Subsurface Geology of Eniwetok Atoll

GEOLOGICAL SURVEY PROFESSIONAL PAPER 260-BB

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By SEYMOUR O. SCHLANGER

With sections on CARBONATE MINERALOGY

By DONALD L. GRAF *and* JULIAN R. GOLDSMITH

PETROGRAPHY OF THE BASALT BENEATH THE LIMESTONES

By GORDON A. MACDONALD

DATING OF CARBONATE ROCKS BY IONIUM-URANIUM RATIOS

By WILLIAM M. SACKETT *and* HERBERT A. POTRATZ

BIKINI AND NEARBY ATOLLS, MARSHALL ISLANDS

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A study of limestone and dolomite recovered during deep drilling on Eniwetok

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By Seymour O. Schlanger

ABSTRACT

Two deep holes, drilled on opposite sides of Eniwetok Atoll, reached the basement below the cap of Recent to Eocene limestone at depths of 4,610 and 4,158 feet. The subsurface geology of Eniwetok Atoll, as deduced from these borings, is related to that of Bikini and Funafuti Atolls and to the emerged island of Kita-daitō-jima.

Below both Eniwetok and Bikini Atolls, intervals characterized by fossil molds and solution channels alternate vertically with intervals marked by the presence of primary skeletal aragonite. The leached intervals are directly and sharply overlain by unaltered unconsolidated sediments. The tops of the leached zones are termed "solution unconformities." These unconformities were formed during periods when the atolls were emergent, and they can be precisely correlated between Eniwetok Atoll and Bikini Atoll, 210 miles away. Below both atolls there are well-defined unconformities at approximately 300 and 1,100 feet below sea level; at Eniwetok, another is present at 2,780 feet below sea level. The unconformities generally coincide with faunal breaks, which indicate that periods of nondeposition interrupted the formation of the 4,600-foot-thick section below Eniwetok Atoll and at least the upper 2,556 feet of the limestone column below Bikini Atoll.

The post-Eocene limestones beneath Eniwetok are of shallow-water, mostly lagoonal, origin. The correlative sections at Bikini are also of shallow-water origin. The coincidence of solution unconformities at both atolls and the common origin of the limestones indicate that both atolls followed an identical course of development from Miocene time to the present. At Eniwetok the Eocene section in hole F–1 is of fore-reef, outer-slope origin, whereas correlative deposits in hole E–1 are of shallower water origin—no comparable section at Bikini was reached by drilling. The earliest reef at Eniwetok grew below what is now the southeast side of the atoll; through the Tertiary the atoll gradually developed in a northwesterly direction until it reached its present configuration. The atoll was emergent in early Miocene, in late Miocene, and again in Pleistocene time. The thickness of the leached intervals indicates emergence of as much as 700 feet.

Chemical analyses show that the highest $MgCO_3$ content is 38.8 percent, 7 percent less than the theoretical $MgCO_3$ content of pure dolomite, although X-ray analyses show more than 98 percent dolomite. Dolomite from both Funafuti and Kita-daitō-jima also show excess calcium. X-ray studies by Graf and Goldsmith show that the excess calcium is due to the presence of calcium ions in some magnesium positions in the dolomite structure. Mineralogical analyses indicate that nowhere in these atolls do aragonite and dolomite coexist, a situation that suggests that either the removal of aragonite by solution or its replacement by calcite is a prerequisite to dolomitization. Spectrographic analyses show these limestones and dolomites to be very low in magnesium and iron; the strontium content drops as recrystallization and dolomitization proceed.

A review of the stratigraphic distribution and a study of the comparative petrography of dolomite from Eniwetok, Funafuti, and Kita-daitō-jima indicate that even within the restricted conditions that prevail during deposition and diagenesis of atoll limestones, dolomite can apparently form in at least three ways:

1. By development of dolomite from metastable, high-magnesian calcite originally precipitated by coralline algae.
2. By reaction of sea water with low-magnesian calcite.
3. By direct precipitation of dolomite in vugs in the limestone.

Cores and cottings from drill holes E–1 and F–1 on Eniwetok Atoll are described in detail.

Alkali olivine basalt containing analcime was cored between depths of 4,208 and 4,222 feet in drill hole E–1 on Parry Island, Eniwetok Atoll. Petrographic study shows that the rock consists of olivine, plagioclase feldspar, titanian augite, magnetite, ilmenite, alkali feldspar, and analcime. Parts of the core are nearly fresh, but much of it is intensely altered to saponite and chlorite. The alteration is related to numerous calcite veins that cut the basalt. Chlorite, zeolite, and collophane veins also are present.

The rock is similar to alkali olivine basalts and basanites among the late lavas from the volcanoes of the State of Hawaii and other islands of the central Pacific Ocean. Its extreme denseness is not evidence of extrusion in deep water, as some subaerial lavas of Hawaii are equally dense. All the core appears to belong to the dense part of a single flow. The alteration of the lava resembles that effected by hydrothermal solutions elsewhere, but it and the vein formation are believed to have been caused by epigene solutions that dissolved calcium carbonate from overlying limestones at a time when the limestones were emergent and the basalt platform beneath them stood near sea level.

Th^{230}/U^{238} ratios in ocean water and marine limestones were determined to ascertain the conditions under which this ratio may serve as a measure of geologic age. Marine limestones contain uranium in amounts that range from 0.10 to 5.0 ppm (parts per million). The highest uranium values are associated with aragonitic limestones, whereas calcitic materials are almost invariably low in uranium. All newly deposited marine limestones are, however, virtually free of Th^{230}.

If a calcium carbonate deposit is formed that (1) contains a measurable amount of uranium, (2) has very much less than the equilibrium amount of Th^{230}, and (3) does not gain or lose

uranium or lose the Th^{230}, that grows into the calcium carbonate from the radioactive decay of uranium, then the time at which the calcium carbonate was deposited can be determined from the Th^{230}/U^{238} ratio within the experimental error of the analyses for materials from 1,000 to 300,000 years old.

In all marine carbonates analyzed, conditions (1) and (2) seem to be satisfied. In some of these materials, however, condition (3) has apparently been violated, and a lack of agreement between C^{14} ages and ages determined from Th^{230}/U^{238} ratios is observed in which C^{14} ages are generally younger. Two explanations are suggested. In some marine carbonates, conversion of aragonite to calcite has occurred through a solution-redeposition process in which C^{14} was gained and uranium was lost. Other samples of older limestones have been contaminated with younger material that increases the C^{14} content.

Apparent ages have been calculated from the Th^{230}/U^{238} ratios in samples that were obtained from drill hole E–1 on Parry Island The ratios indicate that deposition of all material lying above

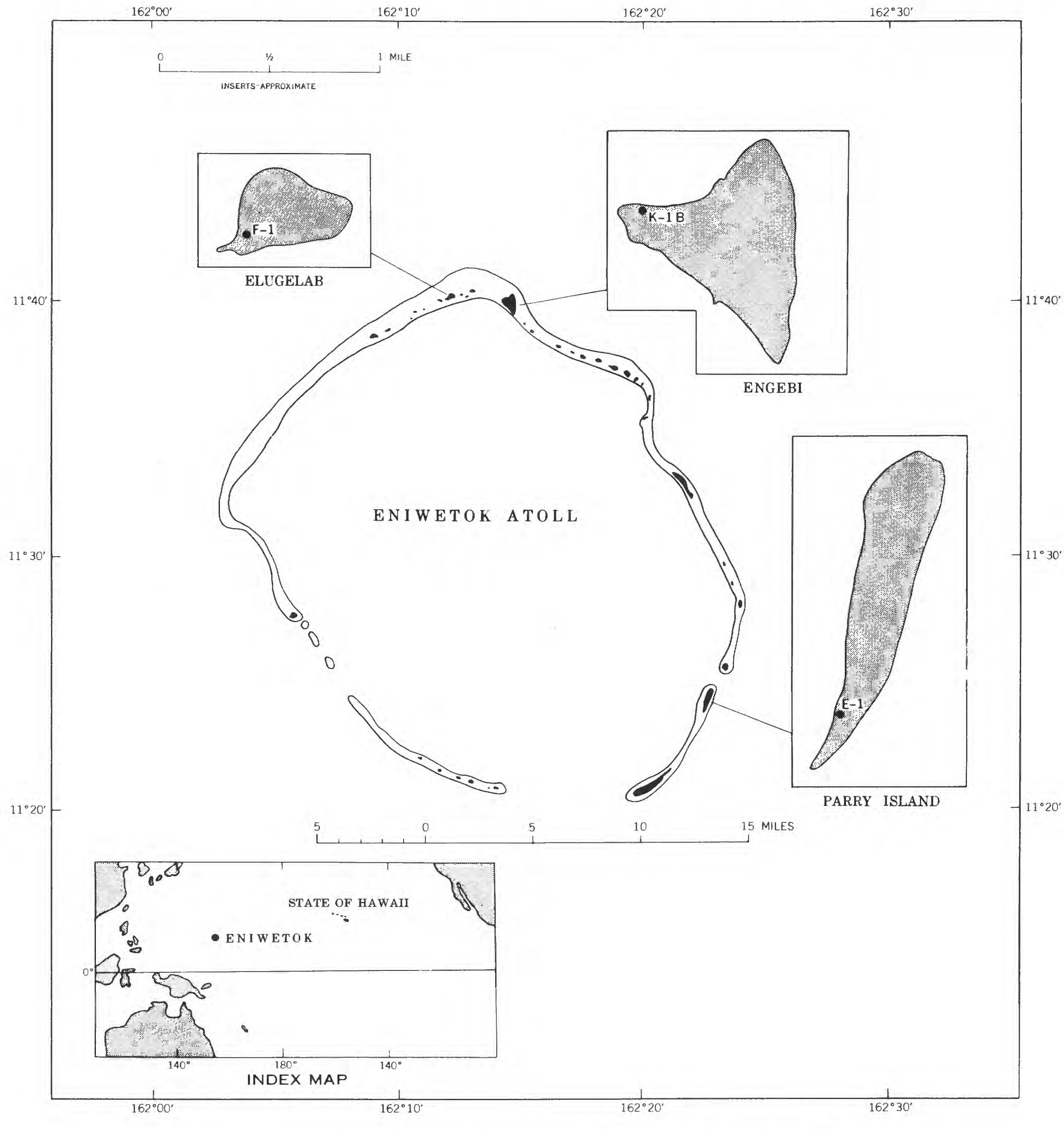

FIGURE 306.—Map of Eniwetok Atoll showing location of holes E–1, F–1, and K–1B.

the 60-foot depth has occurred during the last 12,000 years. Samples taken at greater depths gave the following apparent ages: 70 to 80 feet, 38,000 years; 90 to 100 feet, 106,000 years; 100 to 110 feet, 160,000 years; 120 to 130 feet, 280,000 years. Two additional radiochemical procedures for dating recent marine limestones are suggested.

INTRODUCTION

In 1952, two deep holes drilled on Eniwetok Atoll (fig. 306) reached the volcanic basement below the limestone cap. Hole F–1 struck hard basement rock at 4,610 feet; in hole E–1, basalt cuttings were recovered at 4,158 feet, and solid basalt cores were taken from 4,208 to 4,222 feet. This report contains a detailed petrographic description of the cores and cuttings recovered from these drill holes, and these are the bases for interpretations of the geologic history of the atoll. Comparisons are drawn between the histories of Bikini and Eniwetok Atolls, and the problem of dolomitization in Pacific atolls is discussed with reference to both Funafuti Atoll and Kita-daitō-jima (fig. 307).

