crossed nicols the material forming the matrix is seen to contain matted needlelike birefringent crystals about one micron in length. In some areas that appear nearly isotropic the needles are scattered; more commonly they are closely spaced, and the material has a resultant light-yellowish-brown aggregate birefringence under crossed nicols. The relief of the material is low, the index apparently being somewhat higher than Canada balsam. A few minute patches on the slide are filled with resinous-looking yellow to brown material that is isotropic with no birefringence observable under high magnification. In some places, apparently the centers of altered foraminifers, the yellow to brown material is composed of fibrous parallel crystals that have a waxy extinction.

It is possible that these are extremely fine fibers of aragonite, and that most of the material is composed of acicular micro-crystalline to crypto-crystalline aragonite in an organic medium. Carbonate analysis of some of the tan porous material by F. J. Flanagan showed 93.61 percent $CaCO_3$, and 1.27 percent $MgCO_3$. The 5.12 percent undetermined matter presumably includes organic matter and sesquioxides. The material, therefore, is almost entirely calcium carbonate. But if so, why is there so little obviously crystalline calcite or aragonite in thin section? Even as much as 5 percent organic material or clay cannot account for all the material surrounding and filling the mat of acicular carbonate.

Further work is necessary to identify the material. It is probably the result of an alteration of some kind, possibly a breaking down of carbonates into microgranular or crypto-crystalline form, or even a migration and concentration of organic matter. The extremely porous nature of the material suggests that it may have formed under subaerial conditions.

Specimen 2–2–11.—Broken fragments and fine material. Part of the material is tan and porous, like that described in specimen 2–2–10 above. The rest is white, chalky *Halimeda* and foraminiferal debris.

Specimen 2–2–12.—Broken fragments and fine material. White, chalky *Halimeda* and foraminiferal debris. It contains about 50 percent white, somewhat crumbly *Halimeda* segments; 10 percent coral and mollusk fragments from 1 mm to 1 cm in length; 30 percent foraminiferal tests from less than 1 mm to 2 mm., dominantly *Calcarina spengleri,* and 10 percent fine detrital material, mostly less than 1 mm. It is probable that the proportion of fine material was larger, but that much of it was lost in coring. The interval of *Halimeda* debris, which continues into the next core run, will be considered as starting at a depth of 50 feet.

Interpretation.—In the core run 43–53.5 feet, the abundance of large corals at the top, some of them in positions of growth; the encrusting *Homotrema rubrum* and *Lithothamnion;* and the prevalence of worm tubes and particularly of unworn tests of *Calcarina spengleri,* all suggest that the material grew on a reef in very shallow water. On the other hand, the dominance of *Halimeda* at the base of the core suggests that the detritus accumulated in a lagoon. The presence of unworn *Calcarina* with the *Halimeda* indicates that the water was shallow and that the reef was near by. Deposition may have been continuous as reef corals encroached on the lagoon. The thinly laminated brown porous carbonate between the corals and the *Halimeda* debris, however, shows the possibility of a break in deposition, possibly even a period of subaerial exposure after the *Halimeda* debris was laid down and before the large corals grew. Such a break cannot be postulated until more is known of the nature of the brown laminated and porous material.

Uncemented chalk-white *Halimeda* and foraminiferal debris (pl. 36, fig. 4). Several core pieces as much as 9.5 cm long were recovered. These were completely uncemented and slacked quickly in water. The material is extremely porous. An approximate size analysis of loose material from the top of the core follows:

Method and recovery	*Depth (feet)*	*Thickness (feet)*
Core run; 4 ft	64	10.5

Size, in millimeters	Percent	Description
0.01–0.5	25	Angular to rounded chalky grains with a few clear crystalline grains.
0.5 –1.5	15	Foraminifera (about half) and angular chalky grains.
1.5 –3	30	*Halimeda*, Foraminifera, a few gastropods.
3 –5	15	Coral fragments, *Halimeda*, a few gastropods.
5 –10+	15	Coral fragments, broken limestone fragments.

The corals are dominantly branching *Porites*, with some fragile *Acropora*. The Foraminifera are mainly *Calcarina spengleri*, *Marginopora*, and *Amphistegina*. A few encrusting *Sagenina* and a very few bryozoans are found on worn *Halimeda* segments.

Two thin sections made from specimen 2–3–4 show about the same distribution of grain size and organisms reported above, although no corals or gastropods are present. Some sections of *Halimeda* are medium-brown with dark-brown to black cloudy areas near the well-defined borders, as in sections made of fresh *Halimeda* from dredge hauls. Others are light-brown with no black areas, and have less well defined borders of microgranular carbonate that grades into the matrix (pl. 60, fig. 1), showing that some disintegration of the segments has taken place. *Calcarina* and *Amphistegina* are unworn, and some of the *Calcarina* tests have carbonaceous coloring in the fibrous calcite of the cell walls.

Interpretation.—The material in this core run is very fresh, although a few *Halimeda* segments are partly disintegrated. From the assemblage of organisms it is apparently a shallow lagoonal sediment, and from the number and freshness of the *Calcarina* tests, must have been deposited very close to the lagoon margin of the reef.

The core probably came from below 70 feet, for the first part of the interval drilled rapidly, as if it were unconsolidated sand. The material is light-tan moderately cemented coral and foraminiferal sand. *Calcarina spengleri* and *Halimeda* are abundant, small mollusk shells and angular, broken fragments of large mollusks are common. The material is porous, and there is fine chalky powder in the interstices of grains. The *Calcarina* tests are tan and fresh looking, but *Halimeda* segments are chalky and partly decomposed. Corals, some of them encrusted with *Lithothamnion*, include *Acropora* and types similar to *Montipora* and *Platygyra.* The more massive corals have little apparent alteration even under the binocular microscope, but the delicate *Acropora* digits are soft and chalky in their interiors, though they have a dense outer crust.

Method and recovery	*Depth (feet)*	*Thickness (feet)*
Core run; 2 ft	74.5	10.5

Coral makes up more than half of the recovered core, but probably does not represent more than 20 percent of the total material in the cored interval as it is more likely to be recovered than fine friable material, which washes away in drilling. *Calcarina spengleri*, *Amphistegina*, and other foraminifers probably make up about 40 percent, *Halimeda* about 20 percent of the total material. The proportions in this estimate are based on the assumptions that the recovered core came from the interval 70–74.5 feet, and that none of the material from 64 to 70 feet was recovered. The unrecovered part presumably contained fewer large corals.

Specimen 2–4–2 (5.2-cm core).—Packed, cemented but friable foraminiferal sand. *Calcarina spengleri* are very abundant, *Halimeda* are abundant, and some mollusk shells are present. In thin section the *Halimeda* segments are a pale translucent yellow, with low relief and a slight birefringence due to included minute acicular crystals. Borders of the *Halimeda* are irregular and the central pores are completely filled with finely crystallized carbonate.

Specimen 2–4–3 (5.4-cm core).—This is similar to the preceding specimen, but *Halimeda* segments in thin section are brown with dark, well-preserved borders.

Specimen 2–4–4 (5.4-cm core).—White to pale yellowish-tan coral. One coral is growing over another of different type, separated from it by a microgranular mud or paste that is dark brown in thin section. Under crossed nicols the paste is resolvable into a mat of finely crystalline, moderately birefringent carbonate.

The corals are apparently unaltered, although a few of the pore spaces are filled with a mosaic of fine recrystallized carbonate.

Specimen 2–4–4A (4.8-cm core).—Two corals are separated by 4 to 5 mm of *Lithothamnion.* The lower coral in particular has several small cavities that are half filled with a compact white limy paste. The surface of the paste is parallel in all cavities and normal to the sides of the core.

	Method and recovery	Depth (feet)	Thickness (feet)

In thin section the cavity-filling paste is a microgranular carbonate; the flat top surface of the paste is coated with finely crystalline carbonate. The coral preserves an original fibrous aragonite structure only in part. Much of it is altered to a light-gray microgranular carbonate that preserves only faintly the wavy extinction of the original feathered aragonite.

Specimen 2–4–5 (5.6-cm core).—Coral limestone containing fine foraminiferal sand in crevices. In several half-filled cavities, the tops of the filled surfaces are oriented perpendicular to the sides of the core. Some of the coral is unaltered but the center of a delicate *Acropora* is altered to a chalky powder. In thin section most of the corals show a strong aragonitic feather structure under crossed nicols. The chalky center of the *Acropora* just mentioned preserves the structure of delicate septa, and even shows a faint wavy extinction under crossed nicols, but under high magnification is seen to be formed of unoriented microcrystalline needles, probably of aragonite. The original parallel acicular crystals of aragonite have partly broken down into very fine needles that are only partially oriented to give a roughly parallel extinction.

Specimen 2–4–6 (7-cm core).—Branching coral, probably *Acropora,* in a matrix of *Halimeda* and foraminiferal sand. Abundant Foraminifera are mostly *Calcarina spengleri,* with many *Amphistegina* and some *Marginopora.* They are tightly packed, but the rock is porous and friable. The coral is overgrown by about 5 mm of *Lithothamnion* and in one place by an encrusting foraminifer.

In thin section the original aragonitic structure of the coral is well shown. A few pores are coated with aragonite needles in optical continuity with the coral, and are separated from it by a brown "dark line" marking the original surface of the pore. The unaltered coral is pale yellow under plane light whereas aragonite coating the pores is colorless.

Halimeda segments are yellow brown to dark brown in plane-polarized light. Central pores are filled with a clear mat of microgranular carbonate. *Calcarina* tests are well preserved, but some have a very hackly surface in thin section and are broken down to fine-grained calcite with some optical continuity.

	Method and recovery	Depth (feet)	Thickness (feet)
The material cored is very similar to that in the preceding core run. More than 75 percent of the recovered core is made up of corals, including several colonies in position of growth. They are in a matrix of foraminiferal-algal sand containing abundant mollusk shells and fragments. The corals include *Acropora, Stylophora, Heliopora, Montipora*? and *Favia*?, and some are coated with *Lithothamnion,* encrusting foraminifers, worn tubes and gastropod borings. Some of the core pieces are moderately well cemented but others are friable. All are very porous.	Core run; 4 ft.	95. 5	21

In the interval from 80 to 88 feet the cuttings consisted almost entirely of white *Halimeda* segments, according to J. H. Johnson, who was watching the drilling at that depth. The proportion of *Halimeda* in the recovered core, however, is small.

If we assume that corals are much easier to recover than *Halimeda,* and if we consider that the foraminifers dominate *Halimeda* in the recovered core, we may roughly estimate the proportions of organisms in the interval 74.5–95.5 feet to be about 40 percent Foraminifera; 30 percent *Halimeda*; 20 percent corals; and 10 percent mollusks, *Lithothamnion,* other organisms, and unrecognizable detrital grains.

Specimen 2–5–1 (6.8-cm core).—Foraminiferal-algal debris containing coral (*Acropora*) with some encrusting *Lithothamnion.* The Foraminifera mostly *Calcarina* and *Amphistegina,* are well cemented. *Halimeda* segments are chalky. In thin section the coral consists of strongly feathered aragonite with minor acicular aragonite encrusting small pores. Dark-brown, nearly opaque *Lithothamnion* encrusts a part of the coral. *Halimeda* is brown to brownish gray and microgranular, and shows poorly defined borders that appear disintegrated. In thin section some of the *Calcarina* tests are seen to be calcite that appears massive but shows a wavy extinction cross. Others appear fractured, and under high magnification are seen to be microgranular, but they still show faint extinction crosses. The "limy mud" matrix of the core is a fine-grained to microgranular paste. Grains of organic origin are present but poorly defined, and a mosaic of calcite crystals from 0.05 mm to less than 1 micron has filled pores and grown through the paste, obliterating some of the organic structures. Paste that fills cavities in the coral is gray, microgranular, and contains small spherulites 0.02 to 0.04 mm in diameter.

	Method and recovery	Depth (feet)	Thickness (feet)

Specimen 2–5–8 (4.5-cm core).—Coral (*Acropora*) encrusted with *Halimeda* and *Calcarina spengleri*. Between individual fingers of the coral is a porous, cellular coral growth, probably a part of the same colony. In thin section the material of both the *Acropora* fingers and the cellular growth between, is seen to be unaltered aragonite. Several cavities are half-filled with gray microgranular carbonite paste, and the surface of the paste in each cavity is normal to the core axis.

Specimen 2–5–10 (6.2-cm core).—Coral, probably, *Acropora*, with some cavities and with encrustations of *Calcarina spengleri*, *Amphistegina* and *Halimeda*. In thin section the structure of the coral is seen to be largely unaltered although in a few small areas the aragonite of the original coral has apparently recrystallized to larger crystals that may be calcite.

Specimen 2–5–12 (8.6-cm core).—Coral, probably *Porites*, apparently impregnated with carbonate in places. In thin section most of the coral shows finely feathered aragonite. In some areas tiny needles of aragonite line pore spaces in optical continuity with the original crystals. In other patches within the coral walls, the rudely oriented aragonite crystals have broken down into a very fine, almost microgranular mosaic of calcite.

Specimen 2–5–13.—Light-tan foraminiferal sand. The Foraminifera (about 50 percent, mostly *Calcarina spengleri*) and *Halimeda* segments (about 25 percent; chalky and disintegrated) are packed in a white, powdery matrix (25 percent) that is cemented in some places, but very friable in others.

In thin section the organic fragments and grains are seen to be cemented by fringes or coatings 0.03 to 0.1 mm thick, of elongate needles, probably aragonite. The needles in some places are parallel and well formed, though closely packed. In others, they appear to have broken down into a jumble of tiny broken fragments, but have not been recrystallized into a calcite mosaic. The breaking down was not caused by grinding of the thin section, but is a disintegration in the rock itself that extends across the former cementing fringe into the central parts of some of the *Halimeda* segments and foraminifer tests.

Interpretation.—A thick cementing fringe of acicular aragonite is rarely found in any of the material cored at Bikini. Fringes of aragonite as well developed as in specimen 2–5–13 have been seen only in thin sections of beach sandstone from present-day beaches. There is, however, no other evidence to suggest any of the material cored in this interval represents a former beach deposit. No stratification is apparent, and there are no rounded and polished grains or coral fragments such as are found in almost all present-day beaches. It is not known whether beach conditions or emergence are necessary for the formation of thick acicular cementing aragonite, or whether such material can form below sea level.

The organisms from 64 to 95 feet all suggest shallow, near reef conditions, probably in a lagoon bordering the reef. Recrystallization is minor, but the acicular cementing material at least suggests a possible origin at beach level, or an elevation to or above low-tide level at some stage in the reef's later history.

	Method and recovery	Depth (feet)	Thickness (feet)
The first 10.5 feet of this interval was cored in only 12 minutes, the second in 23 minutes, suggesting a change in lithology at about 105 feet. The upper part of the recovered core consists of broken coral fragments and coarse, cemented detritus containing a number of well-worn, rounded and somewhat polished pieces of coral 1 to 3 cm long. Their resemblance to beach pebbles is striking. Under the ultraviolet lamp they fluoresce with a dull to medium orange-yellow color that resembles but is not as bright as the orange fluorescence of wave-polished surfaces of beach rock. Numerous tests of *Calcarina spengleri* are found in the cemented detritus.	Core run; 1 ft	116. 5	21

The lower part of the recovered core is tan to white, compact, well-indurated limestone. Corals are common, especially fragile *Acropora*, in a compact, fine-grained matrix indurated by crystalline carbonate. The corals are coated with a layer of *Lithothamnion* 1 to 3 mm thick. Outer parts of corals are compact and crystalline, but are riddled with tiny cavities that are filled or partly filled with white porcelaneous carbonate. Centers of the corals preserve original structure but cell walls are powdery and friable. *Halimeda* segments, *Marginopora* tests, and small gastropod shells are common. Most of them seem to be unaltered. *Calcarina spengleri* is not present in the lower part of the core.

Specimen 2–6–4 (4.5-cm core).—This is composed of about 50 percent angular to well-rounded pieces of coral in a well-cemented matrix of detrital limestone containing foraminiferal tests. The coral pebbles include staghorn *Acropora* and *Stylophora*. They are white, some are polished and pitted, and a few have a faint orange to pink stain on them.

Specimen 2–6–5 (7.3-cm core).—Moderately firm, white coralliferous limestone. The corals, encrusted with foraminifers, are in a matrix consisting of foraminiferal tests, mollusk shells, and fine detrital grains.

In thin section the matrix surrounding the corals is seen to consist of organic remains and of angular calcite grains 0.01 to 0.1 mm in size, in a brown microgranular paste.

Under high magnification with crossed nicols the paste appears to be a mat of highly birefringent grains of needles mostly less than 1 micron in length.

Corals are apparently unaltered and contain cavities as much as 1 mm across, filled or partly filled with a gray paste of microgranular carbonate. A solid mosiac of clear crystalline calcite fills the rest of the cavities and in many places has partly replaced the paste in irregular veinlets. Some cavities near the center of the coral are filled with fragile needles, probably of aragonite, that have grown from the coral walls. Mollusk shells are apparently unaltered aragonite, but many of the foraminiferal tests are indistinct and appear to be altered.

Specimen 2–6–6 (3.8-cm core).—Similar to specimen 2–6–5. In thin section the coral is seen to be surrounded by a *Lithothamnion* crust. The coral is apparently unaltered near its borders, but the central part has been recrystallized to a mass of acicular crystals. The needles have grown from both sides of fine dark lines that form a labyrinth-like maze through the center of the coral. The lines, under high magnification, are apparently cracks 0.002 mm thick or less, on either side of which is a zone of microgranular carbonate 0.004 to 0.01 mm thick, from which the acicular crystals 0.05 to 0.1 mm long extend normal to the dark lines. The outer ends of the crystals meet others in irregular fashion, or they terminate with good crystal boundaries in small open spaces. Parts of the coral, between the central mazelike part and the outer unaltered part, have broken down or recrystallized into a mosaic of fine grains. Cavities in the coral are filled partly by gray microgranular paste, the rest by a finely crystalline mosaic of clear calcite that has partly replaced the gray paste.

This specimen was stained by boiling in Meigen's solution. Unaltered parts of the coral were stained a lavender color, but the altered center as well as the filled cavities were unstained, suggesting that they have recrystallized to calcite.

Interpretation.—In this core run there is a change, probably at 105 feet, from a poorly cemented, rather coarse sand containing worn and polished pebbles, to a dense coralliferous limestone in which the centers of corals have recrystallized, and a crystalline mosaic of carbonate, probably calcite, has filled empty cavities or has replaced and veined microgranular carbonate paste.

Method and recovery	Depth (feet)	Thickness (feet)
Core run; 1.5 ft	137. 5	21

The top foot of the recovered core consists of broken fragments of friable fossiliferous "chalk." It is fine-grained and crumbles to a powder with a gritty feel. *Halimeda* segments are common, very chalky and altered. *Marginopora* and coarsely crystalline *Amphistegina* are the most abundant foraminifers. No *Calcarina spengleri* are present but Rita Post found numerous tests of *Calcarina hispida.* Thin-walled pelecypod shells, seemingly unaltered, are common. The bottom one-half foot of the core is part of a large coral, *Astreopora*, massive and apparently unaltered.

It seems probable that the whole interval was friable fine-grained material and that no more was recovered after the bit cut through the large coral because the coral prevented loose material below from entering the core barrel.

Specimen 2–7–2 (6.2-cm core).—White chalky fine-grained, very friable limestone. Some small patches are compact and crystalline. In thin section (pl. 60, fig. 2) the material is seen to consist of angular detrital grains mostly 0.05 to 0.5 mm in diameter. Most are recognizably of organic origin, and rare larger pieces as much as 1 or 2 mm in length are fragments of *Halimeda, Marginopora* and mollusk shells. In part the grains are poorly cemented by finely crystalline to microcrystalline carbonate that fills small cavities. Under crossed nicols most of the grains as well as the cement are seen to be finely crystalline to microcrystalline. Only a few mollusk fragments seem to preserve any original crystalline structure. The *Halimeda* and *Marginopora* fragments are tan to yellowish brown and are almost opaque under crossed nicols. Under high magnification the brown material is seen to contain scattered grains or needles, 1 micron or less in length, that are highly birefringent.

Interpretation.—The material of this interval is considered to be a lagoonal facies. The occurrence of *Calcarina hispida* is significant, for this species is abundant in the present-day lagoon below 10 fathoms. The material is probably similar to that cored in the bottom of the previous run, and the change from gravelly sand containing *Calcarina spengleri* to partially recrystallized rock containing *Calcarina hispida* is considered to be at 105 feet. This correlates with a similar change at 95 feet in hole 1, and 61.5 feet in hole 3. It is also at a depth slightly lower than the present lagoon terrace at Bikini island.

Method and recovery	Depth (feet)	Thickness (feet)
Core run; 2 ft	158.5	21

The interval from 137.5 to 147.5 feet drilled quickly and smoothly, whereas from 147.5 to 158 feet the drill chattered noisily. Samples of cuttings consisted mostly of fine material. As the recovered core was largely coral fragments, it probably came from the lower part of the interval, which drilled noisily. The corals were probably embedded in a detrital, friable matrix, very little of which was recovered.

The corals, *Porites*, *Astreopora*, and *Seriatopora*, are well preserved. Some pores are filled with a fine chalky material, but most are open. Worm tubes, burrows of gastropods, and encrusting Foraminifera are common. The matrix material is unsorted detritus containing abundant *Halimeda*, and common *Amphistegina*, *Marginopora*, and *Calcarina hispida*. Small coral fragments are preserved only as powdery white molds, and most mollusks seem to be present only as molds.

Specimen 2–8–7 (5.1-cm core).—Coral similar to *Porites*. The pores are filled with a dense white material that has a crystalline sparkle under the binocular microscope, although the coral itself is apparently unaltered.

In thin section, the coral structure seems little altered although in places the aragonite is disorganized and the feathered structure is obliterated. Many of the pores are filled with a gray microgranular paste containing small spherulites and abundant small organic fragments. Most of the unfilled pores are lined with acicular needles, probably aragonite, that are optically continuous with the coral structure. Some of the pores are completely filled by the growth of these fine crystals.

Specimen 2–8–13 (4.7-cm core).—Coral (*Porites*) with no evidence of any alteration. A few of the pores are filled with a very fine microgranular carbonate which under high magnification is seen to be formed of needles about 4 microns long and 1 micron wide. Some patches or fragments of calcite are present, generally not more than 0.05 mm in diameter. Some are angular; others have a nearly circular cross section.

Method and recovery	Depth (feet)	Thickness (feet)
Core run; 5 ft	169	10.5

Of the 5 feet recovered in this unit, more than 80 percent is coral. This means that at least 40 percent of the 10.5-foot interval was coral; and as some of the coral, as well as fragmental detritus of other organisms, was no doubt lost in the coring, it is probable that more than 50 percent of the material in the interval was composed of coral.

Corals, some of which are upright, include *Astreopora*, *Heliopora*, *Pocillopora*, *Porites*, *Seriatopora*, *Favia*? and possibly *Galaxea*, a Recent genus not known on the present reefs at Bikini Atoll. The surfaces of the colonies are coated with encrusting foraminifers, worm tubes, bryozoans, or *Lithothamnion*. Cavities in the corals are lined with *Halimeda* segments or with small Foraminifera, mostly *Amphistegina*, *Marginopora*, and *Calcarina hispida*. The matrix surrounding the corals is a rather coarse, poorly cemented white foraminiferal-algal detritus.

Specimen 2–9–3 (10-cm core).—Coral (*Porites*) on which there is an encrusting foraminifer. Both are covered by a layer of coarse coral. Both corals are apparently in position of growth. Some *Halimeda* segments and *Marginopora* are clinging to the surface of the *Porites*. A thin section was made across the *Porites* and the encrusting coral. Under the microscope part of the surface of the *Porites* is coated with an encrusting foraminifer, probably *Homotrema*; the rest is covered by a thin layer of a coarse coral, which has completely recrystallized to a coarse calcite mosaic. Pores in the encrusting coral are filled with a carbonate that in places is finely acicular. Dark carbonaceous lines form a network within the pore filling and appear to be remnants of gray microgranular paste that had filled the pores but has since been recrystallized.

The structure of the large *Porites* is apparently unaltered. It is formed of finely fibrous acicular aragonite that is rather disorganized in many places.

Specimen 2–9–8 (5-cm core).—A coral rock, probably a *Heliopora*, still preserving a faint yellow-green color. Several cavities within the coral are partially filled with compact white porcelaneous limestone. All surfaces of the white filling are flat and are parallel, normal to the core axis.

In thin section the solid parts of the coral structure are acicular aragonite in most places, but here and there this has broken down to a fine crystalline mosaic.

Specimen 2–9–16 (11.5-cm core).—Coral, probably *Porites*, apparently unaltered except for a small recrystallized patch at one end of the specimen. Under the ultraviolet lamp, this patch fluoresces with a white color whereas the rest of the coral fluoresces a medium yellowish-brown. A thin section was cut across the crystalline patch.

Under the microscope the unaltered coral is composed of aragonite that is finely fibrous in thin walls and coarsely fibrous in thick walls. The coral walls are plainly apparent in the recrystallized part of the coral, but coral walls and pores alike are pervaded by a coarsely crystalline calcite mosaic with well-developed interlocking grains.

The border between the recrystallized patch and the unaltered coral is abrupt in a few places, but in most there is a narrow zone of transition in which the fibrous aragonite of the coral has broken down into a mat of disorganized fine grains and needles. The crystalline mosaic seems to have grown in this mat, at first near the centers of the coral walls, and later near the edges.

Specimen 2–9–22 (7.5-cm core).—Coral (*Astreopora*) containing coarse pores, some of which are filled with crystalline carbonate. Top surfaces of partially filled pores are oriented with respect to the core axis. In thin section delicate cell walls are seen to be unaltered fibrous aragonite. Pores are filled with dark-gray fine-grained to microgranular paste containing small organic fragments of which a few are recognizable tiny Foraminifera. Part of the coral retains its original aragonitic structure but pores are filled with acicular aragonite. The aragonite needles are in optical continuity with the aragonite of the coral where they join it, but under plane-polarized light the coral aragonite is pale yellow, while that filling pores is clear and colorless. In areas where acicular aragonite has grown into some empty pores, other pores are filled with gray microgranular paste cut by an irregular network of clear microgranular carbonate that seems to be replacing the gray material.

Specimen 2–9–23 (4.6-cm core).—White moderately well cemented but chalky calcareous detritus—dominantly *Halimeda* segments. In thin section the constituents are seen to be largely coarse organic grains and fragments cemented by acicular aragonite. The materials in the slide are approximately 40 percent *Halimeda*, 10 percent *Amphistegina*, *Marginopora* and smaller Foraminifera, 5 percent mollusk fragments, 1 or 2 percent coral fragments and encrusting foraminifers, about 15 percent grains of unknown origin, and about 30 percent cementing material and empty spaces. Grain size ranges from 0.1 to 3 mm or more and averages about 0.5 mm. The needles of the acicular aragonite cement range in length from 0.02 to 0.2 mm averaging about 0.01 mm.

The borders of most grains are clear and sharp, but those of *Halimeda* fragments are very irregular and jagged as if the acicular needles of the cement were growing into as well as away from the grain. A fine "dust line" of black specks, marking the original boundary of the *Halimeda* grains, forms a rather sharp line which the acicular aragonite crystals penetrate. Such dust lines are not present about grains of any other organisms. The *Halimeda* fragments are yellow in plane-polarized light, but under crossed nicols they are medium to dark yellowish brown and under high magnification they show minute needles of high birefringence. The needles form a microgranular mat in light areas, but are scattered in darker areas.

Intrepretation.—In summary, the interval 158.5–169 feet contains a much higher proportion of corals than is generally found in the core. Some of these were apparently in position of growth, and many were encrusted with bryozoans, worms, and foraminifers. The absence of *Calcarina spengleri* and the presence of *Calcarina hispida* suggests that the water was more than 10 fathoms in depth, and the great abundance of corals suggests the possibility that the drill may have penetrated a former coral knoll within the lagoon. Inasmuch as the rock at this depth in hole 1 is likewise rich in corals, some in position of growth, it is more likely that the material accumulated at a time when coral growth was stimulated over much of the lagoon. The development of acicular aragonite in coral pores and in the cement, and the growth of crystalline calcite in corals, suggests a possible uplift above sea level. On the whole, alteration is minor, though much more pronounced than it was above 105 feet.

Method and recovery	Depth (feet)	Thickness (feet)
Core run; 1 ft	179.5	10.5

The core consists of broken fragments of coral, and a few fragments of moderately cemented detrital limestone containing *Halimeda* and Foraminifera, similar to that in the preceding core run. The interval drilled quickly and smoothly, and it seems likely that the proportion of coral in the rock is much lower than in the preceding core. Cementation is poor and patchy, and only small local areas were cemented firmly enough to hold up in coring. The relatively small amount of firm coral in this core run, when considered together with the preceding run, suggests that the drill had passed through firm rock in the upper part of a coral knoll into more detrital and fragmentary rock below.

Method and recovery	Depth (feet)	Thickness (feet)
Core run; 5.5 ft	190	10.5

The core is white, compact limestone, moderately to firmly cemented for the most part, but friable to unconsolidated at the very top, and chalky at the base. There are three apparent facies in this core although no abrupt breaks in deposition were noted. In the top foot are a number of remarkably well preserved gastropods and bivalves. The shells have their original luster and in a few places their original color. The shells and a rootlike mold more than 12 cm long, discussed below, are in a friable matrix of unsorted chalky detritus containing abundant small mollusks, Foraminifera and *Halimeda*. The next 2 feet of the recovered core is detritus, more consolidated than but similar in appearance to that in the first foot, containing several small gray to brown rounded pebbles in which there is a fauna somewhat distinct from that in the matrix. In the lower part of this interval the mollusk shells are molds or calcite casts.

The bottom 2.5 feet of the recovered core is fine detritus with small, sparse mollusk shells and fragments of Foraminifera and *Halimeda*. It is well consolidated in the upper foot, but friable and chalky at the bottom. Several pieces of core from this run were boiled in Meigen's solution. Specimens from the top part were deeply stained indicating that much aragonite is present; specimens from the middle part were lightly stained in small, friable areas but were unstained in compact crystalline areas; specimens from the bottom part were unstained, indicating that aragonite is absent.

Rita Post and Ruth Todd have identified *Rotalia calcar* from the lower part of this core run. The species was also identified by them at an equivalent depth in hole 1. *Rotalia calcar* is a Recent species common in shallow waters of the Indo-Pacific region, but not found in the lagoon, reef, or offshore dredge samples studied from Bikini Atoll.

Ladd has studied a suite of mollusks from the core run and had identified a number of species including *Lioconcha* cf. *L. picta* Lamarck, *Cerithium vertagus* (Linnaeus), and *Strombus gibberulus* Linnaeus. *L. picta* lives today in Bikini Lagoon at depths of 2 to 25 fathoms; *C. vertagus* is not found at Bikini Atoll but is common in shallow waters of the Indo-Pacific region. *Strombus gibberulus* is a widely distributed Pacific species very common in the Marshall Islands. At Bikini Atoll it was very abundant in the lagoon at depths of 3 to 15 fathoms. Shells are found in the intertidal zone and may therefore reach outer slopes.

In the following detailed descriptions, specimens 2–11–1a, 2–11–3 and 2–11–4 come from the top foot; specimens 2–11–7, 2–11–15 and 2–11–16 from the middle 2 feet; and specimens 2–11–19 and 2–11–20 from the bottom 2.5 feet of the recovered core.

Specimen 2–11–1a.—Broken fragments containing a rootlike mold. The fragments when pieced together form a roughly round to oval hollow tube, 5 to 8 mm in diameter and at least 12 cm long, nearly straight but gently and irregularly twisted. It was almost vertical in the rock, otherwise such a long piece could not have been cored. The rock around the mold consists of poorly consolidated white chalky detritus which contains small mollusks, Foraminifera, and *Halimeda*, and which has been indurated irregularly for 1 to 10 mm around the cavity. Where indurated, the rock is light- to dark-brown, compact carbonate. All organic remains are destroyed in the darker part of the indurated rock. The inside surface of the cavity is encrusted with a thin carbonate coating less than 0.5 mm thick, but in a few places there is a poorly visible longitudinal fibrous striation.

Frederick Bayer of the U. S. National Museum has suggested that the mold may be a twisted gorgonid stem, although no spicules were found in the detrital material, nor was the solid calcite base found.

Specimen 2–11–3 (2.9-cm core).—White, compact, moderately cemented but somewhat chalky detrital limestone containing abundant mollusks (some rather disintegrated), *Halimeda*, and Foraminifera. In thin section the constituents may be divided in three groups. Grains from 3 to 0.5 mm in size, mostly less than 1 mm, form about 20 percent of the slide including 5 percent recognizable mollusk shells and fragments, 5 percent *Halimeda* segments, and 10 percent broken fragments mostly of *Halimeda* and *Lithothamnion*. Grains from 0.5 to 0.03 mm, mostly about 0.1

mm, form about 50 percent of the slide; these grains are subangular to angular fragments of organic origin and are cemented by microgranular to finely granular carbonate that fills pores in parts of the slide, and forms a very thin fringe about grains in other parts. Open pores plus cementing material form the remaining 30 percent of the slide. The cementing carbonate is not acicular. Where it fills the pore spaces fine interlocking calcite crystals have grown in the microgranular material. Under the ultra-violet lamp most of the specimen fluoresces with a yellow to pinkish-tan color, whereas well-cemented patches are medium to dark brown.

Specimen 2–11–4 (4.6-cm core).—This piece is very similar to the one preceding. In thin section the cementing material is microgranular next to grains, but is fine grained and crystallized toward open spaces. The cementing crystals are elongate and although they appear to be a mosaic under low magnification, they show a poor parallel orientation under high magnification (×350).

When the specimen was boiled in Meigen's solution, the chalky spaces between grains were stained lavender, indicating that the cementing material is aragonite rather than calcite.

Specimen 2–11–7 (3.6-cm core).—This piece, similar to the two preceding, contains shell cavities as well as powdery, somewhat disintegrated mollusk shells.

In thin section coral fragments form about 20 percent, mollusk shells about 10 percent, and unsorted angular grains make up the remainder. Coral fragments are present, coated with *Lithothamnion* and encrusting Foraminifera. The structure of the coral fragments is partly broken down, but they are apparently aragonite. Some cavities are filled with a coarsely crystalline calcite mosaic.

Specimen 2–11–15 (12-cm core).—White, well-cemented detritus containing several large gastropod molds. There are several small pebbles 5 mm to 3 cm in length, of compact tan to brown foraminiferal limestone. The detritus is composed of abundant mollusks, coral fragments, some broken small *Halimeda* grains, a few small *Marginopora* fragments and much fine angular debris. The pebbles mentioned contain abundant unbroken *Marginopora, Rotalia calcar* (first occurrence in the hole), large *Halimeda* segments, and medium detrital grains. No mollusks or corals are present.

In thin section many of the mollusk molds are filled with a medium-grained mosaic of calcite with good rhombohedral cleavage. Some shells still have their original fibrous structure. A few that appear unchanged under plane-polarized light and show a brown lineation parallel to the shell, are seen under crossed nicols to be formed of interlocking, roughly parallel crystals that are perpendicular to the shell walls. In these the original material has recrystallized, whereas the clear calcite mosaic filling some molds may have been deposited as a cavity filling. In some places the fragmental grains of the limestone have been replaced by crystalline calcite, for both grains and matrix are formed of clear medium-grained calcite mosaic. The relict grains are distinguished only by their borders that remain as fine dark lines of microgranular carbonate.

Within the pebbles the organic shells and detrital grains are in a tan microgranular paste that grades to brown near the borders of the pebbles. The outermost 1 or 2 mm of the border is dark brown, and any organic structures originally present have been obliterated (pl. 57, figs. 2, 3). Several cavities in the pebbles, some cutting through the brown border, are filled with fine detrital grains similar to those surrounding the pebbles. In several cavities the lower half is filled with detritus, the upper half with a calcite mosaic. The flat upper surfaces of the cavity fillings in the pebbles are all upright in the core. The calcite mosaic that forms the cement both outside the pebbles, and in the cavities within the pebbles, has penetrated and replaced the borders of the pebbles in tiny veinlets. Remnant shreds and patches of the brown pebble borders are surrounded by clear calcite mosaic. A lesser amount of calcite crystallization has developed within the brown microgranular paste in the pebbles. This is clear and well crystallized, and probably formed at the same time as the calcite cement outside the pebbles.

The central part of the pebble is less altered than the borders, and organic remains, especially tests of foraminifers, stand in sharp contrast to the finely crystalline clear calcite that surrounds the grains (see pls. 6, 3, in report on fossil Foraminifera by Todd and Post, Prof. Paper 260–N, vol. 3, pt. 4.

The specimen was boiled in Meigen's solution, and most of the rock was unstained. Small chalky patches were stained a pale lavender, but the recrystallized areas and the pebbles were unstained.

Interpretation.—There are several successive stages of deposition recorded here. The pebbles come from an older deposit. Whether they were indurated before or after they were formed from the parent deposit is not known, but a "weathering" process of some sort altered their borders and effaced the organic remains. Boring organisms riddled them with cavities that were filled as the pebbles were covered by sediments. Lastly, calcite was deposited filling all open cavities and pore spaces, and partly replacing some shells and pebbles.

Specimen 2–11–16 (5.4-cm core).—Compact, well-consolidated detrital limestone containing some gray to tan rounded pebbles of limestone.

In thin section the matrix is seen to contain grains of microcrystalline to fine-grained carbonate, *Halimeda* fragments, rare fragments of *Marginopora,* and some *Amphistegina* and miliolid tests in a fine-grained to microgranular, clear, crystalline calcite mosaic. Mollusk shells and fragments are casts of clear calcite in interlocking grains. The pebbles contain abundant tan to brown grains of microcrystalline carbonate, abundant *Halimeda* segments, *Marginopora, Rotalia calcar, Amphistegina,* and miliolids, in a microgranular paste that is tan to brown under plane-polarized light and medium to dark yellowish brown under crossed nicols. Fine-grained crystalline calcite in interlocking grains has formed within the pebble, clear where it fills pore spaces, and pale yellow where it has recrystallized from the tan microgranular paste.

The largest pebble, 3.4 by 2 by 1.5 cm in size, is brown microcrystalline to nearly cryptocrystalline carbonate. Under low magnification it shows cloudy, irregular light- and dark-brown bands and only vague traces of organic remains. The boundaries of the pebbles are rather irregular under high magnification and are penetrated by tiny veinlets and apophyses of the clear finely crystalline calcite that fills pore spaces in the material outside the pebbles. Shreds of the pebble borders are separated from the pebble and are apparently replaced by clear calcite. The relations are in all respects similar to those observed in thin section in the preceding specimen, 2–11–15; although no partially filled cavities were observed in pebbles in this specimen.

Specimen 2–11–19 (2.5-cm core).—Fine-grained, compact, well-consolidated white limestone. A few brown patches of dense, crystalline carbonate are present but the borders are irregular and they are evidently not pebbles.

In thin section the constituents are mainly small detrital grains. Minute foraminifers, *Marginopora* and *Halimeda* are abundant, and *Rotalia calcar* and *Amphistegina* are common. The detrital grains are gray or brown, microgranular, with rather vague dark borders. Some *Marginopora* and *Halimeda* have indistinct borders. Smaller Foraminifera are brown and resinous in appearance, and under crossed nicols are dark. *Calcarina* and *Amphistegina* are rather coarsely crystalline, with wavy extinction. The grains lie in a gray microgranular paste that fills pore spaces within as well as outside the organisms. In the centers of some of the pore spaces is a finely crystalline calcite mosaic, and some open pores are lined with a very finely crystalline calcite. (See photomicrograph of the adjacent specimen 2–11–20, pl. 61, fig. 1). The brown patches in the specimen appear brown in thin section, are microgranular to very finely granular, and they grade into the gray microgranular paste. In places within the brown areas organic remains that were present have been almost obliterated; in other places they are apparently unaltered.

Specimen 2–11–21 (3-cm core).—Similar to specimen 2–11–19, but in thin section the material is more recrystallized. Many detrital grains as well as some of the foraminiferal tests are present only as dark outlines. Such grains as well as the matrix are clear, finely crystalline calcite mosaic that is microgranular at the dark lines of the borders. No fine opaque particles are present at the dark borderlines of the grains; they appear dark only because of their microgranular nature. *Rotalia calcar, Amphistegina, Marginopora,* and many small foraminifers are abundant. Mollusks are present as open molds or crystallized casts.

Interpretation.—The dominance of mollusks in the top part of the core run 179.5–190 feet, the abundance of small *Marginopora* and *Rotalia calcar* in the bottom part, and in the middle the presence of altered pebbles containing organisms of the lower part in a matrix similar to the upper part, suggest that the run represents two dissimilar environments separated by some erosion, not necessarily at or above sea level. Two types of alteration are present: the first characterized by the breaking down of grains into microgranular material and into brown microcrystalline carbonate that appears to have obliterated some organic remains, and the second by the filling of cavities with finely crystalline mosaic, and by the strong development of crystalline calcite in microgranular material. Both types are present from top to bottom of the core, but both are strongest in the middle and bottom parts of the interval.

Drill hole 2A

[At a depth of 190 feet, in attempting to set casing in hole 2, a pipe wrench was dropped in the hole. The rig was moved 9 feet, the hole was redrilled to 192 feet, and 189 feet of casing was set. The hole was numbered 2A; total depth 1,346 feet]

	Method and recovery	*Depth (feet)*	*Thickness (feet)*
The material is a friable, chalky, white calcareous detritus containing abundant small thin-shelled mollusks (specimen 2A–12–9, pl. 61, fig. 2).	Core run; 4. 5 ft	200. 5	8. 5

The material is a friable, chalky, white calcareous detritus containing abundant small thin-shelled mollusks (specimen 2A–12–9, pl. 61, fig. 2). There are many tests of *Calcarina hispida* and *Rotalia calcar*, and some of *Marginopora*. *Halimeda* is present but does not form a significant percentage of the material. Gastropods and pelecypods are well preserved, white, and lustrous. Some shell fragments are present but most shells are unbroken; many bivalves are hinged together. H. S. Ladd has identified *Parvilucina* sp., 2 species of *Cardium*, 4 tellinids, and 3 cerithids from the core. The tellinids are especially significant, as all 4 species are identical with Recent species dredged in the lagoon at Bikini and Eniwetok Atolls at depths of 12 to 25 fathoms.

Specimen 2A–12–4 (4.5-cm core).—Friable fine-grained calcareous detritus containing abundant small mollusks and Foraminifera. In thin section, mollusks, Foraminifera, and *Halimeda* form only about 5 percent of the area. *Marginopora* is common; *Amphistegina*, miliolids and smaller foraminifers are present. The bulk of the material consists of broken subrounded grains of carbonate 0.02 to 0.5 mm in maximum diameter that are poorly cemented by thin ragged fringes of microgranular to fine-grained carbonate, apparently calcite. Pore spaces between grains are open and occupy about 20 percent of the area of the slide. Many grains have thin dark borders that result from the breaking down of the surface of the grain into microgranular carbonate, but there is no recrystallization or replacement within grains by calcite mosaic, as in the bottom of the 179.5–190 foot core run immediately above this. Borders of foraminiferal tests are somewhat ragged, but those of mollusks are smooth.

Specimen 2A–12–7 (core fragment).—Constituents are very similar to specimen 2A–12–4. The thin section contains several small areas of fine grains in a brown microgranular paste similar to the pebbles in the 179.5–190-foot core. These areas have fairly well defined borders and apparently are pebbles.

Specimen 2A–12–15 (2.9-cm core).—Very friable calcareous detritus as in specimens above. Mollusks are common and some appear unaltered. *Marginopora* is common, mostly in broken fragments. A very few *Rotalia calcar* are present. Cementing material is even less in evidence than in the two preceding specimens. Borders of grains, however, are altered to a dark microgranular line.

Interpretation.—Core from this unit is similar to the top foot of the 179.5–190-foot core. Small, thin-walled bivalves and gastropods are abundant; *Marginopora* and *Amphistegina* are common, but Foraminifera form only a small part of the material which is dominantly fine but unsorted detritus, chalky and very friable. The chalky material is largely calcite but much aragonite is present. Cavity filling and recrystallization of calcite in the microgranular matrix are much less than in the preceding core (179.5–190 feet).