This report is but one chapter of a long series on the geology of Bikini and nearby atolls published as U.S. Geological Survey Professional Paper 260. It supplements and expands data published in chapter Y (Ladd and Schlanger, 1960), which covers the drilling operations on Eniwetok Atoll and contains logs of deep holes F–1, E–1, and K–1B, as well as those of many shallower holes. The surface and marine geology of Eniwetok Atoll is covered in chapter A (Emery, Tracey, and Ladd, 1954). Essential to an understanding of the present report is a knowledge of the subsurface geology of Bikini Atoll as discussed by Tracey in chapter A. The stratigraphic divisions used in this report are based on foraminiferal zones defined by Cole (1957) in chapter V and by Todd and Low (1960) in chapter X.

ACKNOWLEDGMENTS

In the study of the Eniwetok cores and cuttings, the findings of many of the workers who contributed to U.S. Geological Survey Professional Paper 260 were used as essential background material. The chapters on larger Foraminifera by W. Storrs Cole, smaller Foraminifera by Ruth Todd and Doris Low, and subsurface geology of Bikini by J. I. Tracey, Jr. (in chapter A) were particularly valuable. Special thanks, regrettably posthumous, are due the members of the Coral Reef Committee of the Royal Society, particularly G. J. Hinde and J. W. Judd; the classic report of C. G. Cullis (1904) on the Atoll of Funafuti stands as a model for atoll research. Discussions on the dolomite problem with Donald L. Graf, Illinois State Geological Survey, and Julian R. Goldsmith, Department of Geology, University of Chicago, were of great help.

The materials described in this report were recovered during deep drilling on Eniwetok that was supported by the Armed Forces Special Weapons Project and carried out for the U.S. Atomic Energy Commission and the Los Alamos Scientific Laboratory in cooperation with the Office of Naval Research.

The work by William M. Sackett and Herbert A. Potratz, Department of Chemistry, Washington Uni-

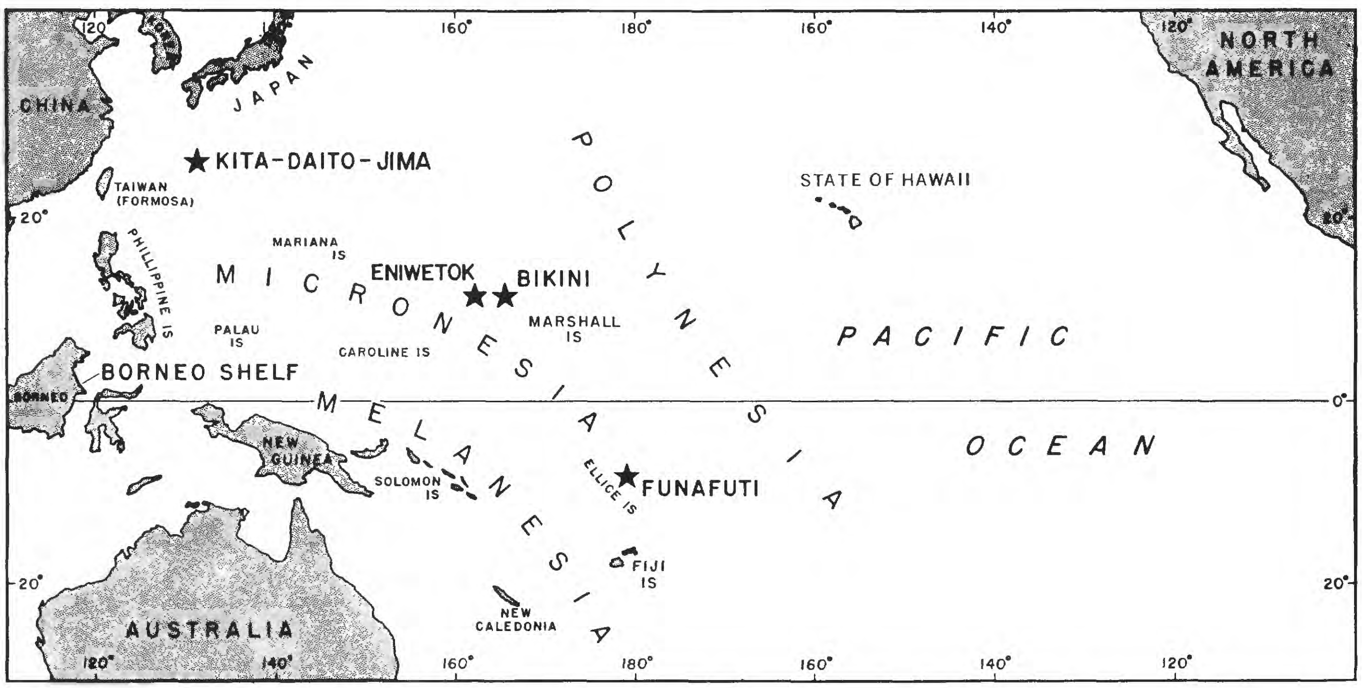

FIGURE 307.—Map of the western Pacific Ocean showing location of Kita-daitō-jima, Funafuti, Bikini, and Eniwetok.

versity, St. Louis, Mo., on uranium and thorium was supported by the Aluminum Company of America and the Van Blarcum Fund of Washington University through fellowships, and by the U.S. Atomic Energy Commission under contract number AT (11-1)-581. The Los Alamos Scientific Laboratory furnished equipment. Meyer Rubin and W. S. Broecker of the Geological Survey obtained radiocarbon dates on several marine carbonates. E. D. Goldberg, of Scripps Institution of Oceanography, Thor V. N. Karlstrom, of the Geological Survey, J. C. Brice, R. P. Bullen, and C. R. McGimsey supplied some samples.

LEACHED ZONES AND UNCONFORMITIES

Below both Eniwetok and Bikini Atolls, zones characterized by fossil molds and solution channels alternate vertically with zones marked by the presence of primary skeletal aragonite.[1] Figure 308 is a plot of the five deep holes—K–1B, F–1, and E–1 on Eniwetok and 2A and 2B on Bikini—and shows that there is a remarkable similarity in the vertical extent of these zones.

Leached zones overlain by unaltered unconsolidated sediments and separated from them by sharp boundaries are found in all five of the holes studied. The upper surfaces of the leached zones are here termed "solution unconformities." These solution unconformities, leached zones, and unaltered zones can be correlated even though the holes are widely separated. Drill hole K–1B is on Engebi, F–1 is on Elugelab, and E–1 is on Parry Island, Eniwetok Atoll (fig. 1). Drill holes 2A and 2B are 180 feet apart on Bikini island, Bikini Atoll, 210 miles east of Eniwetok Atoll (Emery, Tracey, and Ladd, 1954, fig. 33).

Ladd, Tracey, and Lill (1948, p. 52) suggested that the leached zones below Bikini were developed under subaerial conditions and thus recorded periods of emergence of parts of the marine sediments of the atoll. The unaltered zones were believed to represent rocks that were never emergent (Emery, Tracey, and Ladd, 1954, p. 2, 132–133, 244, 247).

Rocks in which primary aragonite either has been leached out or still persists are shown on figure 308. The limestones (calcite) are dense, well-lithified rocks that show molds of originally aragonitic shells and skeletons of mollusks, corals, and *Halimeda*. In places the aragonite has been completely leached out, and the molds are filled or lined with fibrous and drusy calcite deposited from solution. The original mud[2] and sand matrix has been largely recrystallized to calcite, and irregular channels and vugs are common. These voids truncate fossils and are commonly lined with laminar deposits of calcite. The overall effect is one of removal of aragonite and addition of calcite.

The limestones with unlithified sediments differ strikingly from the leached limestones. These unaltered sediments are generally unconsolidated and are made up of fossil debris that includes abundant corals and mollusks with aragonite skeletons and shells. Originally calcitic fossils such as Foraminifera and coralline algae are mixed with the corals and mollusks, but the sediments have not been cemented by the addition of calcite.

The leached rocks grade downward into unaltered ones through transition zones (shown on fig. 308 by saw-toothed boundaries) as much as 200 feet thick. These transition zones are composed of lithified limestones made up of partly replaced and recrystallized aragonitic fossils in a calcite matrix. In many places within the transition zones, aragonitic fossils are filled and cemented by calcite, and this indicates the addition of calcite without solution of aragonite. Aragonite fossils in these zones commonly show a tendency to disintegrate into loose aragonite powder.

Detailed descriptions of the lithology of the above rocks on Eniwetok are given on pages 1011–1038, and the rocks on Bikini are described in chapter A (Emery, Tracey, and Ladd, 1954, p. 80–94, 214–259). Above a depth of 75 feet in K–1B, 70 feet in F–1, 80 feet in E–1, and 105 feet in 2A, the sediments are unconsolidated and unaltered, except for a few layers of cemented beach rock at or near present sea level. Below these depths in all four holes (drilling records for the upper part of 2B are too poor for interpretation), however, partly recrystallized and leached limestones are found; thus, poorly developed solution unconformities are probably present at the depths indicated. Figure 308 shows the patchy and discontinuous nature of the alteration.

A lower, better developed unconformity shows up at 302 feet in K–1B, 330 feet in F–1, 300 feet in E–1, 294 feet in 2A, and 290 feet in 2B; this will be referred to as the 300-foot unconformity. At these depths, moderately to well-consolidated limestones containing prominent molds of coral and mollusks were encountered; coarsely crystalline calcite fills many cavities in this rock. Below these levels, leached and cemented limestone persists for 200 to 400 feet, as shown on figure 308, but the interval varies in thickness from one hole to another. All five holes penetrate a transition zone in and below which the sediments take on a brown color that may be due to the presence of unbleached organic matter. Below the transition zone, the lowermost part of the unaltered zone under the 300-foot uncomformity

[1] All depths given are measured from an assumed drilling platform elevation of 0 feet. Platforms actually were at the following approximate elevations (above MLWS): K-1B, 4 feet; F-1, 17 feet; E-1, 19 feet; 2A, 17 feet; and 2B, 20 feet.

[2] The term "mud" is here used to include all fine sediments—clay size, silt size, and fine sand. Clay minerals do not occur in the Eniwetok section; all clay-size material is pure calcium carbonate.