	Method and recovery	*Depth (feet)*	*Thickness (feet)*
The recovered core consists of several solid pieces 3 to 10 cm in length of chalky white, compact, moderately well cemented detrital limestone.	Core run; 2.0 ft	211	10. 5

The recovered core consists of several solid pieces 3 to 10 cm in length of chalky white, compact, moderately well cemented detrital limestone. Small mollusks are abundant, though less so than in the preceding core run. They are generally preserved as molds or as crystalline casts, although a few appear to preserve the original shell. Foraminifers, including *Marginopora*, *Amphistegina*, and *Rotalia calcar* are more abundant than in the preceding core. Corals are common, especially small pieces of *Seriatopora*. These are encrusted with Foraminifera about 1 mm in thickness, and although the cell structure is perfectly preserved their centers are soft and powdery. *Halimeda* segments are abundant.

Specimen 2A–13–3 (10.2-cm core).—Compact, moderately well cemented limestone. Corals are common, and form about 10 percent of the specimen. A small brown patch shows well-preserved *Marginopora* and other Foraminifera, but there is no apparent difference in the fossils inside and outside the patch, and its borders are vague and irregular. It is probably a well-cemented area rather than a pebble.

In thin section the material is composed principally of recognizable organic fragments. Foraminifers are abundant and form at least 40 percent of the matrix around the corals. Fine detrital grains are prominent but form less than 10 percent of the matrix. About 40 percent fine-grained calcite cement and 10 percent open pore space form the remainder of the matrix. The cement is coarser in the centers of filled pores and in the centers of chambers in organisms, and fine grained to microgranular near the walls of such openings. *Marginopora*, *Halimeda*, miliolids and smaller Foraminifera are brown and translucent in plane-polarized light and almost opaque under crossed nicols. In some places the borders of these organisms with the microgranular cement are well defined, but in most places they

	Method and recovery	*Depth (feet)*	*Thickness (feet)*
are diffuse and apparently gradational. Tests of *Amphistegina* have apparently recrystallized to solid calcite with a wavy extinction, and those of *Rotalia calcar* are grayish and microgranular in appearance. The chalky and extremely friable coral centers are finely granular to microgranular in thin section. The original acicular aragonitic structure apparently is completely broken down although outlines of coral cells are perfectly preserved. Outer edges of the coral colonies seem less altered and have a good feathered texture under crossed nicols, but under high magnification the crystals appear small and rather disorganized. *Interpretation.*—In this core run two types of alteration are evident that may be essentially contemporaneous. The first is the breaking down of some of the organisms into microgranular material, and the filling of pore spaces with gray microgranular paste; the second is the alteration of the microgranular material and paste into finely crystalline calcite. It should be pointed out that the greater lithification of specimens in this interval as compared with those of the preceding core run may be confined to the few pieces of recovered core. For the whole interval the development of recrystallized calcite may be no greater than that in the 192–200.5 foot core immediately preceding.			
Foraminiferal detrital limestone containing corals. The only solid cylindrical piece of core was a coral, and this piece seemingly prevented any more core being recovered. The interval drilled easily and quickly, and therefore was probably poorly cemented detritus like the preceding core runs. Specimen 2A–14–1 (fragments).—Mostly poorly to moderately cemented detrital limestone containing abundant Foraminifera, including large, chalky *Marginopora* and one large well-preserved *Heterostegina.* Some *Halimeda* is present, and mollusk molds are abundant. A few coral fragments are riddled, possibly by boring sponges. Specimen 2A–14–2 (9.5 cm core).—This piece is largely coral. Part of it looks like relatively unaltered *Acropora.* The rest is a large undetermined coral, partly coated by a thin brown carbonate, and apparently upside down, its pores filled with a porcelaneous white calcite. Within the coral is a large cavity 1 cm wide, partially filled with fine-grained compact white limestone. The surface of the filling is flat and perpendicular to the core wall. On the surface of the cavity and of the filling are some foraminifers. The surfaces of the cavity, of the filling material, and of the foraminiferal tests are coated with fine well-crystallized calcite. The specimen was boiled in Meignen's solution, and most of the coral was stained lavender. Pore fillings, detrital material, and patches of altered crystalline coral were unstained. The coral areas that have broken down into fine-grained, disorganized needles are stained lavender, and are probably still aragonite. In thin section the coral structure is seen to be well preserved, but thin cellular walls have broken down from strongly feathered acicular aragonite to finely crystalline, disorganized needles. Pores are filled with a gray microgranular paste that has been replaced or recrystallized around the edges and invaded by fine veinlets of a finely crystalline mosaic of calcite. Where this recrystallization is strong the fine disorganized needles of the altered coral have likewise been recrystallized to calcite mosaic. Under the ultra-violet lamp the unaltered part of the coral fluoresces a medium reddish-brown; the rest of the coral is bluish-white. Material filling pores and cavities in the coral fluoresces white. *Interpretation.*—Alteration is stronger in the one thin section made of this core than in previous cores, but as so little of the 10.5-foot interval was recovered, the total amount of alteration may be small. No change of any consequence is evident in the fauna.	Core run; 1 ft	221. 5	10. 5
The recovered material includes some fragments of foraminiferal limestone in a fine-grained chalky matrix that was packed in the core bit. Organisms present are *Amphistegina,* also some well-preserved small shell fragments and echinoid spines. A few thin branches of *Seriatopora* are the only fragments of coral present.	Core run..	232	10. 5

	Method and recovery	*Depth (feet)*	*Thickness (feet)*
White, extremely friable chalk, containing thin-shelled bivalves. Fragments of the material placed in water slack in a few minutes to a white limy paste, extremely fined-grained with a gritty feel due to the presence of scattered foraminiferal tests and mollusk shell fragments. Specimen 2A–16–5 (fragment).—In thin section the material is visibly granular. The range of grain size is from about 0.01 to 1 mm, but of this granular part only 10 percent is larger than 0.1 mm, and few fragments are larger than 0.5 mm. Most of these are mollusk or coral fragments, but some are foraminifers. Some of the fragments are unaltered but others are casts of recrystallized calcite. The matrix of the grains is a tan to light-brown carbonate almost isotropic under crossed nicols. The 90 percent of finer material seems to consist mostly of angular grains of calcite and small spherulites of uncertain origin, but some of the grains are of organic origin and a few are small whole foraminifers. Under high magnification (× 360) and crossed nicols the material shows barely visible highly birefringent grains or acicular crystals 1 micron or less in length. In some places these are scattered, and the material is nearly isotropic. In other places they form a mat that gives a uniform birefringence. Less commonly the matrix is made up of somewhat larger crystals, 2 to 4 microns in length, that have a fairly bright aggregate birefringence. The matrix material is too fine grained to determine under immersion oils. Some of the chalky powder from this specimen was boiled in Meigen's solution, and was stained a deep lavender. Under the binocular microscope the material seemed to be rather uniformly stained except for rare white grains. However, when the fine grains were spread thin on white paper, individual grains appeared only slightly stained and the smallest grains were apparently unstained. It is impossible by these tests to determine the exact nature of the microgranular material.	Core run; 0.6 ft	242. 5	10. 5
The recovered material includes several fragments of core very similar to specimen 2A–16–5 just described. Mollusk shells and fragments are abundant. Some molds are present, but most shells are original aragonite that is rather friable and has a dull luster. Some thick clam shells are present. Among the mollusks identified by Ladd are an unworn shell of *Tellina* sp., and a worn shell of *Columbella* cf. *borealis* Pilsbry. The tellinid shell is identical to specimens dredged alive in Bikini Lagoon at a depth of 12 fathoms. Worn shells of *Columbella* comparable to the specimen from the core were dredged in Bikini Lagoon at 12 fathoms. Coral is rather abundant, especially broken staghorn *Acropora*. Most fragments have a thin limy encrustation, probably *Lithothamnion*, but a few are fresh in appearance. Some are recrystallized at their center to tan carbonate.	Core run; 0.3 ft.	253	10. 5
Coral, mostly staghorn *Acropora*, and mollusk shells and fragments are abundant as in the preceding interval. The matrix is a fine chalky detritus but is more consolidated than in previous core runs. Throughout the whole interval (253–263.5 feet), which was drilled much the same as the intervals above, the recovered fragments probably are scattered, well-cemented patches in a loose uncemented chalk.	Core run; 0.3 ft.	263. 5	10. 5
Rather compact, white, fine to medium-grained detrital limestone. Some of the core fragments are compact and well consolidated, others are rather friable. Mollusk molds are abundant in several consolidated core pieces and well-preserved bivalves are common, evidently from unconsolidated layers. Ladd identified *Arca* sp., *Cardium* sp., *Lioconcha* cf. *picta* Lamarck, *Circe*, and two tellinids, all identical or similar to species dredged from Bikini Lagoon, most of them at depths from 12 to 30 fathoms. Foraminiferal tests, especially of *Marginopora* and *Amphistegina*, are abundant but form only a small percentage of the core. Recrystallization and cementation of the core, although apparently greater than in previous core runs, may be minor for the interval as a whole and may even be limited to the few recovered pieces of core.	Core run; 0.7 ft.	274	10. 5
Crumbly, chalky, fine detrital limestone. Mollusk shells are present but poorly preserved. Corals are rare and those seen are powdery and barely recognizable. The fine material is similar to that in preceding intervals but is more friable and less cemented than in the 263.5- to 274-foot core.	Core run; 0.3 ft	284. 5	10. 5
The first 9 feet of this interval drilled rather fast, but the bottom 1.5 feet was firm and the core came probably from this part of the run. One piece is cylindrical core 13.6 cm in length, but most of the material is in fragments. The rock is a compact coralliferous white limestone, rather rotten in appearance, but moderately well cemented. Gastropod molds form large cavities. Corals form about 25 percent of the rock. Some are completely recrystallized to coarsely crystalline calcite whereas others have a central skeleton with open pores that appear to be etched and corroded. Friable powdery segments of *Halimeda*, and tests of *Amphistegina* and smaller Foraminifera are abundant.	Core run; 1 ft	295	10. 5

	Method and recovery	Depth (feet)	Thickness (feet)

Specimen 2A–21–2 (13.6-cm core).—Compact, white coralliferous limestone containing gastropod molds. Two thin sections made from this piece are so different that they will be discussed separately.

The first contains the following constituents: coral, about 10 percent; *Halimeda*, 10 percent; Foraminifera, 5 percent; and granular detrital material, mostly very fine, about 75 percent. Corals are completely recrystallized to a coarse mosaic of calcite. Most pores are filled with a dark-gray, extremely fine grained paste. Other pores contain the microgranular paste only at the center. The edges are a clear fine mosaic of calcite that penetrates the gray paste in tiny veinlets and apophyses. *Halimeda* segments have been recrystallized. In many grains the brown resinous-appearing material that makes up the body of the segment is not dark under crossed nicols, as at higher levels in the hole, but is a mosaic of yellowish-brown calcite grains. This is the first specimen in which a complete recrystallization of *Halimeda* has been observed. Both *Halimeda* and corals have internal and external boundaries marked by dark lines that are very thin borders of microgranular carbonate. Mollusks are replaced by or recrystallized to a mosaic of clear coarse calcite, and some of the foraminifers are solid calcite. The detrital material that forms most of the slide is unsorted, but rather fine grained. The grains average about 0.1 mm and are cemented by a microgranular to finely crystalline matrix of calcite.

The second thin section from this piece is similar to the thin section from specimen 2A–16–5 discussed above. A few doubtful fragments may be coral. *Halimeda* forms about 10 percent of the slide. Foraminifers are somewhat less abundant, but are better preserved than in the first thin section from this specimen. The detrital grains are finer and more closely packed. There is less recrystallization in the section and the cementing matrix is microgranular carbonate altered in some places to clear calcite mosaic but it is less well crystallized than in the previous section. Many of the *Halimeda* segments are recrystallized to a coarse mosaic as in the preceding section.

Interpretation.—In this interval the material is more altered, and more calcitic recrystallization has occurred than at higher levels. The patchiness of the alteration is well shown, however, in the two thin sections described from one piece of core. Extreme spottiness of crystallization is apparently a characteristic of material in the hole down to considerable depths.

	Method and recovery	Depth (feet)	Thickness (feet)
White coralliferous detrital limestone.	Core run; 1.5 ft	305. 5	10. 5

White coralliferous detrital limestone. Partial molds of corals preserve the imprint of corallites, and in some places preserve the filled internal pores. Some of the original material remains but it is chalky and friable. *Acropora* and *Porites* may be recognized. Mollusks are abundant as molds or casts. Foraminifera include solid calcite tests of *Amphistegina*, and molds of *Marginopora*. *Halimeda* segments are common. Most are molds containing chalky pillars that fill former internal cells. Echinoid spines and other organic remains are common but are nearly unrecognizable because of crystalline calcite that coats their surfaces.

The recovered core is compact and finely crystalline, but chalky in patches. Large pores and cavities are molds of organisms. There is much finely recrystallized calcite coating surfaces, but large cavities are empty and little carbonate has been added to the rock. The poor recovery is due to the extremely cavernous nature of the limestone because of coral and gastropod molds, and to the patchiness of the calcite recrystallization.

Material from the dense recrystallized patches, and from the crystalline material lining cavities was examined in immersion oil and was observed to contain only calcite. Material from the chalky matrix, and from the friable center of a coral that appeared to be original, was examined and was found to contain crystalline grains of calcite, but no aragonite was observed. A large number of grains were mats of microgranular needles or crystals that were not identified. A specimen of core boiled in Meigen's solution was unstained in compact, crystalline patches, but was stained in small chalky areas. Although the evidence is not conclusive it is probable that the chalky patches consist largely of aragonite that has broken down to microgranular material, which, in turn, has recrystallized to calcite in the compact crystalline areas. Under the ultra-violet lamp the chalky, less consolidated patches fluoresce a light tan. The dense crystalline limestone fluoresces a clear white, and one porous coral center is a medium yellowish brown.

	Method and recovery	Depth (feet)	Thickness (feet)
Fragments and some pieces of core. Compact white coralliferous limestone very similar to the core immediately preceding. Some corals and most mollusks are molds filled or encrusted with crystalline calcite. Corals include *Galaxea*, a ramose *Porites*, fragments of *Acropora* and a mold of *Pocillopora*; recognizable Foraminifera include abundant *Marginopora* and *Amphistegina*. Some of the corals are compact and recrystallized on their borders, but show chalky, powdery original structure in their centers. Irregular tan patches of crystalline calcite are somewhat more abundant than in the preceding core. One core specimen (2A–23–9) was boiled in Meigen's solution. Small chalky patches were stained a pale lavender, whereas dense crystalline areas were unstained. When examined in immersion oils, material from the stained as well as the unstained areas were found to contain calcite, but very few grains of aragonite were identified. Much of the material examined from the stained areas consisted of grains of gray microgranular paste that could not be identified. Under high magnification they are seen to be formed of matted crystalline needles 1 or 2 microns in length, and it is possible that much of this chalky material is aragonite. The bottom piece of core (2A–23–10) has been partially altered to brown carbonate containing thin, rather diffuse, wavy almost horizontal laminae. Small mollusk shells present in part of the brown carbonate do not seem to be much altered. An X-ray analysis of the brown material was made by J. M. Axelrod. He found that it consisted of calcite with a unit cell 0.5 percent short, and very little aragonite.	Core run; 2.8 ft	312	6. 5
Finely crystallized, compact white limestone filled with large cavities that are molds of corals and gastropods. Some clear crystalline areas look like veining or filling of cracks by calcite. Patchy areas on the core surface are only moderately cemented, but most of the recovered material is hard, crystalline limestone similar to that in the preceding interval.	Core run; 0.7 ft	316	4
The top 1.7 feet of the recovered material consists of core and broken fragments of moderately consolidated foraminiferal limestone. The bottom 0.3 foot of the core consists of broken fragments of moderately hard and compact to chalky and friable, fine-grained foraminiferal limestone. The intervening 3 feet is completely uncemented, medium to fine unsorted foraminiferal sand. At the top, tests of *Marginopora* and *Amphistegina* are abundant, but smaller types such as the Miliolidae make up the bulk of the material. Mollusk molds are abundant in one or two pieces of core. A few minute gastropods seem to have their original shells. Only one coral, a large *Astreopora*, was found, but a few small fragments may be altered remnants of a delicate branching coral. The large coral is well-preserved, but pores are filled or coated with finely crystalline calcite. No *Halimeda* was found. All organic remains are cemented by a white limy paste. Some pieces of core are well consolidated, and in small areas the fine limy interstitial paste has recrystallized to calcite. Other pieces are moderately to poorly consolidated, with patchy unconsolidated areas. *Specimen 2A–25–4.*—When boiled in Meigen's solution, poorly to moderately cemented areas in the specimen were stained a pale to medium lavender. Under the binocular microscope the fine chalky interstitial paste was seen to be stained, but in crystalline patches it was unstained, as if aragonitic paste has recrystallized to calcite. Some of the stained material, however, was examined in immersion oil. Most of the crystalline grains were calcite, and only a few small grains were probably aragonite. The composition of the gray microgranular material that took the lavender stain could not be determined in oils. The 3-foot interval of loose foraminiferal sand is composed dominantly of foraminiferal tests 2 mm or less in diameter. These include *Marginopora, Amphistegina,* miliolids, planorbulinids and globigerinids. *Rotalia calcar* and *Calcarina* hispida are common. Part of one sample (2A–25–15) was washed and sieved through a 200-mesh silk screen to clear the material of chalky powder that coated all the grains. The proportion of constituents was estimated under the binocular microscope to be 60 to 75 percent foraminiferal tests, including recognizable fragments, 20 to 35 percent angular grains of calcite of undetermined origin, and 5 percent or less other recognizably organic fragments or shells. Besides Foraminifera, echinoid spines are common; alcyonarian spicules, minute brachiopods, mollusk shells, and *Halimeda* are present but rare. Only one small fragment of coral was recognized in the 3-foot interval.	Core run; 5+ ft	326. 5	10. 5

	Method and recovery	Depth (feet)	Thickness (feet)

The proportion of interstitial chalk in the sand was roughly estimated by shaking the sample in water in a test tube and allowing it to settle. A fairly sharp boundary separated the very fine material from the foraminiferal detritus. Length of the columns in the tube were measured and grains at intervals along the column were examined in immersion oil under the petrographic microscope. About 80 percent of the material consists of Foraminifera and other grains ranging from 2 to 0.2 mm in diameter, most of which lie between 1 and 0.5 mm. About 5 percent consists of grains 0.2 to 0.1 mm in diameter, and the remaining 15 percent consists of grains 0.1 to 0.01 mm in size. Most of the grains 0.1 mm in diameter or less are seen under the microscope to be gray masses of microcrystalline to finely crystalline carbonate. Fine crystalline grains of both aragonite and calcite were determined to be present.

Preservation of the Foraminifera is excellent although *Marginopora*, miliolids, and others break down easily to fine powder. Heavy-walled types such as *Amphistegina*, *Rotalia calcar* and *Calcarina hispida* are nearly solid crystalline calcite. Occasional foraminifers are encrusted with fine calcite crystals. The total addition or recrystallization of calcite is small.

Interpretation.—The conditions under which the material of this core run was deposited are not known, but it may have been deposited within the lagoon at depths greater than those prevailing today—depths too great for much growth of *Halimeda*. Conditions may have been similar to those reported by Emery (1949, p. 58) to exist at present in the center of Eniwetok Lagoon in a large area that is 200 feet or more in depth, where *Halimeda* is virtually absent and Foraminifera are the dominant organisms. The fauna in the interval 316–326.5 is not closely similar to that in the center of Eniwetok Lagoon, but the scarcity of *Halimeda* is at least suggestive. The rarity of corals and gastropods in the sand probably has little significance as they are present in abundance both above and below. The presence of numerous specimens of *Globigerina* and other pelagic forms, although they do not exceed 1 percent of the material in the core, indicates that the lagoon was open to the sea, possibly more so than at present.

	Method and recovery	Depth (feet)	Thickness (feet)
Chalky-white friable fine-grained detrital limestone, indurated in patches by clear crystalline calcite. Corals, especially branching *Seriatopora* and *Acropora*, are abundant, and are altered to a chalky powder or are partial molds filled with coarsely crystalline calcite. *Marginopora* and *Amphistegina* are abundant and well preserved, but mollusks are present only as molds. One *Halimeda* segment is preserved in a brown dense patch of carbonate. The patch has irregular borders, but is possibly a pebble.	Core run; 4 ft	337	10. 5

Specimen 2A–26–1 (8.6-cm core).—Light-gray to white coralliferous foraminiferal detritus (pl. 62, fig. 3). Friable, porous patches in the rock appear similar to the foraminiferal sand in the preceding interval (316–326.5 feet). Fragments of both *Acropora* and *Seriatopora* are present but altered, and their surfaces are coated with a dense calcite rind 1 to 3 mm thick. Some corals have hollow centers but others are filled with coarsely crystalline calcite, or with a chalky powder. Many hollow molds of corals and mollusks are coated with euhedral crystals of calcite. Most of the core is impregnated by fine-grained calcite.

The chalky powder filling coral molds was determined from X-ray patterns by J. M. Axelrod to be calcite with a little aragonite. Some of the powder was examined in immersion oil. Under low magnification much of it appeared to be grains of gray to brown microgranular carbonate similar to the interstitial paste of the core, but under high magnification (× 350) the grains were observed to be formed of matted acicular crystals of calcite 0.005 to 0.05 mm long. No organic remains of any kind were recognized. All of the crystals tested were calcite; no aragonite was found.

One specimen tested with Meigen's solution was for the most part unstained, but small patches of detritus that were uncemented were stained lavender, as were the more chalky portions of coral interiors. Even the calcite *Marginopora* that were rather disintegrated were somewhat stained.

Specimen 2A–26–3 (5.8-cm core).—Similar to specimen 2A–26–1 just discussed, but most corals are dense crystalline calcite.

In thin section the material is seen to consist mostly of closely packed foraminiferal tests. These are clear yellow to grayish-brown in ordinary light, and dark dray under crossed nicols. Under high magnification (× 350) they are seen to be microcrystalline to cryptocrystalline. Borders of the tests are obscure, and their walls merge with finely crystalline calcite that fills cells and pore spaces. The matrix is in places a gray microgranular paste, but over most of the area of the slide it is a mosaic of finely crystalline clear calcite that has apparently recrystallized from the gray material.

	Method and recovery	Depth (feet)	Thickness (feet)
Corals are coated with an encrusting foraminifer, *Homotrema*?, about 0.5 mm thick (pl. 62, figs. 1, 4). Some corals are completely altered to a medium-grained calcite mosaic that has obliterated all cellular walls and open pores. Others show a semblance of coral structure, for pores exist that are filled with finely crystalline calcite. An irregular network of fine dark lines of microgranular carbonate cuts coarsely crystalline calcite that occupies the former cellular walls. One coral has open pores that are lined with fine crystals of calcite. The skeleton is formed of coarsely crystalline calcite, the crystals of which are elongate and rudely oriented in much the same manner as was the original feathered aragonite. *Interpretation.*—The thin sections from this core provide strong evidence for the breaking down of organic skeletons into microcrystalline material, and the subsequent growth of finely to coarsely crystalline calcite within the microcrystalline material. Carbonate leached from mollusks and corals that are now left as open molds seems to be sufficient to account for all the growth of crystalline calcite, although a small addition of carbonate to the interval is possible. Inasmuch as the rock that was not recovered in coring was probably less cemented than the 4 feet of rock that was recovered, it is probable that all later calcite recrystallized from carbonates at hand. Most of the aragonite has altered to calcite, and it is significant that at this depth the chalky powder filling some of the coral cavities contains more calcite than aragonite. The powder may be a limy paste that filled coral molds, rather than being disintegrated coral material, but it was not possible to determine this under the microscope. The interval is especially significant for two reasons. The prevalence of corals of delicate, branching types, and of mollusks in association with a rich foraminiferal fauna similar to that in the interval immediately preceding, and the virtual absence of *Halimeda*, makes it seem probable that the material was deposited at some depth—possibly more than 30 fathoms, in a lagoon.			
Rounded fragments of core, worn apparently during the drilling, were recovered. The material is similar to that of the interval immediately above. All fragments are hard, well-cemented limestone containing molds of *Seriatopora* and mollusks. *Marginopora* is present, but other Foraminifera were not recognized on the worn surfaces of the fragments. From the manner of drilling, with many thin hard intervals separated by softer ones, it seems probable that on the whole the rock was poorly consolidated and that only well-crystallized patches were recovered. At this depth coring had become difficult as the hole was losing water rapidly in the extremely porous soft limestone. It was decided to continue drilling with a 5⅞-inch roller rock bit, and to take a 10-foot core at intervals of 50 to 100 feet.	Core run; 1+ ft	347. 5	10. 5
This section consists of alternate hard and soft intervals from a few inches to 5 or 10 feet in thickness. The hard intervals, that drilled noisily and relatively slowly, may be mostly colonies or aggregates of coral, but more probably they are indurated patches in the rock. The soft intervals are evidently unconsolidated fine detritus. The cuttings apparently do not differ from the last-described cores in either lithology or fossils. When the drill encountered a hard interval, good cuttings were obtained of angular chips of white crystalline limestone containing molds of mollusks and corals. When the drill encountered soft intervals, however, cuttings were finely divided and the material cut by the bit could not be distinguished from loose foraminiferal sand and fine material that caved into the hole from higher levels.	Rock bit__	441	93. 5
The core probably came from the top part of the interval as the bottom 5 feet (447–452.5 feet) was unconsolidated and sandy. The rock is moderately to well-consolidated, light-gray to white forminiferal limestone containing open molds of corals and mollusks. Corals form about 5 percent of the recovered core. *Acropora*, *Seriatopora*, and *Porites*? are present. Foraminifera include *Marginopora*, *Amphistegina* (abundant), *Heterostegina* (rare), and some specimens of *Rotalia calcar*(?). In thin sections delicate smaller foraminiferal tests are common but they are not apparent on a core surface. Encrusting foraminifers intergrown with thin layers of *Lithothamnion* are abundant and occupy a significant volume of the core—possibly 5 to 10 percent. Both *Homotrema*? and *Carpenteria*? are seen in thin section to be similar to those figured by Chapman (1900, pl. 2, figs. 4, 5, 6; 1901, pl. 20, figs. 6, 7). J. H. Johnson reports that one core specimen from this interval contains abundant *Halimeda* sp., *Porolithon* sp., and types of calcareous algae different from near-surface samples. From cuttings at this depth he has identified a *Lithophyllum* different from any previously encountered.	Core run; 2.7 ft	452. 5	10. 5

Halimeda is apparently not prevalent throughout the interval, but is abundant here and there. In several of the core pieces there are masses of minute calcite spicules 2 to 3 mm in length. These are probably octocorallian spicules, according to F. M. Bayer, of the National Museum, and may be either nephthyids or alcyoniids. They could also be from deep-water muriceids, but this does not seem probable, as the spicules are associated with a shallow-water fauna.

Small patches of the core are porous and rather friable, but most of it is compact and well consolidated. Coral molds are empty and show well-preserved imprints of corallites, and some contain a fine threadlike network of calcite pore filling. All original material has disappeared. Some molds are filled with chalky powder containing foraminifers, others are filled with coarsely crystalline calcite. Some cavities in the rock are partially filled with white porcelaneous calcite paste, the top surface of which is perpendicular to the core walls. Other cavities are encrusted with calcite crystals or are filled with chalky powder.

The bottom part of the recovered core contains several large rounded masses of chalky foraminiferal detritus with borders that are well defined megascopically, but are indistinct under the binocular microscope. The rounded masses are possibly pebbles or discrete fragments, but they do not appear to differ significantly from the surrounding material and they may be areas where there is less pore filling by calcite.

Specimen 2A–28–6 (6.4 cm core).—Light-gray compact foraminiferal limestone containing white enveloping "concretionary" masses. In thin section these masses are seen to be encrusting foraminifers, probably *Homotrema* and *Carpenteria*. They are intergrown with thin layers of *Lithothamnion* and are in a dense brown matrix of microgranular paste containing abundant small foraminiferal tests. The small Foraminifera are pale yellow in plane-polarized light, and are dark under crossed nicols. Their borders are seen to be diffuse under high magnification. Encrusting foraminifers, *Lithothamnion*, and brown paste occupy about one-half of the section. The other half is a coarse detritus of tests or fragments of *Marginopora*, *Amphistegina*, and other organisms in a mosaic of clear calcite. About 50 percent of the material in this part of the slide consists of organisms and fragments. The calcite mosaic of the matrix forms about 40 percent, and small dark areas of finely granular to microgranular calcareous paste form the remaining 10 percent. The paste appears to be recrystallizing to the calcite mosaic (pl. 62, fig. 2). The calcite crystals in the mosaic range in size from about 0.01 to 0.5 mm. Areas surrounding echinoid spines are single crystals of calcite in optic continuity with the spine. This is the first observation in the core of calcite forming in optic continuity with any organisms, although at higher levels aragonite needles in coral pores commonly are aligned with aragonite of the coral skeleton although not strictly in optical continuity. *Marginopora* fragments are yellow to dark brown under plane-polarized light and dark under crossed nicols. *Amphistegina* and other similar tests have recrystallized to calcite that shows an extinction cross under crossed nicols.

A piece of this specimen was treated with cobalt nitrate solution. Most of the sawed face of the specimen was unstained including both well-crystallized areas and encrusting foraminifers, but small chalky spots were stained pale pink. Powder from the pink spots was examined in immersion oils, but no crystalline grains of aragonite could be identified.

Specimen 2A–28–17 (5.7-cm core).—Friable, porous, fine-grained detrital limestone. Two round coalescing areas resemble pebbles of white, very porous rock in a light-gray similar material, but under the binocular microscope the borders are indistinct and it is not certain that these are pebbles.

In thin section the material is seen to be a fine-grained foraminiferal limestone. Abundant foraminiferal tests and a few mollusk shells and echinoid spines occupy about 25 percent of the area of the slide. Fine detrital grains 0.03 to 0.2 mm in diameter, many obviously of organic origin, form about 25 percent. The remaining 50 percent of the material is a light to dark-brown microgranular carbonate paste that is almost isotropic under crossed nicols. In a few places the central parts of microgranular areas between detrital grains have recrystallized to a fine-grained mosaic of calcite, but most of the paste seems to be unaltered. Small cavities and pores are lined with finely crystalline calcite.

Under high magnification the boundaries of many detrital grains are seen to be obscure, and they appear to merge with the brown microgranular paste. Some smaller foraminiferal tests appear as indistinct, light-colored tracings in the dark matrix, but most under high magnification appear to have their original tests of fibrous calcite. Thick-walled types such as *Amphistegina* appear unaltered by addition of calcite.

The pebblelike body mentioned above in the thin section, and its boundary with the brown microgranular paste is noticeable only by a darkening of the paste. There is no sharp demarcation between "pebble" and outer matrix, but the paste of the matrix is seen in thin section to have larger open cavities than that within the pebble. In the matrix, large foraminifers are more abundant, especially *Amphistegina,* and some encrusting foraminifers and a small fragment of *Lithothamnion* are present. Whether the whitened chalky patches are pebbles could not be definitely determined, but they appear to be somewhat different from the matrix. This part of the core has much less calcitic crystallization than the top of the interval, and there is little evident alteration of Foraminifera. The impalpable brown matrix fills all pores and crevices. Interiors of minute tests are filled by it, and small spines and spicules have centers and radial walls of the material that has apparently penetrated the solid crystal structure of the spines, for the remaining parts of clear calcite are all optically oriented. In some respects this thin section resembles those from the core obtained from the 232- to 242.5-foot interval.

An X-ray analysis of the chalky paste was made by J. M. Axelrod, who reported that it contained calcite with a unit cell 0.7 percent short, but no aragonite. A piece treated with Meigen's solution was unstained. The microgranular paste in this specimen is evidently calcite, although little distinction could be made in thin section with similar material from higher levels that apparently is aragonite.

Interpretation.—This interval of the core differs from higher intervals in the greater recrystallization of calcite in the top part and in the absence or rarity of aragonite. Relatively stable organisms such as the Foraminifera are more altered than they were at higher levels. Corals are apparently present only as empty molds or as chalky casts, and all mollusks are molds. The faunal assemblage differs from that above in the abundance of encrusting foraminifers such as *Carpenteria* and *Homotrema,* the presence of more *Lithothamnion* than at higher levels, and in the masses of octecorallian spicules. Because of the intergrowths of *Lithothamnion* with the foraminifers the material must have accumulated in lagoonal water less than 25 fathoms and probably less than 10 fathoms in depth. A few corals dredged from Bikini Lagoon at 22 fathoms were thinly encrusted by living *Lithothamnion* (probably *Porolithon*) as well as by foraminifers. The relative sparsity of corals, and the prevalence of delicately branching *Acropora* and *Seriatopora* suggests that the waters were quiet. The absence of any large detrital fragments or blocks also supports the lagoonal interpretation.

	Method and recovery	Depth (feet)	Thickness (feet)
Cuttings appear gradationally somewhat more tan from top to bottom of the interval. From the action of the drill and the nature of the returned cuttings two principal zones in this interval were distinguished. The first, starting at 447 feet in the preceding core run, is an unconsolidated zone that continued to 473 feet. Cuttings from this zone were dominantly fine to medium sand or angular detritus most of which passed through the mesh of the sieve. This zone passed gradationally into the next. From 473 to 514.5 feet the rock was more consolidated, and a few short intervals were lithified and brittle enough to cause the rotary table to chatter slightly. Cuttings produced were a little larger and more angular, yet most of them were so fine that they passed through the strainer and could not be caught. The last 10 feet of the firm zone (504.5–514.5 feet) contained brittle consolidated layers or patches.	Rock bit..	514. 2	62
The recovered core consists of fragments, the largest of which is a broken core 3.5 cm long. The rock is light-tan moderately indurated coralliferous foraminiferal limestone. Molds of mollusks are common. Corals, especially *Acropora,* are abundant in some places. They are white, chalky and very friable and break down into a fine powder, but the internal structure of the colonies is well preserved. Some of them are coated with a tan rind about 1 mm thick that is apparently an encrusting foraminifer. The matrix containing the corals is a moderately hard tan limestone containing abundant chalky *Marginopora,* crystallized *Amphistegina, Rotalia calcar,* and some *Calcarina hispida.* No *Halimeda* segments were seen, and if they are present they are so disintegrated that they cannot be recognized on a core surface. Small cavities in the rock are lined with crystals of yellow-brown dogtooth calcite, some of them 1 to 2 mm long.	Core run; 0.8 ft	525	10. 5

284244—54——17

An X-ray analysis of chalky material from one of the coral centers was made by J. M. Axelrod. He reports that it consists of aragonite and a trace of calcite. When some of the powder from the same coral center was examined in immersion oils, most of the small crystal grains proved to be calcite and only a few small needles were aragonite. Most of the powder, however, consisted of gray finely crystalline grains, made up of matted needles 1 to 10 microns in length that could be resolved under high magnification only at the very edges of the grains. It was not possible to determine the index of the gray grains, but from results of the X-ray analyses it is evident that they are aragonite. Apparently the fibrous aragonite needles of the original coral have broken down to minute disorganized aragonite needles that still preserve the original structure of the coral. Small amounts of crystalline calcite probably represent minor crystallization in open pores.

A specimen of tan limestone representative of the foraminiferal detritus forming most of the material was also analyzed by X-ray. Axelrod reports that aragonite and calcite both are present, and that the unit cell of the calcite is 0.3 percent short.

Specimen 2A-30-2.—Broken fragments mostly of coral. A thin section of one fragment of the specimen shows that the material is dominantly composed of foraminiferal tests in a matrix some of which is microgranular, but most of which is a fine calcite mosaic. The approximate percentages of constituents are: foraminifers, 30 percent; rounded and partially altered organic fragments, 20 percent; empty molds of small mollusks, 5 percent; empty pore spaces, 15 percent; matrix of calcite mosaic including some microgranular material, 30 percent.

Marginoporas are abundant. They are light yellow to medium brown by transmitted light, and yellowish-brown to opaque under crossed nicols. Pores are filled with calcite mosaic. *Amphistegina, Rotalia calcar,* and *Calcarina hispida?* are common. Some tests are formed of heavily crystallized calcite that shows an extinction cross under crossed nicols, whereas others, especially of *Rotalia calcar,* look etched but appear to have their original fibrous calcitic structure. Small tests are numerous, but some have cell walls of yellow to yellow-brown material that is almost isotropic under crossed nicols, whereas others are formed of clear calcite. Encrusting Foraminifera are common. Several rounded fragments of *Lithothamnion* and broken pieces of coral are present. The crystal structure of the coral is strongly feathered aragonite that appears to be unaltered.

The calcite mosaic that forms the matrix is formed of grains that typically range from 0.01 to 0.1 mm in diameter, but near borders of fragments the material is microgranular and forms a dark line. A few small microgranular brown patches may be an original limy paste, or they may represent a disintegration of organic material before the crystallization of mosaic calcite.

Interpretation.—There is no evidence that the material is other than lagoonal. The significance of the tan color of the sediments, which was apparent in cuttings above this interval, is not yet understood.

Some disintegration of primary material has occurred, and addition or more probably recrystallization of calcite is strong, but the material is not nearly so much altered or recrystallized as it was at 442–452.5 feet. Aragonite is more prominent, and according to the two X-ray analyses it dominates calcite, although in thin section and in immersion oils most crystalline material that can be recognized is calcite.

The interval drilled easily and rather fast with some rock bit clatter of the drill through consolidated material. There was no marked difference in drilling from the lowest part of the preceding interval, 504.5 to 525 feet. Cuttings were plentiful and were relatively free from contamination, but they consist mostly of angular fragments from 1 to 5 mm in largest dimension, and it is difficult to estimate the proportion of organic constituents. Small fragments of white, chalky, friable corals form about 5 to 10 percent of the cuttings. The only form recognized is *Seriatopora.* Some small fragments resemble the fine internal network of *Porites.* Many fragments of cuttings contain imprints of mollusks, particularly of bivalves. The matrix is buff to tan fine limestone containing abundant tests of Foraminifera, especially of *Amphistegina* and *Calcarina hispida.* These are crystalline and some break free of the matrix, but other thin-walled types can rarely be recognized as they are more friable than the matrix.

Cavities in the matrix are filled by calcite crystals, but it is impossible to determine the amount of recrystallization or addition of calcite within the matrix. No evidence was obtained of any break in deposition, or of any change in lithology throughout this interval.

	Method and recovery	Depth (feet)	Thickness (feet)
The recovered core consists of fragments of two kinds.	Core run; 0.4 ft	578	10. 5

The recovered core consists of fragments of two kinds. The top 0.2 foot is formed of broken nodular fragments (1 to 3 cm) of tan to light-brown compact foraminiferal limestone. The bottom 0.2 foot that was blocked in the bit consists of light-tan, firm but unconsolidated, fine chalk containing scattered crystalline foraminiferal tests that give the chalk a sandy feel. Molds of corals and mollusks are common though not abundant in the hard nodular material at the top, but are rare in the chalk at the bottom. The nodular fragments seem to be consolidated patches within a friable limestone. Evidently most of the material was incoherent and washed away during the coring. The bottom chalky material was recovered by "dry blocking"—that is, the driller cut off circulation of drilling mud and forced the core barrel down "dry," for a foot or two, to pack the material firmly. The chalky material thus recovered may be representative of the greater part of the core run.

Calcium and magnesium carbonates of the chalk were determined by F. J. Flanagan, who found 97.27 percent $CaCO_3$ and 1.11 percent $MgCO_3$. J. M. Axelrod reports that calcite (normal cell), aragonite, and very little of an unidentified mineral were found to be present by X-ray analysis. Some of the chalk was examined in immersion oil, and only calcite was identified. As in samples at higher levels, however, the aragonite may be confined to interstitial microgranular paste. Some of the matrix was boiled in Meigen's solution, and most of the chalk was stained a deep lavender. Foraminiferal tests and some angular grains were unstained.

In a thin section made of one of the nodular fragments, the rock is seen to be composed of about 40 percent foraminiferal tests, 30 percent angular grains of organic remains, and 30 percent microgranular paste. Forminifera include many *Marginopora, Sorites, Amphistegina,* smaller types, and some fragments of *Homotrema.* Angular grains mostly smaller than 0.5 mm consist of fragments of corals, mollusks, and echinoid spines. One small area of *Lithothamnion* and a doubtful fragment of *Halimeda* are present. The matrix and pore filling is a gray paste that looks microgranular but under high magnification is seen to be formed of carbonate crystals 0.002 to 0.01 mm in size. The paste is more or less uniform near the borders of Formaninfera and detrital grains, but it grades toward the centers of spaces and pores to a mosaic of calcite (pl. 63, fig. 1). Some pores are half filled with paste; the other half is filled with a clear mosaic of calcite, but there seems to be no preferred orientation of the surface of the paste. The calcite mosaic is therefore recrystallized paste rather than a later filling.

Borders of foraminifers and detrital grains appear diffuse and microgranular in contact with the paste of the matrix, but interiors of most shells and fragments are not much altered. Coral grains are apparently original aragonite. Even a few mollusk fragments appear to have their original structure, although most of them are molds filled with a clear mosaic of calcite.

Interpretation.—In this interval corals and mollusks are present as molds, although unaltered fragments persist in the indurated nodules. Possibly the recrystallization of gray paste to calcite mosaic within the nodules protected the fragments from alteration, but because of the very low core recovery we do not know what proportion of the corals and mollusks exists as original aragonite. All in all, the amount of alteration and recrystallization of calcite appears to be rather less in this interval than in the last core run (514.5–525 feet).

	Method and recovery	Depth (feet)	Thickness (feet)
There was no apparent change in the action of the drill throughout this interval.	Rock bit__	631. 5	53. 5

There was no apparent change in the action of the drill throughout this interval, as compared with the interval 525 to 567.5 feet, also drilled by rock bit. Cuttings recovered were also comparable to those above. They are angular tan to brown chips, 2 to 5 mm in size, some of them bearing imprints of mollusks. Much fine sand was carried up in the drilling mud, but little was recovered in the screen. Foraminiferal tests are probably abundant, for sections of them can be seen on the broken faces of fragments. Loose tests of *Amphistegina* form only a minor fraction of the material. Coral fragments are not common down to 603 feet, but the drill penetrated a soft crumbly rock from 603 to 606 feet and cuttings from the interval contain more than 20 percent of *Porites* fragments. From here down to 631.5 feet several kinds of coral fragments are abundant though they form less than 10 percent of the recovered samples. Coral fragments, especially of *Porites,* are so friable that they may be crumbled between the fingers, although the original cellular structure is perfectly preserved, evidently as aragonite, for a small fragment boiled in Meigen's solution was stained a deep lavender. Pores are empty and there is no filling or coating on the pore walls.

Interpretation.—The soft rock from 603 to 606 feet was presumably a large head of *Porites,* and the proportion of well-preserved though friable coral fragments below this depth suggests that the material accumulated in lagoonal waters less than 20 fathoms and probably less than 10 fathoms in depth. Alteration of the corals is less than at higher intervals in the drill hole. Although the original aragonitic crystalline structure of the *Porites* has evidently

	Method and recovery	*Depth (feet)*	*Thickness (feet)*

broken down, it has not altered to calcite. The amount of calcitic recrystallization in the compact material of the matrix is probably comparable, from 578 to 603 feet, to that discussed in the previous core run (567.5 to 578 feet), but from 603 to 631.5 feet, it is less.

	Method and recovery	*Depth (feet)*	*Thickness (feet)*
Fragments of coral, branching *Porites* and *Goniastrea,* and of coarsely crystalline resinous brown calcite. According to J. W. Wells, the *Goniastrea* is probably not either of two species now living at Bikini Atoll. A few apparently unaltered mollusk shell fragments, several borings of gastropods, and possible encrustations of foraminifers are present. A few crystallized small foraminifers, *Amphistegina* and probably *Calcarina hispida*, are stuck on the sides of corals. No sample of a detrital matrix was obtained.	Core run; 0.5 ft	642	10. 5

The *Porites* is tan and friable, and porous internal cells are perfectly preserved. The *Goniastrea* is almost completely filled or replaced by coarsely crystalline brown calcite, but corallites are open, and the septa and dissepiments are apparently unaltered tan material. The brown calcite replaces the solid matter between corallites, and does not fill the delicate cellular structure in open corallites.

Other fragments of brown calcite include pieces with coarse cleavage rhombs 3 or 4 mm long, and botryoidal nodules that are probably calcitic fillings of cavities, or possibly massive replacement of organic shells.

Some of the coral material was analyzed by X-ray, by J. M. Axelrod. He reports that material forming the tan, friable internal cells of *Porites* consists of aragonite and a trace of calcite, whereas material forming fragile septa of *Goniastrea* is calcite, with a unit cell 0.4 percent short, and aragonite.