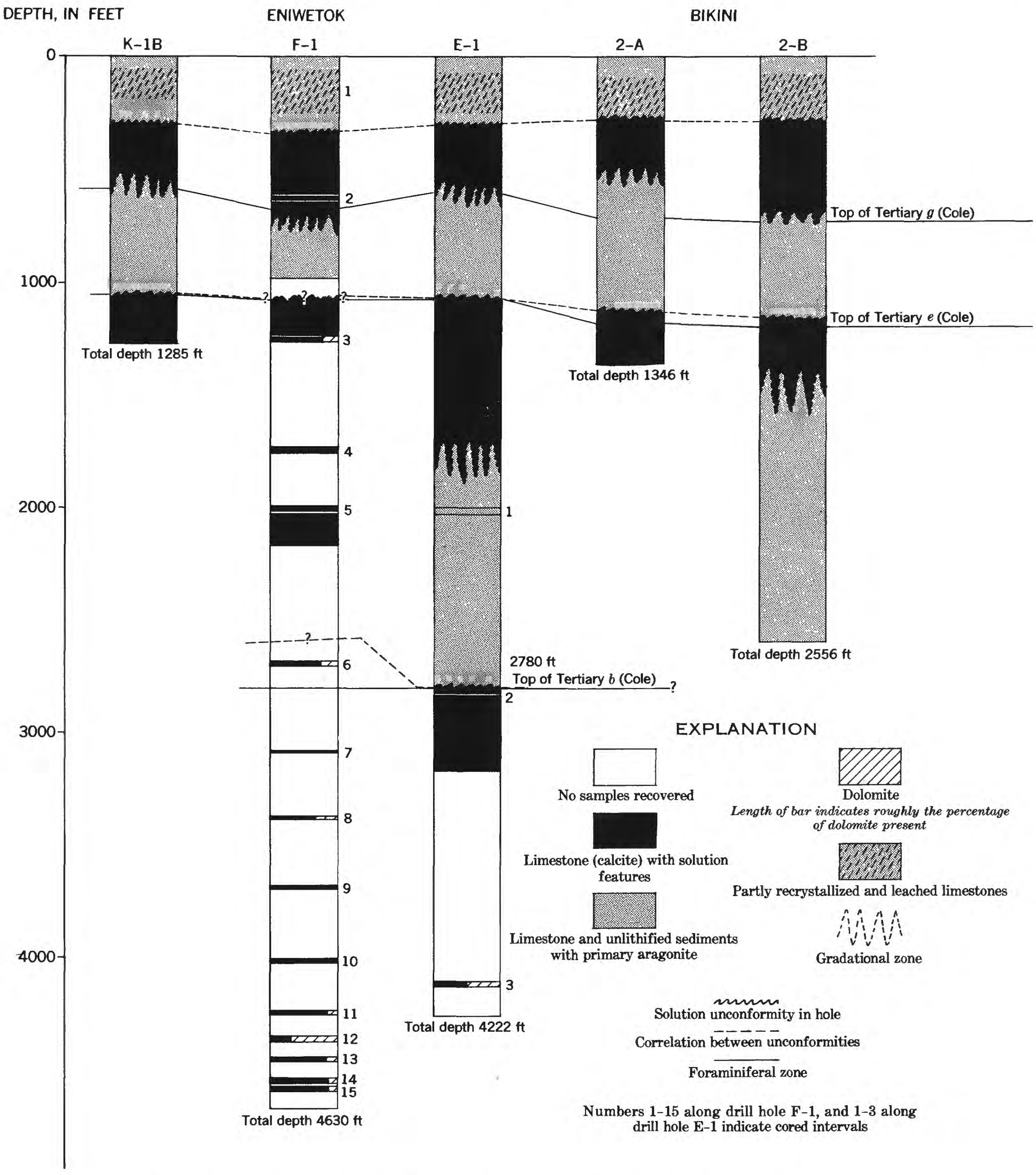

FIGURE 308.—Drill-hole section showing recrystallized and partly dolomitized rock below Eniwetok and Bikini Atolls.

is characterized in all holes by limy mud, unsorted aragonitic sand, and a striking abundance of shallow-water branching corals and perfectly preserved pelecypod and gastropod shells; some of the shells retain traces of their original color patterns.

At 1,080 feet in K–1B, 1,070 feet in E–1, 1,127 feet in 2A, and 1,120 feet in 2B, the drill passed abruptly from the brown unaltered sediments described above into hard, cemented limestone with well-developed molds; aragonite is lacking. A third unconformity, therefore, is placed at these levels and will be referred to as the 1,100-foot unconformity. No cuttings were obtained from hole F–1 between 970 and 1,040 feet, but the contrast in lithology between these two depths indicates that an unconformity is present somewhere in this interval.

On Eniwetok, the top of the Tertiary *e*, as picked by Cole (1957, p. 746) on the basis of larger Foraminifera, lies at the 1,100-foot unconformity; on Bikini this same faunal horizon lies just below the unconformity. This is interpreted as showing a post-Tertiary *e* emergence of the atoll followed by removal by erosion of some limestone of both Tertiary *e* and *f* ages at Eniwetok; at Bikini, erosion did not completely strip off all the limestone of Tertiary *f* age.

Both holes E–1 and 2B show transition zones below the 1,100-foot unconformity that are similar to those below the 300-foot unconformity; holes K–1B and 2A bottomed in the leached zone below the 1,100-foot unconformity. Below the 1,100-foot unconformity hole F–1 is anomalous; all cores and cuttings recovered were crystalline calcitic limestone. Dolomite is present in many of the cores. (See fig. 308).

A fourth unconformity overlain by a thick section of aragonite sediments, was penetrated in hole E–1 at 2.780 feet. Cole (1957, p. 748), again on the basis of larger Foraminifera, picked the top of the Tertiary *b* at this depth. This coincidence of fossil horizon and unconformity suggests post-Eocene emergence and removal of Tertiary *b* limestone prior to deposition of Miocene limestones.

Figure 309 shows diagrammatically the development of a solution unconformity. During stage 1, sediments accumulated as the atoll foundation subsided or as sea

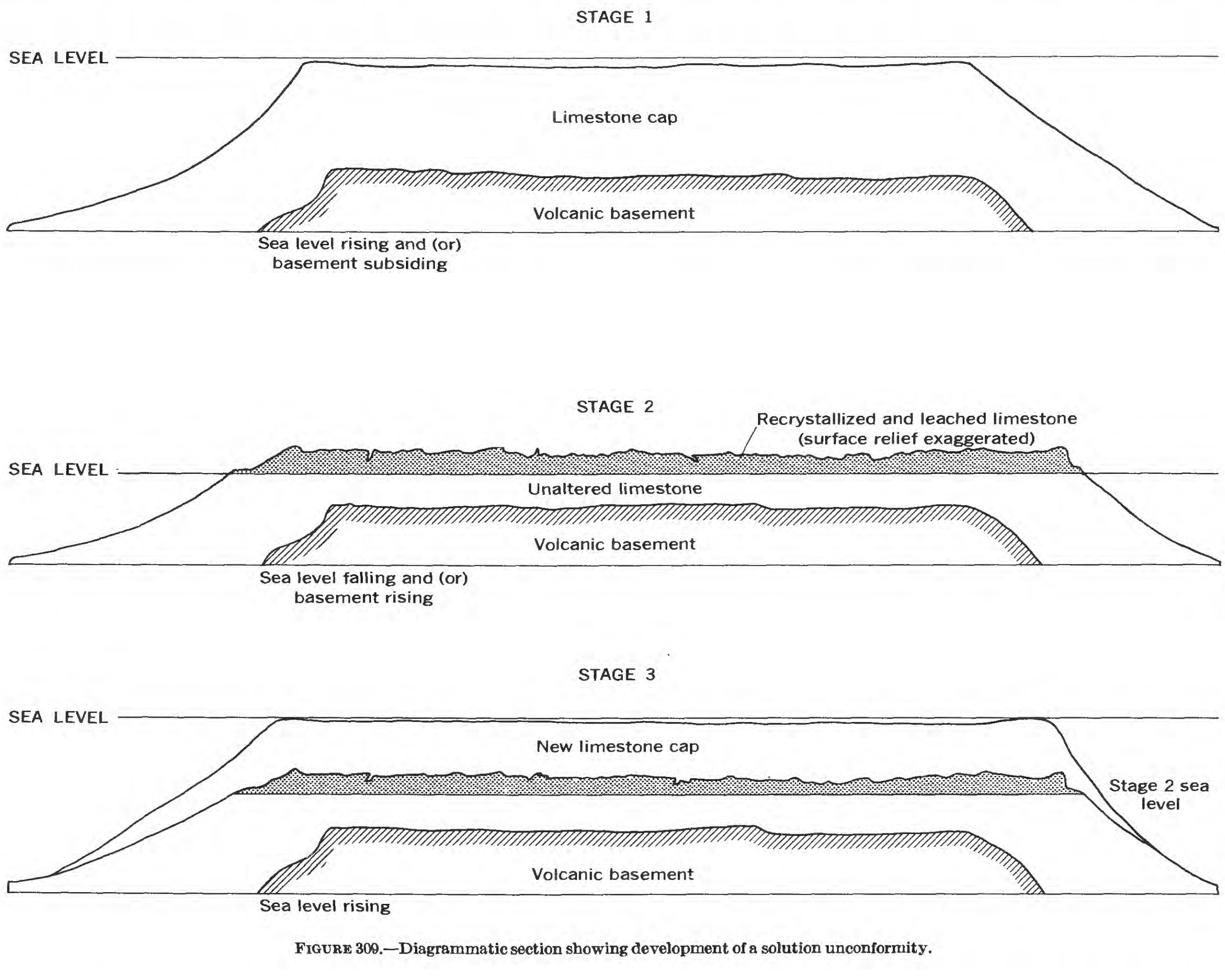

FIGURE 309.—Diagrammatic section showing development of a solution unconformity.

level rose eustatically, so that the aragonite-rich sediments were not exposed to subaerial conditions. In stage 2, emergence of part of the sedimentary column through uplift of the basement or a fall in sea level led to solution of aragonite and deposition of calcite. The recrystallized and leached rocks that resulted are illustrated in figure 309. Upon resubmergence in stage 3, a new cap of aragonite-rich sediment was deposited on the hardened surface of the solution unconformity.

If an atoll some 20 miles in diameter is raised above the sea, a fresh-water lens would develop and would extend several hundred feet below sea level. This lens, called the Ghyben-Herzberg lens, floats upon the sea water and depresses it. The effect on the limestone immersed in this fresh-water lens is not known, but solution of the emergent section takes place probably at least down to the upper surface of the lens. On Guam and other high limestone islands, zones of caves are commonly well developed just above raised relict sea nips along limestone coasts. Carbonate carried down by rainwater may precipitate as calcite in the saturated fresh-water lens and cement aragonitic materials such as are found in the transition zones; thus, the transition zone between thoroughly recrystallized limestone and underlying unaltered sediment may mark the site of a former Ghyben-Herzberg lens.

There is little doubt that the strongly leached zones below the atolls represent intervals that were emergent at one time. Shells of land snails have been described (Ladd, 1958, p. 188–190) from the subsurface of Bikini, Eniwetok, and Funafuti that are of a type found today on high forested islands. Dense concentrations of the pollen and spores from land plants have also been recovered (Ladd, 1958, p. 194).

Presently emergent limestones on Guam (Schlanger, 1963) show the characteristics of the limestone from the leached zones; fossil molds, solution channels, and calcite cement are also present.

On Guam, rare, isolated pockets of limestone contain aragonite in otherwise completely recrystallized masses that are miles in extent. One of these pockets is at an altitude of approximately 600 feet in limestone of probably early Pleistocene age and must have been emergent for some thousands of years. These relict aragonitic limestones are partly recrystallized, however, and the process of solution of aragonite has not progressed to completion; therefore, the occurrence of aragonite does not necessarily indicate a history of nonemergence. Nowhere in these emergent limestones on high islands were thick sections of unconsolidated aragonitic fossil debris found, such as exist in the subsurface of Eniwetok and Bikini.

Even a cursory search of recent literature on limestones shows a prevailing concept that aragonite is unstable in carbonate sediments. Pettijohn (1957, p. 387) states "Aragonite is an unstable form of calcite and is found therefore only in recent materials." Folk (1959, p. 32) states, "Aragonite shell material (most pelecypods, many gastropods) inverts to calcite with time* * *" Weller (1959, p. 299) states, "Aragonite is somewhat more dense than calcite and it is relatively unstable under natural sedimentary conditions and tends to invert to calcite."

The general tone of these remarks is that somehow aragonite inverts spontaneously to calcite, and that the postdepositional history of the sediment has little to do with the inversion. The distribution of primary skeletal aragonite in the subsurface of both Bikini and Eniwetok (fig. 308) shows that time alone is not the factor controlling the replacement of aragonite by calcite. Where the carbonate sediments have been exposed to subaerial conditions, the aragonite has been leached out and partly or wholly replaced by calcite; where the sediments have remained submerged in sea water since their deposition, aragonite persists. Further, the sediments in the aragonite-rich sections are not consolidated; the mollusk shells retain their original nacreous luster; and the sediment closely resembles Recent deposits. Evidently, aragonite under these atolls has shown no tendency to invert to calcite, at least over the span of Tertiary time.