Fragments of *Porites* boiled in Meigen's solution turned a deep lavender; those of *Goniastrea* were unstained in areas of brown calcitic replacement, but the fragile tan septa were faintly stained. In immersion oil, powder scraped from the *Porites* was seen to consist mostly of gray microgranular grains that could not be identified, but small crystalline bunches of acicular aragonite were also present, as were small crystalline grains of calcite.

The gray microgranular material is apparently the principal component of the *Porites,* and probably is formed of matted, disorganized, minute aragonite needles that disintegrated from original fibrous aragonite of the coral.

Brittle tan material that forms the septa of *Goniastrea* was examined in oil and was seen to consist dominantly of cloudy to clear cleavage rhombs of calcite. A few grains of gray microgranular material were present, and on their edges minute crystals of aragonite were identified. The microgranular material is probably matted acicular aragonite, but the relations of calcite to aragonite could not be determined.

Interpretation.—Too little material was recovered in this core run to indicate conditions of origin, but if the presence of branching *Porites* and *Goniastrea* is considered along with the abundance of coral in cuttings from 604 to 631.5 feet, it seems likely that the material accumulated in lagoonal waters that were shallow and possibly near the lagoon edge of a reef.

The coarsely crystalline brown calcite forms about 80 percent of the recovered core, but as recovery was so poor, such calcite did not necessarily form more than a few percent of the total material in the 10.5-foot interval. The lack of interstitial paste in coral pores and the presence of original mollusk and coral fragments suggests that matrix material, which was not recovered, may have been relatively coarse detritus containing very little extremely fine material. Solutions moving through the rock apparently did not leach original material but deposited calcite in pore spaces and replaced some corals. It seems likely that the material in this cored interval was never above sea level for any considerable period. The brown carbonate possibly was leached from limestones higher above sea level, and was deposited at or shortly below sea level.

	Method and recovery	*Depth (feet)*	*Thickness (feet)*
This section of the hole, to judge from the manner of drilling and from the cuttings, is detrital limestone even less consolidated than that at higher levels.	Rock bit--	694. 5	52. 5

Cuttings appear to be relatively free of surface contamination, and are composed of chips of coral, angular white to tan compact limestone, foraminifers and mollusks, and of clear transparent to brown coarsely crystalline calcite. Coral is most prominent of the organic skeletons and forms about 25 percent of the material—a high proportion. About 50 percent of the cuttings consist of white to tan limestone; 10 percent are foraminiferal tests, mollusk fragments and echinoid spines, and 15 percent are coarsely crystalline calcite. Several kinds of coral chips are present, but only *Porites* can be identified by its fine spongy internal network. *Heterostegina, Amphistegina,* and possibly *Calcarina* are present, all coated with clear calcite crystals. W. Storrs Cole has identified *Cycloclypeus carpenteri* from 673 to 678.5 feet.

	Method and recovery	Depth (feet)	Thickness (feet)

The coral chips are all original and unleached, but powdery and friable, and most pores are unfilled by any calcareous paste, although some larger ones are filled with clear crystalline calcite.

Detrital sand, in grains mostly 0.5 to 1 mm in size, is present in small amounts. The original proportion of grains less than 0.5 mm in size and of interstitial paste was apparently small or more would be expected filling coral pores.

Interpretation.—The high proportion of coral in this interval and the low proportion of fine detritus suggest a reef or near-reef environment.

	Method and recovery	Depth (feet)	Thickness (feet)
The rock is an unconsolidated tan to light-brown limestone.	Core run; 1 ft	705	10. 5

The rock is an unconsolidated tan to light-brown limestone. Fragments of corals, encrusting foraminifers, *Lithothamnion*, *Halimeda*, and mollusks are present together with a small amount of tan, chalky, finely divided detritus and foraminiferal tests. The corals identified are *Astreopora* and *Porites*. *Porites* skeletons are fairly well preserved but crumbly, and pores are open. *Astreopora* is filled and partially replaced by brown, coarsely crystalline calcite, but the original structures of septa and dissepiments are preserved. A few large *Amphistegina* tests of crystalline calcite are present, and an undescribed species of *Operculina* has been identified by W. S. Cole. Mollusk fragments have their original shell structures, but are not well preserved.

A piece of the chalky detritus was analyzed for carbonates by F. J. Flanagan, who reported that 97.48 percent $CaCO_3$ and 1.53 percent $MgCO_3$ were present.

Specimen 2A–33–1.—Broken and nodular fragments. Encrusting foraminifers are abundant in the fragments. Some *Lithothamnion* is present, but coral and mollusk fragments are less common than in other specimens of this core. A thin section made of one of the larger pieces of nodular limestone (2 cm), shows about 75 percent *Lithothamnion*, 20 percent encrusting *Homotrema* and *Carpenteria*, and 5 percent gray microgranular paste filling cavities and pores. Two *Amphistegina* tests are enclosed in the *Lithothamnion*, which J. H. Johnson has identified as *Lithoporella*.

Interpretation.—So little material was recovered from this interval that it is impossible to evaluate the proportions of components. Friable but well preserved fragments of *Porites* are similar to all specimens of this genus recovered below 603 feet. The calcite-filled *Astreopora* seems to be identical in preservation to the specimen of *Goniastrea* recovered from 631 feet. The only significant difference between rock of this core run and rock from 603 to 694 feet seems to be the relatively large proportion of *Homotrema*, *Carpenteria*, and *Lithothamnion* at this level indicating a possible reef facies.

	Method and recovery	Depth (feet)	Thickness (feet)
Judging from the drilling and from the cuttings, there are no marked changes in lithology throughout this interval.	Rock bit	862. 5	157. 5

Judging from the drilling and from the cuttings, there are no marked changes in lithology throughout this interval. There are, however, several minor changes that might have been significant if the interval were cored. One core run was made at 757.5 to 768 feet but no core was recovered.

The cuttings contain abundant coral chips, mollusk fragments and small shells, rare to common foraminiferal tests and angular fragments of compact tan to brown limestone.

Mollusk shells, especially small ones 2 to 3 mm in length, are especially plentiful from 726 to 757.5 feet. They are well preserved and many show original nacreous luster on interior surfaces. Several kinds of coral including *Porites* are present, but most cannot be identified. for only chips showing internal structure are present. They are well preserved with unfilled pores, and are rather friable as is all material below 603 feet. Apparently there is a small amount of coarsely crystalline calcite filling and replacing them.

Numerous delicate tips of *Seriatopora* showing well-preserved corallites are found below 726 feet. At 752 to 757 feet *Galaxea* was identified by J. W. Wells. Foraminifers include numerous *Amphistegina* and *Operculina* from 852 to 857 feet.

Below 768 feet, and especially below 785 feet, the material was unconsolidated and fine grained, and it drilled like a loose sand. Cuttings were so finely divided that very little was caught in the screens. Most of the material deposited in the sluice at the collar of the hole consisted of grains about 0.5 to 2 mm in size, but much material even finer may have stayed in suspension in the drilling mud, which had to be kept thick to prevent caving in the hole. From 841 to 862.5 feet, coarser fragments were again abundant in the core.

At several depths between 705 and 862.5 feet the drilling was rough and noisy for several inches to several feet. These thin "hard layers" are probably the result of the rock bit encountering a solid head of coral in the unconsolidated detritus. Several such layers occurred at 746 feet, 800 to 815 feet, and 831 to 848 feet.

	Method and recovery	*Depth (feet)*	*Thickne (feet)*
Fragments, mostly of coral. One nodular fragment is a compact, well-consolidated light-brown limestone containing abundant minute gastropods, foraminifers, *Halimeda* segments, an echinoid spine, and other unidentifiable organic remains. The coral fragments, according to Wells, are mostly *Stylophora* cf. *mordax* and *Porites* cf. *lutea; Porites* fragments are pieces of coral interior, well-preserved but friable, with open pores. *Stylophora* fragments are compact and hard, and much of the coral surface is in an excellent state of preservation. The corallites on some surfaces are fresh and unworn; on others they are slightly worn, but are not leached or polished. Interiors of the corals are hard, excellently preserved, and unfilled. An encrusting foraminifer, *Bdelloidina,* and an encrusting gastropod still with original nacreous luster, are on the coral surface. A partial analysis of a fragment of *Stylophora* from this core was made by F. J. Flanagan, who reported that it contained 95.97 percent $CaCO_3$ and 0.24 percent $MgCO_3$. An X-ray analysis by J. M. Axelrod showed aragonite only. A thin section of the nodular limestone fragment shows an unsorted detritus of organic remains and angular grains in a brown microgranular paste. A pebblelike body more than a centimeter in length is included. Over most of the section the proportion of detritus ranges from 50 to 90 percent and averages about 70 percent of the material; the rest is brown paste. Within the pebblelike body, however, more than 90 percent of the material is paste, in which small angular grains 0.01 to 0.2 mm long are scattered. Half of the detritus is recognizably of organic origin, the other half is composed of angular grains ranging in size from 0.01 to 0.2 mm. A few small corals are present, one of which is coated with *Homotrema*?, and small grains of coral are common. Mollusk shells are present and small angular fragments of shells are abundant. *Halimeda, Porites,* and *Amphistegina* are common and smaller Formanifera are present but rare. The brown paste that forms the matrix of the detritus is medium yellow brown in plane-polarized light, and is slightly darker under crossed nicols. Under high magnification (× 360), it is seen to consist of an aggregate of minute needles 1 micron or less in length. The paste within the pebblelike body is somewhat finer grained than that without, but under high magnification one grades into the other. Under low magnification the border appears to be sharp, but this is because of the massed detrital grains outside the body, as contrasted with the scattered grains inside. Whether the body actually represents a pebble could not be determined. Most corals look unaltered and seem to have an internal structure of feathered aragonite. Some mollusk fragments look unaltered, but others have a wavy irregular extinction under crossed nicols due apparently to partial recrystallization of the fibrous aragonite. *Halimeda* segments are clear yellow and have a low apparent relief. Under crossed nicols some are dark brownish yellow, but others are opaque. Those showing an aggregate birefringence seen under high magnification to be formed of massed needles a micron or so in length, whereas those segments that are nearly or quite isotropic show only a few scattered minute needles. Calcite crystals line or fill a few cavities. One cavity is lined with calcite crystals, on which is a thin layer of gray microgranular mud. The center of the cavity is filled with a calcite mosaic. The specimen was treated with Meigen solution. *Halimeda* segments and porous areas were stained deep lavender, but most of the sawed face of the specimen was lightly but irregularly mottled with pink. The outer surface of the specimen, however, was stained a deep lavender except for foraminiferal tests and other calcitic organisms. Mollusk shells apparently in good preservation were only lightly stained. In this material, which contains both calcite and aragonite, the porosity of the material evidently determines the degree of staining. The presence of *Stylophora* and *Porites* with encrusting foraminifers and *Halimeda* in this interval strongly suggests accumulation in shallow lagoonal waters. The state of preservation of the material is much better than at higher levels.	Core run; 0.3 ft	873	10. 5
Unconsolidated, unsorted, tan to brown detritus very similar to material from the interval 768 to 862.5 feet. From 873 to 883 feet drilling was rapid. Cuttings consisted mainly of angular chips of brown compact limestone, fine to coarse sandy detritus, and fragments of corals and mollusks. From 883 to 898.5 feet drilling was somewhat slower but the material was apparently unconsolidated. Corals and mollusk fragments dominate in the upper part of this interval. From 898.5 feet to 925 feet drilling was very fast; cuttings were mostly small, constituents are hard to recognize, and fragments of corals and mollusks form only a small part of the material. *Interpretation.*—The lithology from 873 to 925 feet is similar to that in immediately preceding intervals. No valid breaks can be assigned either on the basis of cuttings or	Rock bit..	925	52

	Method and recovery	*Depth (feet)*	*Thickness (feet)*
manner of drilling, although it may be possible to establish faunal zones when studies of the fossils are completed.			
The 2.5 feet of core came out of the barrel whole and round but broke down immediately. It is completely unconsolidated, unsorted, light to medium-brown fossiliferous detritus, containing abundant corals and mollusks, a variety of foraminifers including encrusting types, common *Halimeda* segments and rare echinoid spines (pl. 63, fig. 3). Roughly 25 percent of the material is larger than 3 mm in grain size, 25 percent ranges from 3 to 1 mm, 45 percent ranges from 1 to 0.1 mm, and 5 percent is less than 0.1 mm in diameter. Material larger than 3 mm in size is composed dominantly of well-preserved corals and mollusk shells. Material from 3 to 1 mm is composed of small mollusk shells and fragments, foraminiferal tests, and angular grains. That from 1 to 0.1 mm is mostly angular detrital grains and small foraminifers. That part of the material less than 0.1 mm in size is formed entirely of detrital grains. Common corals include staghorn *Acropora,* both massive and thin-branched, *Porites, Stylophora* and *Seriatopora.* Many are unworn, and delicate septa of the corallites are perfectly preserved; but some are riddled, possibly by boring sponges, and others are encrusted with *Carpenteria* and *Sagenina.* Mollusks include *Strombus, Cardium,* and *Gypraea.* A number of the shells show original luster and traces of color pattern. The most abundant Foraminifera are *Marginopora* and *Operculina.* Miliolids, *Textularia,* and a number of smaller pelagic types are common. X-ray patterns of a gastropod shell, probably *Strombus,* was analyzed by J. M. Axelrod, who found aragonite, a trace of calcite, and a trace of an unidentified mineral. No thin sections were made. Corals and mollusks from this core have been studied by J. W. Wells and H. S. Ladd, who report that many species differ from those now living in the Marshall Islands, some of them being new, others being identical with forms occurring in the Miocene and Pliocene of the East Indies. The fossils are probably upper Miocene in age. They are shallow water types that probably accumulated in an open lagoon, shelf, or reef platform, rather than on the steep seaward slope of a reef. *Interpretation.*—By comparing this fossil assemblage faunal groups on the present-day atoll, it seems likely that the material accumulated in a lagoon. It seems unlikely that the material accumulated on a reef because of the delicate branching nature of the corals; particularly because of the association of *Seriatopora* and staghorn *Acropora* which are found on the present-day reef in sheltered places, but never in abundance as compared with other kinds of corals. The absence of *Lithothamnion,* the abundance of foraminifers encrusting coral and the amount of *Halimeda* is indicative of a moderate rather than a very shallow lagoonal depth. Finally, the variety of foraminifers, including pelagic types, indicates that the lagoon was probably open to the sea through passes. The preservation of aragonite skeletons, and indeed of original luster and traces of color pattern, shows that the material since deposition must have had a relatively uneventful history. Connate waters in the material could not have circulated to any extent, and the inference is strong that the rock since deposition has never been raised above sea level.	Core run; 2.5 ft	935.5	10.5
Unconsolidated, unsorted light to medium-brown fossiliferous detritus. The material came out of the core barrel as whole core, but most of it fell apart immediately. Several pieces, one a foot in length, remained as solid core (pl. 63, fig. 2), but these were so friable that they could not be washed without disintegrating. Corals are abundant. In some parts of the core they form 60 percent of the material; in others they form less than 10 percent. Staghorn *Acropora, Alveopora,* and branching *Porites* are most common. Mollusks are common but form less than 5 percent of the material, and there are fewer kinds than in the preceding core. Foraminifera are likewise less common than than they were above. Detrital grains 0.5 to 3 mm in size form the rest of the material. The pieces of core that did not break down into sand differ from the rest of the material in that they contain only 10 to 20 percent of coral and mollusk fragments and a large proportion, 60 to 80 percent, of fine to medium detrital grains bound by a weak limy paste. One sample was dispersed in water in a test tube and allowed to settle. About 10 percent of the material settled very slowly as a tan mud at the top of the sand. It is possible that some of this is drilling mud that completely permeated the porous material, but more likely it is the limy interstitial paste that shows in thin sections described below. Specimen 2A–37–7 (9-cm core).—Light-brown fine to medium detritus. The specimen is soft when wet and sloughs to a sand, but it dries to a compact but friable rock. On freshly broken surfaces, rare small coral and mollusk fragments are visible, but they form less than 5 percent of the specimen.	Core run; 5.5 ft	946	10.5

In thin section the material is seen to consist of scattered grains and organic remains in a yellow to brown microgranular paste (pl. 64, fig. 5). Coral fragments are common. Some are of feathered aragonite, others are of finely acicular carbonate that poorly preserves the original fibrous texture of the coral. Rare mollusk fragments show fibrous shell structure, but some are formed of pale-yellow carbonate whereas others are light to dark brown and have a poor birefringence. *Halimeda* segments are pale yellow and translucent but seem to be completely isotropic. The paste is yellow to brown, finely mottled and rather flaky in appearance. It is microgranular to cryptocrystalline but has a yellow birefringence under crossed nicols.

All grains and fragments are much disintegrated. Most of them have poorly defined boundaries with the paste, even under low magnification. Some of them are fractured and the cracks are filled with interstitial paste resulting in a "flagstone" appearance. A few small grains of calcite are recognizable.

One grain in the section, 0.9 mm in maximum diameter, is a colorless mineral of high relief but low birefringence. It has a roughly parallel fracture probably because it has one good cleavage nearly parallel to the thin section. The grain is nearly isotropic, but has a strained wavy extinction. The interference figure seems to be biaxial and nearly normal to the optic axis, but it is too poor to determine. The boundary with the paste is sharp, and the mineral may be a cavity-filling.

A clear isotropic mineral of low relief that fills the pores of *Halimeda* segments contains scattered birefringent needles or grains too small to determine, but probably of carbonate. The whole aspect of the thin section is one of marked disintegration of organic fragments and grains to microgranular paste.

Specimen 2A–37–14 (6-cm core).—Almost identical to specimen 2A–37–7. In thin section the rock is seen to consist of unsorted detrital grains and organic fragments in a yellow, finely granular to microgranular paste. Scattered coral fragments appear to be much disintegrated, and they contain a net of fine dark lines that under high magnification are diffuse and cloudy. The original feathered aragonite of the coral apparently has disintegrated to finely granular carbonate that preserves a fibrous appearance in a few places. All mollusk shells are stained brown. They show good fibrous shell structure, but under crossed nicols they are poorly birefringent compared to fresh shells, probably because of the staining. *Halimeda, Marginopora,* and some small foraminiferal tests are clear yellowish brown but are isotropic under crossed nicols.

The matrix paste has a yellow aggregate birefringence. In places when the section is ground thin, the paste is apparently granular, and is composed of closely packed grains 0.001 to 0.1 mm in diameter, both of yellow isotropic material and of crystalline carbonate in a pale yellow isotropic matrix.

Specimen 2A–37–15 (5-cm core).—The material, near the bottom of the recovered core, is similar to specimen 2A–37–14 described above. Several analyses were made of this fine detrital sand. A partial analysis by F. J. Flanagan showed 94.32 percent $CaCO_3$ and 1.33 percent $MgCO_3$ present. An X-ray analysis of the material was determined by J. M. Axelrod who reports that it contains aragonite, little calcite, and a little unidentified mineral. Quantitative strontium-calcium ratios by a spectrophotometer were determined by H. T. Odum, of Yale University, who found Sr/Ca to be 0.00392; this is of the same order of magnitude and slightly lower than that of sand samples from the present lagoon, and of corals from the present reef.

Interpretation.—The depositional environment of this unit must be the same as that of the preceding core. The relative rarity of Foraminifera, especially of smaller types, and the zones of poorly fossiliferous, finely detrital material suggest that the organisms may have been exposed to wave action that shifted fine limy material in shallow areas and buried organic colonies.

The disintegration of organisms noted in thin sections has been observed at higher levels, but it has normally been accompanied by recrystallized calcite, and nowhere has it equalled the disintegration seen at this depth. The laboratory analyses indicate that no material was added or taken away, and no recrystallization to calcite was seen. The skeletal structures of organisms, although they remain aragonite, have apparently undergone a breaking down into microgranular or even cryptocrystalline material. This may be an aging phenomenon in the relatively unstable aragonite.

	Method and recovery	Depth (feet)	Thickness (feet)
The top 0.8 foot of recovered core is soft, incoherent, medium to fine detrital sand containing abundant crumbly fragments of coral. The bottom 0.7 foot of core is similar, but is compacted block material jammed in the core bit. Constituents are similar to those of the preceding two core runs. Corals are *Alveopora* and fragile branching *Porites,* some of them encrusted with *Homotrema.* Mollusks are less common than above, but small foraminifers are more abundant than in the core from 935.5 to 946 above, though not so numerous as in the 925 to 935.5 core run. The material appears to be more disintegrated than in the 2 preceding core runs, but this is probably because of the fact that 2 common coral species are both fragile and crumbly; also because much less material was recovered, and most of it was crushed by dry blocking.	Core run; 1.5 ft	956. 6	10. 5
The rock is unconsolidated, unsorted, light-brown fossiliferous detritus that drilled rapidly and smoothly. A core run was made at 1,009 to 1,019.5 feet, but no core was recovered. The rock bit cuttings are mostly fragments 2 to 4 mm in size, and on the whole they consist about half of abundant coral chips, less abundant mollusk shells, rare to common foraminifers, and echinoids spines; the other half is composed of angular to rounded tan detrital grains and white shells and grains obviously from near the surface. Coral fragments, particularly of *Porites,* are somewhat crumbly but well preserved, and pores are empty. Broken mollusk shells and small whole shells are excellently preserved and show original nacreous luster, especially on their interior surfaces. Coarse detrital grains are abundant in cuttings, but fine grains do not constitute more than 5 percent of the material collected. Because small shells are filled with fine tan detritus, and because most of the fines pass through the sampling screens, it is possible that at least half of the original rock was composed of fine-grained material. W. S. Cole reports that *Miogypsinoides* is present at 1,030 to 1,035.5 feet. This is the uppermost larger foraminifer of Miocene age to be recognized. *Interpretation.*—This interval is apparently no different in general lithology from the preceding cored interval, 925 to 956.5 feet. The fossil assemblage is much the same, and the high proportion of corals and of mollusks indicates that the organisms lived in essentially the same shallow lagoonal environment.	Rock bit	1082. 5	126
The material is similar to that of the preceding interval but contains a much higher proportion of mollusk shells and fragments. About half the sample is composed of beautifully preserved gastropod and bivalve shell fragments—the highest proportion seen in any of the Bikini Atoll material. Coral fragments are abundant, and form about one-fourth of the sample; the rest is composed of angular tan detrital grains with a small amount of contaminating material from the surface. Cole reports that *Lepidocyclina rutteni* is present at 1,082.5 feet. This species is a guide fossil for the Tertiary *f* (lower Miocene) of the East Indies. The interval drilled even more rapidly than the preceding ones, but there is no good evidence for any lithologic break at 1,082.5 feet.	Rock bit	1,090	7. 5
At 1,090 feet the bit apparently encountered a "cavity" in the material. The drill rods practically fell to 1,103.5 feet without any resistance, and mud circulation was lost. No cuttings could be obtained. The cavity was cemented and drilling resumed, but cuttings were very poor throughout the rest of the interval. The presence of a cavity at this depth in incoherent detritus is almost inconceivable, as no hard layer existed to form a roof. The bit presumably encountered an extremely porous, incoherent rock that offered practically no resistance to the drill and that was so permeable that no mud wall could form. Possibly all of the material was coarse, or there may have been a strongly leached zone here.	Rock bit	1,127	37
Medium-brown compact limestone. Cuttings are chiefly angular chips 3 to 7 mm size. Rather commonly, on the fractured sides of the chips, embedded tests of foraminifers may be seen in section as well as molds of minute gastropods and bivalves. Judging from the action of the drill, the rock in this 24-foot interval was firm but brittle, and fairly well consolidated, especially when compared with the several hundred feet of unconsolidated detritus above. In addition, ample chips of rock freshly broken by the rock bit were recovered in the mud return, as contrasted with the preceding 37-foot interval in which cuttings were scarce or absent. Cole has identified *Miogypsina indonesiensis* in cuttings from 1,135 to 1,145.5 feet; this species has been reported from Tertiary *f* horizons in Indonesia. This 24-foot section of comparatively well consolidated limestone was logged by Gordon Lill who noted also the presence of abundant molluskan molds. It was not possible to take a core because of the amount of soft uncased hole above. This same layer was also encountered in hole 2B.	Rock bit	1,151	24

Specimen 1135–1145.—Cuttings of medium-brown compact limestone. The fragments are angular chips 3 to 7 mm in size, and they contain common mollusk impressions and internal molds of small gastropod shells. Foraminifers are present as embedded, broken tests. A thin section made of a number of rock chips shows tan, very fine grained detrital limestone containing abundant foraminiferal tests, both whole and broken. A few fragments of *Sorites*? and *Homotrema*? are present, but most tests are small, thin-walled types. They form roughly 30 to 40 percent of the rock and are in a matrix paste that, under low magnification, appears gray and microgranular but, under high magnification, is seen to be formed of finely crystalline calcite. The crystal grains are about 0.01 mm in size in the centers of spaces between foraminiferal tests, but grade to microgranular material at the borders. Most of the tests are formed of clear yellow to brown material. Some are opaque under crossed nicols and apparently are cryptocrystalline; others are dull yellow and contain a mat of minute crystals less than 1 micron in length. Boundaries of isotropic yellow tests with gray paste are distinct, whereas boundaries of the birefringent, microgranular tests with the gray paste are gradational. Centers of some tests are filled with a fine-grained mosaic of calcite crystals.

A group of chips from this sample was analyzed by C. M. Warshaw. She reports that they contain 97.25 percent $CaCO_3$, 2.09 percent $MgCO_3$, and 0.38 percent insoluble residue. An X-ray analysis of the chips was made by J. M. Axelrod, who reports that it contains only calcite with a unit cell 0.1 percent short. Powder from a mollusk shell embedded in one of the fragments was analyzed also, and proved to be calcite with a unit cell 0.5 percent short. The shell therefore either was a cast, or was original shell material recrystallized to calcite.

Interpretation.—The fossils of the interval 1,127 to 1,151 feet are poorly preserved, and appear to be dominantly foraminiferal. The environment in which they were deposited was therefore different from environments of material above 1,090 feet. Possibly the foraminiferal detritus accumulated in somewhat deeper waters than the coralliferous detritus at high levels, but there is nothing to suggest that deposition was on outer slopes or that the depth of accumulation was more than 30 or 40 fathoms.

The original environment of material of this interval therefore cannot be determined accurately, but several facts may be useful in interpreting the subsequent history of the material. Aragonite is absent, and mollusk shells that originally were aragonite are present as molds. Foraminiferal tests, originally of fibrous calcite, are present as microgranular to cryptocrystalline material and are in a matrix that appears to be recrystallized calcite. It seems likely that material at this depth was at or above sea level for a period of time after deposition and before accumulation of the well-preserved material above 1,090 feet. This period, according to evidence of larger Foraminifera reported by Cole, would have to be before the end of early Miocene time, or within the transition Tertiary *e* to Tertiary *f* of the East Indies section.

	Method and recovery	*Depth (feet)*	*Thickness (feet)*
Unconsolidated tan foraminiferal limestone. Cuttings consist of tan to medium-brown angular chips of compact limestone, foraminiferal tests, friable coral fragments, and crystalline internal molds of small mollusks. Corals, including *Porites*, are rare in some samples and rather common in others, but do not form more than 1 or 2 percent of the material; therefore it is possible that the coral comes from higher levels. Mollusk molds are more common than coral fragments, and rare fragments of original shell are present, possibly from higher levels. Larger foraminiferal tests are very common.	Rock bit	1, 346	195

The fragments of friable detrital limestone are seen under the binocular microscope to be composed mainly of closely packed small foraminiferal tests cemented by crystalline calcite. The cement is stronger than the tests, which is probably the reason why smaller foraminifers are not abundant in fine loose material. Fractured surfaces of brittle, compact limestone chips show good sections of small foraminifers. From the interval 1,240 to 1,250.5 feet, Cole has identified *Lepidocyclina* (*Nephrolepidina*) *verrucosa*.

Interpretation.—The unconsolidated nature of the material was evident from the manner of drilling. The bit bored through the material rapidly, cuttings were mostly small (2 to 5 mm) and friable, and the material was so porous that there was a continuously high loss of drilling mud throughout the interval.

The incoherent material of this interval is similar to that of the consolidated rock from 1,127 to 1,151 feet. Corals and mollusks are apparently not major contributors to the detritus, although this is difficult to judge as the skeletons are so altered that most of them might easily disintegrate to unrecognizable fine detritus, due to the grinding of the bit and the churning of the mud in the long trip to the surface. Foraminiferal tests are common in the cuttings, and are probably the chief constituent of the material in place, although most of the smaller ones in incoherent material would probably pass through the cuttings screen. The material could have accumulated in lagoonal waters 20 to 30 fathoms in depth. From the preservation of most mollusks as molds, the friable nature of most corals and detritus, and the abundance of finely recrystallized calcite, it appears that the interval may have been above sea level for a period of time after deposition.

Because the real proportions of the rock components cannot be estimated accurately, it is difficult to tell the ecologic conditions under which the shells accumulated. The scarcity of corals and abundance of foraminifers makes a depth of 20 to 30 fathoms seem plausible, and a sheltered lagoon bottom or protected bank is probably necessary for the accumulation of such incoherent material.

Drill hole 2B

[The drill was located on a broad sandy knoll, the highest point of the island, 179 feet N. 60° E. of holes 2 and 2A (fig. 31). The elevation of the collar of the hole was approximately 20 feet above extreme low-tide level, or 3 feet higher than holes 2 and 2A. The entire hole was drilled by rock bit; total depth 2,556 feet. As the hole was essentially a redrill of holes 2 and 2A, and as no core was taken, the descriptions will be brief, and from 0 to 1,324.5 feet will be limited to observations that may be helpful in interpreting holes 2 and 2A. A diagrammatic section of hole 2B is shown in figure 35.]

	Depth (feet)	*Thickness (feet)*
Unconsolidated foraminiferal sand and coral gravel	26	26
Hard limestone. This rock is below low-tide level, and may be lithified rock at reef level on which the island sand and gravel accumulated.	27.5	1.5
Unconsolidated white detrital limestone. The material drilled like a loose, gravelly sand with numerous relatively thin hard layers that represent either consolidated bodies of rock, or large coral colonies. No significant change was noted in the cuttings or in the action of the drill, corresponding to the change at approximately 100 feet in hole 2, from shallow, near-reef to deeper lagoonal material (*Calcarina spengleri* to *Calcarina hispida* zones). At 177 to 187 feet the material was harder and apparently more coralliferous than at higher levels. This hard zone may correspond to the coral-rich interval from 158.5 to 169 feet in hole 2.	187	159.5
White, chalky, poorly consolidated detrital limestone. The interval drilled rapidly and the cuttings were comparable to material cored in hole 2A at the same depth.	290	103
White, recrystallized detrital limestone. To judge from the drilling, the interval was more consolidated than the preceding one. Cuttings are angular chips of compact white limestone containing small molds of mollusks and cavities coated with calcite crystals. The interval is apparently comparable to that in hole 2A at the same depth.	425	135
Cuttings are white to buff angular chips of porous limestone that are somewhat more friable than the compact white limestone of the preceding interval. Mollusk molds are common. The rock is poorly consolidated and contains considerably more fine-grained loose sandy detritus than the rock from 290 to 425 feet. The rock is white at the top of the interval and buff to light tan at the base. Hard rocks about 1 foot thick were encountered at 425 and 431 feet. These were probably beds or lenses, for there was considerable loss of drilling mud in loose sand under each of these rocks.	550	125
Tan to light-brown angular cuttings of friable, porous limestone. Coral fragments are common but normally do not form more than 5 percent of the material. Molds of small mollusks, both internal and external, are common. There is much light-brown compact rock that forms angular cuttings with finely granular surfaces. Crystalline calcite filling cavities is common. The entire interval drilled rapidly; the material is less consolidated than that at higher levels.	715	165
Light to medium-brown unsorted unconsolidated detritus. Coral fragments are abundant and well preserved, and foraminiferal tests are common. Tan to brown well-preserved mollusk shells and fragments showing original nacreous luster are common. These were first noticed in cuttings from 715 to 725.5 feet and are the reason for placing the top of the interval at 715 feet. Fragments of angular tan limestone and of crystalline calcite are abundant, but because of the presence of original shell material, alteration of the rock is evidently much less below than above 715 feet. Below 750 feet there was a noticeable increase in the proportion of fine material.	832	117

	Depth (feet)	*Thickness (feet)*
Unconsolidated, unsorted tan to medium-brown fossiliferous detritus. Fossils are especially abundant at about 900 feet and from 1,000 to 1,100 feet. These consist chiefly of coral fragments, mollusk shells, and foraminiferal tests in an excellent state of preservation. Some of the shells show their original color markings. The fossils are unevenly distributed, for cuttings from some 10.5-foot intervals are mostly fossil fragments whereas cuttings from other places are finely detrital material, or angular chips of friable, rather barren limestone. This distribution is in accord with the cores recovered from 925 to 956.5 feet in hole 2A, containing both richly fossiliferous and relatively barren sandy intervals. The interval 832 to 1,120 feet showed no change in lithology at the top and seemed to be essentially continuous with the interval above (715 to 832 feet). The top of the unit was chosen at 832 feet because of the presence of a few hard layers and because the material seemed to be a little more fossiliferous at this depth. Miocene fossils are present in this interval, certainly at 925 feet and probably at 852 feet, as will be discussed in a later chapter on age of the rocks. However, the apparent lithologic continuity of the material throughout indicates that deposition was probably continuous from Miocene into Pliocene time, and that no significant alteration, such as might be expected from a relative lowering of sea level, has occurred from 715 to 1,120 feet.	1, 120	288
This unit is compact brown limestone containing molds of small mollusks. The rock is relatively well consolidated, poorly fossiliferous, and is apparently the same as that encountered from 1,127 to 1,151 feet in hole 2A.	1, 155	35
Unconsolidated, porous, light to medium-brown foraminiferal detritus. From 1,155 to 1,219.5 feet cuttings are friable, porous, and contain molds of small gastropods. Some original shell material and coral fragments are probably from the interval drilled although they may be from the fossiliferous zones at higher levels. Larger foraminifers are prominent although they form but a small percentage of the material. Cole has identified *Miogypsina* and *Lepidocyclina* from cuttings at 1,167 feet, and considers that the rock is lower Miocene, probably to be correlated with the transition zone from Tertiary *e* to Tertiary *f* in the East Indies Tertiary section. At 1,219.5 feet, mollusk and coral fragments are relatively minor, but there is a marked increase in the proportion of larger Foraminifera, and their tests form at least 20 percent of the material. The larger foraminifers are the chief recognizable organic remains from 1,219.5 to 1,314.5 feet, where they decrease and mollusk shells increase. The bottom of this unit was so chosen only because 1,324.5 feet marked the end of good cuttings. There is no evidence that a lithologic or faunal change occurs here. *Explanation.*—At 1,324.5 feet the hole was cased with 4-inch casing. The casing stuck at 804 feet, and drilling was continued with a 3⅞-inch rock bit. Because the rest of the hole was drilled with a small bit, and because of excessive contamination from the uncased part of the hole as well as from surface material, the cuttings were exceedingly poor from 1,324.5 to about 1,500 feet. The cuttings are mostly beach sand from the surface and upper part of the hole containing both fresh and worn tests of *Calcarina spengleri*, broken mollusk shells, and white angular fragments of limestone. These probably fell into the hole while it was being cased, for in order to case the hole the drilling mud had been thickened and it could only be thinned gradually after drilling was resumed, otherwise serious caving might have started in the lower, uncased part of the hole. Below 1,500 feet contaminating material in the cuttings decreased gradually, but some of it was in evidence to the bottom of the hole.	1, 324. 5	169. 5
The material is apparently unconsolidated, unsorted, medium-brown detritus containing many fragments of friable coral, mollusk shells, and foraminiferal tests. The entire 430.5 feet drilled rapidly, with only a few thin hard layers. The tan to brown fragments of friable coral, mollusk shells and foraminiferal tests presumably are freshly cut material in part, although it is possible that most of them sloughed in from the uncased portion of the hole, especially from loose fossiliferous beds at 850 to 1,100 feet. Reasons for believing that much of the material was freshly cut rather than being caved material are: first, that the proportion of coral and mollusk fragments in the cuttings increases from 1,500 to 1,755 feet; and secondly, that they are wholly composed of ground-up fragments 1 to 3 mm in size, whereas if they had sloughed in from above a considerable number of larger shells and fragments would be expected. Coral fragments are friable but have unfilled pore spaces. Mollusk shells show original nacreous luster. Foraminiferal tests are normally clean and free of any matrix material. It is of course impossible to estimate accurately the proportions of organic remains in the original material, but because of the poor cuttings and the unconsolidated state of the material it seems likely that finely detrital matrix material comprised a greater part of the	1, 755	430. 5

rock than well-preserved organic remains. There is no evidence that the lithology is any different from that between 830 and 1,120 feet, except that it is less fossiliferous.

W. S. Cole reports that *Miogyosinoides dehaarti*, an index for Tertiary *e* (lower Miocene), appears in cuttings at 1,387.5 to 1,398 feet. In cuttings from 1,597.5 to 1,608 he reports *Spiroclypeus leupoldi, Spiroclypeus margaritatus, Miogypsinoides borodinensis,* and an unidentified *Lepidocyclina* (*Nephrolepidina*). He therefore places the top of the *Spiroclypeus* zone of Tertiary *e* above 1,597.5 feet. He identified *Lepidocyclina* (*Eulepidina*) *formosa* in cuttings from 1,723.5 to 1,734 feet, and he places the top of the *Eulepidina* zone of Tertiary *e* above 1,723.5 feet.

	Depth (feet)	*Thickness (feet)*
Unconsolidated, unsorted medium-brown detritus. The material is similar to that in the preceding interval (1,324.5 to 1,755 feet) except that tests of larger Foraminifera are more prominent whereas fragments of corals and mollusks are rare. Fine material less than 1 mm in size averages about two-thirds of the cuttings samples. Coarse material (1 to 3 mm) is composed of angular hard and compact to crumbly and porous fine-grained limestone; larger foraminiferal tests, which in some samples form as much as 20 percent of the coarse fraction; contaminating material; and fragments of corals and mollusks. Larger Foraminifera identified by Cole include *Spiroclypeus* and *Lepidocyclina* (*Eulepidina*) of the *Eulepidina* zone of Tertiary *e*.	1, 870	115
Unconsolidated, unsorted, medium-brown detritus. Material less than 1 mm in size forms two-thirds to three-fourths of the cuttings. The interval drilled even more rapidly than did preceding intervals, and the material is much the same. In the coarse fraction (1 to 3 mm) of the cuttings, larger Foraminifera are abundant, but much less so than in the preceding interval (1,755 to 1,870 feet) whereas coral and mollusk fragments are rather more abundant. The relative abundance of these fossils is the only criterion used in differentiating this interval and the one preceding.	2, 070	200
Unconsolidated, unsorted medium-brown detritus. The material drilled increasingly rapidly with depth, and was apparently more porous, for the rate of loss of drilling mud in the hole, which had been fairly constant, increased markedly at 2,080 feet and remained high throughout the rest of the hole. The cuttings consist about 20 to 40 percent of detrital fragments 1 to 2 mm in size with some larger fragments; the rest of the material is less than 1 mm in size, some of which is a fine tan powder. The coarser fraction contains angular compact to friable fragments of brown limestone, coral, mollusk shells, and larger foraminifers, whole tests of smaller foraminifers, and tan to brown broken cylindrical rods of calcareous algae. Corals, mollusks, and Foraminifera are common at 2,070 feet, but decrease notably with depth. The rods of algae, on the other hand, are the dominant constituent of most of the interval. Above 2,070 feet they are rare; only 1 or 2 fragments were found in samples above 2,070 feet. In the sample from 2,070 to 2,080.5 feet they are common, and in succeeding samples they increase in amount until they form 50 percent or more of the coarse fraction of all cuttings samples between 2,288 and 2,370 feet. In the sample from 2,317 to 2,327.5 feet they form about 70 percent of all material larger than 1 mm. From 2,370 to 2,401 feet, the algal rods decrease from 50 to 10 percent of the coarse fraction of the cuttings. The calcareous algae form tiny broken cylindrical rods 0.5 to 1.5 mm in diameter and 1 to 4 mm long. They fracture with a clean break nearly normal to the rod axis, and are formed of compact porcellaneous white calcite. Unbroken ends of rods are blunt and round, and exterior surfaces are tan to brown. A thin section was made of several rods from sample cuttings from 2,338.5 to 2,349 feet. Under the microscope they are seen to have a dark-brown color and finely cellular structure characteristic of *Lithothamnion*, although they are much smaller than any rodlike *Lithothamnion* seen on the present reef. J. H. Johnson reports that the small rods represent fragments of long slender branches belonging to a species of the genus *Lithophyllum*. A chip of brown limestone 2 mm in diameter from the same sample was sectioned, and it proved to be detrital material composed of angular grains of *Lithothamnion* 0.5 to 1.0 mm in size cemented by a fine-grained mosaic of calcite. Several small tests of foraminifers are present, some of them completely enclosed by the *Lithothamnion*. The fine detritus, less than 1 mm in size, that forms about 70 percent of the samples probably consists in part of comminuted grains of *Lithothamnion*, although most grains are too small to identify with any certainty, and therefore, the proportion of *Lithothamnion* to the whole sample cannot be established. A species of *Halkyardia* was identified by W. Storrs Cole from cuttings at 2,380 feet. This species has since been found by Cole in rocks of unquestioned late Eocene age on Saipan in the Mariana Islands. It is possible, therefore, that the portion of the "Oligocene(?)" referred	2, 401	331

Depth (feet) *Thickness (feet)*

to "Tertiary *c*" of the Bikini section may eventually be assigned to the late Eocene. Cole reports that the genus at its type locality in Europe is middle Eocene, and that it has recently been reported from definite Oligocene in the Moluccas and from supposed Miocene in New Zealand. Rita Post and Ruth Todd report that a distinct change in fauna occurs between 2,298.5 and 2,349 feet, and they have identified *Halkyardia* from cuttings at 2,349 feet.

Cole has tentatively placed the interval 2,070 to 2,349 feet in the Tertiary *d* (Oligocene), and the interval 2,349 to 2,556 feet in the Tertiary *c* (Oligocene) of the East Indies section.

Interpretation.—The presence throughout the interval 2,070 to 2,401 feet of the calcareous alga, *Lithophyllum*, is indicative that the material accumulated in shallow water where photosynthesis was possible. Although algal debris may be swept to considerable depths, the material drilled must certainly represent thick beds of algae in place of growth for two reasons. First, the broken ends of the algal rods almost invariably show fresh, clean fractures, whereas the cylindrical sides or blunt ends of the rods appear to be original unworn surfaces—a combination to be expected if most of the material ground by the rock bit were in its position of growth, but not likely if the material were detrital. Second, the proportion in the cuttings of delicate *Lithophyllum* rods is so great, especially from 2,288 to 2,370 feet, and the proportion of other recognizable organic remains is so small, that the only reasonable explanation is that the bit was grinding on thick beds containing little besides calcareous algae.

The *Lithophyllum* of the cuttings is far more delicate than any common forms observed on the present-day reef or lagoon. Two kinds of ecological conditions are possible. If the *Lithophyllum* of the cuttings required conditions similar to those required by present-day species, then the thick algal beds from 2,070 to 2,401 feet must have accumulated at sea level or a few feet beneath, in the zone of maximum sunlight and aeration, but sheltered from heavy surf favored by massive forms of *Lithothamnion.* They, therefore, must either have grown on the lagoon edge of a reef or formed algal banks in a sheltered lagoon.

If, on the other hand, the rodlike *Lithophyllum* did not require so shallow an environment, the thick beds of algae may have developed at a somewhat greater depth. They may have lived under conditions comparable to those favorable to present-day *Halimeda,* namely, a lagoon bottom environment in 10 to 25 fathoms of water.

The first hypothesis seems more reasonable until more is learned of the ecology of the rodlike alga. The evidence, however, strongly suggests that the material of this interval was deposited in shallow waters less than 30 fathoms, in an environment similar to that of the present-day atoll. If these sediments be Oligocene or lower Miocene, or even Eocene, we are led to believe that reefs and lagoons not much different from present ones may have existed in Tertiary times.