Another implication of some recent writings on the aragonite-calcite relationship is that the aragonite simply goes through an inversion in which the orthorhombic aragonite structure rearranges itself to form the rhombohedral calcite structure. The writer has seen no compelling evidence for such a crystallographic inversion. Rather he believes that the process is one in which the aragonite is dissolved and replaced by calcite on a volume for volume basis. This solution-replacement idea was originally suggested by J. I. Tracey, Jr. (oral communication), who came to such a conclusion after his study of the Bikini drill samples.

In individual pieces of coral the results of this process can be clearly seen. The boundary between the original aragonite and the replacing calcite closely resembles a stylolitic seam and is occupied by a thin film of powdery aragonite. Under the action of solutions during subaerial exposure, the aragonite evidently breaks down into a powder and is then dissolved and replaced by the more coarsely crystalline calcite.

It should also be pointed out that if the primary aragonite inverted structurally, it would retain its content of strontium, which is high relative to the strontium content of calcite. Spectrographic analyses (table 3) show that corals that are now calcitic have lost much of their original strontium. This loss is understandable if the aragonite is first dissolved and then replaced by calcite that has a low tolerance for the trapping of large cations during crystallization.

The sequential development of the unconformities described above is discussed on pages 1001–1003.

PALEOECOLOGY

The high percentage of recognizable fossil material in the subsurface limestones permits interpretations of the depth and site of deposition of the sediments with reference to the reef complex. Many of the corals, Foraminifera, algae, and mollusks are known to have fairly restricted habitats in the reef complex today, and therefore fossil assemblages are the main guide in making paleoecologic interpretations. As the ecology of these faunal and floral groups has been discussed by Finckh, 1904, p. 125–150; Tracey, Ladd, and Hoffmeister, 1948, p. 861–878; Ladd, Tracey, Wells, and Emery, 1950, p. 410–425; Cloud, 1952, p. 2125–2149; Emery, Tracey, and Ladd, 1954, p. 79–80; and Forman and Schlanger, 1957, p. 611–627, it will not be repeated here. Paleoecological interpretations of the sediments in holes E–1 and F–1 are tabulated below. More detailed descriptions of the individual rocks are given on pages 1011–1038.

Drill hole E–1

Interval (ft)	*Environment and significant fossil groups*
0–30	Near reef, lagoonal, and beach; rich in coral and worn and broken reef Foraminifera.
30–45	Lagoonal; made up of small *Halimeda* segments probably deposited in water 20 to 30 fathoms deep.
45–70	Shallow lagoonal; coarse, rounded coral debris, Foraminifera, and *Halimeda.*
70–140	Lagoonal; rich in reef Foraminifera and *Halimeda.*
140–300	Reef knoll or reef wall; abundant coral and encrusting algae.
	Solution unconformity
300–430	Shallow lagoonal; dominated by corals and mollusks.
430–590	Shallow water, probably lagoonal; corals, mollusks, and *Halimeda.*
590–1, 070	Shallow bank or lagoonal; well preserved brown fragments of delicate branching coral, pelecypods and gastropods.
	Solution unconformity
1, 070–2, 003	Shallow water; miliolid Foraminifera and coral.
2, 003–2, 028	Shallow water, lagoonal; rich in miliolids and mollusks.
2, 028–2, 290	Shallow water; rich in fragments of *Lithophyllum.* Lower part of the interval contains abundant larger Foraminifera and probably represents open, shoal-water deposits containing local fore-reef sediments.
2, 290–2, 410	Shallow water, locally lagoonal; abundant *Lithophyllum* and mollusks.
2, 410–2, 540	Lagoonal; in part laminated mudstones with mollusks.

Drill hole E–1—Continued

Interval (ft)	*Environment and significant fossil groups*
2, 540–2, 780	Shallow water, lagoonal; coral and molluscan remains are especially abundant near base of the section, as in the 590–1,070 foot interval.
	Solution unconformity
2, 780–3, 130	Fore reef or open shoal water; abundant benthonic smaller Foraminifera. Locally abundant dasycladacean algae are indicative of water only a few feet deep and occur with typically lagoonal faunal elements, indicating that local lagoonal conditions existed nearby.
3, 130–4, 078	No recovery.
4, 078–4, 100	Shallow lagoonal and reef wall; massive corals, coralline algae, and mollusks.
4, 100–4, 170	No recovery.
4, 170–4, 190	Basalt.
4, 190–4, 208	No recovery.
4, 208–4, 222	(Total depth) Basalt.

Drill hole F–1

Interval (ft)	*Environment and significant fossil groups*
0–55	Near reef, lagoonal, and beach deposits; worn and broken reef Foraminifera, coral, and *Halimeda.*
55–70	Fore reef; abundant segments of large *Halimeda.*
70–110	Shallow water; *Halimeda*, coral, and molluscan debris.
110–170	Lagoonal; abundant coral algae and mollusks.
170–190	Lagoonal; miliolids and *Halimeda.*
190–330	Lagoonal; local concentrations of *Halimeda* indicate deposition in 20 to 30 fathoms of water.
	Solution unconformity
330–600	Lagoonal; corals, mollusks, and miliolids.
600–970	Lagoonal or shoal banks; abundant fragments of delicate, branching coral and numerous gastropods and pelecypods. Towards the bottom of the interval the sediments take on a tan to brown color. Sedimentation conditions were like those in the 590- to 1,070-foot interval in hole E–1.
970–1, 040	No recovery. (Solution unconformity somewhere in this interval.)
1, 040–1, 230	Shallow water, probably lagoonal in part; *Halimeda*, mollusks, and smaller Foraminifera.
1, 230–1, 248	Shallow water, probably lagoonal in part; miliolids, algae, corals, and *Halimeda.*
1, 248–1, 718	No recovery.
1, 718–1, 740	Near reef, shallow water near top of interval, lagoonal toward bottom of the interval, quiet-water conditions prevailed.
1, 740–1, 978	No recovery.
1, 978–2, 130	Reef wall and near reef; massive coral and algae.
2, 130–2, 662	No recovery.
2, 662–2, 687	Fore reef; coral debris and globigerinid Foraminifera. Coral probably represents material swept downslope from a nearby reef.
2, 687–3, 052	No recovery.
3, 052–3, 055	Fore reef; globigerinid Foraminifera with transported reef debris laid down in water not less than 100 fathoms deep.
3, 055–3, 350	No recovery.

Drill hole F-1—Continued

Interval (ft)	*Environment and significant fossil groups*
3, 350–3, 353	Fore reef; globigerinid Foraminifera mixed with reef debris deposited in water not less than 100 fathoms deep.
3, 353–3, 655	No recovery.
3, 655–3, 665	Fore reef globigerinids mixed with heavy contributions of shallow-water, reef-derived coral conglomerate.
3, 665–3, 963	No recovery.
3, 963–3, 988	Fore reef; larger Foraminifera and globigerinids with coral pebbles swept down from nearby reef.
3, 988–4, 107	No recovery.
4, 107–4, 222	Fore reef; planktonic Foraminifera with high concentrations of shallow-water sediments swept down from nearby reef.
4, 222–4, 316	No recovery.
4, 316–4, 341	Fore reef; rich in broken and worn larger Foraminifera and fragments of coralline algae and corals of shallow water origin.
4, 341–4, 406	No recovery.
4, 406–4, 431	Fore reef; planktonic Foraminifera and pebbles of shallow-water limestone.
4, 431–4, 500	No recovery.
4, 500–4, 525	Fore reef as above; local concentrations of shallow-water sediment from upslope.
4, 525–4, 528	No recovery.
4, 528–4, 553	Fore reef; rich in coarse debris of worn and broken larger Foraminifera and coralline algae.
4, 553–4, 630	No recovery.

COMPARISON OF ENIWETOK DRILL HOLES WITH BIKINI DRILL HOLES

The above logs show that the post-Eocene sediments below Eniwetok are all of shallow-water, lagoonal, shoal bank, or reef-wall origin. According to Emery, Tracey, and Ladd (1954, p. 90–91) "* * * the entire 2,556-foot section of limestone at Bikini accumulated in a shallow-lagoonal, or near-reef environment." In hole F–1, at Eniwetok, shallow-water deposits extend to a depth of at least 2,130 feet and possibly to 2,600 feet (no material was recovered between 2,130 and 2,662 feet). In hole E–1, shallow-water deposits persist without interruption down to the solution unconformity at 2,780 feet.

Very high concentrations of rod-shaped fragments of *Lithophyllum* were noted between 2,070 and 2,401 feet at Bikini and between 2,028 and 2,410 feet in hole E–1 at Eniwetok; all the fragments were in sediments of Tertiary *e* age. Between 2,288 and 2,327 feet at Bikini and between 2,200 and 2,300 feet in hole E–1, fragments of *Lithophyllum* make up 50 to 75 percent of the cuttings. At Bikini, the following species contribute to the sediments that are rich in algal remains (Johnson, 1954, p. 537):

	Depth (ft)
L. oblongum Johnson	2, 100–2, 500
L. kladosum Johnson	2, 300–2, 600
L. profundum Johnson	2, 200–2, 500

L. oblongum was not found at Eniwetok, and *L. kladosum* and *L. profundum* show the following ranges (Johnson, 1962):

	F-1 (ft)	*E-1 (ft)*
L. kladosum Johnson	1, 720–2, 000	2, 100–2, 680
L. profundum Johnson	1, 978–2, 003	2, 690–2, 700

Thus, at Eniwetok, *L. kladosum* is the only species that contributes to the abundance of fragments between 2,200 and 2,300 feet in hole E–1. In hole F–1 these algae occur higher in the section than they do in hole E–1. In hole F–1 the algae are associated with reef-wall and near-reef limestones, whereas in hole E–1 the section is composed entirely of lagoonal or open shoal-bank sediments (fig. 310). It is probable that reef sediments at hole F–1 were contemporaneous with off-reef sediments deposited in water 200 feet deeper at hole E–1.

Another striking lithologic similarity between the Eniwetok and Bikini sections is the high concentration of sticklike fragments of delicate branching coral and large pelecypods and gastropods that is found just above the 1,100-foot solution unconformity in all the holes studied. Figure 310 shows the distribution of sediments of this composition in holes E–1, F–1, 2A and 2B. In all the holes these sediments are unaltered and have a characteristic brown color. In addition, in hole E–1 there is a similar concentration of coral and mollusks directly above the solution unconformity at 2,780 feet. Evidently the first organisms to grow on the recrystallized surface of these unconformities after resubmergence were thicket-like colonies of delicate coral, around which lived a rich population of gastropods and pelecypods. Coral thickets such as these are found today only in shallow sheltered back-reef and lagoonal areas, where the energy of incoming waves is absorbed by the reef wall.

LOWER PARTS OF ENIWETOK DRILL HOLES

The section of hole F–1 below core 6 (2,662–2,687 feet) and that part of hole E–1 below the solution unconformity at 2,780 feet have no counterpart at Bikini, as the deepest Bikini hole did not reach this depth. Except for core 6, all these sediments are of Tertiary *b* age (Cole, 1957, p. 749). In hole F–1, all these sediments are fore-reef, outer-slope deposits characterized by the presence of planktonic Foraminifera mixed with worn and broken debris composed

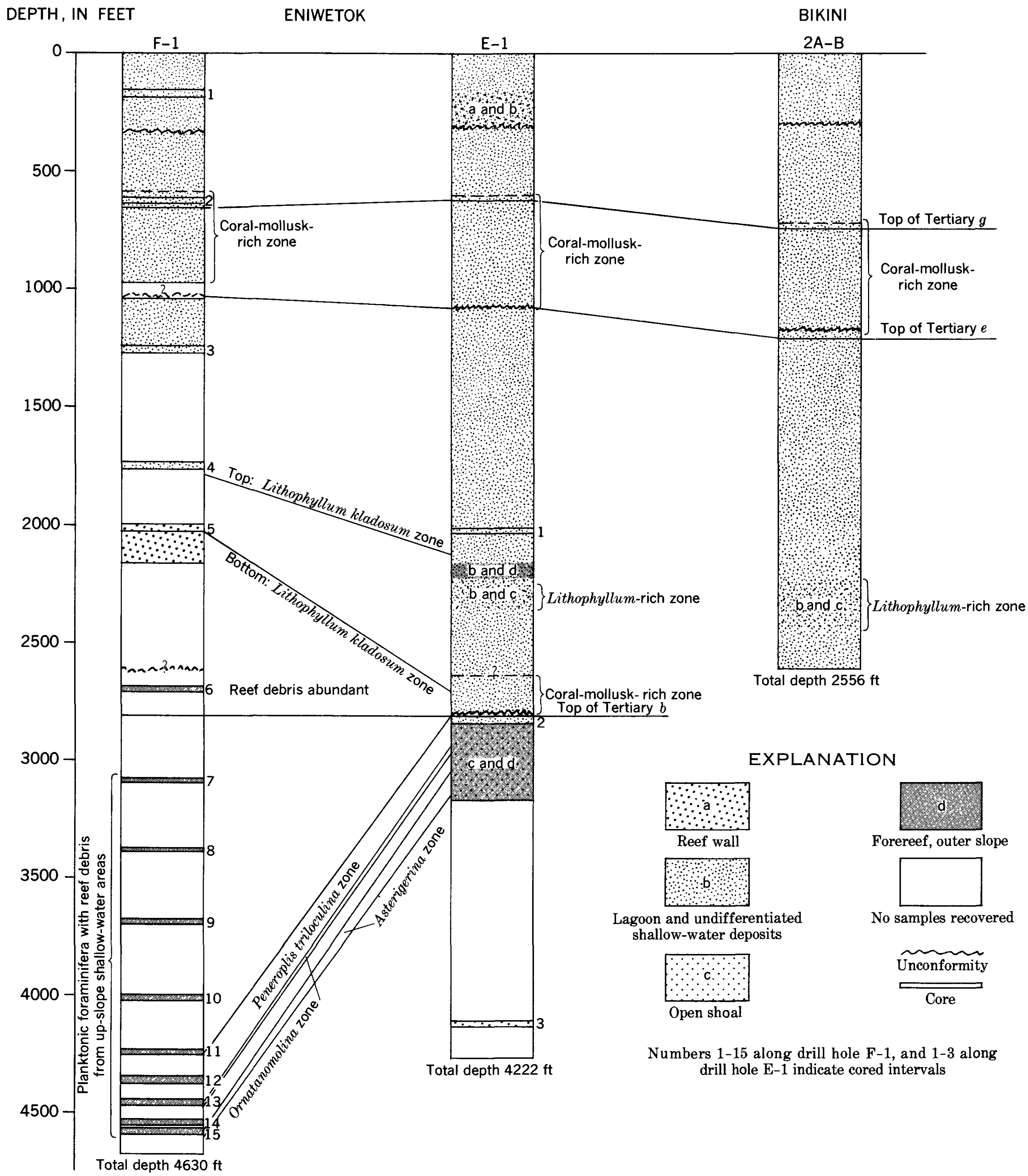

FIGURE 310.—Paleoecology logs of drill holes E-1 and F-1 on Eniwetok and drill hole 2A-B on Bikini.

of shallow-water organisms such as corals, coralline algae, and larger Foraminifera. As shown on figure 310, the three foraminiferal zones in these two holes are as follows (Todd and Low, 1960, p. 812):

	F-1 (ft)	*E-1 (ft)*
Peneroplis-Triloculina assemblage	4, 200–4, 400	2, 770–2, 940
Ornatamolina assemblage	4, 420	2, 940–2, 960
Asterigerina rotula assemblage	4, 500–4, 550	3, 010–3, 120

There is a 1,400-to 1,600-foot difference in elevation between the zones in the two holes. Todd and Low (1960, p. 813) state that "* * * in hole F–1 the three above-mentioned assemblages are accompanied by minor amounts of planktonic specimens; in hole E–1, on the other hand, no planktonic specimens were found in the Eocene section and none of the accompanying benthonic species are of known deepwater types." The F–1 section between 4,200 and 4,550 feet therefore represents outer-slope deposits contemporaneous with near-reef, shallow-water deposits in hole E–1 from 2,770 to 3,120 feet.

As shown on figure 310, the section of fore-reef deposits in hole F–1 down to 4,200 feet has no counterpart in hole E–1. While this thick section, represented by cores 7 through 10, was accumulating in F–1, it may be assumed that reef or near-reef deposits were building up at E–1 and that the shallow-water debris moved downslope from E–1 to F–1. The solution unconformity at 2,780 feet in hole E–1 coincides (within 10 feet) with the uppermost of the three foraminiferal zones. The writer believes, therefore, that a section of sediment was removed at hole E–1 during the development of the solution unconformity. This section probably corresponded to the section in hole F–1 that is still preserved down to 4,200 feet. Thus, a truncated wedge of fore-reef sediment that tapers from a thickness of at least 1,000 feet at hole F–1 to 0 feet at E–1 now exists beneath Eniwetok.

The deepest sediments in hole E–1 have no counterpart in hole F–1, as the deepest part of the F–1 section correlates with the 3,120-foot level in hole E–1. The deepest limestones in hole E–1 consist of massive coral-rich reef-wall deposits that represent the earliest deposits on the volcanic foundation.

GEOLOGIC HISTORY

DEPOSITION AND TRUNCATION OF EOCENE SEDIMENTS

Seismic refraction studies at Eniwetok (Raitt, 1957, 685–698) show that the upper surface of the volcanic foundation of the atoll slopes gently to the northwest,[3] and that it is shallower below Eniwetok and Parry Island than below Elugelab. This slope probably influenced the deposition of Eocene limestones, and thus also the striking differences in facies and thickness of correlative foraminiferal zones in the deepest parts of holes F–1 and E–1 (pl. 281).

The following discussion of the geologic history is highly interpretative. It is based entirely on records from two widely separated holes, and in these records there are large gaps where no limestone was recovered.

The oldest sediments recovered were reef-wall limestones found between 4,070 feet and 4,100 feet in hole E–1; the limestones in the unsampled interval between 4,553 feet and 4,630 feet in hole F–1 may contain beds that are time equivalent. If so, about 900 feet of sediments, part of which was reef-wall limestone, accumulated at the site of hole E–1 while only 80 feet of sediments were deposited below the site of F–1. Plate 281*A* shows a schematic representation of conditions prior to the deposition of the *Asterigerina rotula* zone. A thick reef grew on the higher part of the volcanic foundation while thin fore-reef deposits accumulated on the outer slopes. During this period the atoll foundation was slowly subsiding.

Deposition of the three foraminiferal zones shown on figure 310 followed. As discussed in the preceding section on paleoecology, these zones in hole F–1 are fore-reef, outer-slope deposits characterized by planktonic Foraminifera, whereas the equivalent rocks in hole E–1 lack planktonic species and were laid down in shallower water. The Miocene history of the atoll indicates that the shallow-water deposits migrated northwestward from the location of hole E–1 until they extended entirely across the present site of the atoll. As the reef was expanded and moved northwestward, it left small local reefs to the southeast, in the vicinity of hole E–1, and shallow-water foraminiferal sands accumulated around them. At F–1 the water was deeper, and planktonic species were more significant; however, much of the rock (cores 12, 13, 14, 15) is made up of reef and shallow-water debris that was transported downslope.

The thick fore-reef deposits, represented by cores 7 through 10 from hole F–1, accumulated as the atoll foundation continued to subside slowly. The presence of abundant shallow-water skeletal debris in these fore-reef limestones shows that a reef grew upward nearby, in pace with subsidence. Plate 281*C* illustrates conditions prior to the formation of the solution unconformity at 2,780 feet in hole E–1, during deposition of the youngest Eoçene and oldest Miocene limestones. The three foraminiferal zones were deeply buried at F–1, whereas at E–1 an unknown thickness of post-*Peneroplis*-zone sediments was laid down.

[3] A detailed discussion of guyots and their relation to the foundations of atolls is given in Emery, Tracey, and Ladd (1954, p. 125-131).

The scheme developed so far calls for considerable asymmetry in deposition. However, the differences in elevation between time-equivalent foraminiferal zones and the thick section of fore-reef deposits in hole F–1 are most easily and logically explained in this way.

Sometime early in Tertiary *e* time the atoll was emergent and a solution unconformity developed (pl. 281*D*), as explained in the preceding section. The truncation of the asymmetrical deposits resulted in the exposure of the *Peneroplis* zone at the site of hole E–1 while the equivalent zone in hole F–1 remained buried beneath approximately 1,000 feet of Eocene sediments and a hundred feet of basal Miocene fore-reef sediments. Definite Oligocene deposits have not been recognized by Cole (1957) or Todd and Low (1960), although these would be expected if the deposition were continuous from Eocene to Miocene.

DEPOSITION AND TRUNCATION OF LOWER MIOCENE SEDIMENTS

The foundation of the atoll subsided after the early Tertiary *e* emergence, and a thick section of Miocene sediment was deposited. At the site of hole E–1, lagoonal sediments make up the lowest Miocene deposits; corals and mollusks dominated the first population. Therefore, a protecting reef probably grew to the southeast of hole E–1.

Environmental conditions varied somewhat through time. The laminated mollusk-rich mudstones from 2, 410 to 2,540 feet represent quiet-water, lagoonal deposits, whereas the interval of rock from 2,028 to 2,290 feet is rich in fragments of *Lithophyllum* and was probably laid down in more open but still shallow and protected water. The whole picture is one of a slowly subsiding platform on which sedimentation kept pace with subsidence. In hole F–1, the oldest postemergent Miocene rock is reef-wall limestone and probably represents an early reef that grew on the truncated fore-reef Miocene limestone represented by core 6. This part of the atoll must have grown vertically more rapidly than the southeastern part, because the *Lithophyllum* zones found at 2,100–2,700 feet in hole E–1 are at 1,720–2,000 feet in F–1 (fig. 310); thus, while a reef existed at F–1 topographically lower *Lithophyllum*-rich sands were being deposited at E–1; plate 281*E* shows the atoll at this stage.

Deposition of shallow-water sediments under conditions of slow foundation subsidence probably continued through Tertiary *e* and part of Tertiary *f* time, and the atoll probably had a configuration much like its present one. Subsidence may have been discontinuous, however. The recrystallized limestone in the 1,978- to 2,130-foot interval in hole F–1 (fig. 308) correlates with unaltered sediment in hole E–1. This suggests that an emergence during Tertiary *e* time affected only the northwestern part of the atoll and resulted in solution and recrystallization of the reef and near-reef limestone (represented, by the 1,978- to 2,130-foot interval in hole F–1). The correlative *Lithopyllum*-rich sediments in E–1 being topographically lower as deposited, were not exposed by the lowered sea level and hence were not subjected to subaerial solution.

The 1,100-foot unconformity indicates that a major emergence occurred after deposition of the Tertiary *e* sediments. At Eniwetok the unconformity coincides with the top of the Tertiary *e*, but at Bikini some Tertiary *f* limestones are found below the same unconformity (fig. 308). This suggests that the emergence took place during Tertiary *f* time. At Bikini the Tertiary *f* sediments were not removed; but at Eniwetok, solution removed all the Tertiary *f* and some of the Tertiary *e* limestone.

The thickness of the recrystallized zone in hole E–1 indicates that at least 700 feet of Eniwetok Atoll was exposed above sea level during early Tertiary *f* time, whereas at Bikini the maximum altitude was probably from 200 to 300 feet.