The fine mosaic of calcite seen in thin section to cement grains of *Lithophyllum* indicates that some calcite has recrystallized. This fine mosaic may be a cementation that occurred at a time when the reef grew close to sea level and may be comparable to the development of crystalline calcite seen on the existing reef. The proportionate amount of recrystallization is negligible, however, for the material drilled was as completely unconsolidated and porous as a loose coarse sand. There is no evidence that the material ever stood above sea level.

Unconsolidated, unsorted but rather fine-grained, light to medium-brown detritus. The interval is similar to the preceding one (2,070 to 2,401 feet), for the bit drilled rapidly through loose material, and a constant loss of drilling mud showed that the limestone was exceedingly porous. 2, 556 155

The cuttings contain 10 to 20 percent grains from 1 to 2 mm in size, with a few larger ones; the rest are finer than 1 mm. Coral fragments and mollusk shells are rare; all the coral may be contamination from higher levels, but it is possible that a study of the mollusks will reveal species not found at higher levels. The algal rods so abundant in the preceding interval form roughly 10 percent of the coarse fraction of each sample in this 155-foot interval. Beginning at 2,370 feet, the decrease with depth in the proportion of algae in cuttings may mean that they are actually absent from 2,401 to 2,556 feet; and the presence of algae in cuttings may be due to contamination from the rich algal zone above. The fact that they consistently form about 10 percent of the coarse material below 2,401 feet, however, makes it more probable that the *Lithophyllum* is actually present in the rock drilled although not so abundant as it was from 2,288 to 2,370 feet.

The fine material consists of angular grains and rather rare small foraminiferal tests.

Interpretation.—The material of this interval is apparently a loose finely detrital sand, containing rods of *Lithophyllum* and some foraminiferal tests. The similarity should be noted between this sand and the fine to medium sand deposited in the outer periphery of the present-day lagoon, within a few miles of the encircling reef, but there are no other indications of the environment of the material.

Drill hole 3

[The drill rig was located on the flat sand berm, near the crest of the beach at the south end of Bikini island, about 800 feet from the seaward margin of the reef (fig. 31), and 6 feet above the reef flat, or about 8 feet above low-tide level; total depth 118 feet. From the beach line near the drill, several consolidated rock bars or groins extended 50 feet or more out on the reef. These were composed of lithified boulders and sand rather than of reef rock, and their tops were about 2 feet above the reef level. A diagrammatic section of the hole is shown in figure 36]

	Method and recovery	*Depth (feet)*	*Thickness (feet)*
Coarse beach sand and coral gravel	Rock bit	6	6
Coarse conglomeratic rock, well-indurated, probably comparable in the top 2 feet to the nearby rock bars that are covered by beach sand.	Rock bit	10. 7	4. 7
Well-consolidated coarse foraminiferal limestone and coral-algal limestone. The recovered core all came from the top of the interval. Below 16 feet the material was friable and unconsolidated. The top foot of recovered core consists of unbedded foraminiferal sand containing about 85 percent worn tests of *Calcarina spengleri* and a few *Marginopora;* 10 percent fragments of *Lithothamnion* and mollusks; and 5 percent echinoid spines, red encrusting foraminifers, and angular grains of coral. The next foot consists of masses of branching *Lithothamnion*, probably *Porolithon*, and poorly-bedded foraminiferal sand containing large pebbles of coral. Below this is 2 feet of *Lithothamnion* apparently in position of growth, and interstitial detritus (pl. 64, fig. 3). The bottom 1.5 feet of the recovered core consists of coarse pebbles and cobbles of coral in an unsorted matrix mostly of foraminifers. The rock of the entire core is well cemented by aragonite that thinly coats individual grains and tests like shellac and that completely fills pore spaces. Small cavities in the rock are partly filled by fine detrital material. Grains and tests coat the horizontal surface of the fillings, and the empty parts of the cavities are coated by a thin crust of carbonate (pl. 64, fig. 4). *Interpretation.*—Because all of the core came from below the present reef level, and because parts of it seem to have grown in place, it is probable that the whole interval including the bedded foraminiferal sand is reef-formed.	Core run; 5.3 ft	22	11. 3
The interval drilled like an unconsolidated gravelly sand. Cuttings show abundant segments of *Halimeda*, fragments of *Lithothamnion*, and unworn tests of *Calcarina spengleri* and *Marginopora.*	Core run; 0 ft	32. 5	10. 5
Poorly consolidated, coarse coralliferous detritus. The recovered core consists of broken and worn coral fragments from a few millimeters to a few centimeters in diameter in a coarse matrix of *Halimeda* segments, foraminiferal tests (especially *Marginopora*), rare mollusk shells, and angular to subrounded detrital grains. Corals include *Astreopora*, *Acropora*, and *Heliopora*. The outer surfaces of some contain a few encrusting *Homotrema rubrum.* The recovered material is all moderately consolidated but is very porous. The rock as a whole is poorly consolidated, however, for it drilled rather rapidly and contained only a few hard layers that were probably either colonies of coral, or well-cemented patches in the rock. *Interpretation.*—The material of this core run contains some worn, poorly rounded coral pebbles and therefore must have accumulated in shallow water, possibly on a reef but more probably in the lagoon close to the reef edge because of the abundant *Halimeda.* The presence of *Halimeda* in this core, contrasted with the *Lithothamnion* near the surface, may possible be correlated with the abundance of *Halimeda* in hole 1, at 43 feet, and in hole 2, at about 50 feet.	Core run; 1 ft	43	10. 5
The recovered core consists almost entirely of large fragments of coral, especially *Astreopora* and *Acropora.* Unsorted, friable detritus coats a few small surfaces of the coral. The detritus consists mostly of broken segments of *Halimeda* and tests of small Foraminifera. Cavities in the coral are encrusted with small worm tubes. A few worn, rounded pieces of coral at the bottom of the recovered core have a surficial brownish-orange stain, about 1 mm thick, that resembles the stain seen on some coral pebbles on present day beaches. Specimen–3–4–12 (fragments).—Several worn, rounded pieces of coral 2 to 4.7 cm in maximum diameter. The fragments are stained brownish orange on their outer surfaces. A sawed face on one fragment shows two branches of *Acropora*? formed of porcelaneous, compact carbonate, overgrown by fragile open cells of the same coral. The stain is seen to coat the outer part of the compact coral, but not of the porous coral. In thin section the staining is apparent to the naked eye but not under the microscope. The coral is apparently unaltered fibrous yellow aragonite containing diffuse dark lines that are probably carbonaceous material. Most pores are open. Some are coated with minute needles, probably of aragonite; some are lined with minute crystals of calcite; and a few are completely filled by a coarse mosaic of clear calcite.	Core run; 1 ft	53. 5	10. 5

Method and recovery	Depth (feet)	Thickness (feet)

Interpretation.—The dominance of coral in this interval suggests a reef or near-reef environment, but recovery was too poor to estimate the actual proportions of material present.

The worn, stained fragments of coral containing a little coarsely crystalline calcite suggest a possible beach origin, but no other indications were seen.

Method and recovery	Depth (feet)	Thickness (feet)
Core run; 1 ft	58	5

Fragments and a few core pieces of coral and of rather friable, unsorted detritus. The coral consists of *Acropora*, *Goniastrea*?, and *Astreopora*, and the detritus consists mostly of *Halimeda*, unworn tests of *Calcarina spengleri*, and angular chalky grains. One *Acropora* colony contains a cavity 5 mm in diameter half filled with fine chalky detritus. One piece of porous, unsorted detritus consists of *Halimeda* segments, encrusting foraminifers and several masses of matted branching tubules less than 0.1 mm in diameter that resemble the encrusting foraminifer *Sagenina*. Several small worn and polished grains, are scattered through the material.

Specimen 3–5–2 (7.8-cm core).—*Acropora*, apparently unaltered. In thin section the coral is seen to be made of brownish-yellow fibrous aragonite containing small diffuse streaks apparently of carbonaceous matter. Many pores are empty, but some are filled with finely detrital to microgranular gray paste. Many of the pores are lined and some are filled with needlelike crystals of aragonite.

Interpretation.—The material of this core apparently accumulated in shallow water. The nature of the encrusting organisms, and the porosity of the detrital material suggest that much of the finer material accumulated essentially in place, although scattered worn grains were obviously transported from some other environment, probably at no great distance.

Method and recovery	Depth (feet)	Thickness (feet)
Core run; 4.5 ft	63. 5	5. 5

Unsorted, poorly to moderately consolidated coralliferous detritus. Coral forms roughly 30 percent of the recovered material, and it consists of broken fragments and a few colonies apparently in position of growth, of *Astreopora*, *Acropora*, *Pocillopora*?, and *Seriatopora*?. On the base of one colony is a small encrusting coral, *Cyphastrea*?. The rest of the core consists of numerous mollusk shells, one with original color; *Halimeda* segments; and unworn tests of foraminifers, especially *Calcarina spengleri*. Irregular layers of *Lithothamnion* and encrusting foraminifers, both *Homotrema* and *Carpenteria*, are common. The organic remains are loosely packed and contain open cavities, but much medium to fine-grained angular detritus is irregularly distributed in the rock.

The material became noticeably harder at 61.5 feet, and the lower part of the core run drilled more slowly than the upper part.

Specimen 3–6–11 (6.8 cm core).—Friable detrital limestone containing segments of *Halimeda*, tests of free and encrusting foraminifers, and a pitted fragment of coral in a fine sandy matrix. In thin section the detrital matrix is seen to be a fine-grained to microgranular gray paste. The coral is riddled with small holes, most of which are filled or half filled with the gray paste. The angular grains in the paste are mostly fragments of coral, *Halimeda*, and shells 0.05 to 0.2 mm in diameter. Under high magnification the paste is seen to be finely crystalline to microcrystalline, and it seems to have been partially recrystallized.

Specimen 3–6–15 (7.5 cm core).—Porous detrital limestone; the broken face of core contains one large cavity and numerous small cavities in the loosely-packed, coarse organic remains of *Halimeda*, *Lithothamnion*, corals, and foraminiferal tests. Fine material and powdery chalk are present only in small patches.

Specimen 3–6–18 (6.5 cm core).—Friable, unsorted coarse detritus of organic remains in a fine-grained matrix. In thin section the unsorted material is seen to consist of coral and of rather coarse detrital material containing abundant *Halimeda* segments and grains, tests of *Calcarina spengleri* and *Marginopora*, broken mollusk shells, and angular grains 0.02 to 3 mm in size. The grains and shells are cemented by fibrous carbonate and by microgranular gray paste. The thin section differs from that of specimen 3–6–11, although the two rock specimens are similar. Specimen 3–6–11 contains much microgranular paste and fine grains, but large grains are scattered; whereas this specimen contains packed coarse grains, relatively few fine grains and paste, and much acicular carbonate cement.

Interpretation.—The material of this interval is rich in coral and organic remains including abundant *Lithothamnion*, *Halimeda* and unworn test of *Calcarina spengleri*. It accumulated probably in shallow quiet water. The loosely-packed nature of the material, the presence of abundant open cavities within the detrital material and of encrusting organisms in these cavities, as well as in the cavities in corals, is evidence that few of the organisms in the assemblage have been transported any distance. The material therefore probably accumulated in shallow water on a reef.

	Method and recovery	Depth (feet)	Thickness (feet)
Moderately consolidated coralliferous limestone.	Core run; 2 ft	68.5	5

Moderately consolidated coralliferous limestone. Corals form about 40 percent of the recovered core, and they include colonies of *Astreopora* in position of growth (pl. 63, fig. 4). Masses of encrusting *Carpenteria* form more than 30 percent of the material. *Lithothamnion* crusts and nodules are common, and *Halimeda* segments are abundant in cavities. Minute worm tubes commonly encrust segments of *Halimeda*, tests of *Carpenteria*, and surfaces of cavities in corals. No tests of *Calcarina spengleri* were found in any of the core pieces.

Interpretation.—The material is similar to that of the interval above (58 to 63.5 feet) in that it is apparently an assemblage of shallow-water organisms probably from a reef environment. The absence of *Calcarina spengleri* and the abundance of *Carpenteria* suggest that a considerable change occurred between the deposition of rocks of this core run and rocks above. The change was probably marked by the increased hardness of the rock near the bottom of the preceding core run, at 61.5 feet, and it is comparable to the changes already described in Hole 1 at 95 feet, and in Hole 2 probably at 105 feet, from a *Calcarina hispida* zone below to a *Calcarina spengleri* zone above. The probable depth of the change, at 61.5 feet, is also significant, for it is approximately 50 feet below low-tide level, at the same depth as the seaward terrace that fringes the reefs.

	Method and recovery	Depth (feet)	Thickness (feet)
Unsorted, well-consolidated, coralliferous detrital limestone.	Core run; 2.5 ft	73.5	5

Unsorted, well-consolidated, coralliferous detrital limestone. Coral, including *Porites* and *Acropora*, are mostly unaltered in appearance but pores are filled with porcelaneous white limy paste. Outer surfaces of coral are encrusted by *Lithothamnion*, *Carpenteria*, and tubes of small worms; coral interiors are riddled by borings. Mollusk shells are common and include a large piece of *Tridacna* shell and a *Turbo* operculum. *Halimeda* segments are abundant. The organic remains are in a matrix of fine to coarse detrital grains. In some places the matrix consists mostly of grains 1 to 2 mm in diameter, in others it is a chalky powder. It is well consolidated as a whole and is apparently cemented by crystalline calcite, for specimens show a fine sparkle under a light, and some calcite cleavage faces 1 mm in diameter are scattered through the material. A few small areas of the core are pervaded by compact tan to brown crystalline carbonate.

Specimen 3–8–14 (11 cm core).—Well-consolidated, unsorted coarse detrital limestone containing large masses of layered *Lithothamnion*, one large and numerous small fragments of coral, many loosely-packed segments of *Halimeda*, a few large echinoid spines, and scattered detrital grains. The matrix is chalky powder in a few small areas, but in most places it is buff to brown, hard carbonate. The brown material is compact but has many small open pores.

A thin section was made across the large coral fragment and the *Halimeda* detritus. The coral is seen under the microscope to be formed of finely fibrous yellow aragonite, partly altered to dark-brown, nearly opaque, microgranular to cryptocrystalline paste. The alteration is nearly complete at the borders of the coral and it diminishes to the center. The dark-brown paste apparently has formed at the expense of the fibrous aragonite, which it penetrates as fine branching diffuse veinlets and irregular masses. The brown paste seems to be the result of disintegration of the fibrous aragonite, and it is probably colored by organic matter. Pores of the coral are filled both by clear acicular carbonate and by a mosaic of clear fine-grained calcite.

The detrital half of the slide contains loosely packed segments and grains of *Halimeda*, nodules and fragments of *Lithothamnion*, and rare shells and echinoid spines. These are contained in a fine-grained mosaic of calcite. Open cavities in the mosaic are rimmed by dark-brown microgranular paste that appears to be later than the mosaic; but in some places there are diffuse patches of brown paste that appear to be shreds and remnants in the clear calcite mosaic.

Most of the organic remains and detrital fragments are thinly rimmed by dark-brown microgranular paste. Some grains have diffuse borders and are apparently in process of being replaced. Some *Halimeda* segments seem to be unaltered and have sharp boundaries with the calcite mosaic, but others seem to be much altered and they merge with the calcite.

There are two types of alteration seen in this section, one a disintegration (especially of aragonitic organic remains) to brown microgranular paste; the other a crystallization of clear calcite. It is not known whether the brown paste formed at one time, or whether some formed before and some after the mosaic of calcite.

284244—54——18

	Method and recovery	*Depth (feet)*	*Thickness (feet)*
Interpretation.—The rock in this core run contains, in abundance, both *Halimeda* and *Lithothamnion*, as well as coral, and it accumulated in very shallow water—probably on a reef. If this core is considered along with the preceding cores, it seems likely that all the material below about 60 feet was deposited on a reef in a few feet of water. The degree of consolidation and the amount of recrystallized calcite indicate a possible uplift relative to sea level after the material accumulated.			
Moderately consolidated coralliferous detritus. The material is cemented by compact carbonate. Coral cell walls are friable and pores are filled by calcite. Cavities in the material contain tests of foraminifers thinly coated with carbonate that looks like shellac. Some brown carbonate is present in small patches.	Core run; 2 ft	76. 3	2. 8
Unsorted, well-consolidated detrital limestone. The core is continuous and apparently came from the top 5 feet of the run, for circulation was lost at 81 feet and was not regained during the rest of the run. The top 2 feet of core is white to buff limestone and it contains abundant coral (probably *Acropora*), nodular pieces of *Lithothamnion*, and encrusting foraminifers, numerous segments of *Halimeda* and mollusk molds, moderately numerous tests of small foraminifers, and echinoid spines. Corals are generally chalky and pores are filled with crystalline calcite so that, on outer surfaces of core, only the pore filling remains as a mold. *Lithothamnion* and encrusting foraminiferal tests are compact and apparently unaltered, but *Halimeda* segments are chalky and tests of small foraminifers are disintegrated and are almost unrecognizable.	Core run; 4.3 ft	86. 3	10

The lower 2.3 feet of core from this run are formed of organic remains similar to those in the upper 2 feet, but the rock is exceedingly cavernous because spaces between coral and other fragments are not filled by fine detritus. The cavities range from a few millimeters to several centimeters in size, and they are encrusted by medium to dark-brown, finely to coarsely crystalline calcite. The calcite crusts are 1 to 10 mm in thickness and most of them are formed of several layers of interlocking, elongate, coarse calcite crystals that are roughly normal to the surface on which they grow. Some cavities contain clusters of euhedral crystals of dogtooth calcite.

Specimen 3–10–8 (10 cm core).—Cavernous coral limestone. Large coral pieces form most of the specimen, but there are a few small segments of *Halimeda* and possibly nodules of *Lithothamnion*. Some coral fragments are compact and are filled with crystalline calcite, but others are molds. The cavities are encrusted by tan to brown crystalline calcite (pl. 64, fig. 2). Tan calcite is seen on a sawed face to be formed of interlocking subparallel calcite crystals that are banded by fine concentric zones of light and dark color cutting across the crystals. Similar agatelike banding from the Funafuti core is discussed by Cullis (1904, p. 410), who attributes the banding to inclusion of finely divided mud in the carbonate in successive periods of crystallization. In this specimen, however, the banding is apparently a concretionary phenomenon that developed after the material crystallized. The dark-brown calcite is coarsely crystalline. At least two stages of calcite filling seem to have occurred, as the dark-brown filling meets the light-brown in sharp contact. The dark-brown calcite fills veins and irregular spaces, whereas the light-brown calcite has smooth, rounded outer surfaces. Which is older has not been determined. Both types alter and replace the coral as well as fill cavities.

Specimen 3–10–11 (5.8 cm core).—Large coral completely encrusted by brown coarsely crystalline calcite. In thin section, surficial cavities in the coral are seen to be coated with several layers of encrusting foraminifers, probably *Homotrema*. Coarsely crystalline calcite coats both coral and foraminifers. The crystals are elongate, interlocking, and are alined normal to the coral surface.

The coral is recrystallized to a coarse mosaic of clear calcite (pl. 61. fig. 3) in which the cellular structure of the coral remains as a dark pattern. The crystals of calcite are continuous through and independent of the coral structure.

Specimen 3–10–12 (11.8 cm core).—Consolidated, cavernous limestone consisting of pieces of coral thickly encrusted by dark-brown calcite (pl. 64, fig. 4). The coral is altered to chalky material that is filled and consolidated by crystalline calcite in some places. *Halimeda* segments and fine detritus in a few of the cavities are firmly cemented by brown calcite. Cavities are lined by coarsely crystalline brown calcite, and some thin horizontal layers of calcite cut the open cavities.

	Method and recovery	*Depth (feet)*	*Thickness (feet)*
Specimen 3–10–13 (5.3 cm core).—Two large pieces of coral coated with brown coarsely crystalline calcite. At the bottom of the specimen is a crust of brown calcite 1.5 cm thick. The core piece was boiled in Meigen's solution and was unstained except for small chalky areas of the coral interior. The brown calcite was analyzed by J. M. Axelrod, who found calcite with a unit cell less than 0.1 percent short. *Interpretation.*—The large amount of coral, *Lithothamnion,* and encrusting foraminifers in this core run, and the cavernous nature of the material indicate that it is a reef deposit. The amount of calcite recrystallization and replacement suggest that the reef and the terrace were raised relative to sea level after formation, allowing percolation of solutions through the rock and deposition of calcite in cavities.			
The top part of the material consists mostly of large pieces of compact broken coral coated in places with *Halimeda* and encrusted by *Carpenteria* and *Homotrema.* These pieces resemble coral from the interval 43 to 53 feet, and may be large fragments that dropped from that level. The rest of the recovered core consists of leached and altered coral, encrusted with yellow to brown crystalline calcite. Several coral fragments show a thin hard black coating between the coral and the brown calcite crust. The black material, according to Axelrod, was determined by X-ray analysis to be "Mineral T," a new manganese oxide mineral not yet fully described. The limestone at the bottom of the core is leached in appearance. It is compact and consolidated, but contains numerous irregular cavities with a subhorizontal alinement. Some of them resemble mollusk or *Halimeda* molds.	Core run; 2.5 ft	96. 8	10. 5
White, porous, moderately consolidated, hard limestone. The rock is riddled by open pores 1 to 10 mm long, most of which appear to be molds of small mollusks or *Halimeda.* Interiors of the cavities are coated with friable, porous calcite that is lacelike and etched in appearance and seems to be a leached residue of material that originally filled the cavity. The limestone surrounding cavities is hard and compact, and it contains few recognizable traces of organic remains. Under the binocular microscope it is seen to be well crystallized, for minute cleavage faces of calcite are visible. Although 10 to 20 percent of the rock is open cavities, the rock is as dense as any of the core recovered in the hole. Apparently carbonates that dissolved, leaving open cavities, were redeposited in the matrix. Specimen 3–12–19 (5-cm core).—White consolidated limestone containing abundant open cavities, possibly molds of *Halimeda* and mollusks. The limestone is fine-grained, compact to porcelaneous calcite. In thin section the material is seen to be gray, fine-grained to microgranular paste containing a few recognizable small fragments of *Homotrema, Carpenteria*?, and tests of small foraminifers. Fine detrital grains in the gray paste are seen under high magnification to be blurred, and they grade into microgranular material. In spaces between the grains, the microgranular material grades into a fine-grained mosaic of clear calcite. Disintegration to microgranular material and recrystallization to calcite mosaic may be observed.	Core run; 4 ft	107. 3	10. 5
White porous, consolidated, hard limestone. The recovered core is similar to that recovered in the previous core run (96.8 to 107.3 feet), and it contains abundant cavities in a compact, porcelaneous limestone. A thin section made from one core specimen was very similar to that described above, from specimen 3–12–19. The rock looks leached and etched, but it is so compact that apparently there has been no removal of total carbonate. *Interpretation.*—The material from about 90 feet to the bottom of the hole is so altered that few recognizable fossils can be seen. Thin sections show much fine detritus and microgranular paste, but the origin of the rock is not known. The strongly leached appearance of the limestone suggests that considerable percolation of water occurred, probably above sea level.	Core run; 1 ft	117. 8	10. 5

284244—54——19

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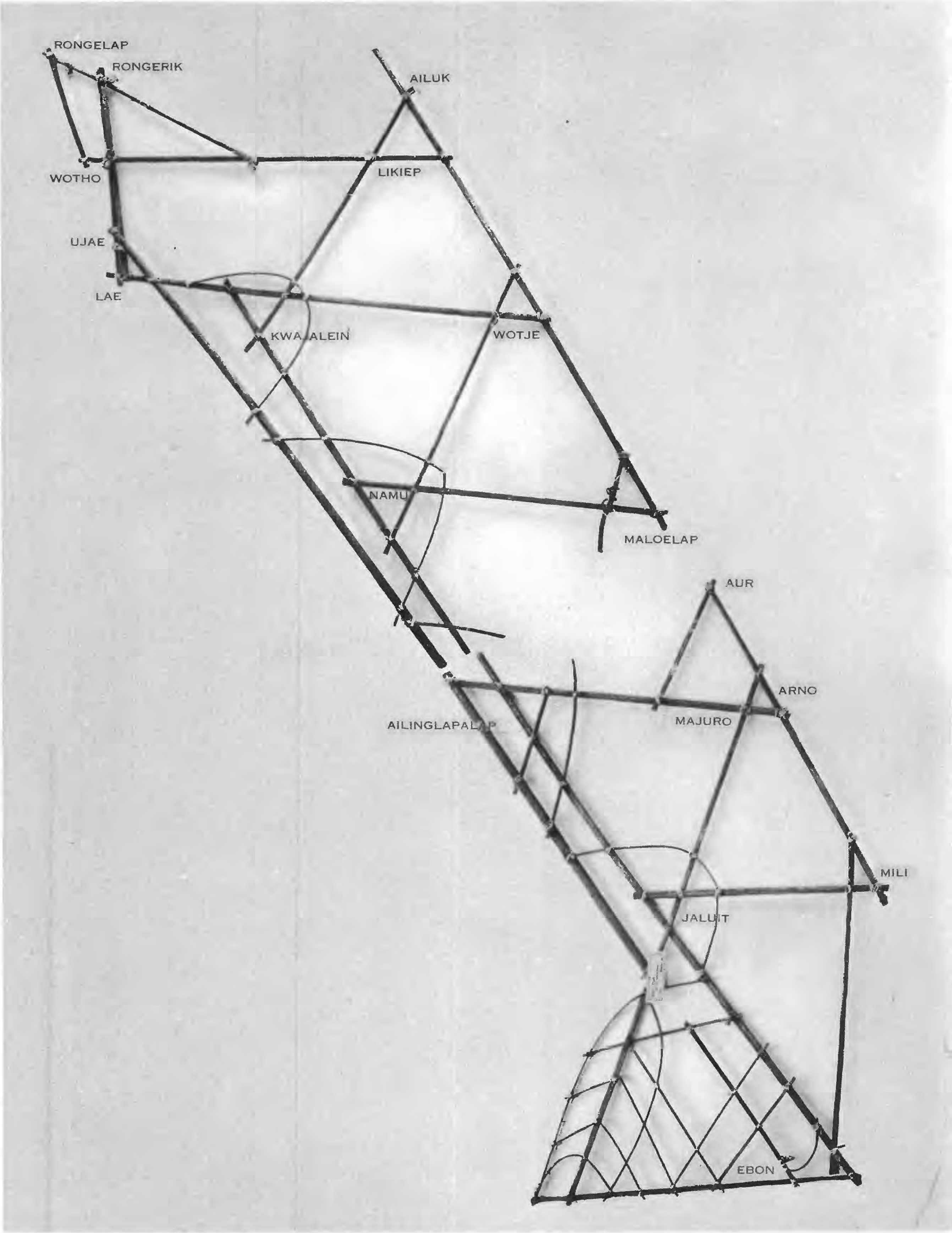
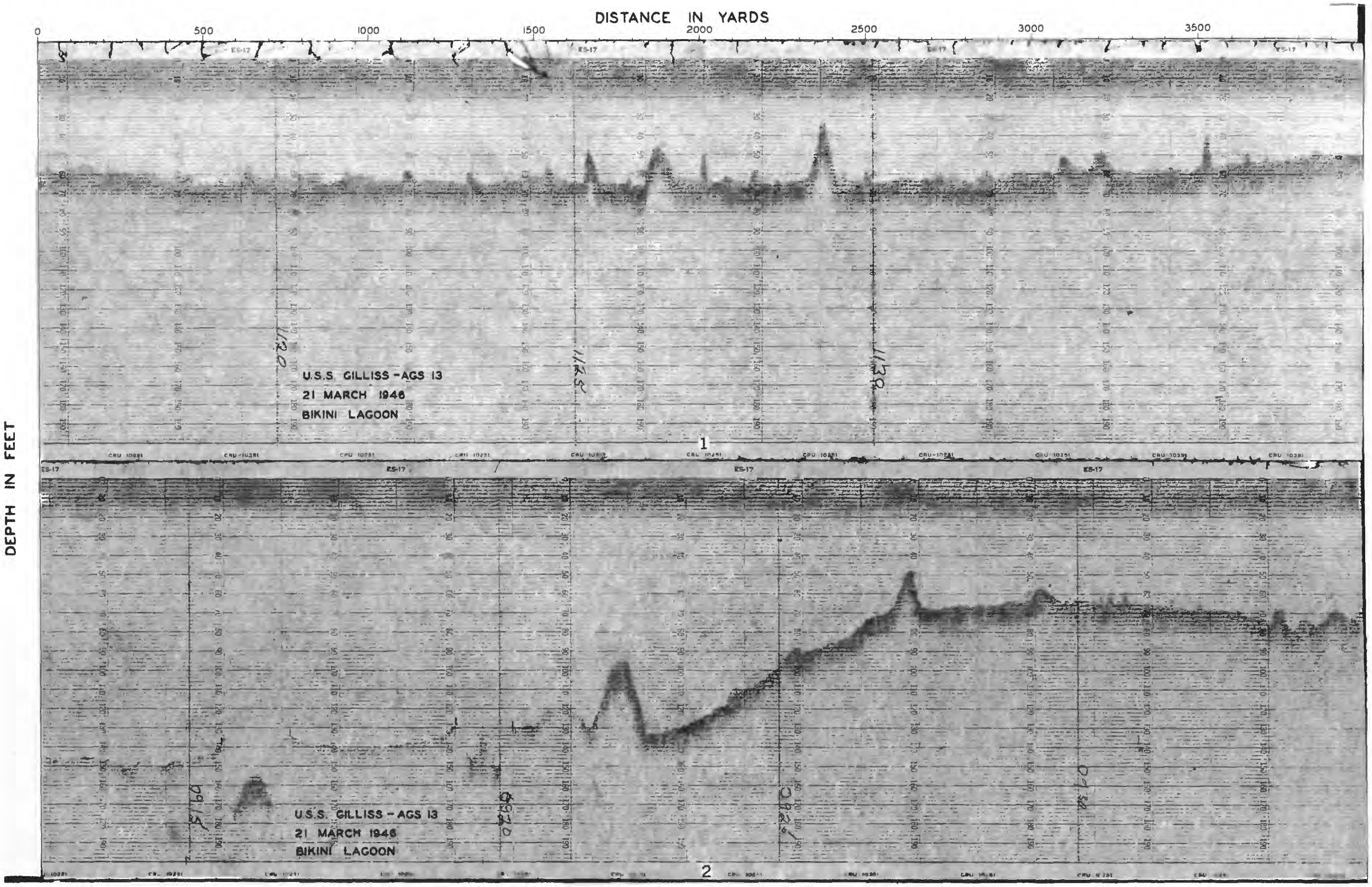
[Asterisks indicate names referred to throughout report]



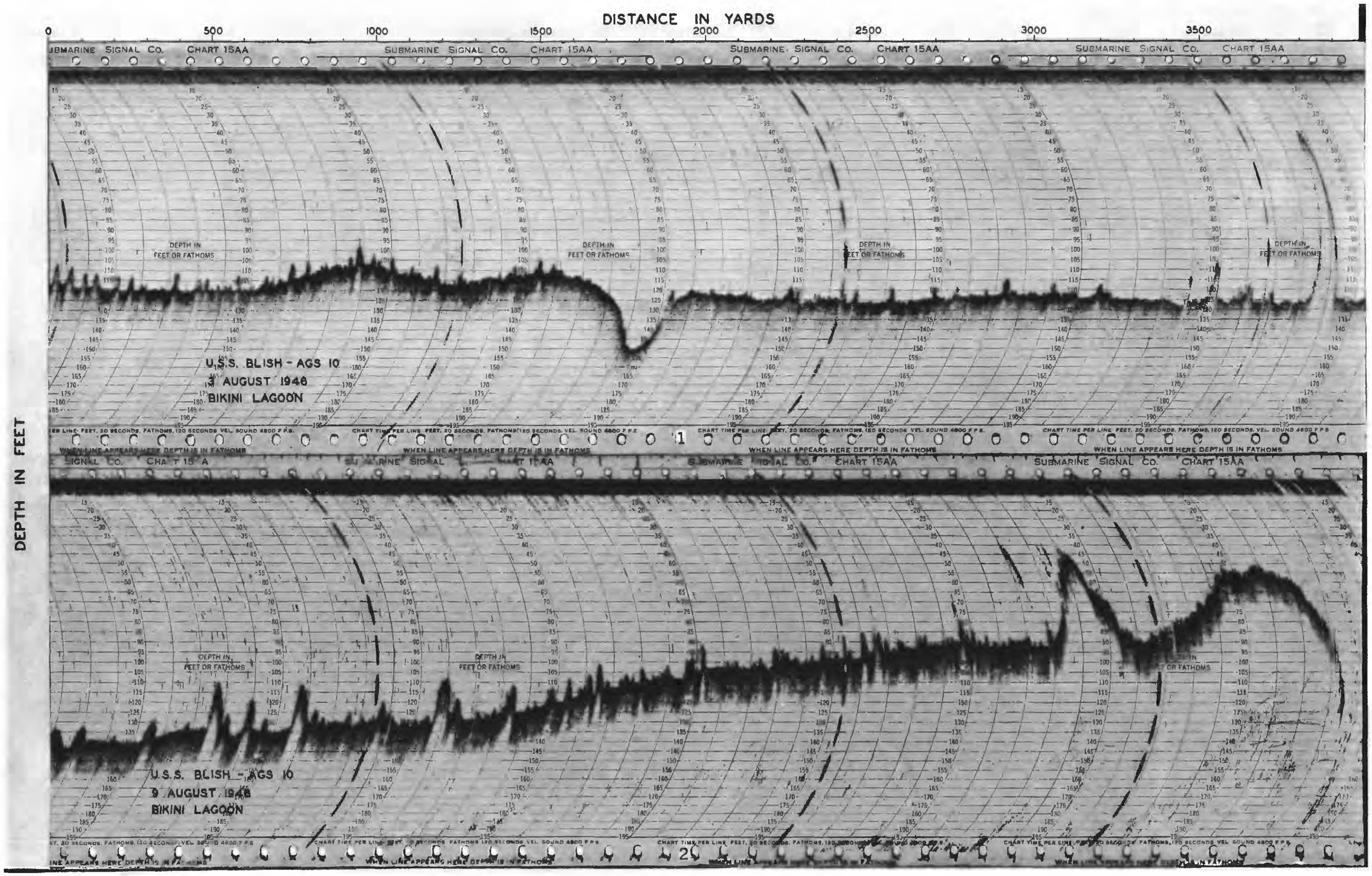
MARSHALL ISLANDS "STICK" CHART

"Stick" chart made by Marshall Islander, with interpretations. Original at Bernice P. Bishop Museum, Honolulu.



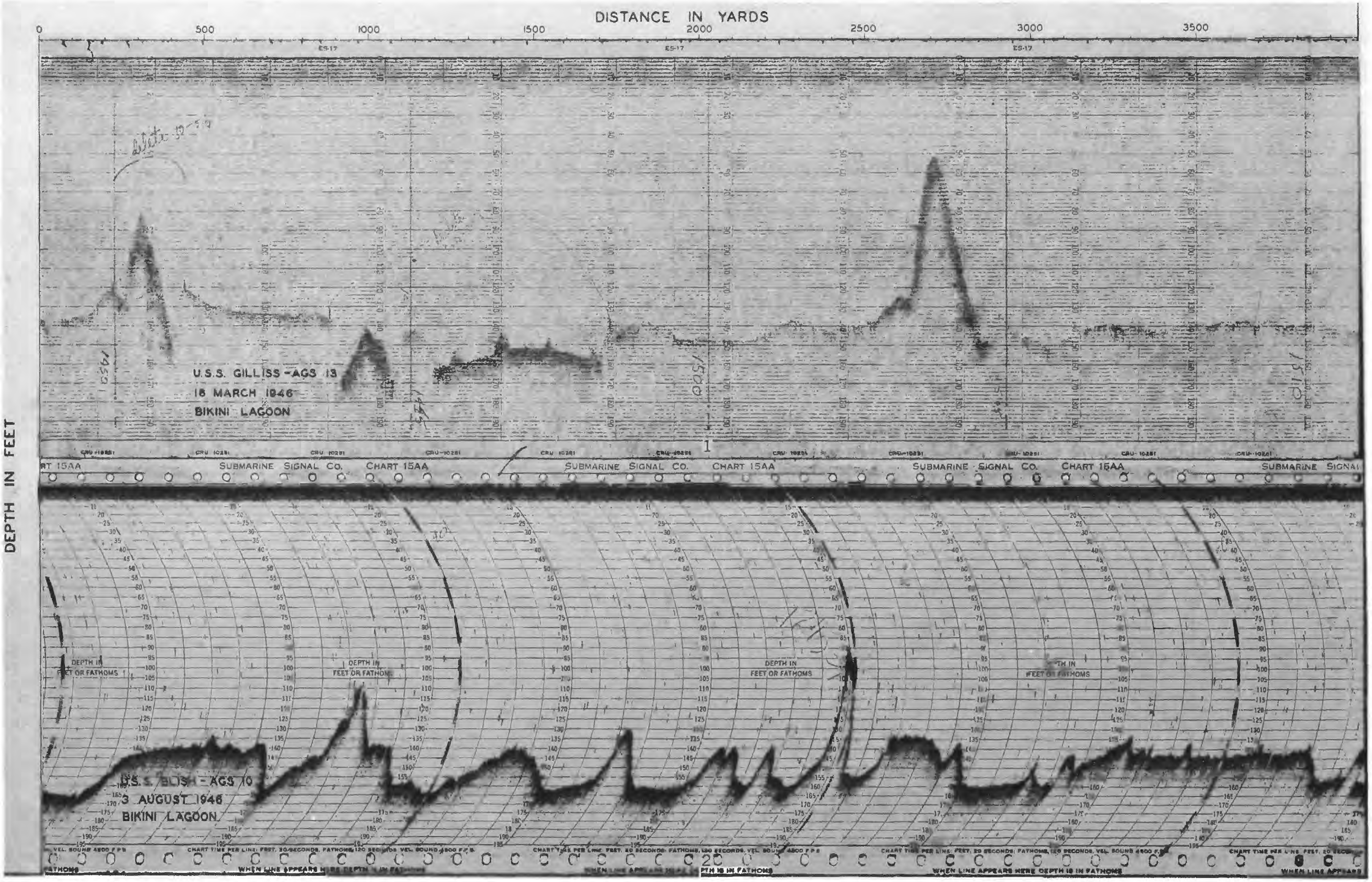
FATHOGRAMS OF BIKINI LAGOON

1. Surface of 10-fathom terrace near Bikini island.
2. Slope of 10-fathom terrace to deep lagoon floor near Bikini island.



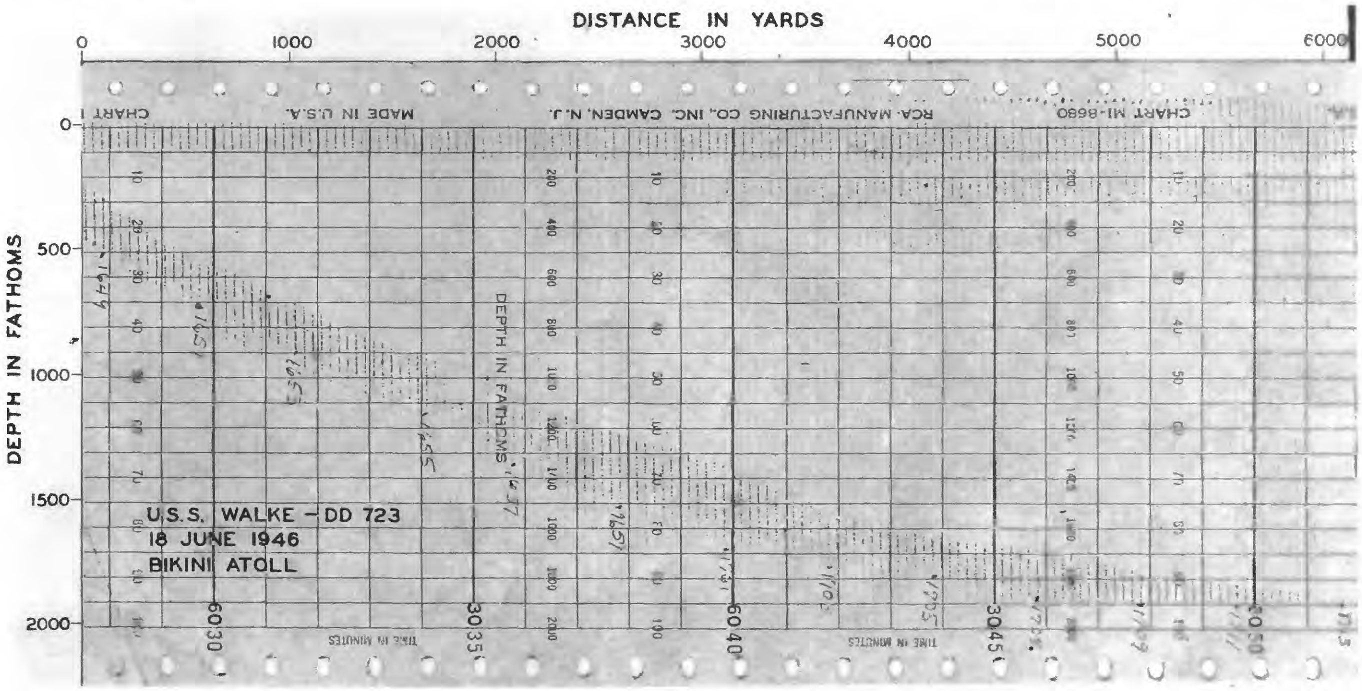
FATHOGRAMS OF BIKINI LAGOON

1. High coral knolls near Bikini island.
2. Intermediate coral knolls in west end of lagoon.



FATHOGRAMS OF BIKINI LAGOON

1. Small coral knolls and deep channel near Enirik island.
2. Profile taken along the axis of Bokororyuru Pass, showing the steepening to deep water on left side.



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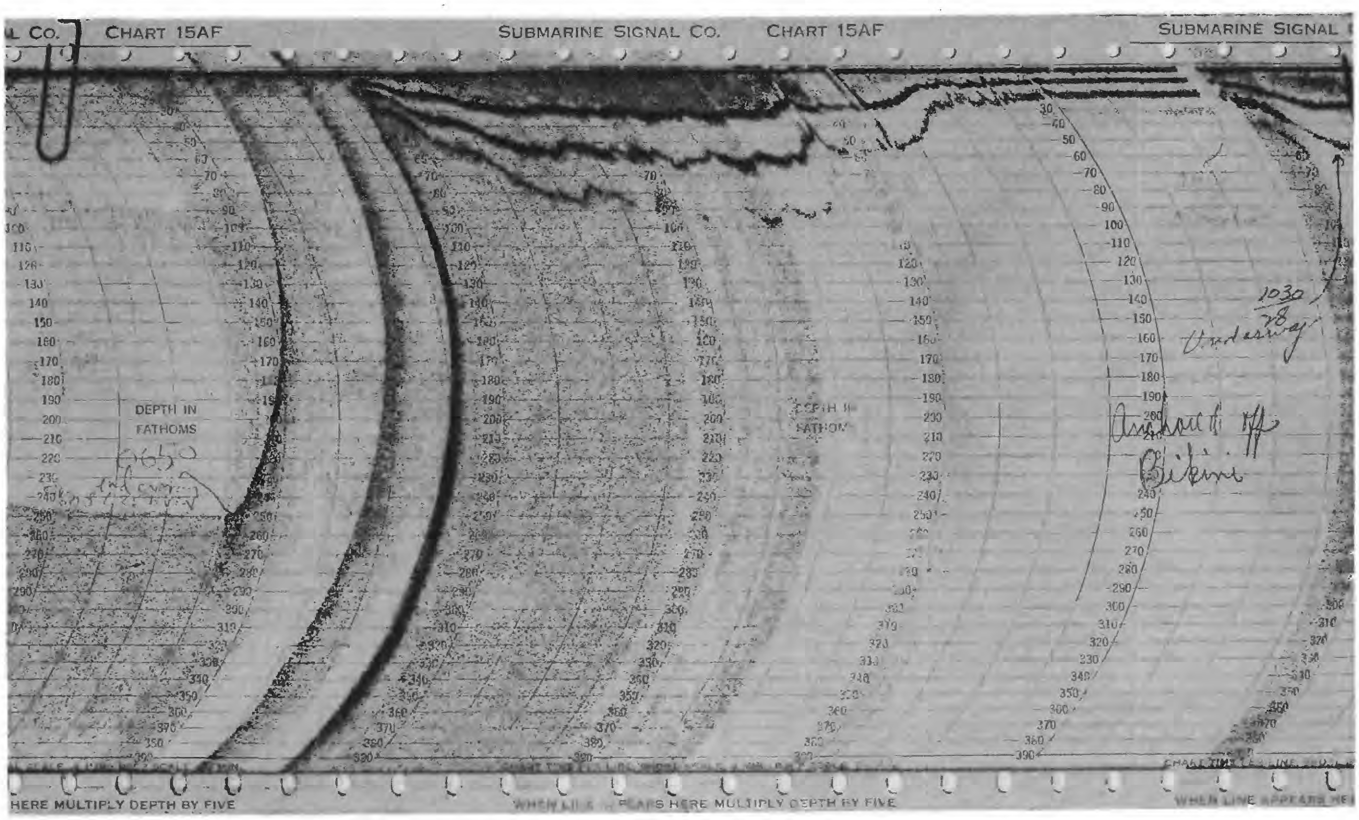

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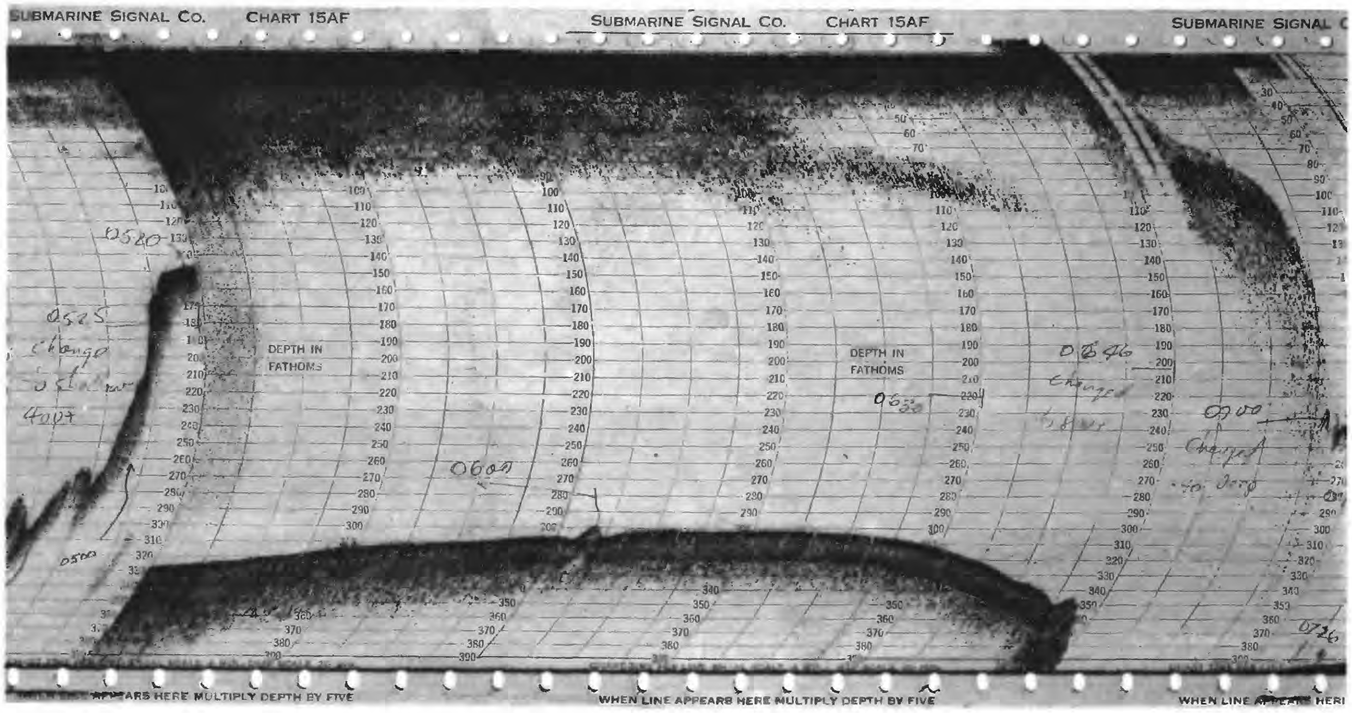
FATHOGRAMS OF OUTER SLOPE, BIKINI ATOLL

1. Fathogram made aboard U. S. S. *Walke.*
2. Fathogram made aboard U. S. S. *Horizon* on September 28, 1950. At the left is the abrupt outer slope at Enyu Channel, Bikini Atoll. The 3 traces on the lagoon floor were produced by multiple reflections of the same signal, whereas the 3 traces of the outer slope are additive, so that the beginning of the trace at the left-hand margin is 1,050 fathoms.



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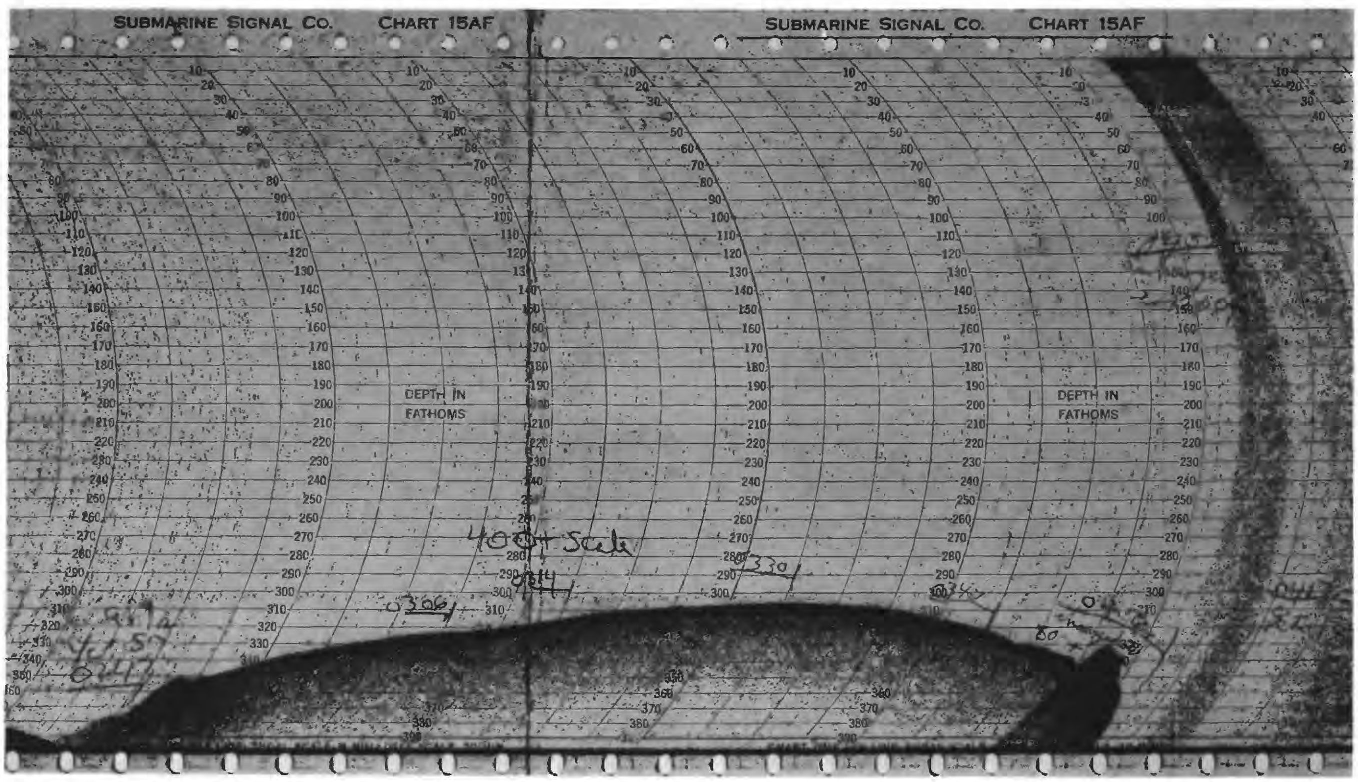

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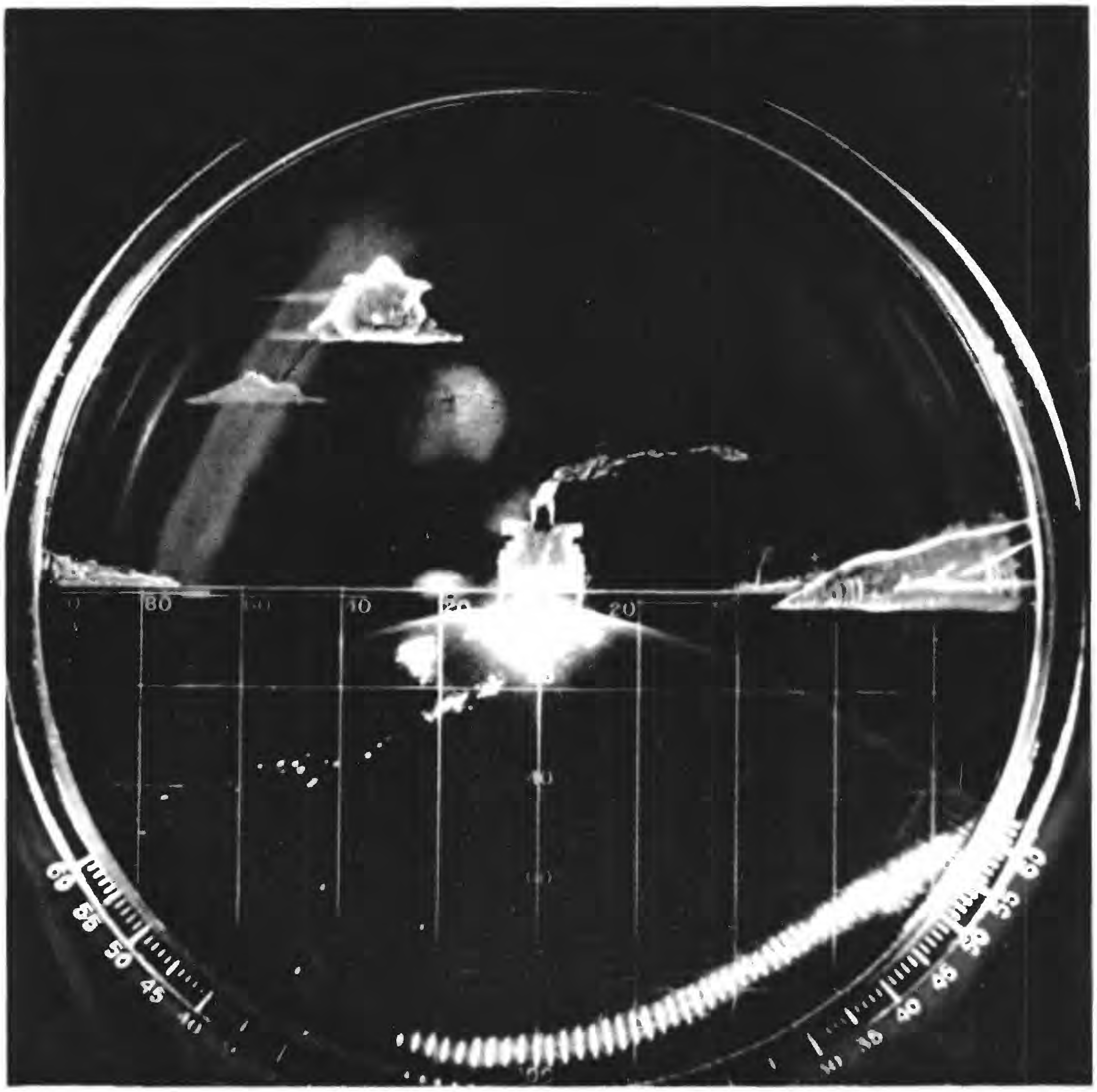
FATHOGRAMS OF SYLVANIA GUYOT

1. Fathogram made aboard U. S. S. *Horizon* on September 25, 1950. Profile is from southeast (left) to northwest (right) and shows a small hill at lat. 11°54′1″ N., long. 164°56′7″ E. Edges of guyot are shown at left at 755 fathoms and on the right at 745 fathoms.
2. Fathogram made aboard EPCE (R) 857. Profile which extends from lat. 11°50′ N., long. 164°52′ E. (left) northeastward to lat. 11°57′ N., long. 165°0′ E. (right), shows a marginal ridge at both edges that appears to be characteristic of the southeastern half of the structure.



PROFILE OF CORAL KNOLLS, BIKINI LAGOON, MADE BY BOTTOM SCANNER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5

1. Underway bottom sampler, "scoopfish".
2. Snapper; the jaws close when the instrument strikes bottom and cable strain is released.
3. Snapper with sample of calcareous sand.
4. Small gravity coring tube.
5. Short core of *Halimeda* debris ready for bottling.

SAMPLING INSTRUMENTS

2

1

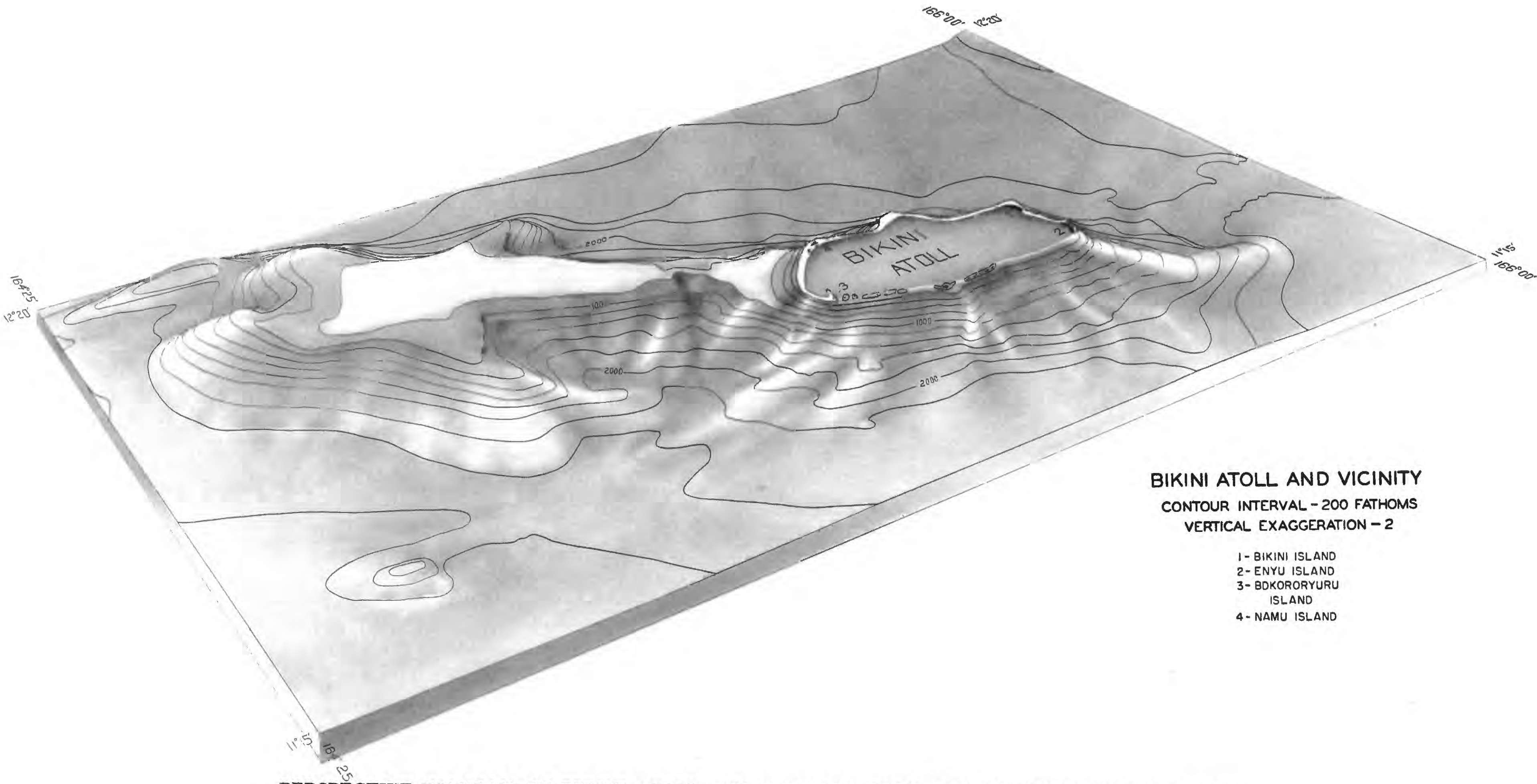
3

4

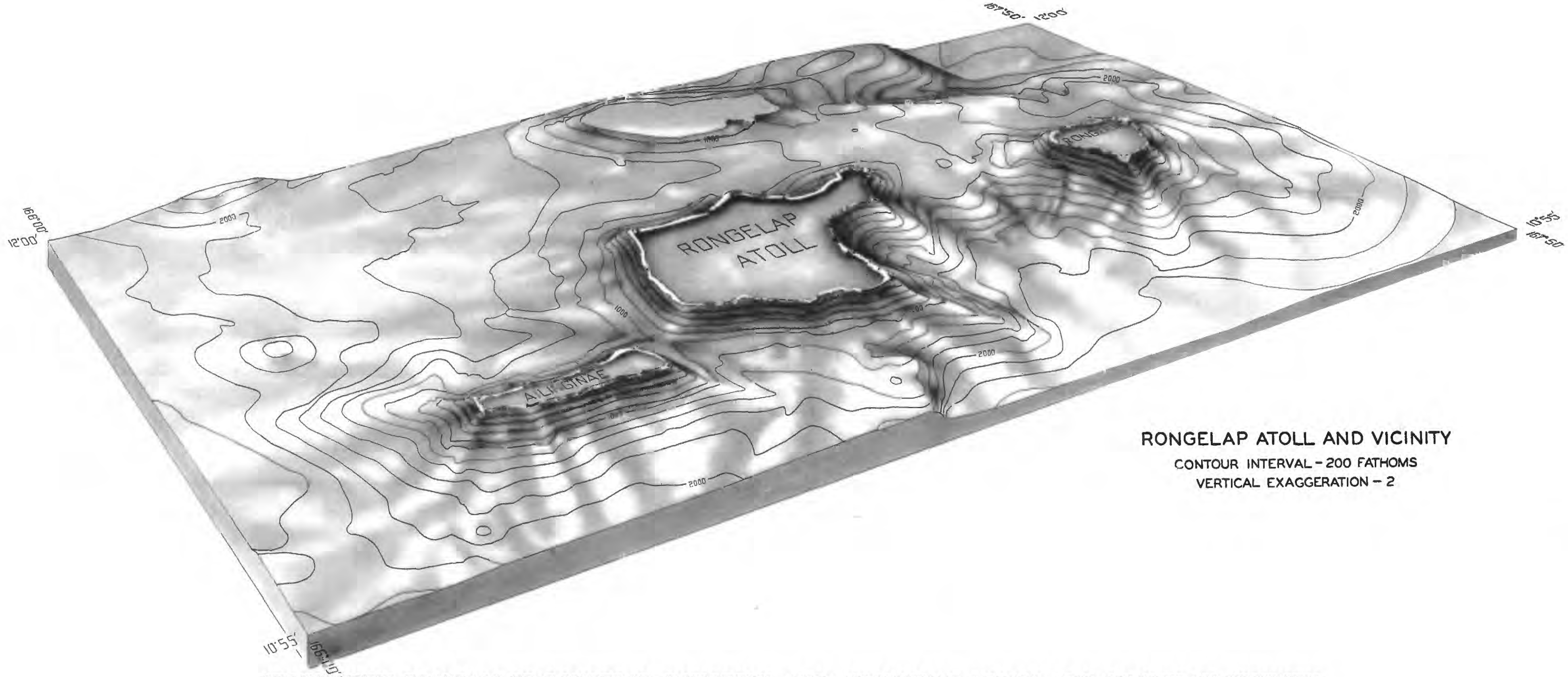
5

UNDERWATER PHOTOGRAPHY AND SAMPLING

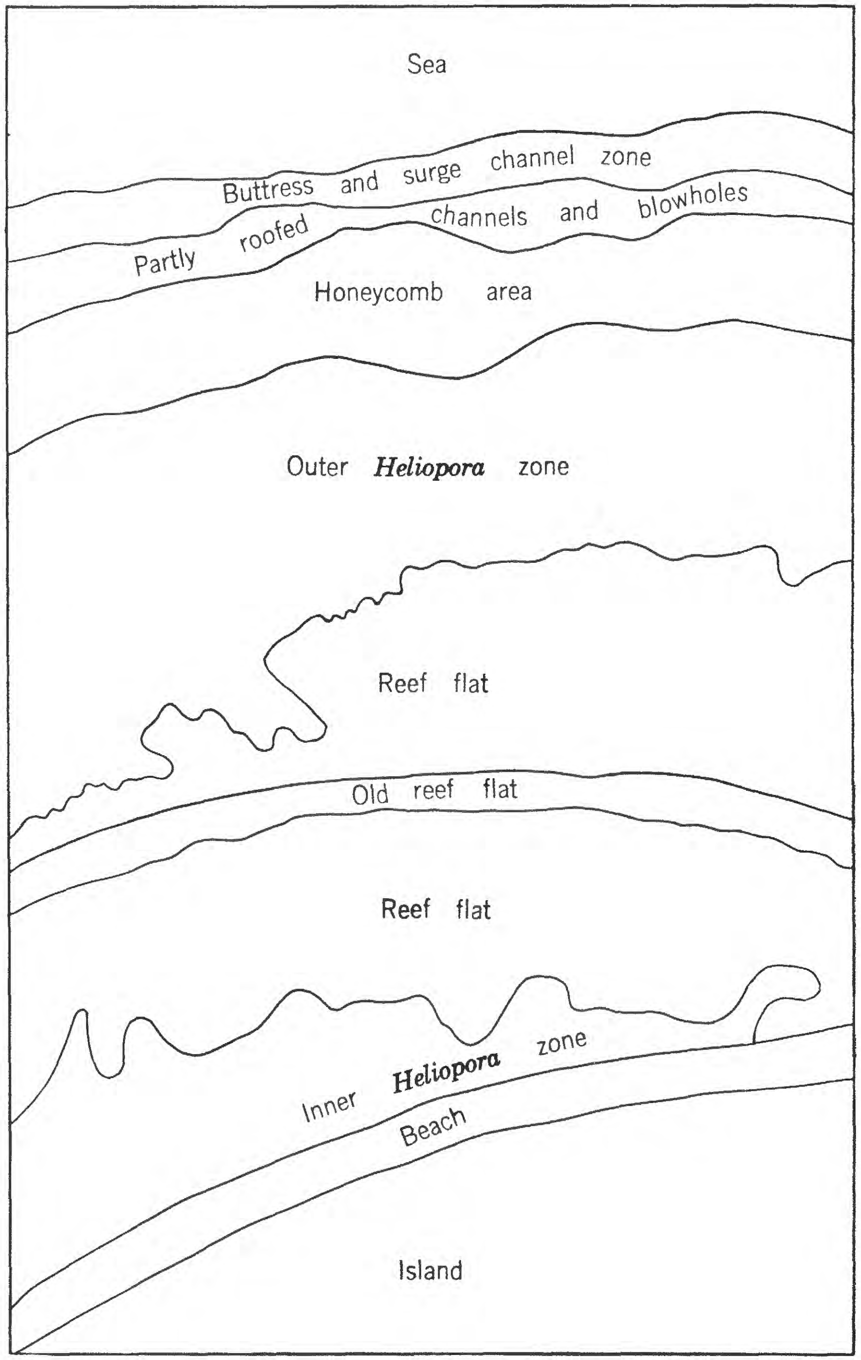
1. Underwater camera rigged on pole with light source and trip line.
2. Underwater camera in brass housing.
3. Recovery of coral on anchor.
4. Underway sampler in operation.
5. Plotting positions aboard U. S. S. *Gilliss*.

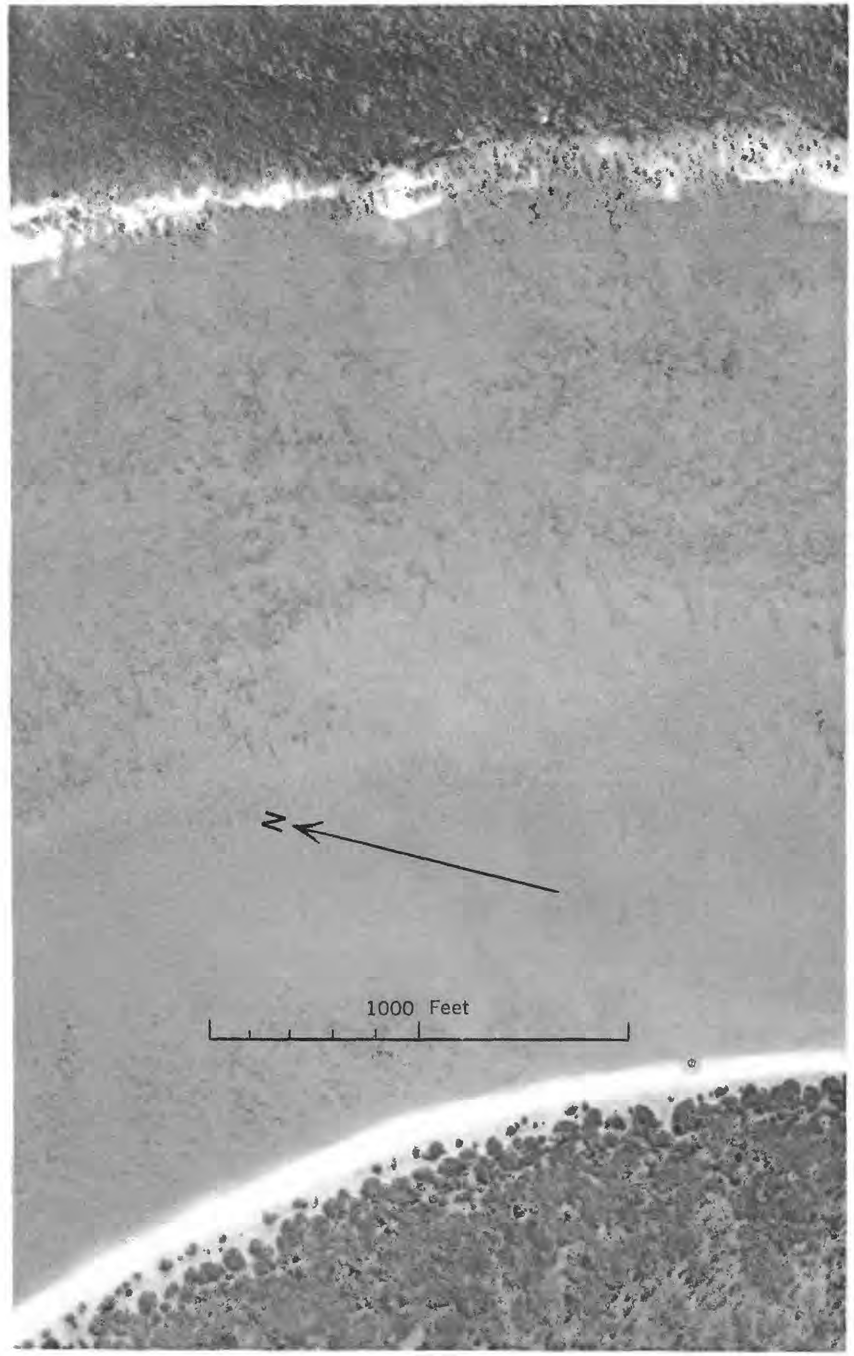


PERSPECTIVE DIAGRAM OF BIKINI ATOLL AND SYLVANIA GUYOT ADJOINING IT ON THE WEST



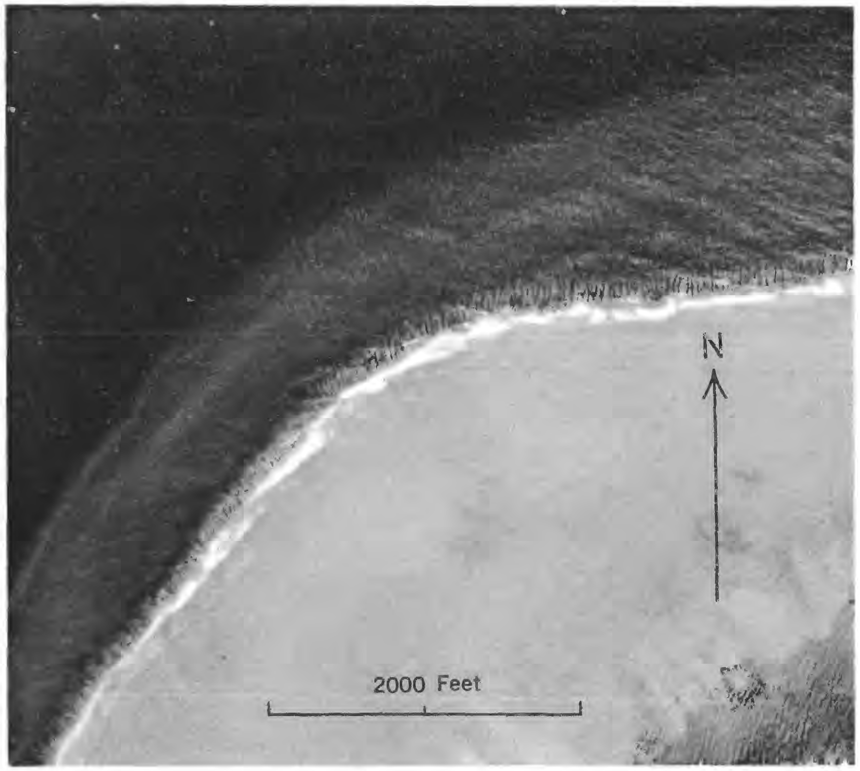
PERSPECTIVE DIAGRAM OF RONGELAP, RONGERIK, AND AILINGINAE ATOLLS AND GUYOTS IN VICINITY





REEF ZONATION

Aerial photograph of sea reef on northeast side of Bikini island and diagram showing division of the reef into zones parallel to the margin. Photograph by U. S. Navy.



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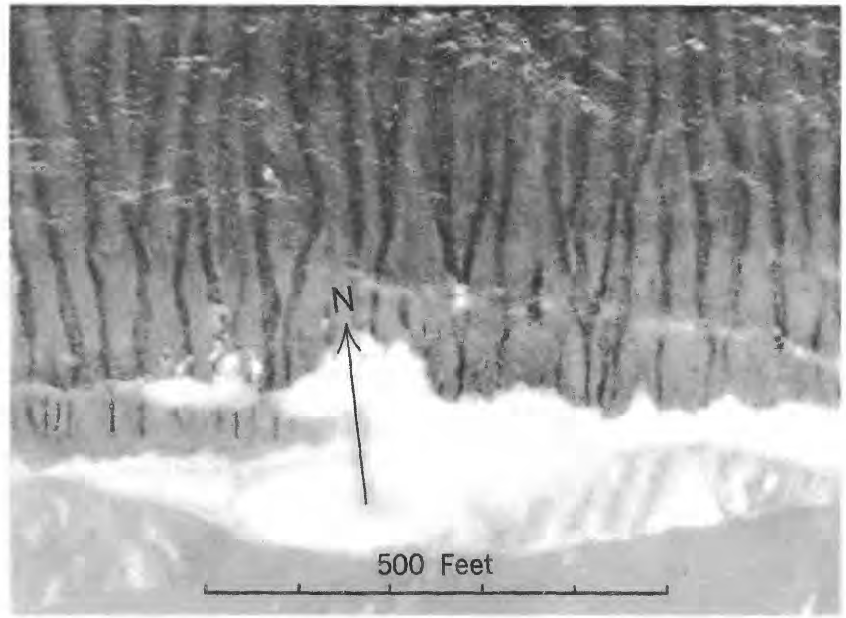

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AERIAL VIEWS, RONGERIK AND BIKINI ATOLLS

1. Airplane photograph showing broad terrace outside reef margin on northwest part of Rongerik reef. The grooves in the marginal zone are well developed on the north edge but diminish in size and development on the northwest reef edge. (Reef type I–A.) Photograph by U. S. Navy.
2. Strong grooves developed on the seaward slope below low-tide level. The *Lithothamnion* ridge is covered by breakers. Aerial view of northern reef of Bikini Atoll, 2 miles east of Namu island. Reef type I–A.
3. Eroded reef margin Eninman island, south side of Bikini Atoll. The marginal zone of this lee reef has been damaged by storm waves. The flat on the seaward side (foreground) is narrow; beyond the island a poorly developed reef extends into Bikini Lagoon. Air view northwest, taken from altitude of about 500 feet by J. I. Tracey, Jr., Reef type II–B–(1).
4. Large, irregular erosional reentrant on the ungrooved reef off the southwest side of Enirik island, on the southwest reef of Bikini Atoll. Airphoto by U. S. Navy. Reef type II–B–(1).

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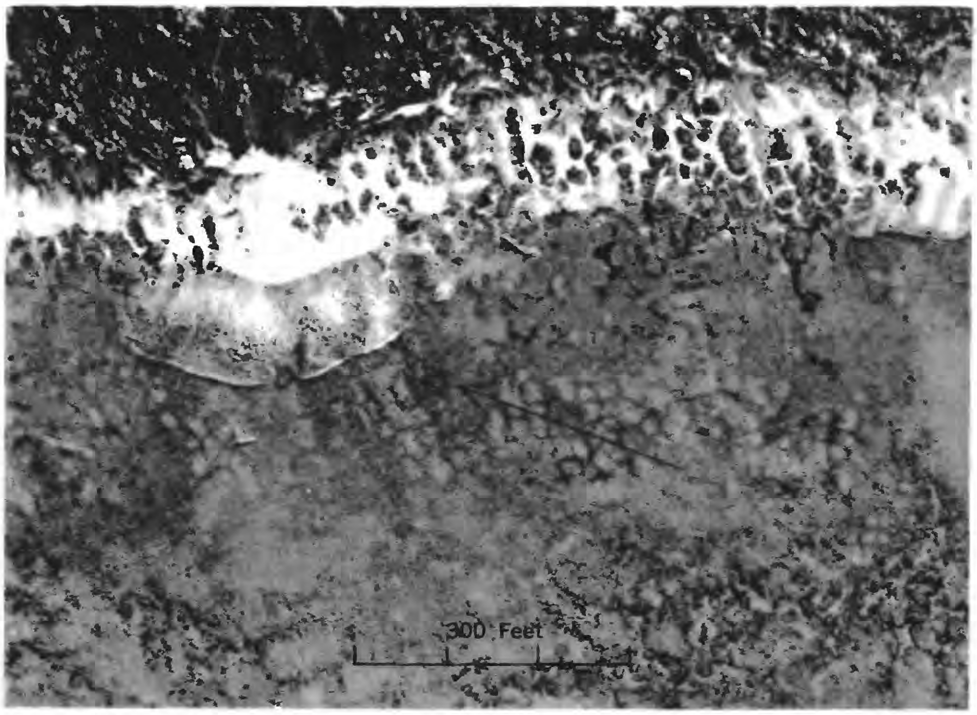

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LITHOTHAMNION RIDGE, BIKINI ISLAND

1. *Lithothamnion* ridge, Bikini island. View showing algal buttresses and surge channels. Reef type I–B–(1).
2. Irregular edge of *Lithothamnion* ridge showing buttresses or separate bosses separated by intersecting surge channels. Below them are irregular pools not yet completely roofed over. In the middle ground the honeycomb pattern outlines an area where the roofing-over is completed; this part of reef underlain by room-and-pillar structure. At the bottom of the photograph a part of the *Heliopora* zone is shown. Aerial view off the central part of Bikini island. Photograph by U. S. Navy. Reef type I–B–(1).

1

2

AERIAL VIEWS, BIKINI ATOLL

1. Aerial view of the ungrooved, slightly scalloped reef edge of the broad leeward reef on the west side of Bikini Atoll. Zonation parallel to the edge is well developed. The irregular lagoon margin of the reef is in the middle ground; below is a shallow shelf 10 to 20 feet deep with a rich coral growth. Photograph by U. S. Navy. Reef type II–A.

2. Seaward terrace off Airukiiji island, adjacent to Enyu Channel, Bikini Atoll. Aerial photograph shows margin of broad terrace near top of photograph; irregular "combtooth" structure of reef margin (type II–B–(2)) center, and lagoon reef sloping to lagoon terrace at bottom of photograph. Photograph by U. S. Navy.

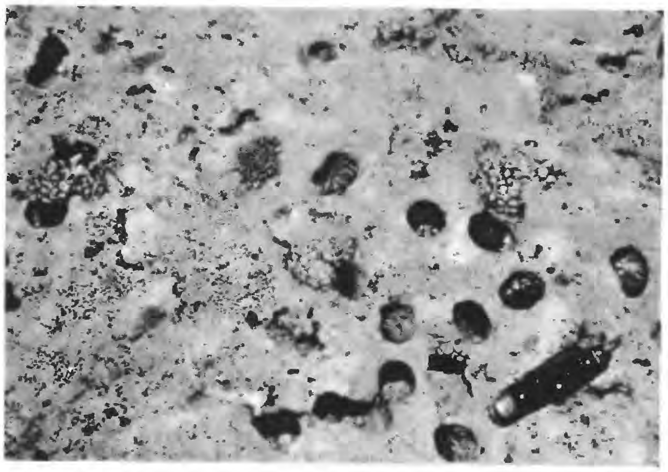
1

2

REEF FEATURES, BIKINI ATOLL

1. Algal growth (mainly *Porolithon gardineri*) along the edge of a surge channel exposed by a receding wave off Bikini island. Photograph by John W. Wells.
2. Cavern under Bikini's seaward reef photographed, horizontally, about 5 feet below the surface. Photograph from R. Dana Russell.

POOL IN REEF FLAT PARTLY ROOFED OVER BY ALGAL GROWTH, BIKINI ATOLL



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REEF FEATURES, BIKINI ATOLL

1. Echinoid borings in algal pavement composed mostly of *Porolithon onkodes*.
2. Coral-algal zone on lee reef southwest of Enirik island, Bikini Atoll. The reef floor is covered by 1 or 2 inches of water and the coral colonies are completely exposed at low tide. The most abundant coral is *Acropora*.
3. Underwater photograph showing two species of *Acropora* (center) and a massive *Porites* (right) growing on the reef flat. Height of corals about one foot.
4. Underwater view in shallow pool in coral-algal zone near Bikini island. Bottom of pool is only 2 feet lower than reef flat and is partly covered with coarse calcareous sand. Growing on bottom are colonies of *Favia* and *Astreopora;* tufts of green algae are common. Much of the submerged reef flat seen on the lee reefs greatly resembles the conditions shown in this windward pool. Base of photograph represents about 4 feet.

1

2

MICROATOLLS, BIKINI ATOLL

1. Typical microatolls in the inner *Heliopora* zone (plate 12). Dark borders are living *Heliopora* except for the near side of microatoll at upper left, which is composed of *Porites*. Flat central areas are veneered with calcareous algae.
2. Microatolls composed mainly of the hydrozoan *Millepora* with algae (*Porolithon craspedium*) in the center. × .10.

1

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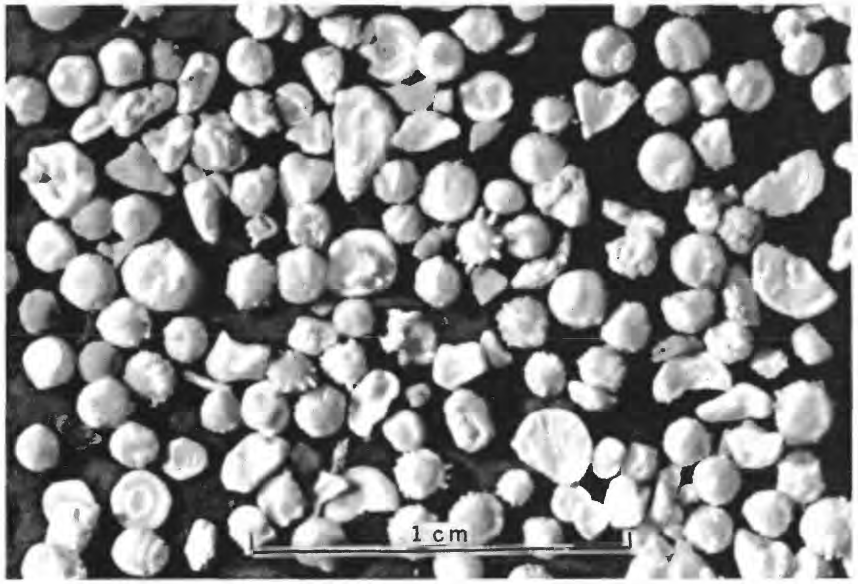
3

REEF FEATURES, BIKINI ATOLL

1. Reef blocks (Negro heads) exposed on reef at low tide. View in Area 1 off Bikini island (figure 9).
2–3. Aerial photographs showing curved spits at ends of islands and lagoonward bulge between islands and bars, Bikini Atoll.



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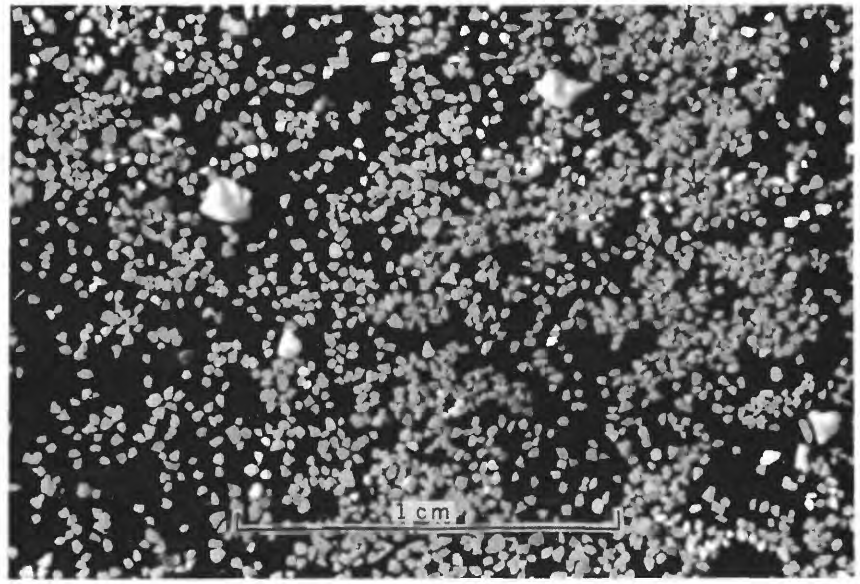

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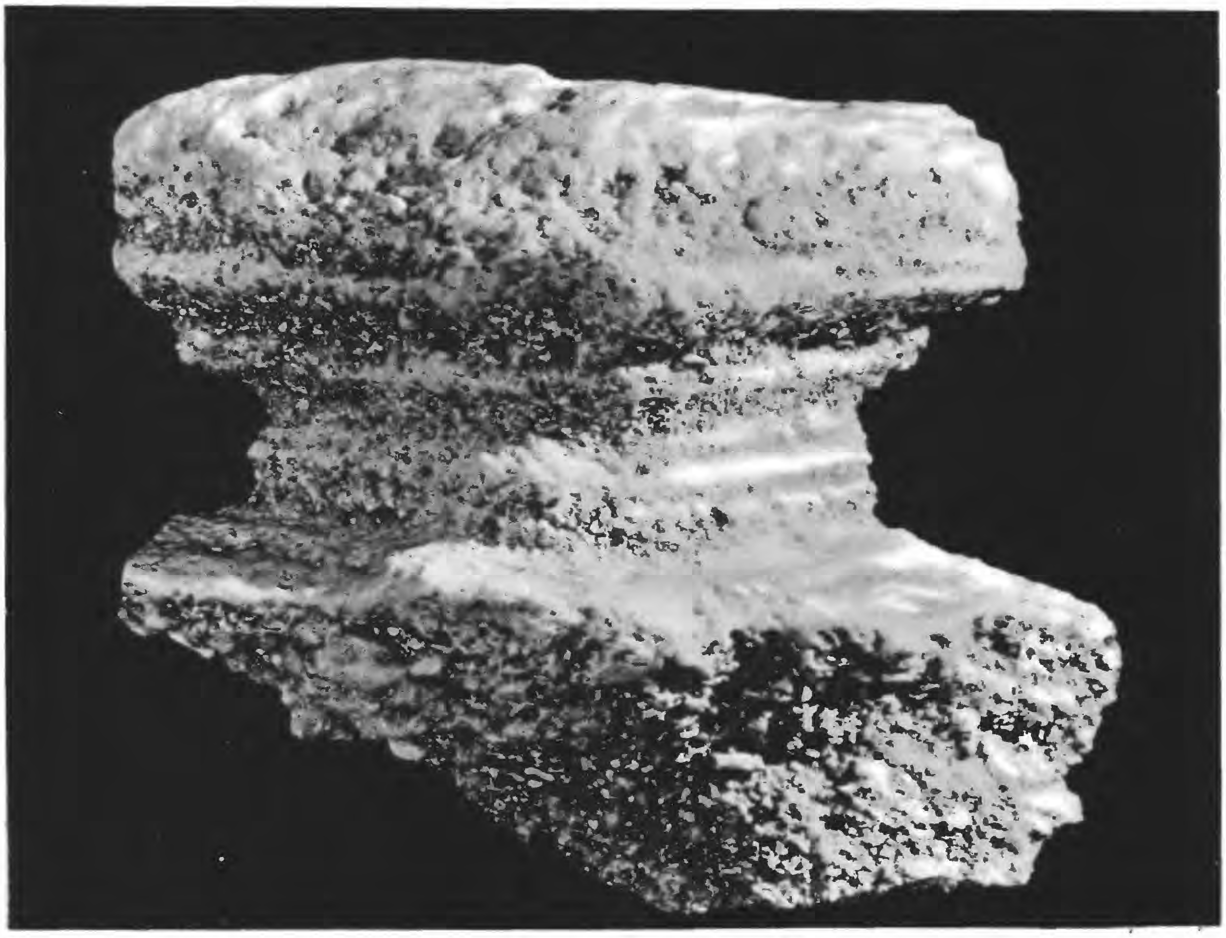
1. Coarse beach sand composed mostly of Foraminifera (Bik. 3, lat. 11°37′45″, long. 165°32′02″) × 5.