UPPER TERTIARY TO RECENT SEDIMENTS

Resubmergence of both Eniwetok and Bikini took place in Tertiary *f* time. On both atolls sediments rich in delicate branching corals and large mollusks formed the initial deposits and this indicates that shallow-water and lagoonal conditions prevailed and were maintained on the truncated platforms through the remainder of Miocene time and throughout the Pliocene and some Pleistocene time. Sediments that now occupy the interval between the 1,100-foot and 300-foot unconformities were deposited under conditions of slow subsidence.

Sometime in the Pleistocene, both Eniwetok and Bikini were again emergent and the 300-foot unconformity formed. The thickness of the recrystallized zones at both atolls indicates emergence of 300 to 400 feet.

Resubmergence again took place, and deposition of still more shallow-water sediments was renewed on the 300-foot platform. Between this submergence and the present time, the atoll was subjected to at least one more period of emergence, which led to the patchy recrystallization found in sediments between approximately 75 and 200 feet in the Eniwetok drill holes and between 105 and 185 feet in hole 2 at Bikini. Above these levels at Eniwetok the sediments are unaltered.

The similarity in geologic history between Eniwetok and Bikini, at least from Tertiary *e* time on, is striking. The two atolls evidently were synchronously affected by repeated emergences and submergences. Probably the entire Marshall Islands area was so affected, but drilling on other atolls in this region will be needed to determine the extent of these solution unconformities.

The post-Miocene emergences can be ascribed to eustatic changes in sea level connected with Pleistocene glaciation. Earlier emergence-submergence cycles may have been effected by subsidence and uplift of the basement. If this is so, the correlation between the 1,100-foot unconformities at Eniwetok and Bikini suggests that basement movements may have affected wide oceanic areas simultaneously.

ANALYSES

Most of the samples listed in tables 1–3 were chips of limestone taken from representative pieces of core. Descriptions of these limestones are given on pages 1011–1038. A few samples were specially chosen, such as pure coral, to check on changes in chemistry and mineralogy due to recrystallization. These special samples are listed below.

Sample	
K-1-24	Pure coral, completely recrystallized and replaced by coarse, granular calcite.
K-1B-16	Pure coral, partly replaced by calcite.
E-1-1-6	Pure coral, entirely unaltered.
E-1-2-5	Shell fragments from mollusk-rich mud.
F-1-5-26	Pure coral, completely replaced by calcite.
F-1-6-30	Pure coral, completely replaced by calcite.
F-1-6-9*a*	Powder scraped from crystals lining vugs in core F-1-6.

Chemical, mineralogical, and spectrographic analyses of similar materials collected during the study of Bikini are given in Emery, Tracey, and Ladd (1954, p. 67, 84–87).

CHEMICAL ANALYSES

Examination of the record of $MgCO_3$ content of the samples analyzed (table 1) shows that none of the rocks contain the theoretical limit of $MgCO_3$ found in pure dolomite, 45.7 percent by weight. Samples F-1-12-4*b*, F-1-12-5*tb*, and F-1-12-7*t* all contained more than 98 percent dolomite by X-ray diffraction analysis; but F-1-12-4*b* and F-1-12-5*tb* each contained only 38 percent, and F-1-12-7*t* contained only 38.8 $MgCO_3$. A similar lack of $MgCO_3$ was noted in the Funafuti material. In connection with chemical analyses of the Funafuti borings, Judd (1904, p. 366) states:

> * * * the sample in which the highest percentage of that substance [$MgCO_3$] was detected, at 950 feet deep, contained 43 percent. As a rule, however, the percentage of magnesium carbonate in this lower part of the bore-hole is about 40, thus falling far short by nearly 6 percent of the quantity required to form a complete dolomite.

At Kita-daitō-jima, Ota (1939, pl. 1) showed that the highest $MgCO_3$ content, 42.0 percent, occurred at a depth of 68 meters (223 feet); most of the dolomitized part of the boring contained between 37 and 40 percent $MgCO_3$ (fig. 311). Thus most dolomite from these atolls lacks 6 to 8 percent $MgCO_3$.

The explanation of the $MgCO_3$ deficiency lies in the fact that the dolomite has an excess of calcium ions in its structure. As noted in the following section on mineralogical analyses, the *d*-spacing of the dolomite was larger than that in dolomite with the ideal $MgCO_3$ content, and this indicates an excess of calcium ions

TABLE 1.—*Chemical analyses, in weight percent, of limestone and dolomite samples from Eniwetok*

[Samples were analyzed by methods similar to those described by Shapiro and Brannock (1956). P. L. D. Elmore, S. D. Botts, H. H. Thomas, and M. D. Mack, analysts]

Sample	$CaCO_3$	$MgCO_3$	Na_2O	P_2O_5	[1]SO_3	Sum
K-1B-16	92.8	2.1	0.60	0.00	0.54	[2]96
E-1-1-4	94.1	2.9	.36	.00	.41	[2]98
E-1-2-1	96.6	2.2	.10	.00	.10	99
E-1-3-10	94.2	4.5	.14	.01	.08	99
E-1-3-42	91.4	7.7	.13	.00	.08	99
F-1-1-2	94.4	1.1	.75	.02	.31	[2]97
F-1-2-1	97.8	1.0	.13	.01	.04	99
F-1-2-9	97.4	1.0	.20	.01	.06	99
F-1-3-4	96.7	2.2	.16	.00	.08	99
F-1-3-10	96.4	2.5	.13	.00	.10	99
F-1-3-20	95.9	2.8	.14	.00	.14	99
F-1-4-2	96.4	2.4	.21	.00	.14	99
F-1-4-10	95.3	3.2	.11	.00	.13	99
F-1-5-3	95.5	3.1	.12	.00	.13	99
F-1-5-26	96.6	2.7	.12	.00	.12	100
F-1-5-41	96.4	2.3	.14	.00	.15	99
F-1-6-1	96.6	2.2	.12	.01	.10	99
F-1-6-9	96.2	2.8	.11	.01	.14	99
F-1-7-3	96.6	2.0	.24	.01	.10	99
F-1-7-7	96.9	1.9	.26	.00	.12	99
F-1-8-1	96.2	2.1	.32	.01	.16	99
F-1-9-2	96.0	2.0	.34	.04	.17	99
F-1-10-5	96.2	2.1	.40	.06	.10	99
F-1-11-1	95.6	2.6	.19	.08	.10	99
F-1-11-9	95.5	2.8	.36	.10	.17	99
F-1-11-18	93.7	4.5	.25	.09	.16	99
F-1-11-29	92.8	5.3	.31	.11	.15	99
F-1-11-37	95.8	2.6	.28	.18	.15	99
F-1-12-(1-2-3)	93.7	4.4	.30	.06	.14	99
F-1-12-4*t*[3]	70.0	28.4	.18	.13	.10	100
F-1-12-4*b*	61.4	38.0	.10	.20	.13	100
F-1-12-5*tb*	61.4	38.0	.12	.18	.11	100
F-1-12-7*t*	60.1	38.8	.14	.04	.08	99
F-1-12-7*b*	63.0	36.5	.14	.04	.14	100
F-1-12-10	63.3	35.9	.10	.03	.11	100
F-1-12-12	81.4	18.2	.24	.03	.11	100
F-1-12-23	82.4	17.2	.22	.04	.11	100
F-1-13-2	96.6	2.1	.30	.04	.17	99
F-1-14-8	96.6	2.2	.28	.02	.18	99
F-1-14-11	96.5	2.2	.26	.00	.16	99
F-1-14-28	96.0	2.8	.32	.06	.16	99
F-1-14-29	97.2	2.1	.13	.04	.14	100
F-1-15-2	96.5	2.4	.28	.06	.12	99
F-1-15-13	97.0	1.9	.19	.04	.13	99

[1] Total sulfur as SO_3 and K_2O was reported in all samples as less than 0.05 percent.
[2] Samples contained appreciable organic matter.
[3] Samples designated by *t*, *b*, and *tb* indicate those taken from the top, bottom, and from both the top and bottom of core pieces respectively. This was done to show how $MgCO_3$ content varies in the space of a few inches.

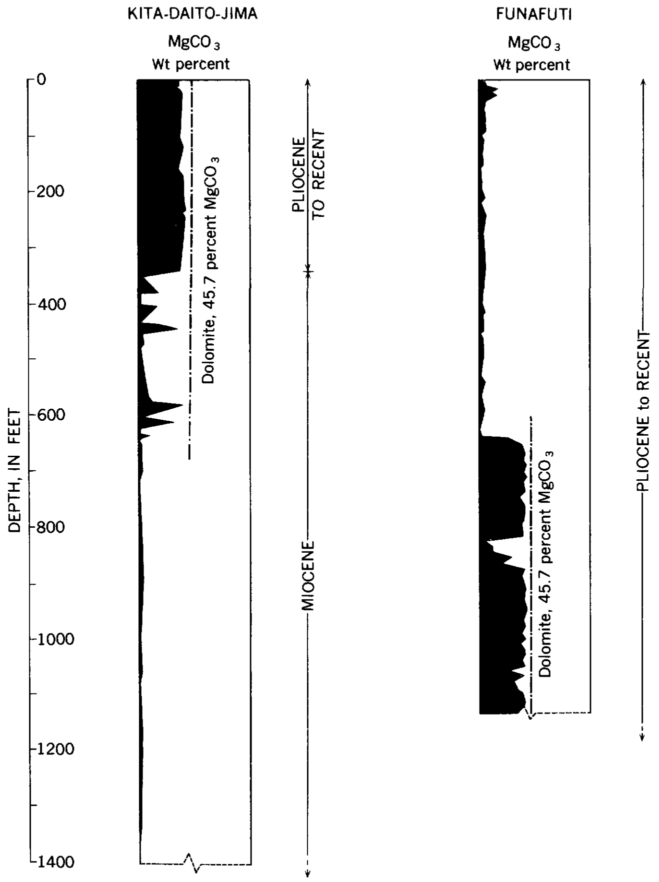

FIGURE 311.—Diagram of $MgCO_3$ analyses of samples from drill holes on Funafuti and Kita-daitō-jima.

that are larger than magnesium ions. Goldsmith and Graf (1958a) investigated a large number of Tertiary dolomites, including material submitted by the writer from Eniwetok, Funafuti, and Kita-daitō-jima and found that the Pacific atoll dolomites contain approximately 5 mol percent excess structural $CaCO_3$. Instead of 50 calcium and 50 magnesium ions per 100 cations, these dolomites contain approximately 55 calcium and 45 magnesium ions per 100 cations. The mineral has a true dolomite structure of alternate calcium and magnesium cation layers separated by CO_3 complex ion layers, rather than merely a magnesium-rich calcite structure in which the magnesium ions are randomly scattered through the cation layers.

The analyses also show that $MgCO_3$ content cannot be used as a safe guide to dolomitized zones. Samples F–1–3–20, F–1–6–9, and F–1–8–1 have 2.8, 2.8, and 2.1 percent $MgCO_3$, respectively, yet all contained dolomite. In checking cores from Kita-daitō-jima, scattered euhedra of dolomite were noted in rock that analyzed 2.74 percent $MgCO_3$ (Ota, 1939, pl. 1); core 203A from Funafuti contained 4.83 percent $MgCO_3$ but had abundant dolomite. Higher percentages of $MgCO_3$ may or may not mean that dolomite is present as a distinct mineral phase. At Eniwetok, samples E–1–3–10 and E–1–3–42 contained 4.5 and 7.7 percent $MgCO_3$ and 5 and 14 percent dolomite, respectively, whereas core 15 from Funafuti (depth 15 feet) showed 16.4 percent $MgCO_3$ (Judd, 1904, p. 364) but no dolomite. Schmalz (1956, p. 185), who studied the Funafuti cores by X-ray diffraction, states, "The magnesium-rich horizon near the top of the core is due not to the presence of dolomite, but to magnesium in metastable solid solution in calcite." The core in question is actually a solid piece of coralline algae, so a high magnesium content is normal.