2. Very fine beach sand (Bik. 5, lat. 11°37′27″, long. 165°32′09″) × 5.

3. Very coarse beach sand containing abundant highly polished fragments of coral (Bik. 27, lat. 11°36′16″, long. 165°33′02″) × 5.

BEACH SAND, BIKINI ATOLL



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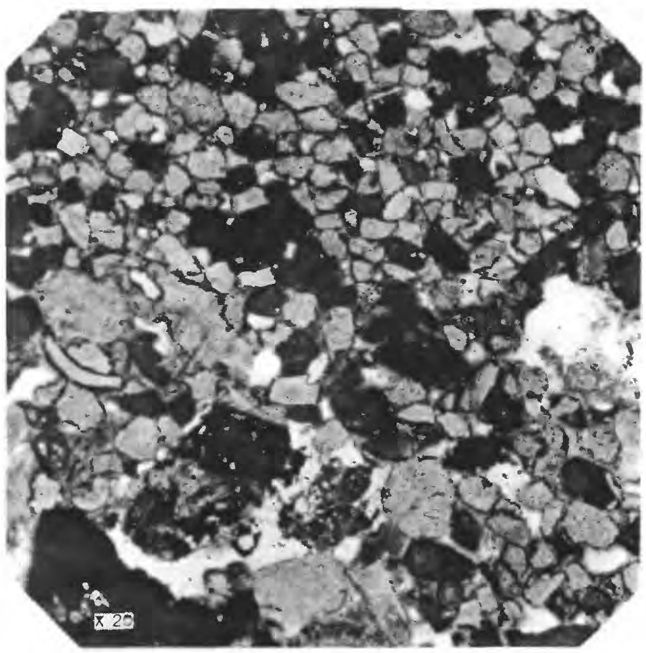

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BEACH ROCK, BIKINI ATOLL

1. Weathered beach rock (Bik. 307), × 0.5.
2. Sawed face of bedded beach sandstone (B–42) showing (left) the high polish that forms on exposed layers of fine material.
3. Photomicrograph, × 20, of thin section of B–42 showing finer grains at top of section, coarser grains below. The cement is a thin coat of acicular carbonate about each grain.

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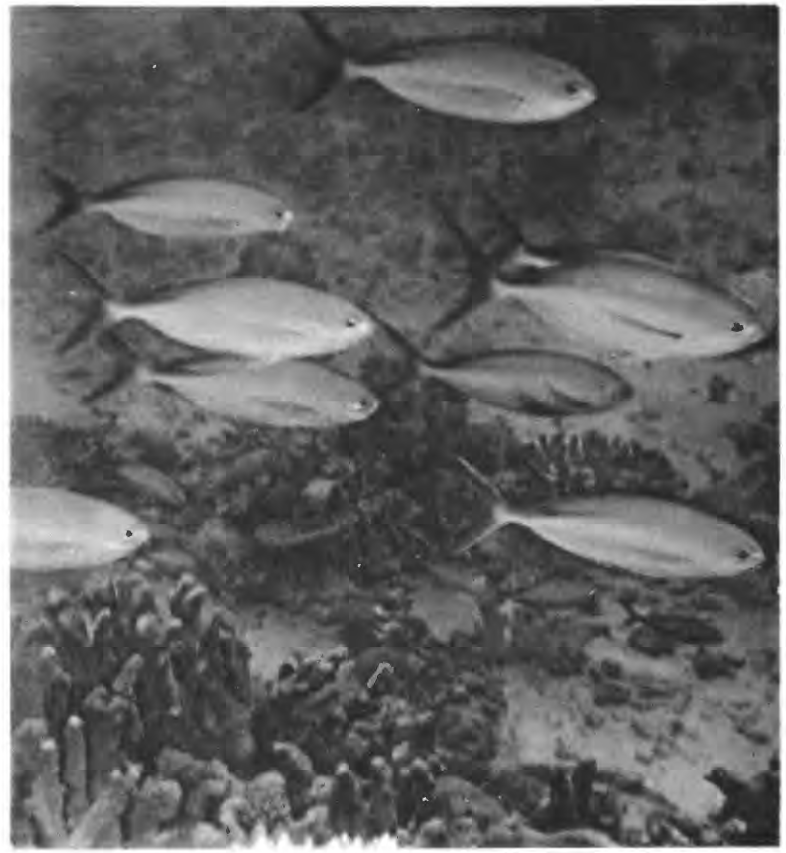

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1–2. Underwater views on top of small coral knoll near south end of Bikini island rising from about 1 fathom to just below low-tide level.

3. School of tuna swimming over coral and sand on top of coral knoll that rises from a depth of 10 fathoms in Enyu Channel.

UNDERWATER VIEWS, BIKINI ATOLL

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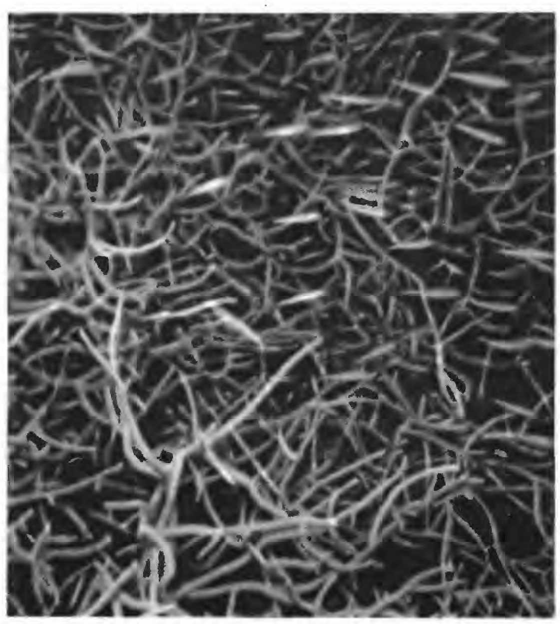

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BEACH AND LAGOON FEATURES, BIKINI ATOLL

1. Large clam (*Tridacna*) on top of coral knoll.
2. Solution basins and miniature karst topography developed on seaward part of beach-rock belt.
3. Thicket of branching coral with numerous small fish; depth 10 fathoms, length of bottom edge about 4 feet.

1

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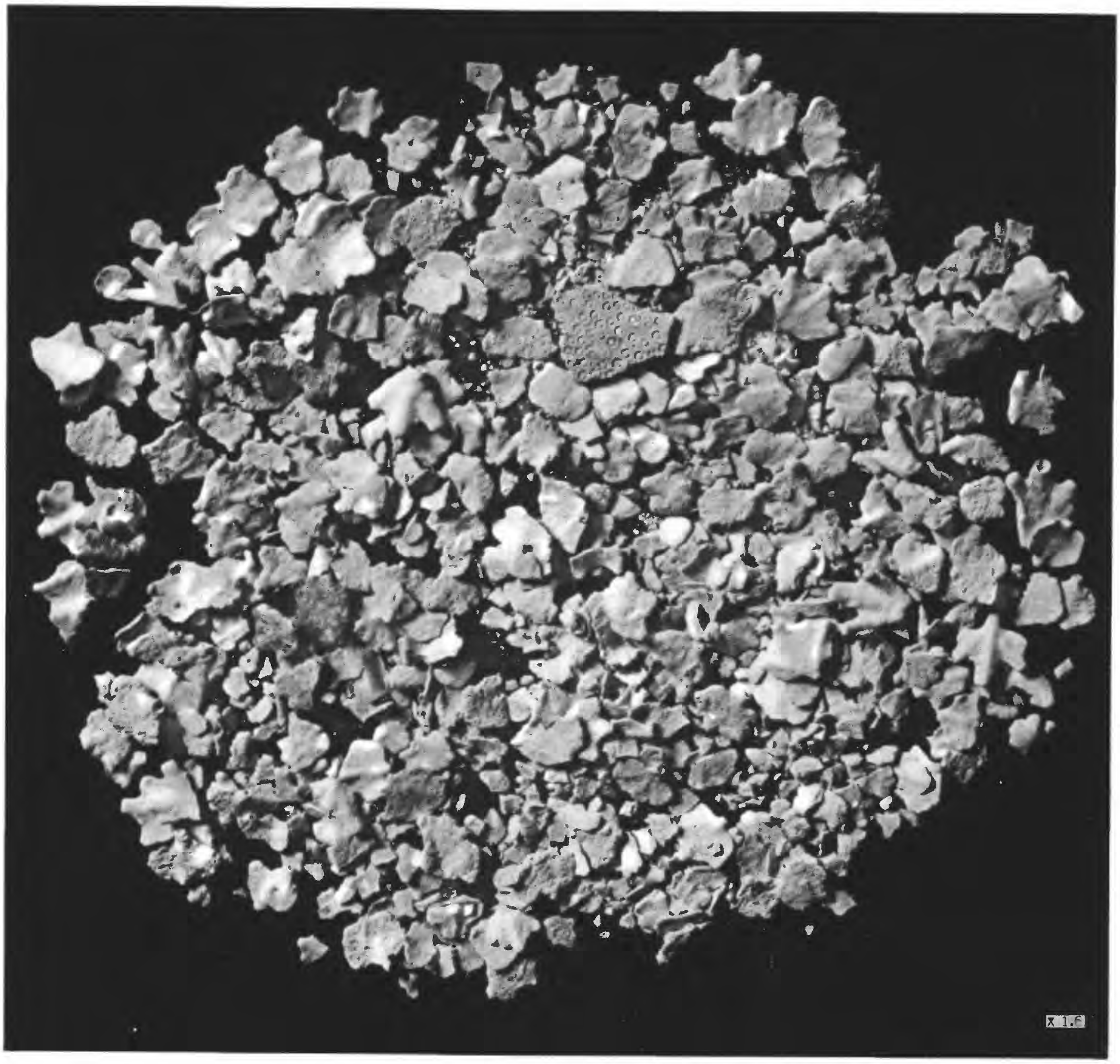
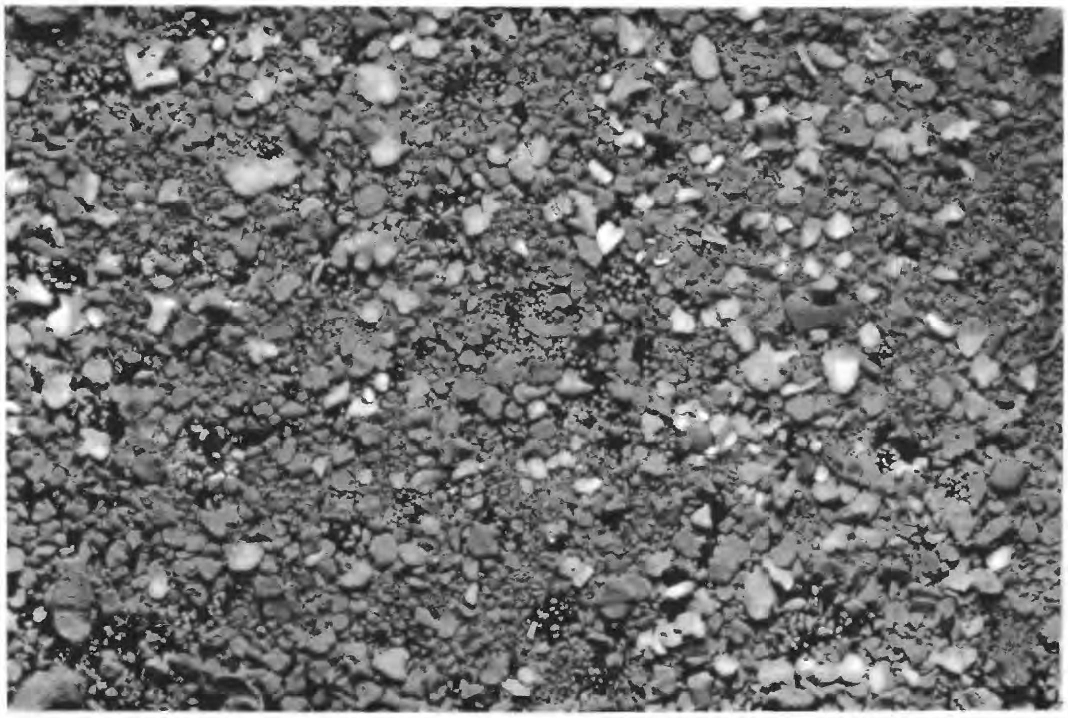
4

LAGOON SEDIMENTS

1. Sand of terrace bordering Bikini island. Depth 11½ fathoms. Bik. 51.
2. Sand from edge of lagoon basin off Bikini island. Depth 18 fathoms. Bik. 713.
3. *Halimeda* debris—typical of most lagoon basins. Depth 30½ fathoms. Bik. 479.
4. *Halimeda* debris with abundant smaller Foraminifera—typical of deeper parts of basin—near middle of lagoon. Depth 30½ fathoms. Bik. 294.



TYPICAL *HELIMEDA* DEBRIS, BIKINI LAGOON (BIK. 113)



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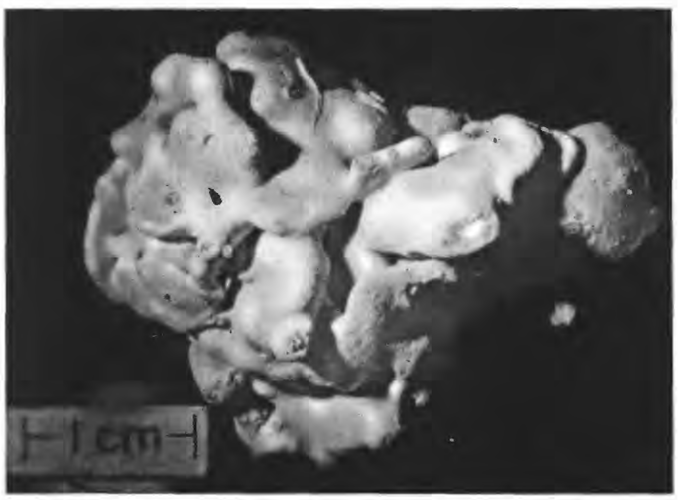

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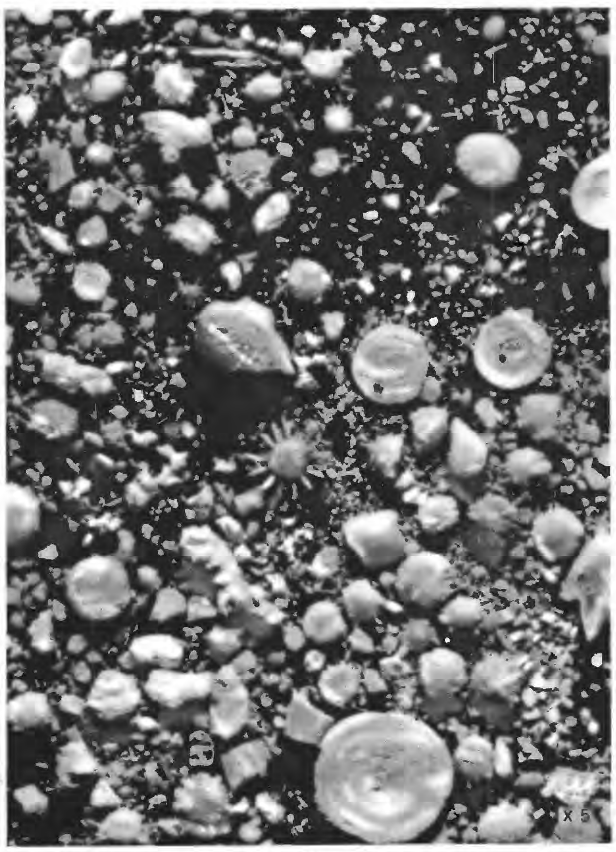

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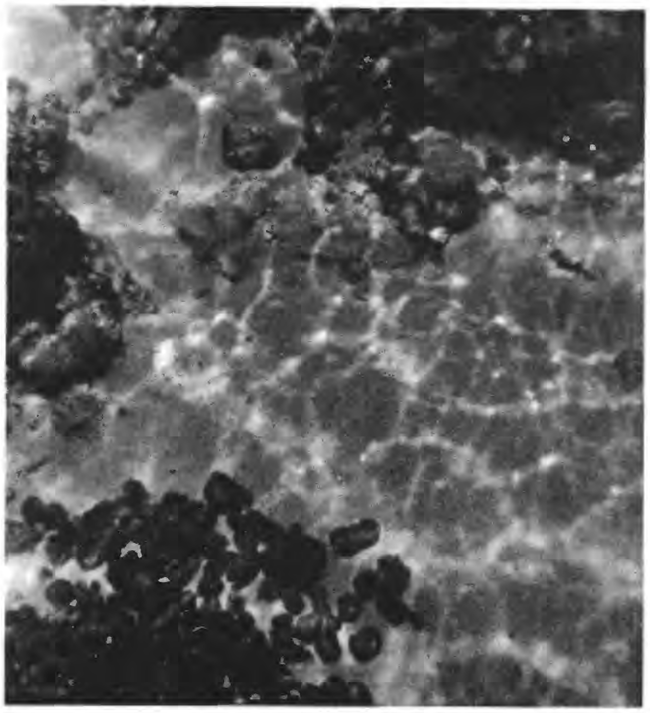
SAND AND *HALIMEDA* DEBRIS, BIKINI LAGOON

1. Sand from top of coral knoll in 6 fathoms of water one-third mile north of Eninman island. Specimen B-307, × 1. Coral grows in profusion on top of the knoll but in the sand *Halimeda* segments predominate.
2. Debris cemented by *Lithothamnion*.
3. Poorly sorted sand from reef flat. Large circular disks (*Marginopora*) and spiny tests (*Calcarina*) are common foraminifera. Bik 701, × 5.



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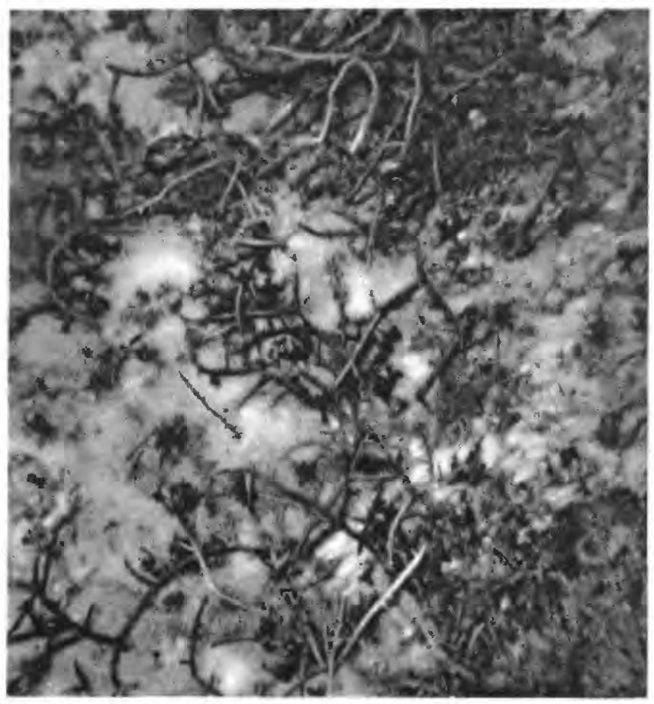

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UNDERWATER VIEWS, BIKINI LAGOON

1. Sand floor between shallow coral knolls. Mottled appearance is result of light refraction by waves. Depth 3 fathoms. Length of bottom edge is about 10 feet. No. 221
2. Sand bottom modified by animal activity. Depth 9 fathoms. Length of bottom edge is about 4 feet. No. 74.
3. Sand bottom abundantly covered by soft algae. Depth 9 fathoms. Length of bottom edge is about 4 feet. No. 82.
4. Sand bottom with litter of branching coral. Depth 6½ fathoms. Length of bottom edge is about 4 feet. No. 80.

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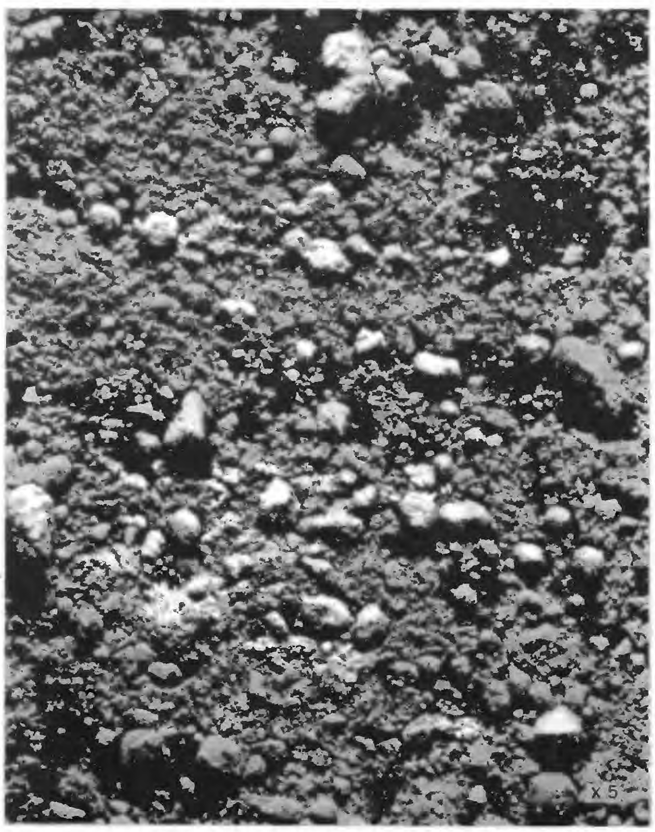

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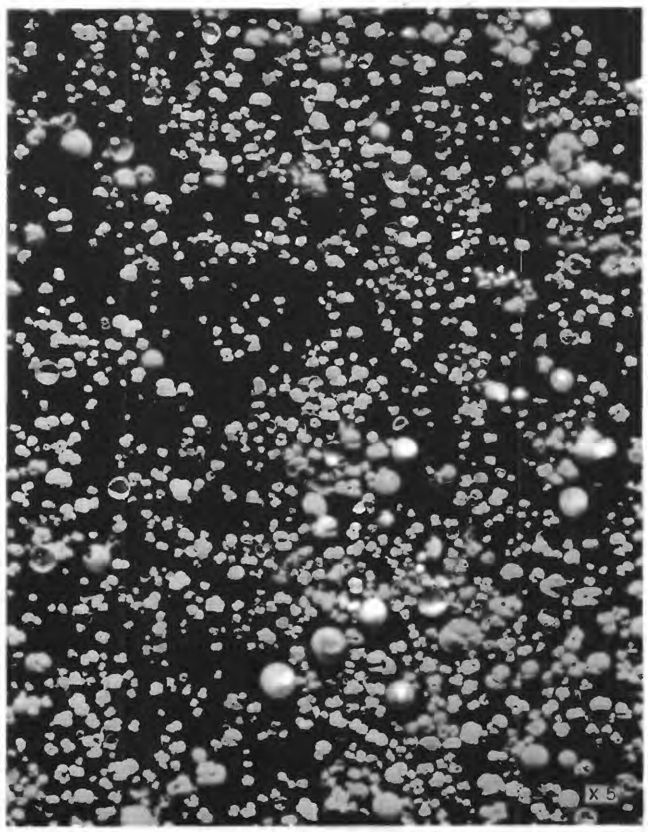

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SEDIMENTS FROM BIKINI ATOLL

1–4. Photomicrographs, × 5, of sediments from outer slopes of Bikini Atoll. 1. *Halimeda* debris and large Foraminifera. Note curved *Halimeda* segment at bottom. Depth 80 fathoms. Bik 812. 2. *Halimeda* debris. Depth 240 fathoms. Bik 1173. 3. Sand and silt largely from comminuted *Halimeda* segments. Depth 410 fathoms. Bik 1174. 4. *Globigerina* sand. Depth 680 to 720 fathoms. Bik 1170.

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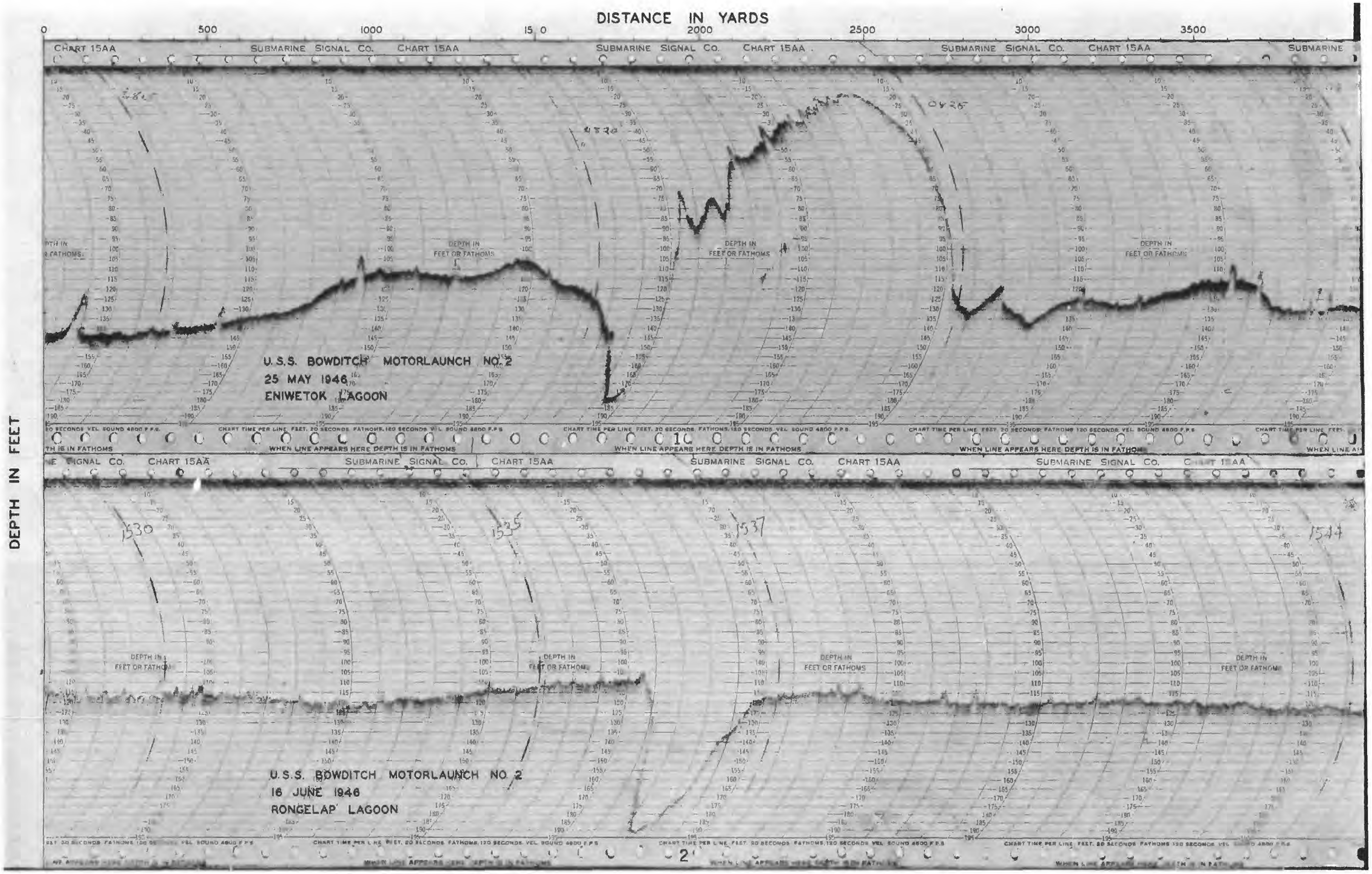
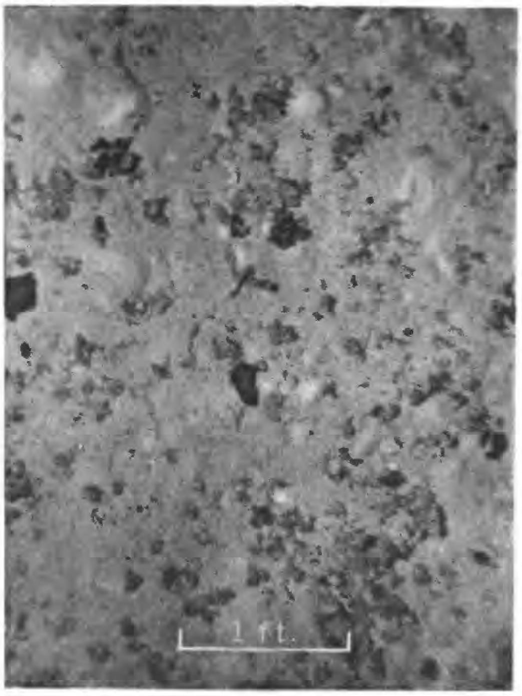
REEF FEATURES, ENIWETOK ATOLL

1. Surface of rock bar or groin off Rujiyoru island, Eniwetok Atoll.
2. Section of submerged reef on the southwest side of Eniwetok Atoll. Dark elongate areas are coral ridges, lighter areas are sand covered.



FATHOGRAMS OF ENIWETOK AND RONGELAP ATOLL

1. Deep channel, Eniwetok Atoll. 2. Deep channel at South Pass, Rongelap Atoll.



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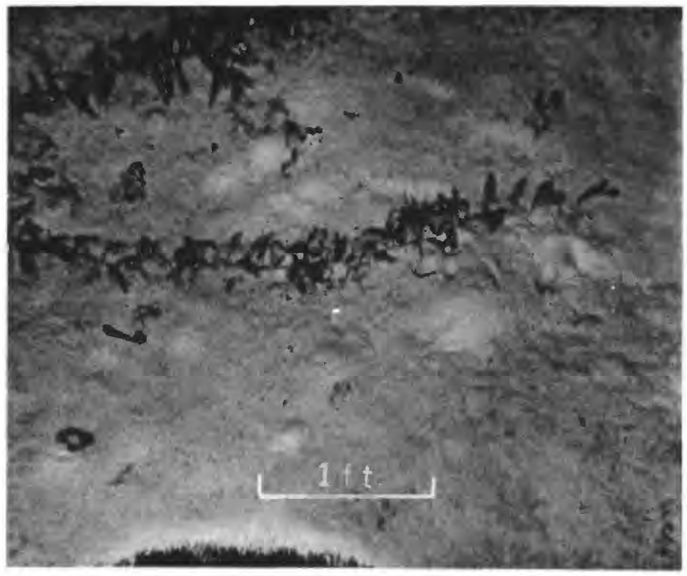

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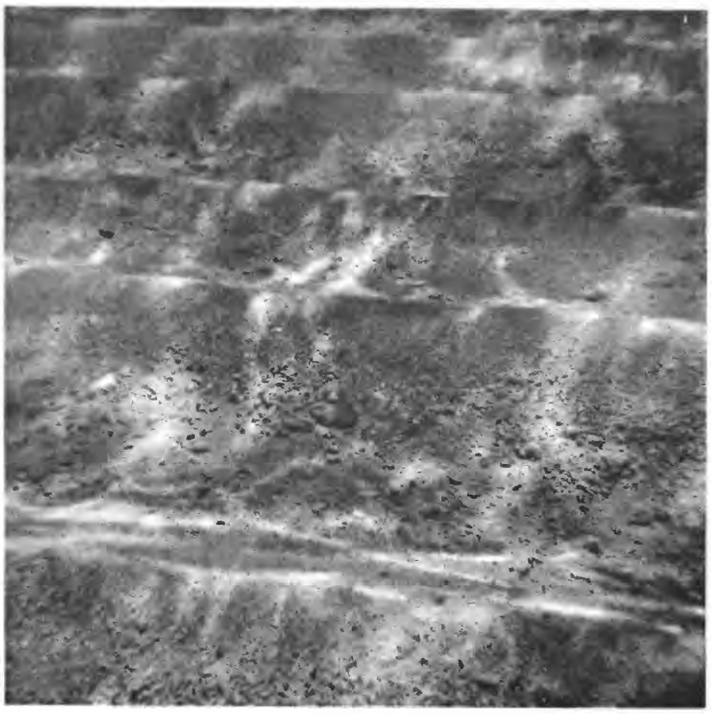

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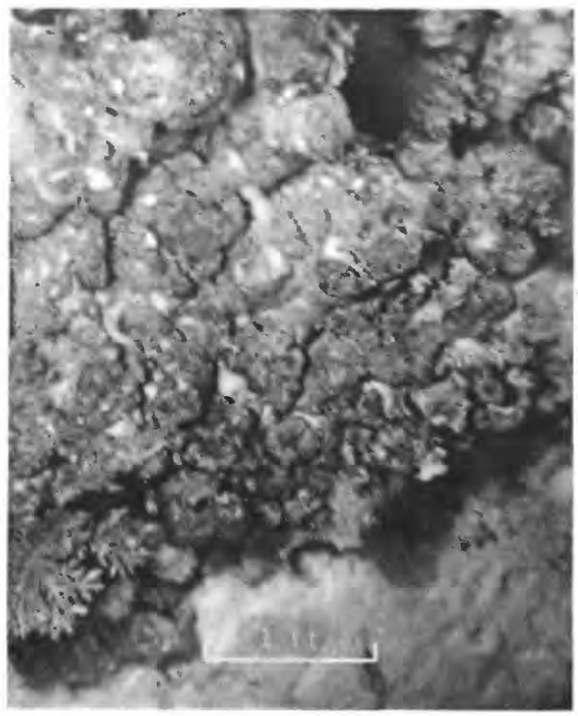

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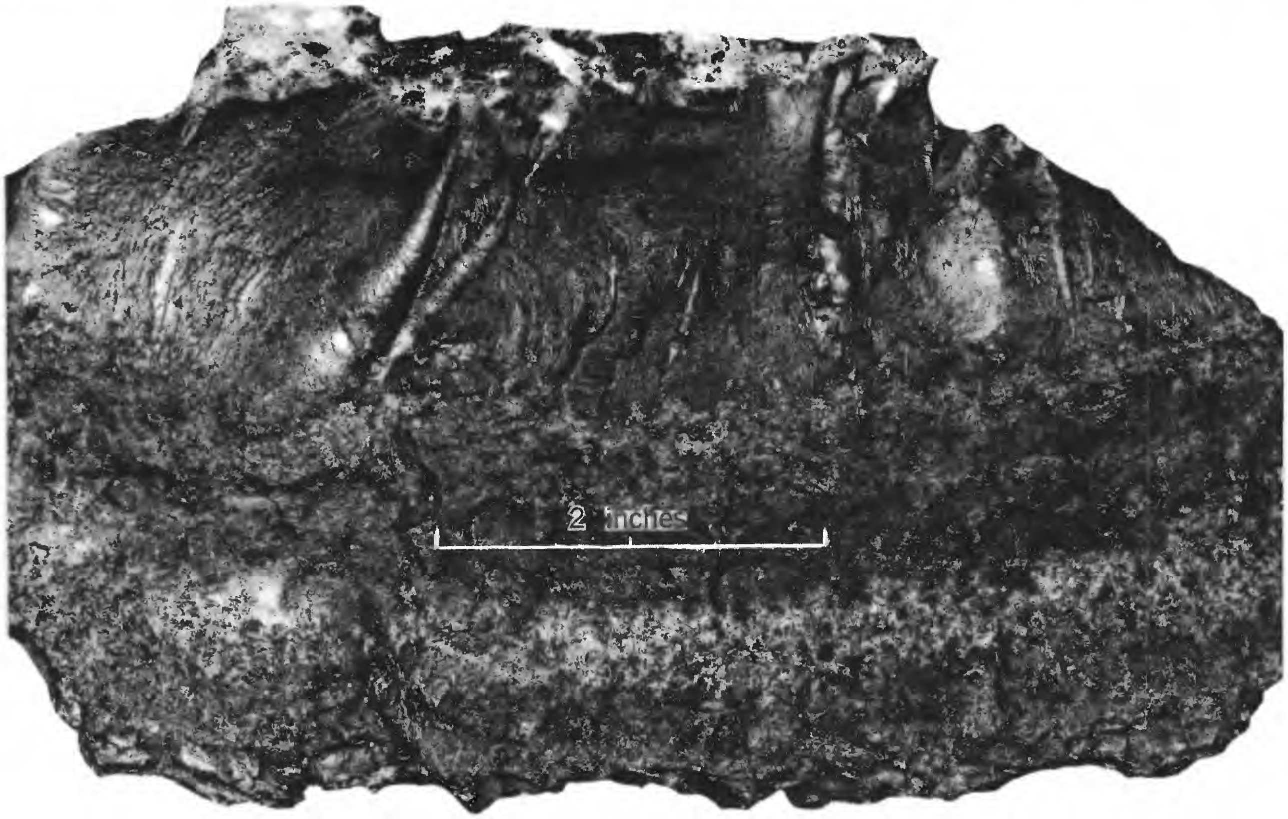
UNDERWATER VIEWS, ENIWETOK ATOLL

1. Sand covered by fragments of coral and soft algae. Depth 5 fathoms. Length of bottom edge is about 3 feet. No. 438.
2. Sand with strand of soft algae. Hummocks and pits produced by animals. Depth 5 fathoms. Length of bottom edge is about 4 feet. No. 444.
3. Ripple marks having a wave length of about 24 inches. Depth 1 to 3 feet. Beach at north end of Eniwetok Island. No. 427.
4. Small coral knoll surrounded by sand. Depth 5 fathoms. Length of bottom edge is about 3 feet. No. 439.



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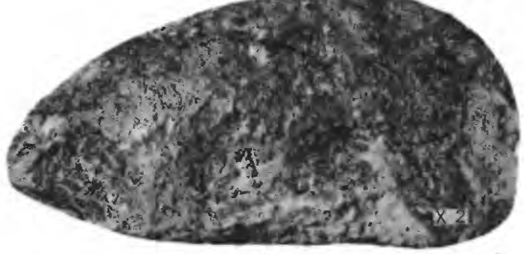

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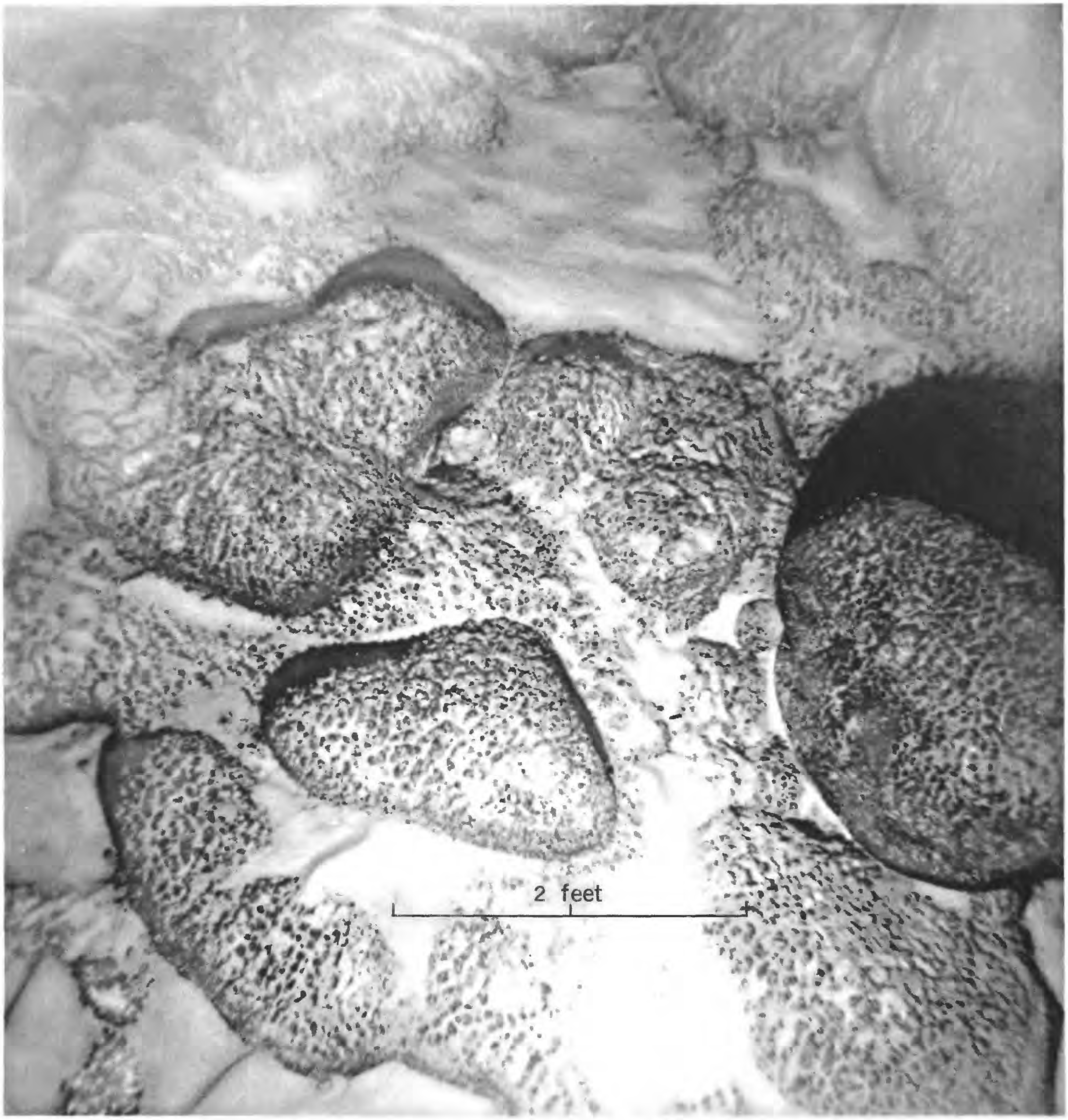
MANGANESE OXIDE INCRUSTATION, SYLVANIA GUYOT

1. Manganese oxide crust from Sylvania Guyot at 1,140 to 820 fathoms MP 43B, × 1.
2. Basalt pebble encrusted with manganese oxide dredged from Sylvania Guyot at depth of 1,150 to 850 fathoms. 43C.

3–5. Views of basalt pebble shown in figure 2 with manganese crust removed to show rounding.