Samples K–1B–16, E–1–1–4, and F–1–1–2 show 2 percent or more organic matter. These three are aragonite-rich limestones (table 2) and are from slightly recrystallized or nonrecrystallized intervals (fig. 308). K–1B–16 and F–1–1–2 are of Pliocene to Pleistocene age, but E–1–1–4 is of Tertiary *e* age. The presence of 3 percent organic matter in this older sample substantiates the idea that the aragonitic rocks above the solution unconformity at 2,780 feet in hole E–1 were never subjected to subaerial leaching. The highest sulfur contents of all the samples analyzed were found in these three samples.

The Na_2O content of all samples may be ascribed to salts from the sea water in which these cores soaked until their removal.

MINERALOGICAL ANALYSES

Aragonite, calcite, and dolomite percentages, given in table 2, were determined by X-ray diffraction techniques by Paul D. Blackman of the U.S. Geological Survey. X-ray patterns of standard mixtures of calcite and aragonite and of calcite and dolomite were used to determine the compositions of the samples. No minerals other than aragonite, calcite, and dolomite were present in sufficient quantity to be detected by the X-ray analyses. All percentages of calcite, aragonite, and dolomite are given with the assumption that other minerals constitute less than 1 percent of the total composition.

The X-ray patterns indicated a slight deficiency of magnesium in all the dolomite. This was shown by an increase in the *d*-spacing of dolomite from 2.882A to approximately 2.9005A.

The calcite in all samples except K–1–24, E–1–3–10, E–1–3–42, F–1–1–2, F–1–2–1, F–1–2–9, F–1–5–41, F–1–6–1, and F–1–7–(6–7) contains small amounts—to approximately 4 mol percent—of $MgCO_3$ substituting for $CaCO_3$. This was indicated by a decrease in the *d*-spacing of calcite from its normal 3.035A to as low as 3.025A.

The $MgCO_3$ substitution can be accounted for in samples that were originally calcitic inasmuch as

TABLE 2.—*Calcite, aragonite, and dolomite content, in weight percent, of representative samples*

[Paul D. Blackman, analyst]

Sample	Calcite	Aragonite	Dolomite
K-1-24	100	0	0
K-1B-16	14	86	0
E-1-1-4	55	45	0
E-1-1-6	<2	98+	0
E-1-2-1	100	0	0
E-1-2-5	80	20	0
E-1-3-10	95	0	5
E-1-3-42	86	0	14
F-1-1-2	40	60	0
F-1-2-1	100	0	0
F-1-2-9	100	0	0
F-1-3-4	98+	0	Trace.
F-1-3-10	100	0	0
F-1-3-20	100	0	[2] 0
F-1-4-2	100	0	0
F-1-4-10	100	0	0
F-1-5-3	100	0	0
F-1-5-9	100	0	0
F-1-5-26	100	0	0
F-1-5-41	100	0	0
F-1-6-1	100	0	0
F-1-6-9	100	0	0
F-1-6-9*a*	98+	0	[3] <2
F-1-6-23	100	0	0
F-1-6-30	100	0	0
F-1-7-3	100	0	0
F-1-7-(6,7) [1]	100−	0	0
F-1-8-1	98+	0	Trace.
F-1-9-2	100	0	0
F-1-9-6	100	0	0
F-1-10-5	100	0	0
F-1-11-1	98+	0	<2
F-1-11-9	98	0	2
F-1-11-18	92	0	8
F-1-11-29	92	0	8
F-1-11-37	98+	0	<2
F-1-12-(1, 2, 3) [1]	89	0	11
F-1-12-4*t*	35	0	65
F-1-12-4*b*	<2	0	98+
F-1-12-5*tb*	<2	0	98+
F-1-12-7*t*	Trace.	0	98+
F-1-12-7*b*	11	0	89
F-1-12-10	7	0	93
F-1-12-12	55	0	45
F-1-12-23	58	0	42
F-1-13-2	100	0	[2] 0
F-1-14-8	98+	0	Trace.
F-1-14-11	98+	0	Trace.
F-1-14-28	98+	0	Trace.
F-1-14-29	100	0	0
F-1-15-2	100	0	[2] 0
F-1-15-13	100	0	[2] 0

[1] Composite sample.
[2] Dolomite was identified in thin sections.
[3] From vug lining in F-1-6-9.

many of the organisms that contribute carbonate to these limestones precipitate calcite skeletons that contain appreciable amounts of $MgCO_3$. Chave (1954a, p. 269–273) lists analyses of Foraminifera and coralline algae that show as much as 15.2 percent and 29 percent $MgCO_3$ by weight, respectively.

Some samples that lack $MgCO_3$ substitution were probably composed of aragonite originally. Organisms such as coral and pelecypods and gastropods secrete aragonite skeletons that are low in magnesium. Ten Madreporian corals analyzed by Chave (1954a, p. 269) showed 0.59 percent or less $MgCO_3$; aragonitic gastropods and pelecypods showed 0.27 percent or less $MgCO_3$. Sample K-1-24, a piece of completely recrystallized coral, now solid calcite, showed no $MgCO_3$ substitution, which is a reflection of its having been originally aragonite. However, samples F-1-5-26 and F-1-6-30 were reported to show $MgCO_3$ substitution. These two samples were pure coral that had been completely replaced by calcite and that had calcite added in the interseptal spaces by deposition from solution. $MgCO_3$ substitution in these corals contrasts to the lack of substitution in K-1-24. Samples F-1-5-26 and F-1-6-30 are of Tertiary *e* age, whereas K-1-24 is of Pliocene to Pleistocene age. Perhaps the substitution in the older limestones is the result of long-term immersion in sea water during which magnesium from the sea water replaced calcium in the secondary calcite.

Some samples did not show $MgCO_3$ substitution although according to their fossil contents they should have. In particular, sample F-1-5-41 is rich in laminar and fragmental coralline algae that normally contain $MgCO_3$, yet the X-ray analysis showed none. This lack may be interpreted as showing that the Mg ions in the original algal calcite have been removed, possibly by leaching when the interval from which this sample came was emergent. Samples E-1-3-10 and E-1-3-42 are both rich in coral and algae and have been dolomitized. In these rocks the coralline algae in particular has been dolomitized, and in many places the relict algal calcite has been removed by postdolomite solution. The lack of $MgCO_3$ substitution may be due to leaching of the Mg ions from the relict algal calcite. Another possibility is that the Mg ions originally scattered through the algal calcite are now concentrated in the dolomite, which leaves the remainder of the calcite free of magnesium.

Dolomite was identified in several samples, although it was not detected by the X-ray method. In some samples the dolomite was identified by staining thin sections with $2N$ copper nitrate, which produces a deep opaque blue in calcite but leaves the dolomite clear and transparent. In sample F-1-3-20, a few rhombs of dolomite were found in a vug lining (pl. 282*A*) by this method; X-ray analysis of a larger bulk sample cut at random from the core failed to reveal dolomite. In sample F-1-6-9, analysis of a bulk sample failed to show dolomite, but analysis of a powder scraped (F-1-6-

9*a*) from a vug lining showed that the lining contained a small amount—less than 2 percent—of dolomite.—In thin sections from cores F–1–13–2, F–1–15–2, and F–1–15–13, rare, small, scattered euhedral rhombs of dolomite make up perhaps 0.1 percent of the rock. The above information is given in detail to emphasize the small amounts of dolomite in some of the samples.

SPECTROGRAPHIC ANALYSES

Twenty-two samples were quantitatively analyzed to trace the behavior of minor elements such as strontium during recrystallization and dolomitization and to add data to that obtained from the Bikini drillings (Emery, Tracey, and Ladd, 1954, p. 86–87). Tracey stated,

1. Corals and detrital sand that show little or no alteration have relatively high percentages of strontium (0.6 to 0.9 percent in Myer's 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 (0.3 to 0.1 percent).

Variation in the strontium content of Eniwetok samples (table 3) seems to be definitely related to the degree and kind of recrystallization, although the relationship is not precise. The least altered samples contain the most strontium, as much as 0.4 percent; and the older, highly recrystallized limestones show low strontium content, less than 0.1 percent. In particular, the intensely dolomitized samples show the lowest content; the strontium percentage drops to 0.003 in sample F–1–12–5*tb*, which is more than 98 percent dolomite.

Strontium content in the less altered limestones from Eniwetok does not correspond quantitatively to the Bikini results. Samples K–1–24 and K–1–16 each contain 0.2 percent strontium. Both were originally coral and wholly aragonitic; but K–1–24 is now completely recrystallized to calcite, and K–1B–16— which is 14 percent calcite—is only slightly recrystallized. Thus K–1–24 has more strontium and K–1B–16 less strontium than would be expected according to the Bikini results. In addition, the highest strontium content in the Eniwetok material, 0.4 percent, in samples E–1–1–6 and E–1–1–4 corresponds to the strontium content in corals recrystallized to microgranular calcite at Bikini. Yet sample E–1–1–6 is a piece of pure, virtually unaltered coral that is now 98 percent aragonite, and E–1–1–4 is a bulk sample of limestone that is now 45 percent aragonite.

Manganese shows a tendency to increase with depth in hole F–1 but here the percentages are too low to be significant. Copper and lead show erratic distribution, and the other elements listed in table 3 show little or no significant variation with age, degree of recrystallization, or original lithology.

TABLE 3.—*Quantitative spectrographic analyses, in weight percent, of limestones from Eniwetok*

[Sodium carbonate and silica were used as matrix material. Sol Berman, analyst. M, element present in major amount (more than 5 percent). O, element not detected. Looked for but not found: Ag, Au, Hg, Ru, Rh, Pd, Os, Ir, Pt, Mo, W, Re, Ge, Sn, As Sb, Bi, Te, Zn, Cd, Tl, In, Co, Ni, Ga, Sc, Y, Yb, La, Zr, Hf, Th, Nb, Ta, U Be, and P]

Sample	Cu	Pb	Mn	Fe	Cr	V	Al	Ti	Mg	Sr	Ba	B
K–1B–16	0.0007	0.02	0.0009	0.02	0.001	0.01	0.008	0.009	0.5	0.2	0.2	0.005
K–1–24	.003	0	.0006	.004	0	.007	.004	.01	.2	.2	.001	0
E–1–1–4	0	0	.0006	.002	.002	.009	.002	.007	.9	.4	0	0
E–1–1–6	0	0	.0005	.01	0	.005	.02	.007	.08	.4	0	.006
E–1–2–1	.0002	0	.0006	.005	.003	.008	.006	.008	.5	.1	0	0
F–1–1–2	.0002	0	.0009	.02	.001	.007	.04	.008	.3	.2	.001	0
F–1–4–2	0	.06	.001	.03	.0008	.008	.008	.004	.7	.08	0	0
F–1–5–26	0	0	.0007	.009	.0006	.007	.002	.007	.6	.1	0	0
F–1–6–30	.0002	0	.002	.003	.0004	.006	.003	.008	.9	.1	0	0
F–1–7–(6–7)	0	.02	.002	.02	.0004	.01	.007	.006	.2	.05	0	0
F–1–8–1	0	0	.003	.02	.0005	.009	.009	.01	.2	.04	0	0
F–1–12–(123)	0	0	.003	.005	.0005	.008	.004	.003	.5	.02	0	.001
F–1–12–4t	.0002	0	.004	.009	.001	.006	.005	.003	M	.02	0	0
F–1–12–4b	.0003	0	.005	.02	.0006	.005	.009	.002	M	.02	0	0
F–1–12–5tb	0	0	.004	.003	.0006	.008	.002	.008	M	.003	0	0
F–1–12–7t	0	.03	.004	.008	.001	.004	.003	.002	M	.04	0	0
F–1–12–7b	0	0	.004	.007	.0006	.008	.003	.01	M	.006	0	0
F–1–12–10	.0006	0	.006	.03	.001	.006	.004	.003	M	.02	0	0
F–1–12–12	0	0	.003	.005	.0006	.009	.001	.004	M	.02	0	0
F–1–12–23	0	0	.003	.003	.0006	.009	.001	.003	M	.01	0	0
F–1–13–2	0	0	.004	.02	.0006	.01	.002	.004	.6	.04	0	0
F–1–14–29	0	0	.01	.009	.0006	.01	.002	.004	.6	.06	0	0

DOLOMITIZATION

The dolomite problem has long engaged the interest of geologists. Within this general problem, the discussion that follows deals only with the formation of dolomite on atolls and limestone islands in the tropical seas, particularly those in the western and southern Pacific. Atolls in this area have attracted students of dolomitization because of their uncomplicated geologic history and setting. The limestone columns below the atolls have not been affected by hydrothermal solutions or magnesium-rich ground waters nor have they been contaminated by extrabasinal sediments which could have disturbed the sea water–limestone system and thus contributed to the formation of dolomitic limestones. Further, the succession of faunal and floral communities that produced these limestones indicates that ecologic conditions, and hence oceanographic conditions, in the region of these atolls remained generally constant through Tertiary time to the Recent. The mineralogy and chemical composition of the skeletal material that formed the limestones are well known from studies of comparable living forms.