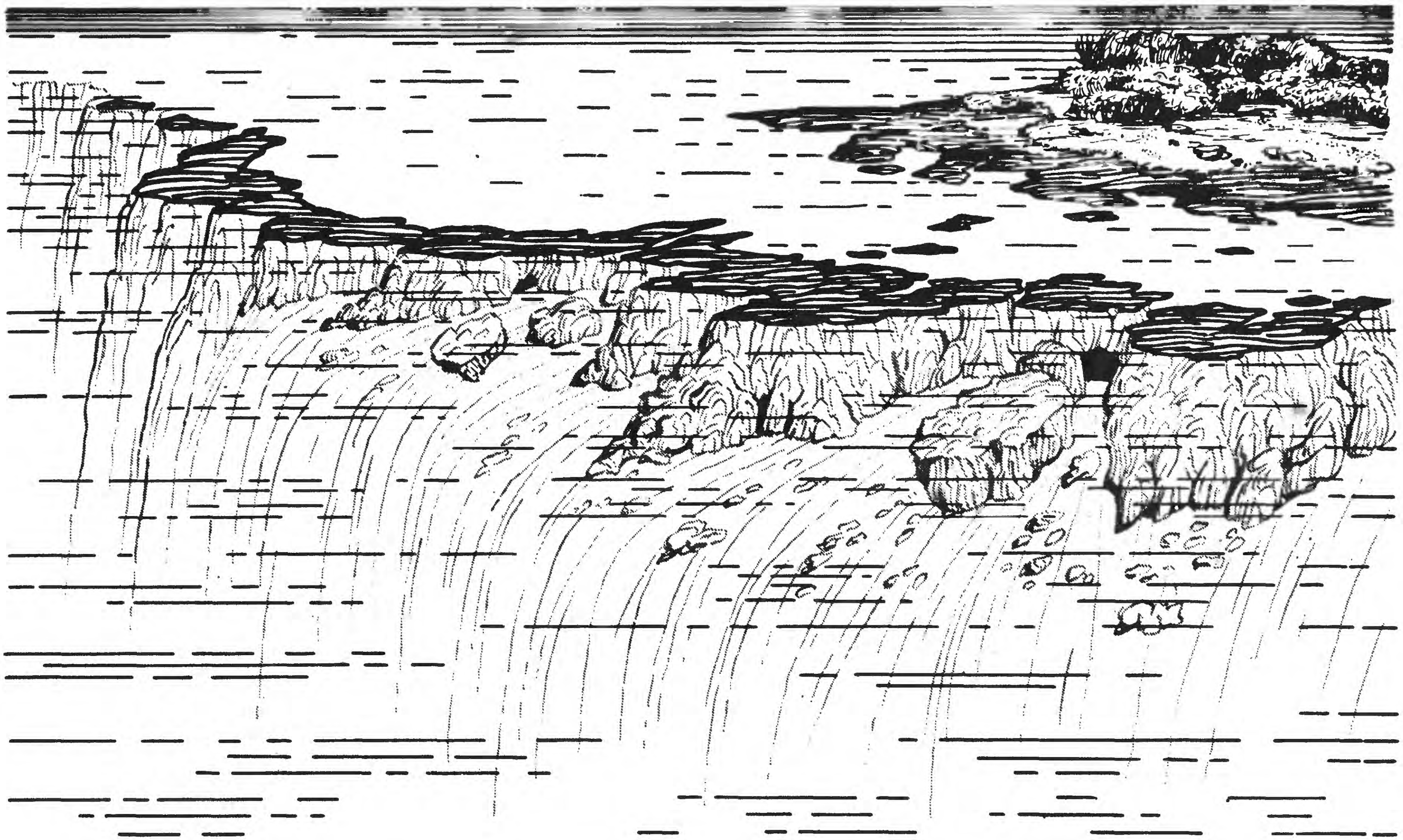
MANGANESE OXIDE NODULES, SYLVANIA GUYOT

Underwater photograph of manganese oxide nodules on Sylvania Guyot at depth 720 fathoms; length of bottom edge is about 6 feet. MP 43 KK (after Menard, 1952).

UNDERWATER VIEW OF RIPPLE MARKS, SYLVANIA GUYOT, AT DEPTH OF 750 FATHOMS, × 1/10. (AFTER MENARD, 1952)

UNCONSOLIDATED MATERIAL DREDGED FROM OUTER SLOPES, BIKINI ATOLL

Unconsolidated material dredged from the outer slopes of Bikini Atoll at a depth of 800 to 580 feet. Composed mainly of Foraminifera: 2 large species of Cycloclypeus and an encrusting type. Delicate pelagic shells are present but the algae, corals, and mollusks of the surface reef are absent. Natural size



EROSIONAL REENTRANTS IN REEF EDGE, RONGELAP ATOLL

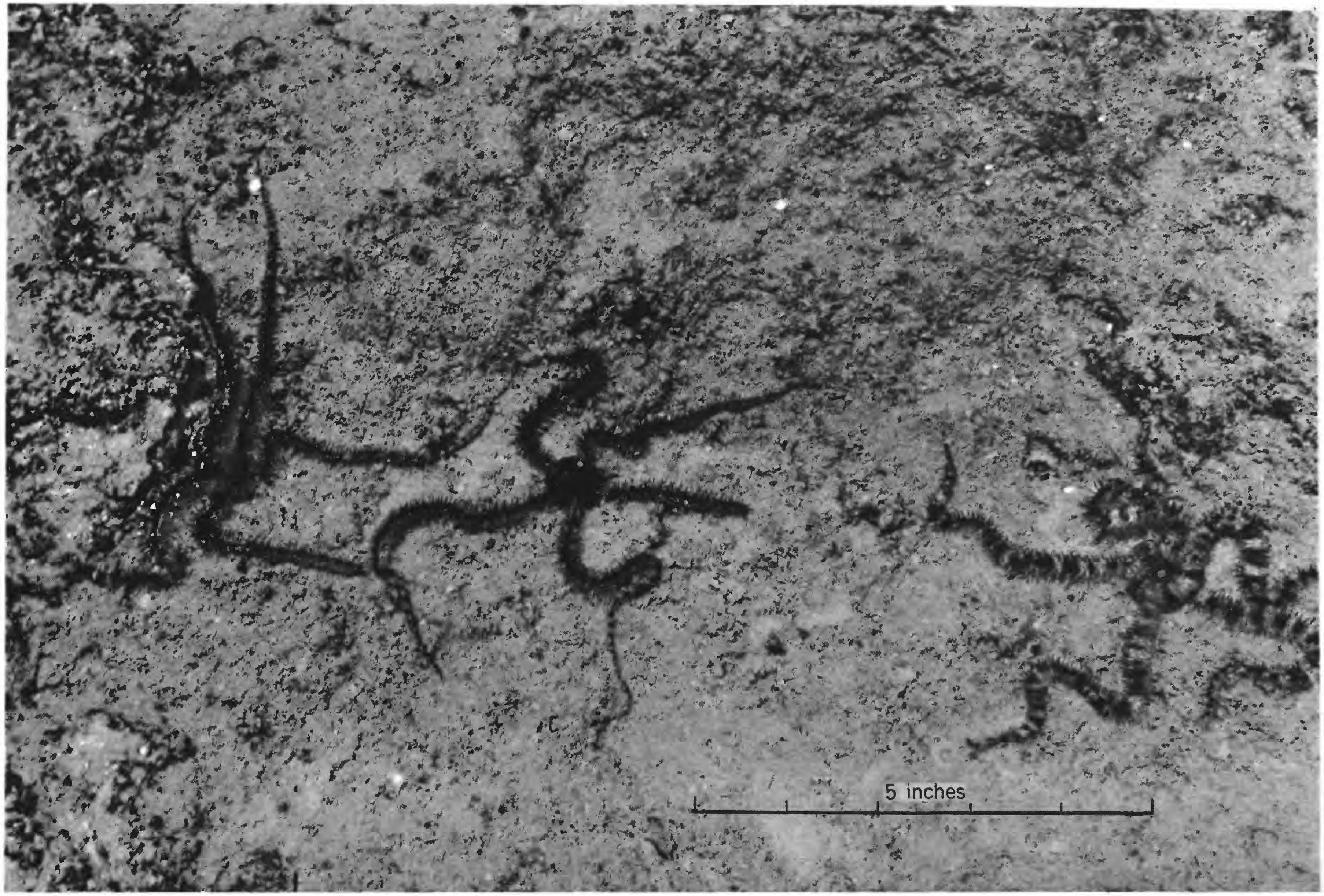
Sketch of lee reef off Burok island, Rongelap Atoll showing large erosional reentrants in the reef edge. The large blocks torn from the margin are resting on a bench in about 30 feet of water. At the extreme left, erosion has not occurred, and the reef margin (type II–A) dips nearly vertically to depths of more than 30 fathoms. Adapted by P. B. King and Margaret Austin from a field sketch by Selwyn Taylor.

CRACK IN REEF FLAT, BIKINI ATOLL

Remnants of an older algal limestone exposed behind the existing *Lithothamnion* ridge and above the level of the main flat. Photograph by Fritz Goro of *Life*.

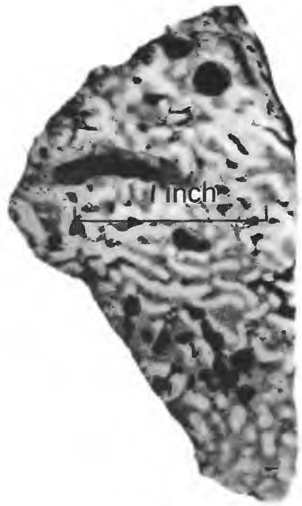
REMNANTS OF OLDER ALGAL LIMESTONE, BIKINI ATOLL

Remnants of an older algal limestone exposed behind the existing *Lithothamnion* ridge and above the level of the main flat. Photograph by Fritz Goro of *Life*.



SERPENT STARS ON REEF FLAT, BIKINI ISLAND, ⅔ NATURAL SIZE.
(PHOTOGRAPH BY FRITZ GORO OF *LIFE*)

HOLOTHURIANS ON REEF FLAT, BIKINI ISLAND, ABOUT ⅓ NATURAL SIZE.
(PHOTOGRAPH BY FRITZ GORO OF *LIFE*)



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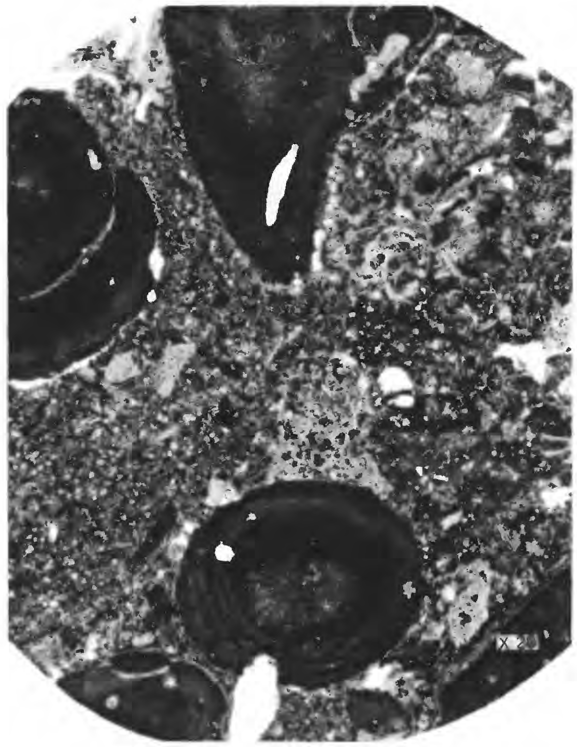

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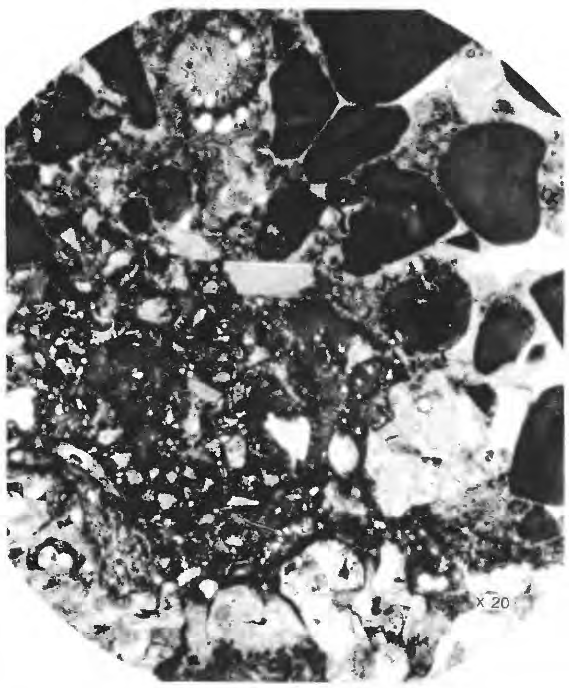

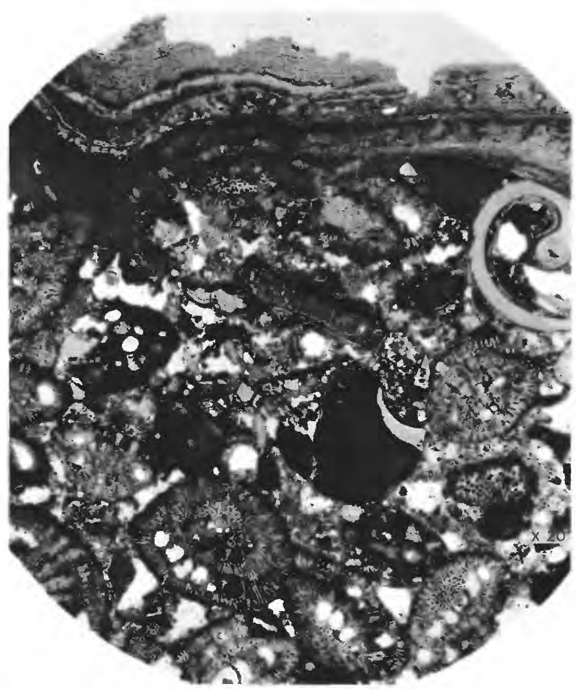

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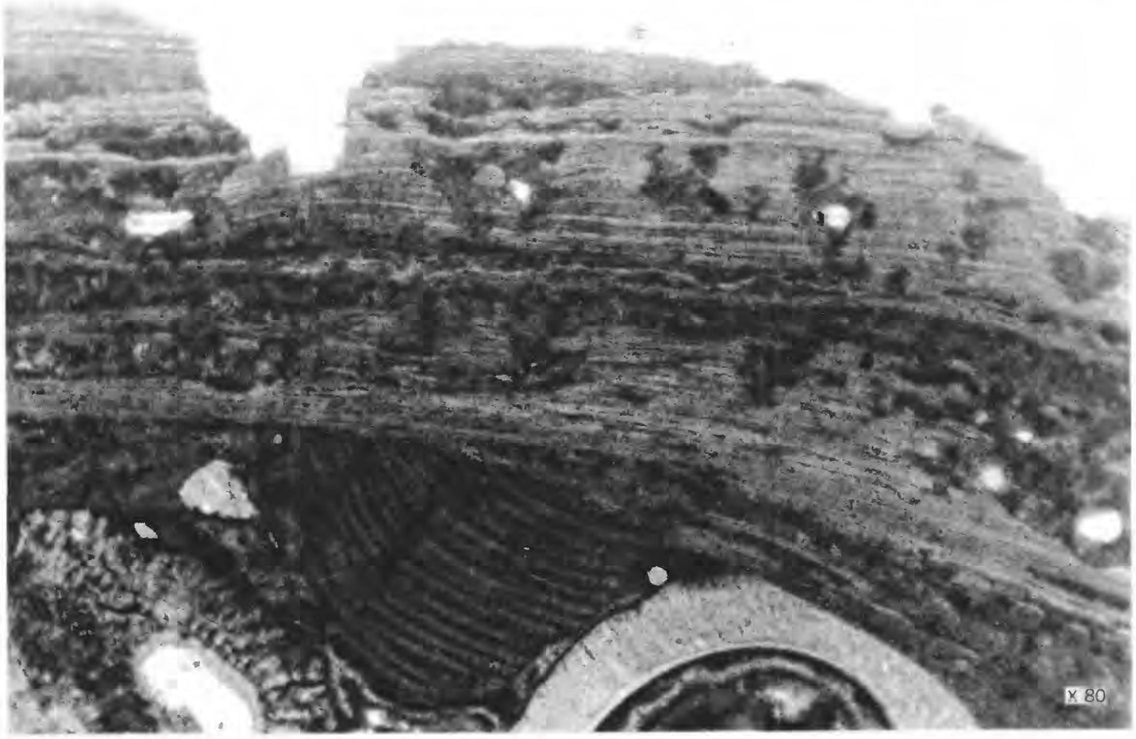
REEF AND BEACH ROCK, BIKINI ATOLL

1–3. Rock (B–300) from remnant of older *Lithothamnion* ridge on reef flat south of Eniairo island, Bikini Atoll. 1. Smoothly worn surface of specimen, pitted by cavities of burrowing organisms, × 1. 2. Sawed face of specimen showing white algal branches and gray fine detrital filling. Borings cut both the algae and the matrix, × 1. 3. Photomicrograph of thin section showing sections of *Lithothamnion* branches and detrital filling. Note that detritus to the right is somewhat coarser, therefore was probably deposited earlier than that to the left. Minute radial spherulites are abundant in the paste, × 20.

4. Photomicrograph of thin section of coarse detrital reef rock (B–315) from reef flat at southeast end of Bikini island. Coarse fragments are embedded in fine detrital paste that has altered around some grains to clear carbonate. Minute spherulites are abundant in the paste, × 20.

5. Photomicrographs of thin section through glazed crust on margin of small solution pit (B–35) in beach rock from southeast end of Bikini island. Fine laminae, × 20, form the crust; they range from 0.001 to 0.01 mm in thickness, averaging about 0.005 mm to form alternating light and dark layers.



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GLAZED CRUST ON BEACH ROCK

1. Detail, × 80, of crust shown in plate 42, figure 5.
2. Basins separated by areas of polished beach rock, Eniwetak Island, Rongerik Atoll.

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REEF FEATURES, BIKINI ATOLL

1. Nodular colonies of *Porites* on reef flat north of Eniairo island. Shingled arrangement of colonies is caused by passage of current from left to right. Photography by Raney.
2. Coarse gravel (B–70) from surge channel at north end of Enyu island, 100 feet seaward from reef margin. Smoothly worn coral pebbles are the most common constituent, × 1.

ZOANTHIDS ON REEF FLAT, RONGELAP ATOLL. (PHOTOGRAPH BY FRITZ GORO OF *LIFE*)

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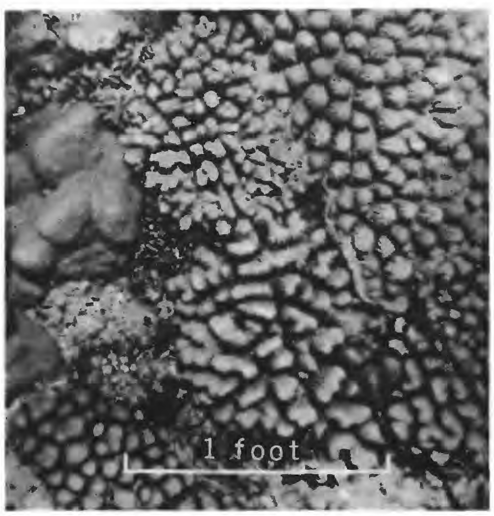

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REEF FEATURES, BIKINI AND RONGELAP ATOLLS

1. Calcareous algae (*Porolithon craspedium*) on the lagoon side of a lee reef, Bikini Atoll. The columnar colonies are a foot in height.
2. Underwater photograph of corals on marginal zone of lee reef of Bikini Atoll. *Pocillopora* in lower center, nodular *Porites* at left and several species of *Acropora*. The area shown is about 2 feet across.
3. Eroded reef block off Enirik island, Bikini Atoll.
4. Blowholes southeast of Enyu island. In the foreground are open pools and crevices. The waterspout is more than 20 feet high.
5. Corals and large sea urchin or reef north of Rongelap island.

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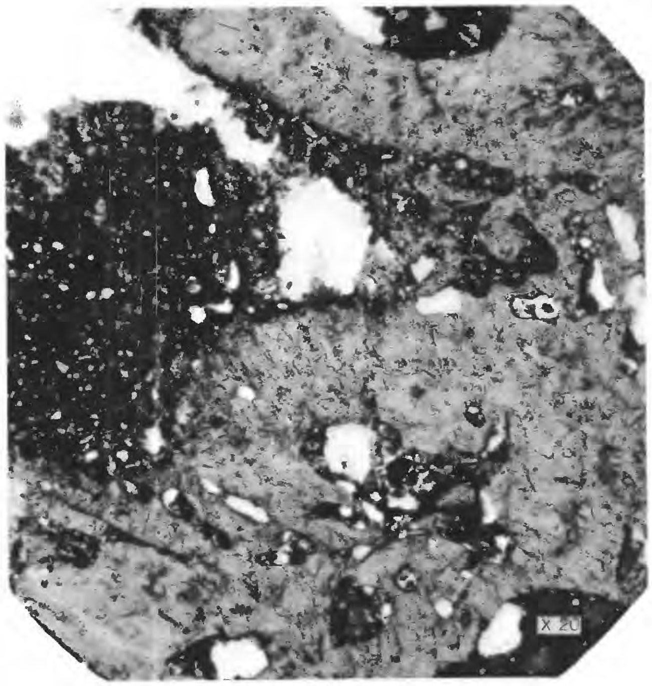

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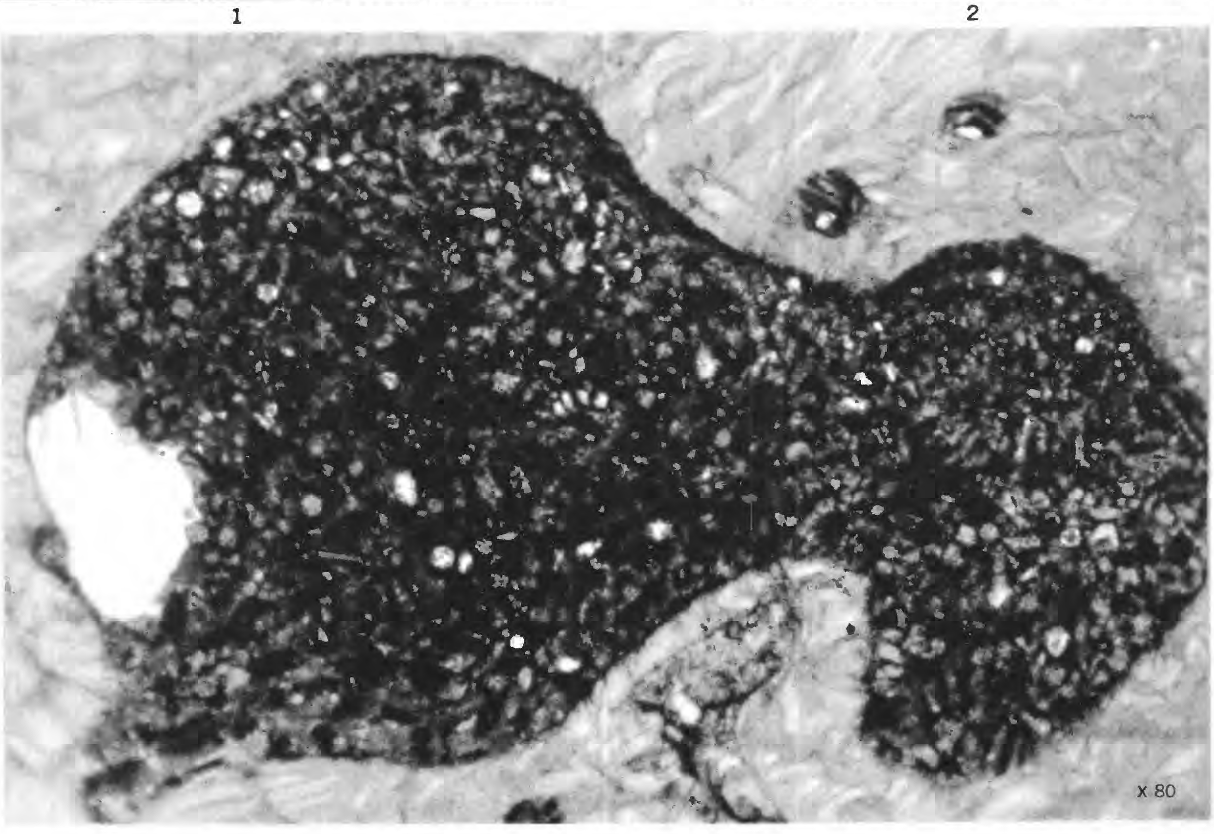

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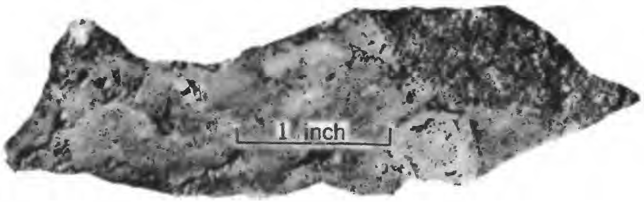
SAND AND ROCK FROM BIKINI ATOLL

1. Sand (B–132) scraped from reef flat near Enyu island. This area is the habitat of the spiny foraminifer, *Calcarina*, which is bound to the reef floor by abundant shreds and fibers of soft algae, × 1.

2–3. Photomicrographs of thin section of rock (B–8) from stack or reef block on Chieerete's reef. 2. Thin section showing coral with pores partly filled by dark, finely detrital limy paste or mud, × 20. 3. A cavity in the same thin section almost completely filled with the finely detrital to microgranular paste. Small spherulites are common. Block areas between grains consist of microgranular to almost cryptocrystalling material that is nearly pure calcium carbonate. Fuzzy appearance of fine grains is due to the high refraction and internal reflection in the material, × 80.



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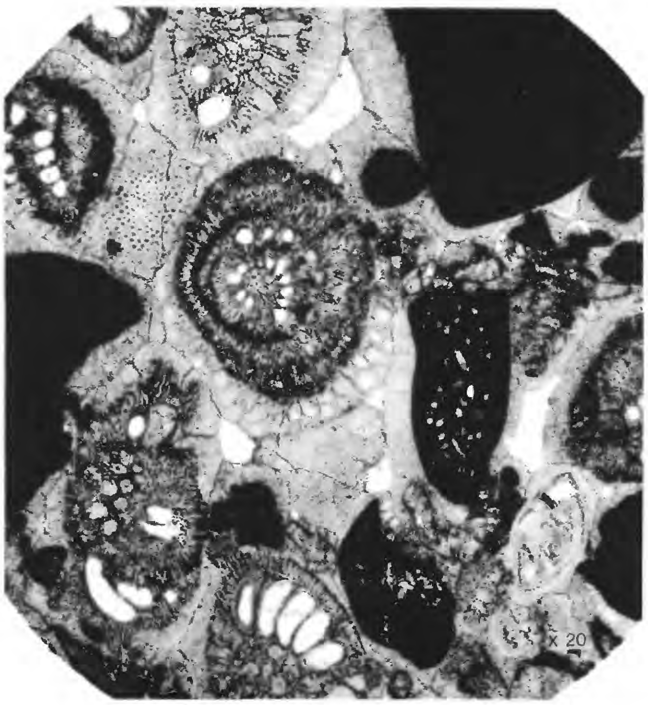

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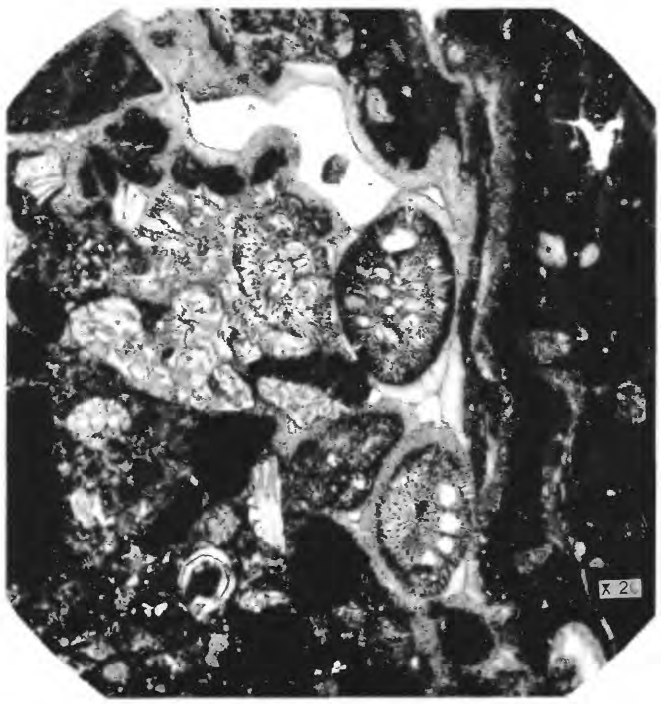

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REEF LIMESTONE, BIKINI ATOLL

1–2. Detrital reef limestone (B–71) from reef flat between Bikini and Aomoen islands near lagoon margin. 1. Sawed face of specimen, $\times$ ¾, showing the well-cemented and compact character of the coarse detritus, and the edge riddled by small boring organisms. 2. Photomicrograph of specimen, $\times$ 20, showing *Calcarina* and encrusting foraminifers embedded in finely detrital matrix. Open cavities are lined with a thin film of clear carbonate.

3. Photomicrograph of thin section of rock (B–306) from top of groin 1,350 feet from beach, northeast side of Bikini island; the coarse foraminiferal-algal detritus is cemented by a coating of acicular aragonite 0.1–0.3 mm in width $\times$ 20.

4. Photomicrograph of algal limestone remnant (B–54) behind existing reef margin, southeast end Bikini island. *Lithothamnion* (black) and detrital material with *Calcarina* and fine paste, cemented by acicular carbonate. In places the clear carbonate can be seen to replace the dark paste ($\times$ 20).

WAVE ENTERING SURGE CHANNEL, BIKINI ATOLL

Wave entering surge channel that crosses *Lithothamnion* ridge, Bikini island.

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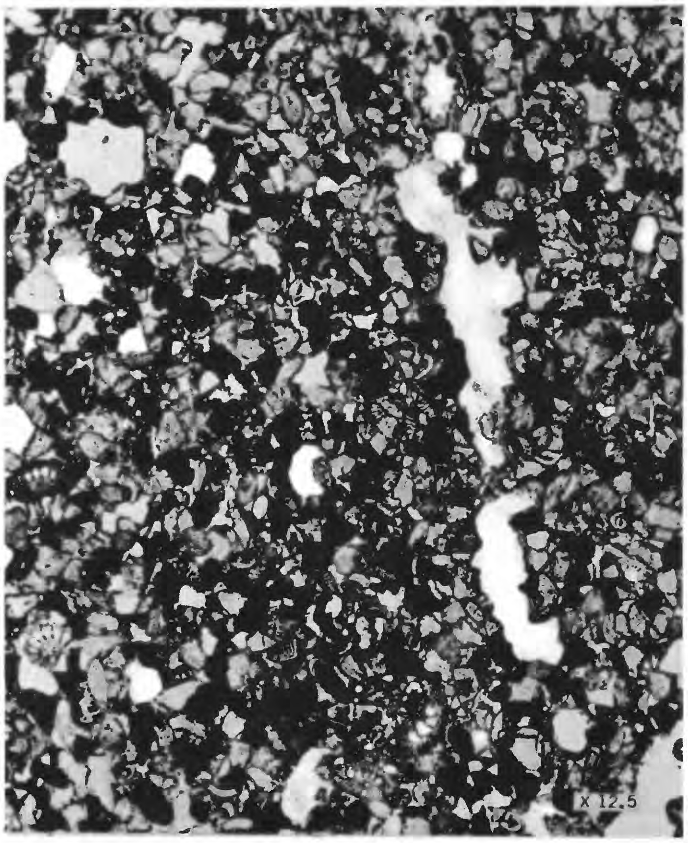

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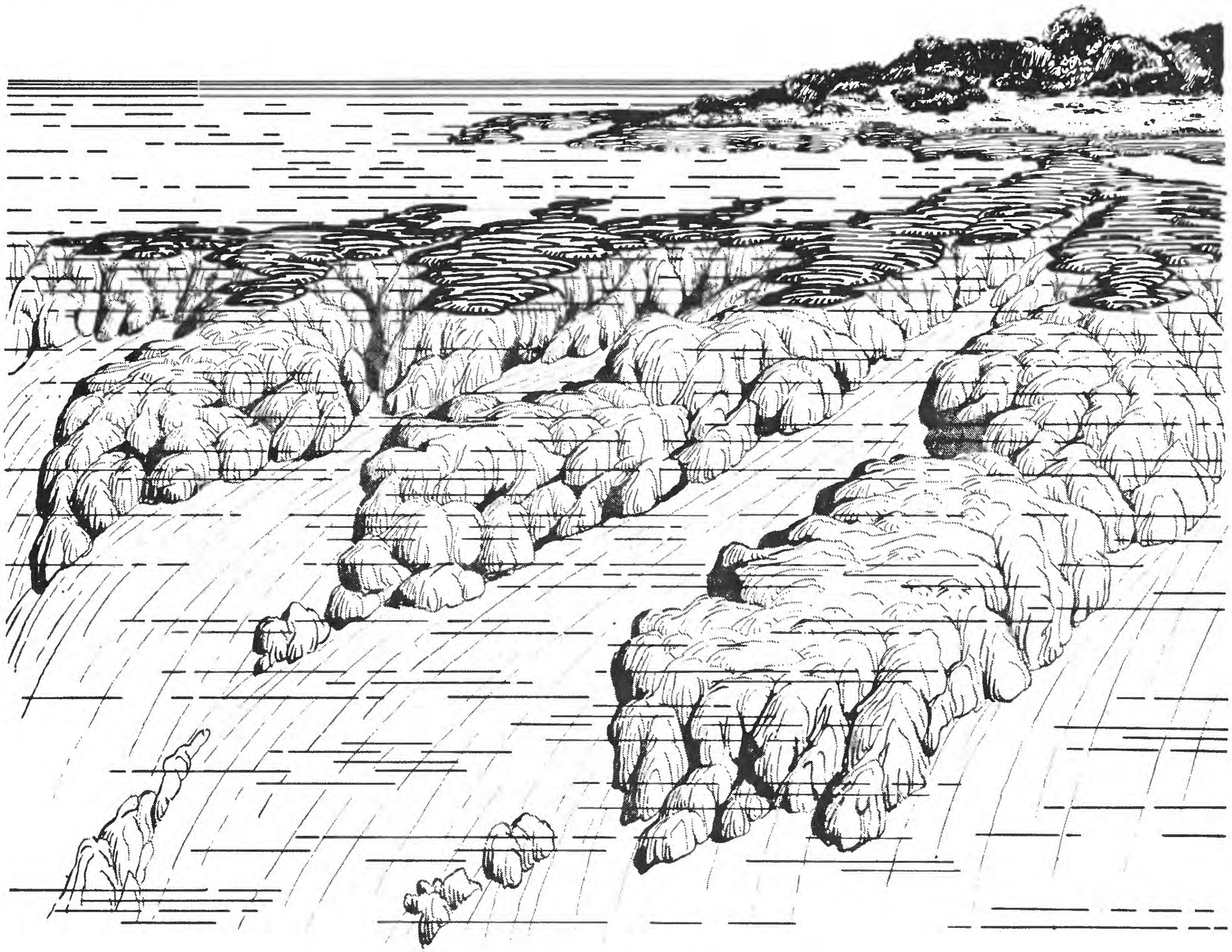
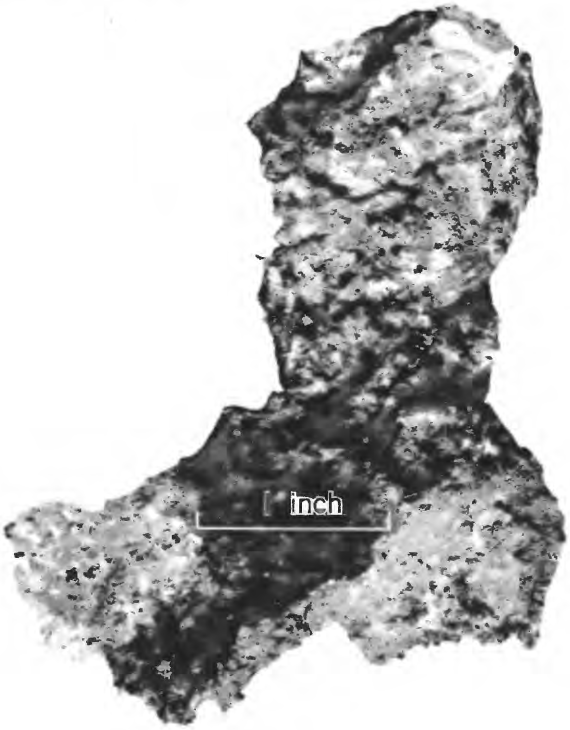
BLOWHOLE AND BEACH SANDSTONE

1. Blowhole near Eniwetok Island. The algal mound is 3 feet high and 18 feet in diameter.
2–3. Beach sandstone (B–60) from lagoon beach, Rongelap island. 2. The leached, porous appearance of the rock and the alternate open and compact horizontal zones are shown. 3. Photomicrograph showing subparallel alinement of open pores in the sandstone (× 12.5).



SEA REEF OF TUFA ISLAND, RONGELAP ATOLL

Sketch of sea reef off Tufa island, Rongelap Atoll, showing relationship of marginal zone of reef and offshore algal ridges or spurs to older surface. Adapted by P. B. King and Margaret Austin from a field sketch by Selwyn Taylor.



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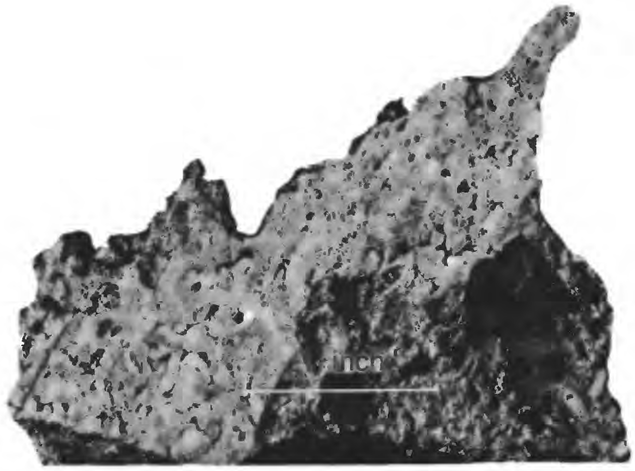

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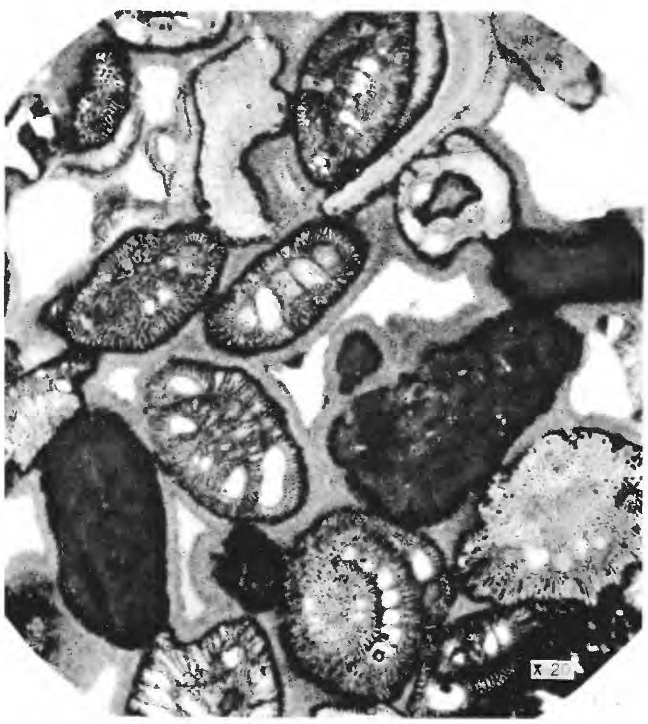

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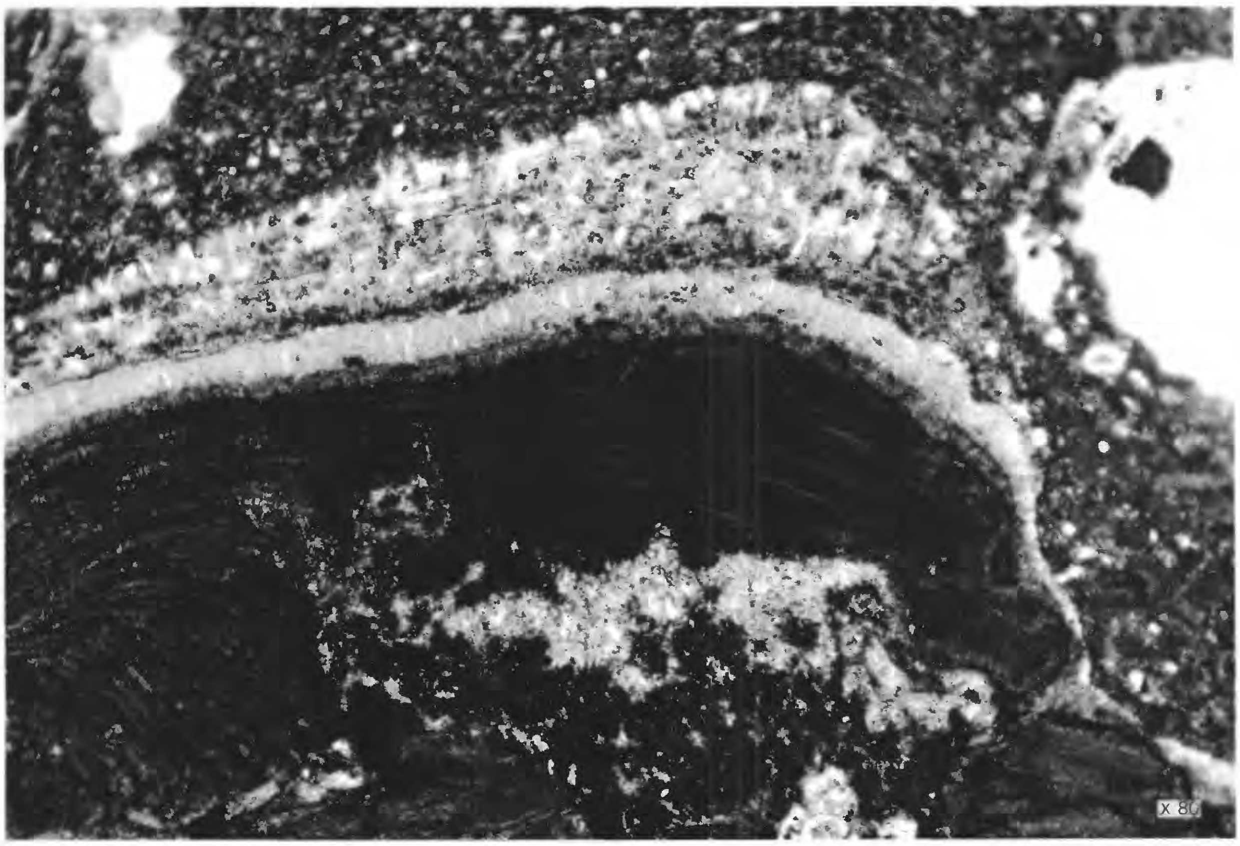
1–3. An eroded sandstone (B–65) from a solution pit on the north beach of Lomuilal island, Rongelap Atoll. 1. Surface of specimen showing rough, pitted and cuspate character resulting from solution, × 1. 2. Sawed face on same specimen showing coarse texture of sandstone, ×1. 3. Photomicrograph of sandstone showing development of acicular carbonate (aragonite) cement around grains. Note the lack of interstitial paste.

ERODED SANDSTONE, RONGELAP ATOLL



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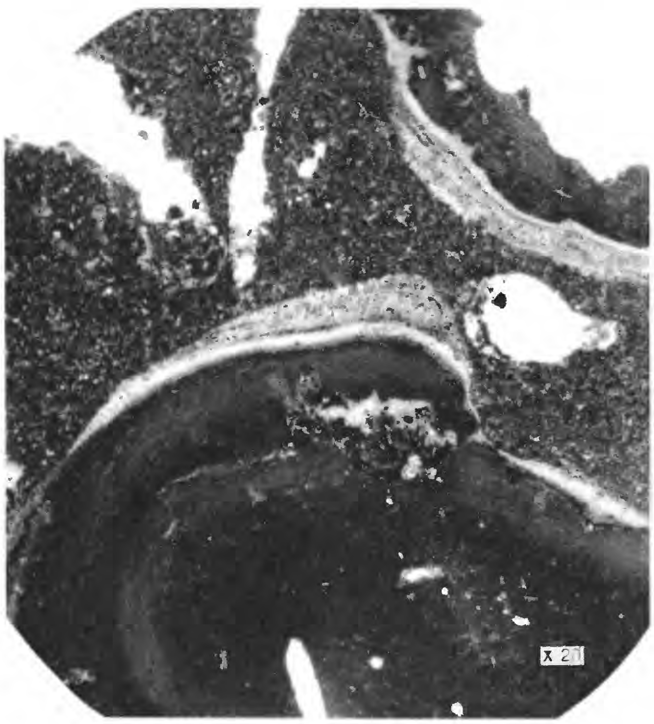

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1–2. Photomicrographs of solution-sculptured detrital limestone (B–64) on the north beach (adjacent to the reef) of Lomuilal island, Rongelap Atoll. 1. *Lithothamnion* fragments (black) embedded in a finely detrital to microgranular gray paste that is altered near the *Lithothamnion* to clear carbonate, × 20. 2. Detail of the above photograph, × 80, showing the finely crystalline clear calcite within the *Lithothamnion* that appears to be an alteration rather than a cavity filling.

DETRITAL LIMESTONE, RONGELAP ATOLL

LAYERS OF BEACH ROCK, BIKINI ATOLL

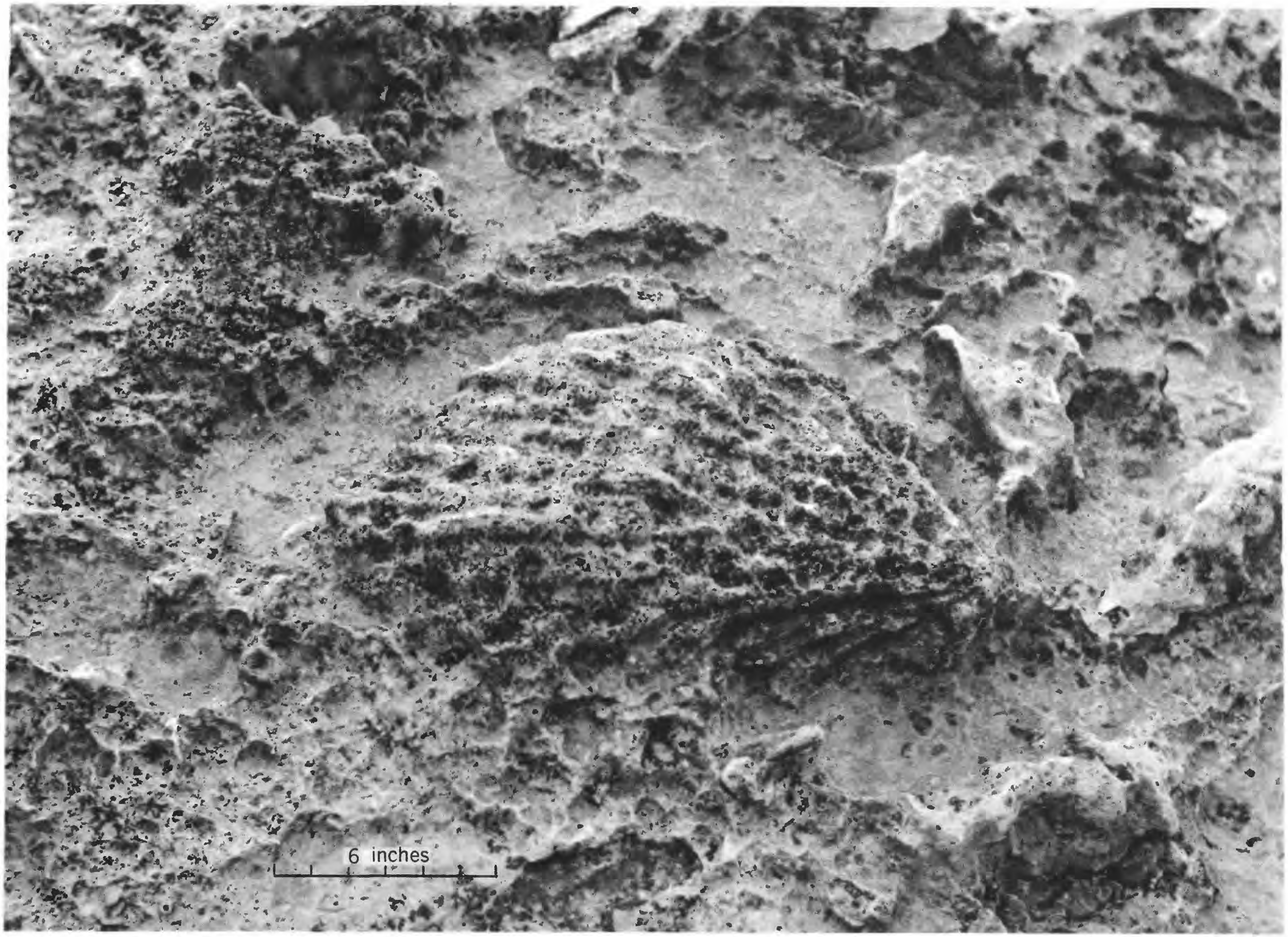
Layers of beach rock near Bokonfuaaku island; Bikini island appears in left background. Layers of rock dip lagoonward and probably were formed on lagoon beach at a time when the island lay farther to seaward. Photograph by Fritz Goro of *Life*.

1

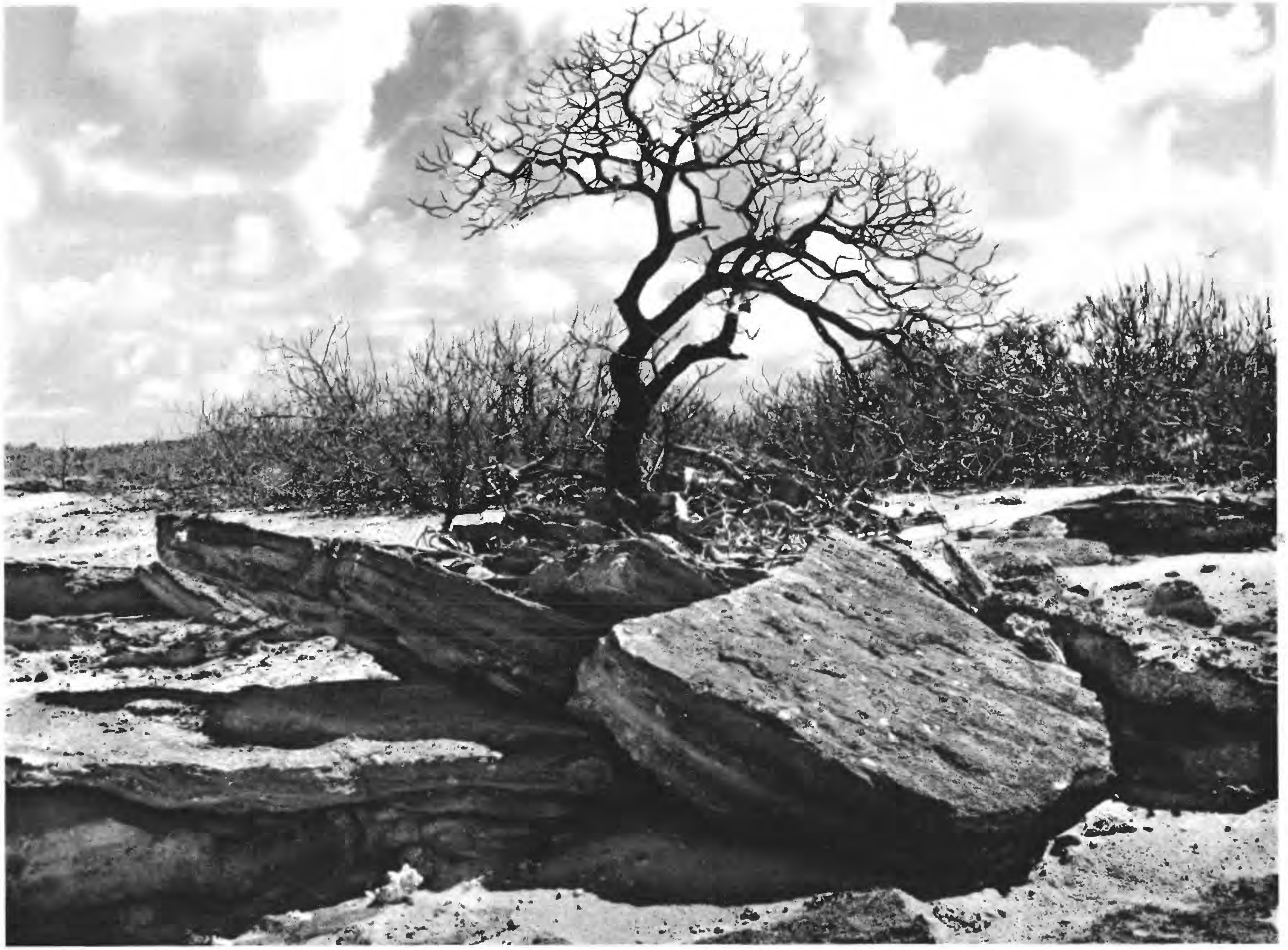
2

SHORE FEATURES, BIKINI ATOLL

1. Boulder rampart, southeast side of Ourukaen island, Bikini Atoll. The top of the rampart is about 10 feet above low-tide level and slopes 15° to 20°. The seaward edge of the reef, marked by whitecaps, is only 200 feet away.
2. Truncated layers of older beach rock, striking into line of present beach, are capped by a thin sandstone that follows the slope of the existing beach. North side of Uorikku island, Bikini Atoll.

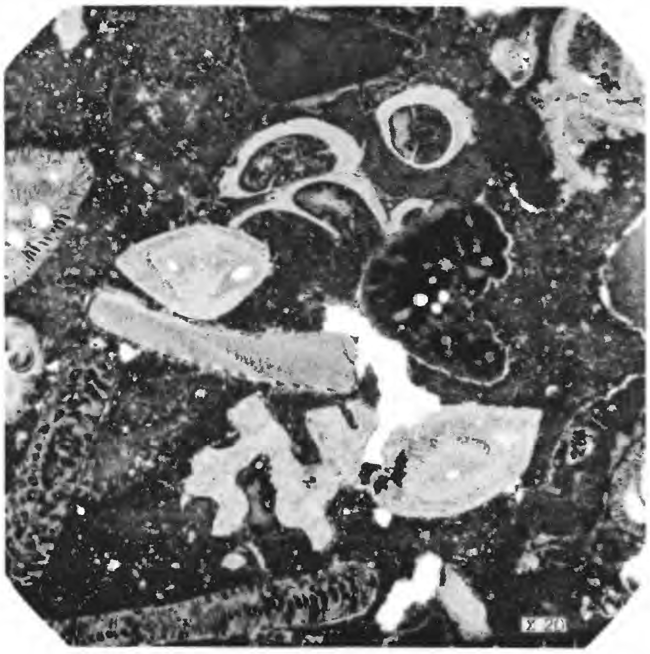


TRUNCATED COLONY OF *HELIOPORA*, AMOEN ISLAND. (PHOTOGRAPH BY FRITZ GORO OF *LIFE*)



BEACH ROCK, BIKINI ATOLL

Blocks of beach rock dislodged by waves, lagoon beach of Aomoen island. Photograph by Fritz Goro of *Life*.



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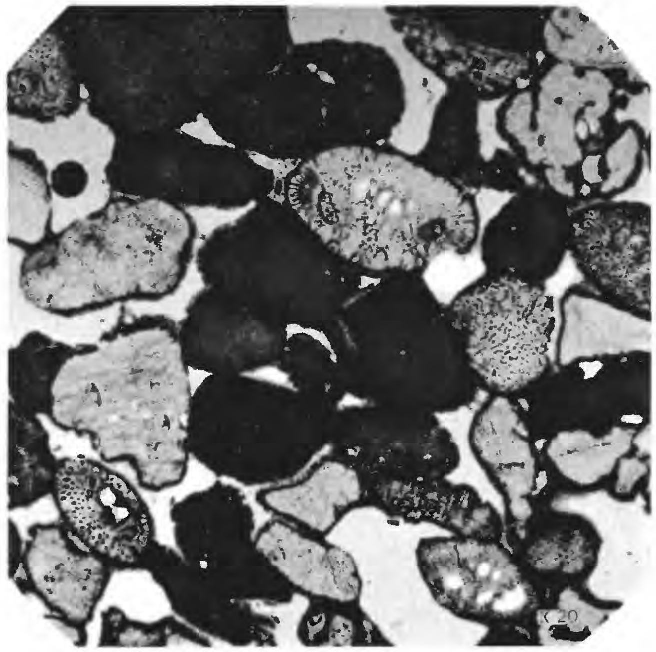

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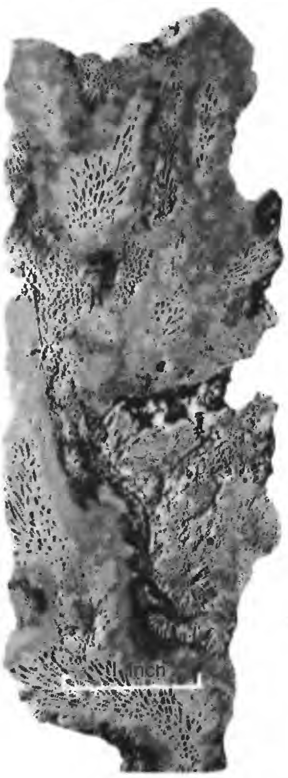

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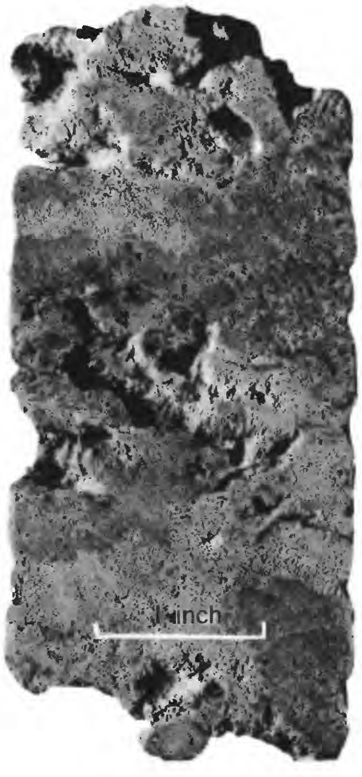

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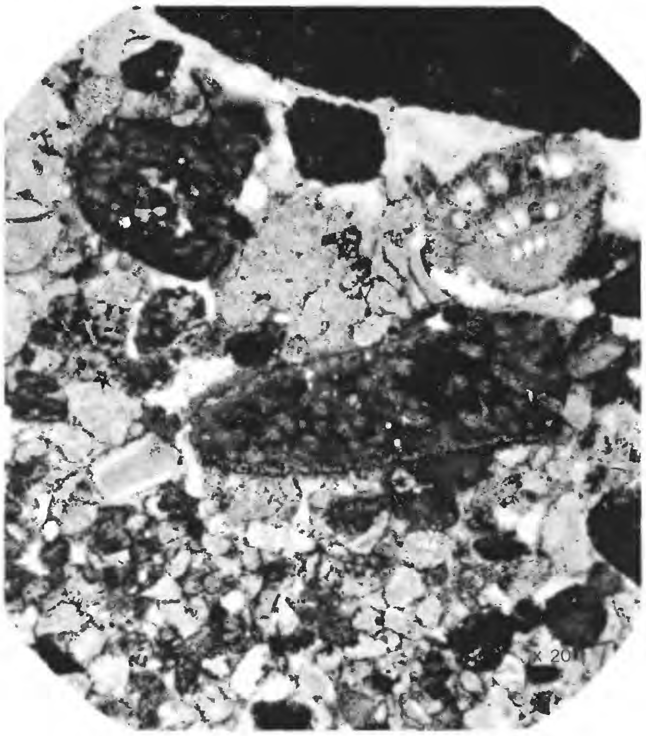
LIMESTONES, BIKINI ATOLL

1. Limestone (B–9) from rubble-block scarp, 12 feet above high-tide level, south side of Chieerete island. Thin section showing fragmental remains of *Lithothamnion*, *Halimeda*, *Calcarina*, *Marginopora*, and mollusk shells in a finely detrital, almost microgranular paste. The specimen appears similar to detrital reef rock, × 20.
2. Polished beach sandstone (B–58) from lagoon side of sandbar, west end of Uorikku island, Bikini Atoll, showing worn grains of *Lithothamnion* (dark), *Calcarina*, and coral. The grains are rimmed by a thin black coating that appears to be an alternation of the grain surface. Fine needles of aragonite are shown growing on the black cement coating the grains, × 20.
3. Core (1–12–2) showing coral in position of growth. Fine detritus fills spaces between branches; there is some recrystallization to calcite. Depth about 150 feet in hole 1.
4. Core (1–14–2) of recrystallized coral detritus; some of coral may be in position of growth. Depth about 175 feet, hole 1.
5. Core (2–1–1) of beach sandstone from depth of 14 feet in hole 2.



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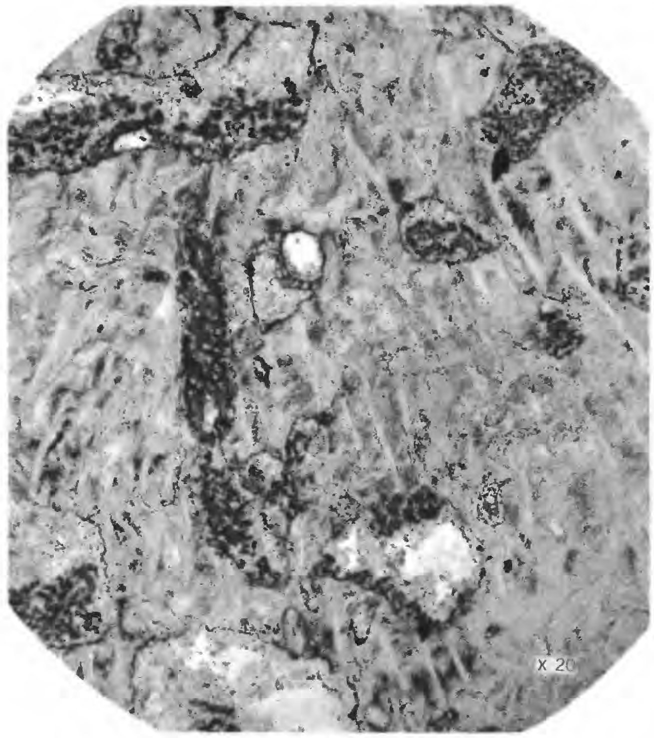

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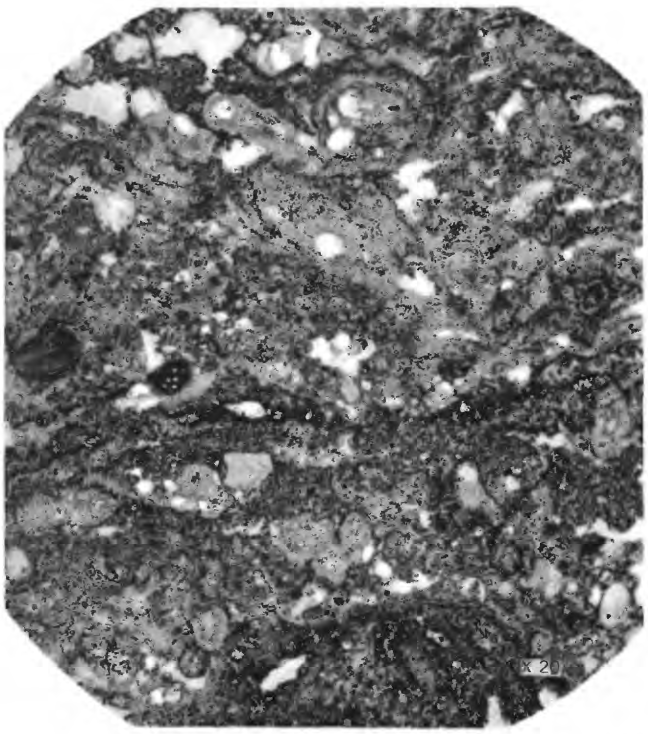

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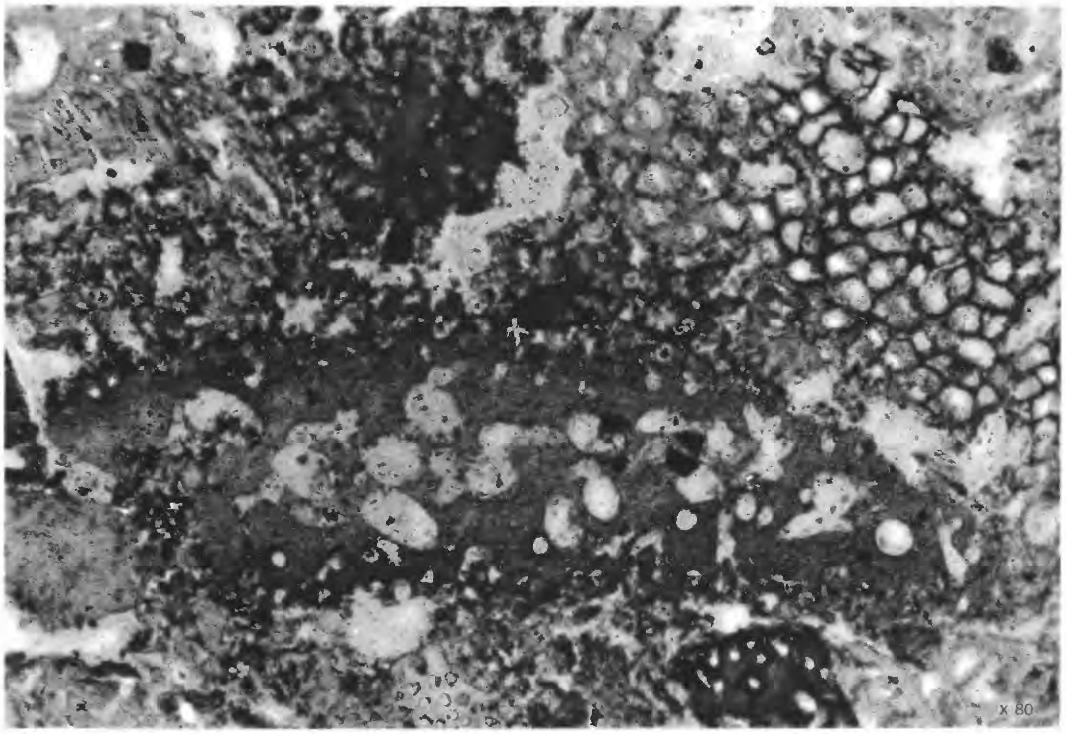
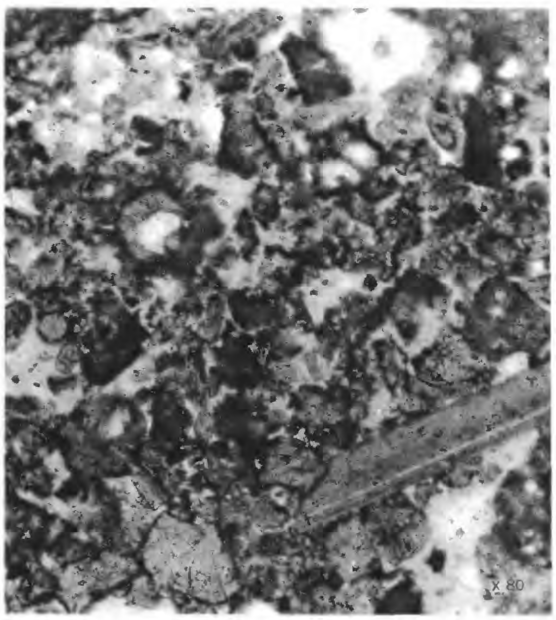
CORE MATERIAL, BIKINI ATOLL

1. Photomicrograph of thin section from center of core (2–1–1) showing coarse material overlying fine sand in the beach rock laminae. A coating of minute aragonite needles cements individual grains. Depth of 14 feet in hole 2, × 20.
2. Photomicrograph of core (2–6–6) of coralliferous limestone from depth of about 105 feet in hole 2. The coral shown is unaltered aragonite. Cavities are filled partly by gray microgranular paste, and the rest by a clear mosaic of finely crystalline calcite. The clear calcite is seen to replace the gray paste, × 20.
3. Photomicrograph of core (2–2–10) of laminated brown carbonate, × 20. The indistinct remains of organic fragments may show somewhat better in a photograph than to the eye under the microscope. The horizontal lamination or banding shows poorly at this magnification, but the apparent concretionary structure is well shown.
4. Photomicrograph of *Halimeda* and Foraminifera in core (2–3–2) of chalky silt from depth of about 55 feet in hole 2.



1

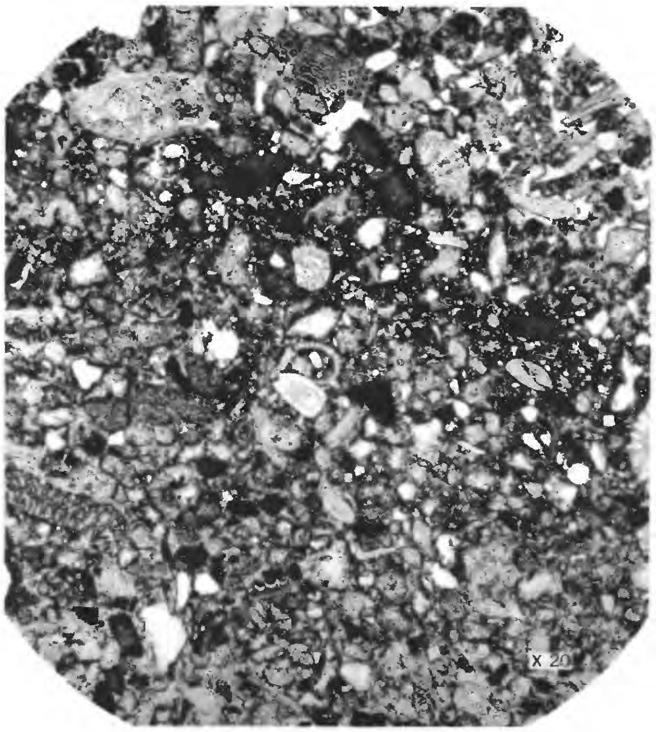


2

3

CORE MATERIAL, BIKINI ATOLL

1. Photomicrograph of core (2–3–4) from depth of about 55 feet in hole 2. The cross section of *Halimeda* that occupies the lower half of the photograph shows the microgranular, almost cryptocrystalline character of the material. It is mostly aragonite, but it is so fine grained that it apparently has a low index, and under crossed nicols appears nearly isotropic, × 80.
2. Photomicrograph of thin section of core (2–7–2) of fine friable, chalky limestone from depth about 120 feet. The fine organic fragments show no recrystallization to calcite, but much of the microgranular powdery material surrounding the fragments results presumably from disintegration of the coarse material. A small part of the microgranular material consists of fine needles of carbonate that tend to cement the loose chalky limestone, × 80.
3. Photomicrograph of section of a pebble contained in detrital matrix of core (2–11–15) from depth of about 185 feet. The dark lower half of the figure, × 20, shows the altered brown microgranular crust of the pebble, and the light upper half shows the matrix of organic fragments cemented by crystalline calcite. The alteration of the crust of the pebble has resulted in the development of vague concretionary structures, and in the obliteration of all organic remains with the exception of the two tests of *Amphistegina* in the lower right of the photograph. Two large cavities in the pebble are shown partly filled by angular detrital grains from above. The clear mosaic of calcite that cements the matrix of the pebble and the grains in the cavities is seen to permeate the dark material of the pebble in small shredlike patches.



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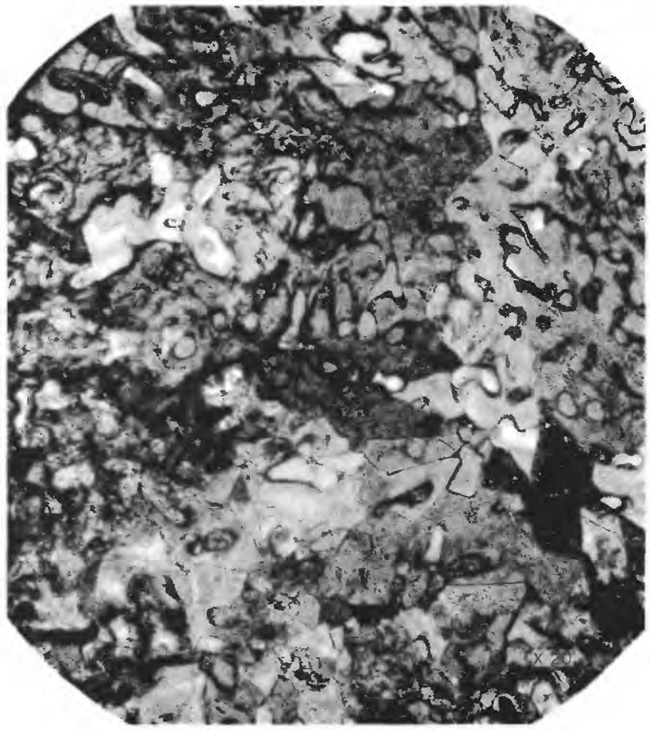

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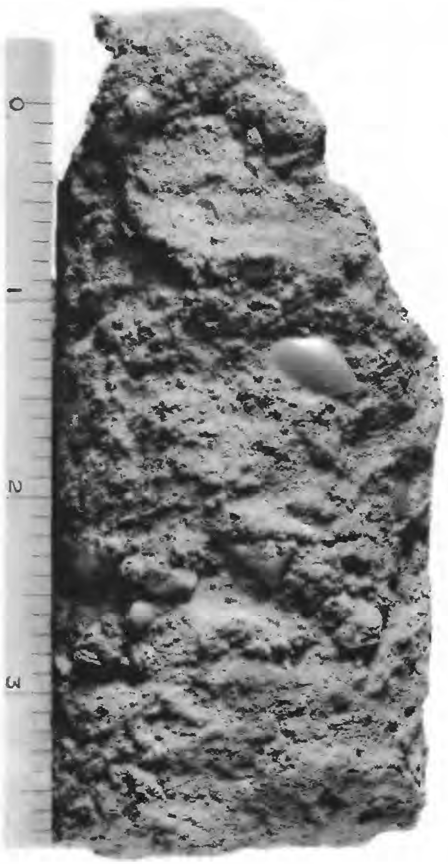


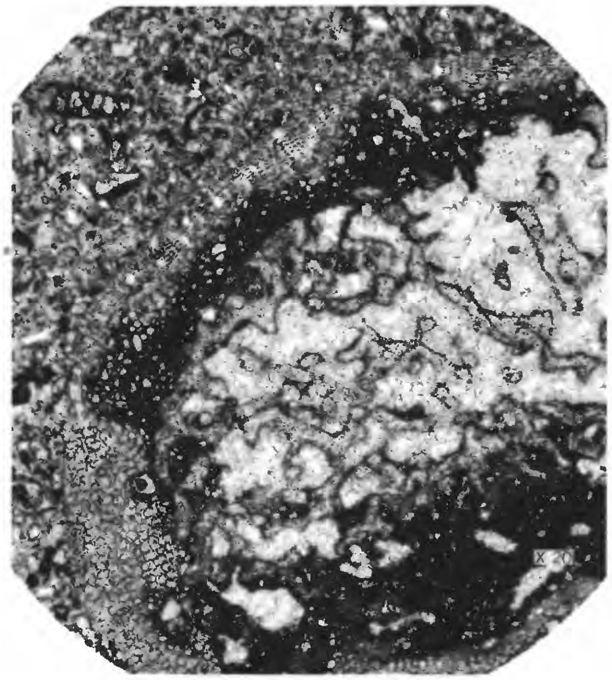
2

1. Photomicrograph of core (2–11–20) of chalky, friable limestone from depth of about 187 feet. The tests of Foraminifera, especially *Marginopora* and *Rotalia calcar*, are distinct, but many angular grains and shells are indistinct. The matrix in the upper part of the photograph is dark microgranular paste, whereas that in the lower part of the photograph is lighter in color and consists of a finely crystalline mosaic of clear calcite, × 20.

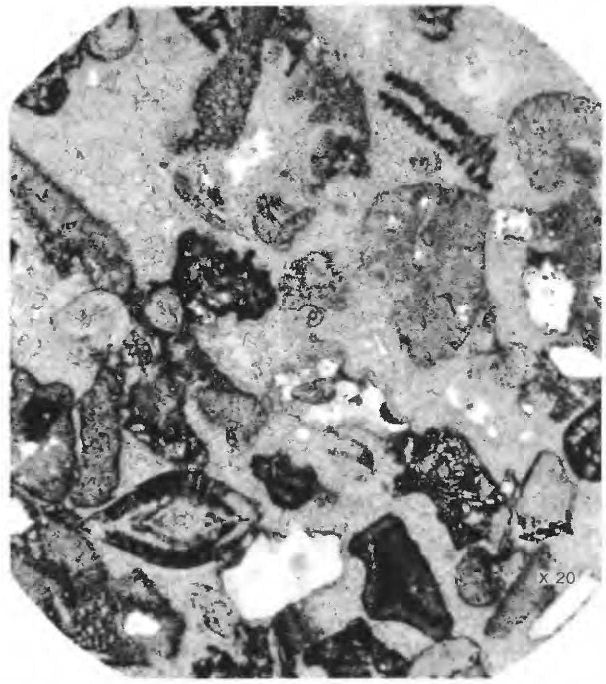
2. Core (2A–12–9) from a depth of about 195 feet. The material is a chalky silt containing numerous well-preserved pelecypods.

3. Photomicrograph of core (3–10–11) from depth of about 80 feet shows coral preserving original cellular structure but completely recrystallized to coarsely crystalline calcite that has replaced both the original coral and open pore spaces, × 20. Photographed under crossed nicols to show crystal boundaries.

CORE MATERIAL, BIKINI ATOLL



1



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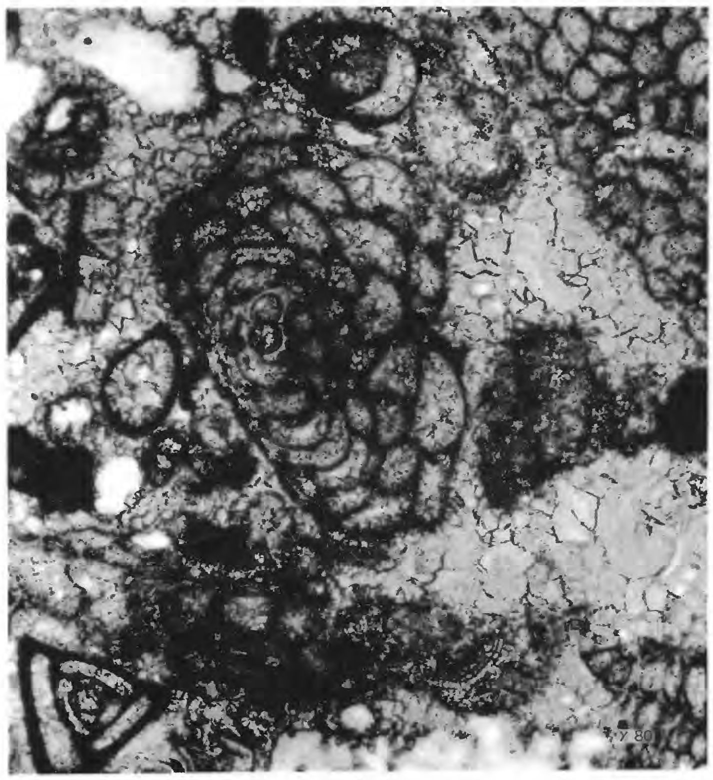


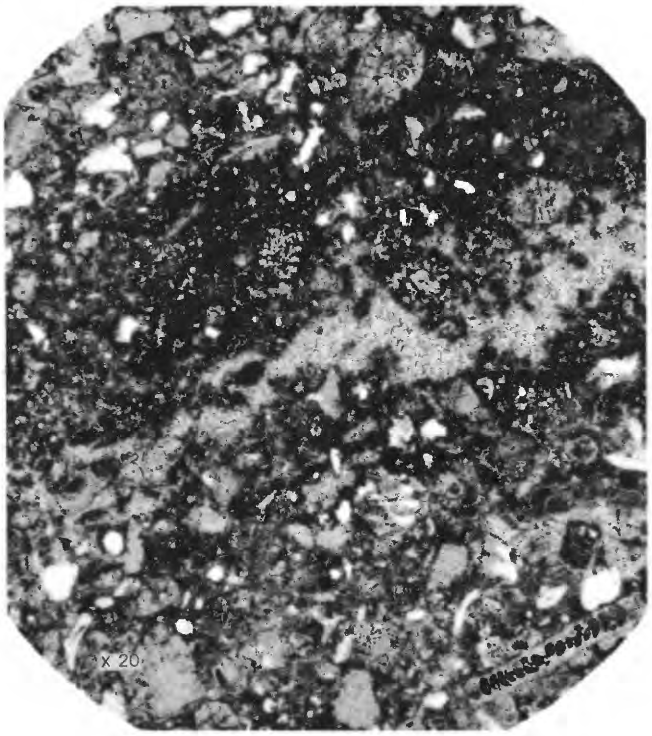
4

CORE MATERIAL, BIKINI ATOLL

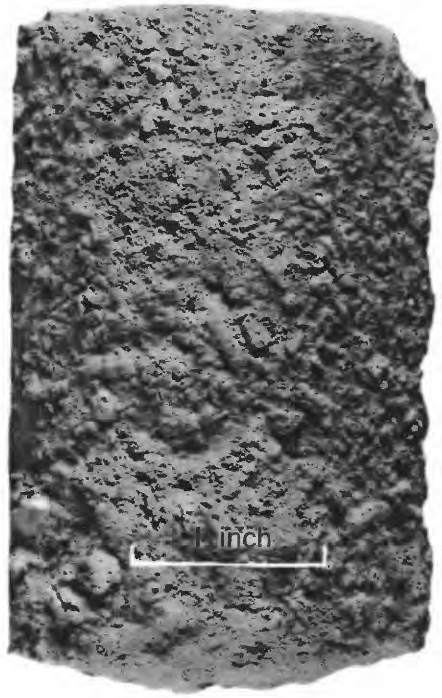
1, 4. Photomicrographs of core (2A–26–3) from depth of about 330 feet. 1. Coral recrystallized to a mosaic of calcite and coated with an encrusting foraminifer, probably *Homotrema*. The finely detrital matrix surrounding the coral contains tests of minute Foraminifera, × 20. 4. Another area on same slide as figure 1, × 80, shows the tests of foraminifers altered from clear fibrous calcite to dark microcrystalline or cryptocrystalline material. The gray microgranular paste forming the matrix has been altered to a mosaic of clear calcite.

2. Core (2A–28–6) of recrystallized foraminiferal limestone from depth of about 445 feet. Gray microgranular paste that occupies a part of the thin section is completely recrystallized to a comparatively coarse clear calcite in the area shown. Tests of some foraminifers are well preserved, but fragments of some organisms are indistinct, × 20.

3. Core (2A–26–1) of coralliferous foraminiferal detritus from a depth of about 350 feet. The corals are preserved as molds.



1



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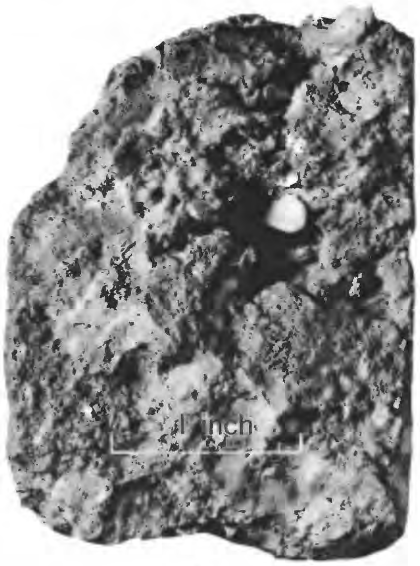
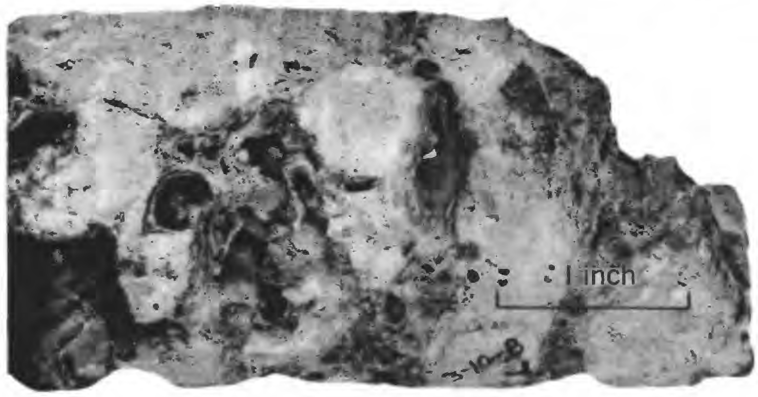
CORE MATERIAL, BIKINI ATOLL

1. Core (2A–31–3) from depth of about 570 feet showing foraminiferal tests and angular detrital grains in a matrix of gray microgranular paste that has altered in places to a mosaic of clear calcite. The recrystallization shown here is less than that at higher levels in the core, × 20.
2. Core (2A–37–4) of fossiliferous sand containing small delicate *Seriatopora* fragments from depth of about 940 feet in hole 2A.
3. Core (2A–36–2) of richly fossiliferous unsorted detrital sand from a depth of about 930 feet in hole 2A.
4. Core (3–7–8) from depth of about 65 feet in hole 3 showing *Astreopora* in position of growth. Open cavities are half filled with fine detritus.



1



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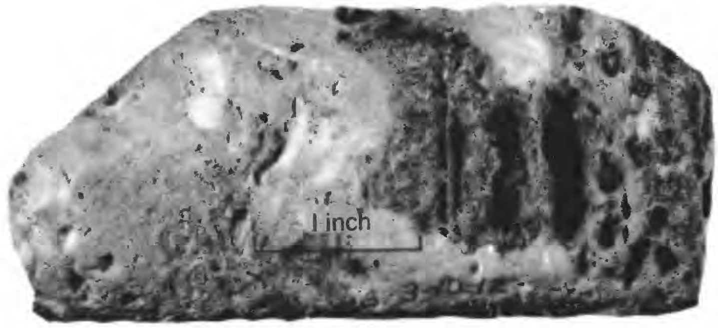

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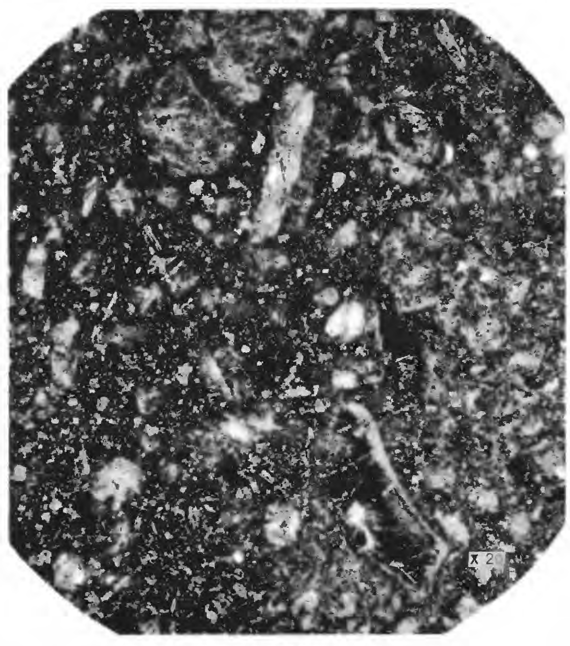

5

CORE MATERIAL, BIKINI ATOLL

1. Core (3–6–15) of loosely packed reef detritus with open cavities.
2. Core (3–10–8) of cavernous coral detritus from depth of about 81 feet in hole 3. Cavities are partly filled with coarsely crystalline brown calcite.
3. Core (3–1–25) showing *Lithothamnion* in position of growth and large half-filled cavities from depth of about 15 feet in hole 3.
4. Core (3–10–12) of cavernous coral detritus with thin horizontal layers of coarsely crystalline calcite from depth of about 82 feet in hole 3.
5. Photomicrograph of core (2A–37–7) showing shells, mostly fragmentary, in a matrix of limy mud. The mud is a brown micrognanular paste, dominantly aragonite, and the shells and coral fragments are also aragonite. The photomicrograph shows the rather blurred outlines and internal structures of the grains, apparently caused by disintegration of the original aragonite fibers to microgranular particles that generally still have the original optical orientation, × 20.