Thus the worker deals with limestones that have well-known primary constituents, that were deposited in marine environments similar to those of today which have been well studied, and that have been subjected only to immersion in normal sea water and to periodic emergences above sea level. Yet even within this simple setting the mode of occurrence of dolomite varies from atoll to atoll. Following a study of the now classic Funafuti borings, Cullis (1904, p. 388) was led to remark:

> While certain portions of a reef may contain a high percentage of magnesium carbonate, other parts of the same reef may be almost free from that salt, and the reason why some parts of the mass are almost completely dolomitized while other parts remain chemically unchanged, is by no means obvious.

The writer is in full agreement with this statement.

Through a brief survey of the vertical distribution and texture of dolomitized limestones from Eniwetok, Funafuti, and Kita-daitō-jima, it is attempted here to outline various lines of evidence that must be considered in any theory of dolomitization applied to these atolls.

STRATIGRAPHIC DISTRIBUTION

Drilling at Funafuti (Judd, 1904), Kita-daitō-jima (Ota, 1939), Bikini (Emery, Tracey, and Ladd, 1954), and Eniwetok, and surface studies on a number of limestone islands (Skeats, 1903; Schlanger, 1963) show that the stratigraphic distribution of dolomite follows no regular pattern through the Pacific Ocean area. Figure 311 shows the $MgCO_3$ content vertically through the Funafuti and Kita-daitō-jima borings. At Funafuti only the section of the hole below a depth of 637 feet is dolomitized; at Kita-daitō-jima the reverse is true, although both dolomitized sections are Pliocene to Pleistocene in age. Further, at Kita-daitō-jima the concentration of $MgCO_3$ at about 425 and 600 feet is as high as in the completely dolomitized upper section. At Bikini, beach rock near the surface, rich in calcareous algae, contains about 8 percent of $MgCO_3$; but at lower levels, through 2,556 feet of drilling that reached rocks of early Miocene age, no strata with a $MgCO_3$ content higher than 3 to 4 percent were found, and no dolomite was identified.

At Eniwetok, dolomite is restricted to rocks of Eocene age, except for traces found in cores F–1–6 and F–1–3. Also, at Eniwetok there are nondolomitic sections such as those represented by cores F–1–7 and F–1–9 between dolomitized sections represented by cores F–1–6 and F–1–8. Studies of core F–1–12 show that within an interval of several feet the dolomite content ranges from 11 to 98 percent. In core F–1–12–4 the dolomite content ranges from 65 percent to more than 98 percent within a distance of 4 inches.

From one point of view, the selection of Funafuti as a drilling site was unfortunate in that the neat concentration of dolomite at depth led to theories based on pressure as a critical factor in dolomitization. Reuling (1934, p. 35) proposed that dolomitization takes place at a depth of approximately 638 feet below the lagoon floor; this idea has persisted and still influences modern thought. Schmalz (1956, p. 186), on physicochemical grounds, suggested that

> The chemical system, limestone plus sea water, lies in the stability field of calcite plus magnesium-ion above 640 feet; below this level, probably due to increased hydrostatic pressure, dolomite is the stable phase.

Fairbridge (1957, p. 148) expands on Reuling's ideas and holds that dolomitization

> * * * could be brought about soon after burial at relatively shallow depth in the sediments at a pressure corresponding to about 100 fathoms (20 atmospheres).

Fairbridge (1957, p. 148, fig. 8) dismissed evidence from Bikini and Eniwetok by stating

> Nondolomitized atolls, such as Bikini and Eniwetok may, for some reason or other, have failed to provide the necessary physico-chemical requirements, such as the reducing conditions (owing to freer circulation) or may have subsided too rapidly.

Inasmuch as the "necessary physicochemical requirements" for dolomitization are as yet not demonstrable, the rejection of evidence from Eniwetok and Bikini is not justified. The geologic history of Eniwetok and Bikini show that, far from subsiding rapidly, these atolls were subjected to several emergences. There would have been ample opportunity for dolomite to develop at Bikini and be more widespread at Eniwetok as various parts of the column passed, or paused at, the depth of 638 feet. Further, if pressure is a determining factor, then the undolomitized portion below Kita-daitō-jima and the deep parts of the Bikini and Eniwetok subsurface are difficult to explain.

Skeats (1903, p. 124) was cognizant of the pressure hypothesis but said that field evidence was against the idea:

Recently it has been suggested that the introduction of magnesium into a coral limestone is only effected when the rock has been submerged for some time to a considerable depth corresponding to a particular pressure. This view is, however, not in harmony with the facts at Christmas Island, Mango, Vatu Vara, Ngillangillah, etc., where the highest rocks of the island are dolomitized, and the only movement of which there is evidence since their formation in shallow water is one of elevation.

Although pressure may be a factor in some occurrences of dolomitization, it is certainly not a limiting one. Petrographic evidence from Funafuti, as outlined below, indicates that even in this atoll dolomitization may be a shallow-water phenomenon.

The apparent random distribution of dolomite with respect to stratigraphic horizons indicates that there was no single period during which dolomitization was widespread. Also, throughout the atolls the faunal and floral successions show no breaks that could be ascribed to radical changes in oceanographic conditions. Therefore, one cannot invoke oceanographic controls over dolomitization, such as changes in temperature and salinity. Each atoll displays a unique pattern of distribution of dolomite, and the cause of the alteration must be sought within the atoll itself.

COMPARATIVE PETROGRAPHY OF DOLOMITE FROM PACIFIC ATOLLS

In addition to the confusing distribution pattern of dolomite, examination of thin sections shows that a wide variety of textures results from dolomitization.

In hole F-1 at Eniwetok the dolomite largely takes the form of discrete rhombs scattered throughout the limestone (pl. 282). Plate 282*B* shows a typical thin section from heavily dolomitized pieces of core F-1-12. In the final stage of dolomitization, the rock becomes a sugary mass of subhedral dolomite crystals. Only rare traces of original texture remain. In some places lens-shaped voids indicate that tests of larger Foraminifera resisted dolomitization and were later completely dissolved (pl. 282*C*). All stages of dolomitization are seen. In some cores, such as F-1-14 and F-1-15, dolomite crystals are rare, and the rock shows no sign of alteration. Only one core piece, F-1-6-9*a*, showed dolomite as a vug lining. In this core subhedral rhombs of dolomite formed part of one lamina.

In hole E-1, much of the dolomite shows selective replacement of certain fossils. Plate 283 shows dolomitized coralline algae. Coralline algae apparently are most prone to replacement, and in many thin sections these are the only fossils dolomitized. In other thin sections mollusk shells are selectively replaced (pl. 283*E*). As shown on plate 283*D* the interseptal mud in coral may be dolomitized, although the original corallum may have been largely dissolved.

The Funafuti dolomite shows quite different textures. Banded cavity fillings are common, and these show alternate layers of calcite and dolomite (pl. 284*A*). Cullis (1904, p. 410), in describing core 205A (pl. 284*C*) stated,

The dolomite layer [*b* in plate 284*C*] may represent part of the original deposit converted into dolomite, or, as seems more probable, it may have been directly deposited as such. The encrusting material, the introduction of which was apparently subsequent to the dolomitization of the rock, is separated from the boundaries of the original organisms by a layer of well-formed water-clear dolomite crystals.

Cullis noted that the number of alternate bands reached 15 in some cores. Skeats (1903, p. 70) noted agatelike deposits in dolomitized limestones from Fiji with as many as six laminae of alternate calcite and dolomite. Such finely banded deposits are lacking at Eniwetok.

It is difficult to see how fine laminae of alternate calcite and dolomite could be formed at depth. A limestone at depth would be replaced, and fine calcite laminae would not persist. Banded deposits are more easily explained if one assumes cyclically changing conditions, and such cyclic changes would be more likely to take place in shallow water than in deep water.

Another feature of dolomitized limestone from both Funafuti and Kita-daitō-jima is the resistance of coralline algae to textural effacement by encroaching dolomite (pl. 284*B*). In many sections from these two atolls, the coralline algae are the only recognizable fossils left in the rock. This is in sharp contrast to the condition of the algae in core E-1-3 from Eniwetok.

Further, most of the completely dolomitized rock at Funafuti and Kita-daitō-jima still shows much of its original texture. Plate 285*D* shows a completely dolomitized foraminiferal limestone from Funafuti. The rock contains about 40 percent $MgCO_3$, but there is little textural evidence to indicate that it is dolomitic. No rhombs are present, and the dolomite is so fine grained that all details of original texture are preserved. Plate 284*D* shows a low-magnesium rock, but it contains abundant dolomite (*a*).

In dolomitized coral from Eniwetok (pl. 283*D*), all the dolomite is in the form of discrete rhombs in the interseptal mud fillings. At Funafuti (pl. 285*C*), no euhedral crystals are seen; the dolomite there lines coral structures.

Plate 285 shows dolomitized limestones from Funafuti and Kita-daitō-jima. The Funafuti material is the "soft dolomite" of Cullis. Evidently the rock has undergone considerable solution since formation of the dolomite. The Kita-daitō-jima material, on the other hand, shows perfectly preserved *Halimeda;* yet the coralline algae (see *a* in pl. 285*B*) have been removed by solution and are not replaced by coarsely crystalline dolomite as are algae in core E–1–3 at Eniwetok.

These textural differences show that the paragenesis of the dolomite varies from atoll to atoll and that each occurrence must be considered separately. Broad general theories on the formation of dolomite in these atolls must take textural differences into account.

FORMATION OF DOLOMITE IN CORALLINE ALGAE

The writer can add nothing to speculation on the formation of dolomite by direct precipitation, as seen in the Funafuti banded deposits (pl. 284*C*), or by the all pervasive replacement by microcrystalline dolomite (pl. 285*A*). However, the dolomite associated with coralline algae in core E–1–3 may have formed from the magnesium-rich calcite of the algae (Schlanger, 1957).

The high magnesium content of calcitic algae has long been known. Recent work by Chave (1954a) shows that these algae, among which he lists *Corallina,* contain from 7 percent to almost 30 percent $MgCO_3$ by weight. He also shows that the $MgCO_3$ content is directly proportional to the temperature of the water in which the algae grew. Goldsmith, Graf, and Joensuu (1955) found magnesium in some algal material in concentrations greater than those indicated by X-ray study. From this they (p. 220) conclude that

"* * * finely divided or adsorbed Mg exists in some other form than in the calcite structure in at least some of the algal materials."

The differentation of high-magnesian calcite from dolomite, in a crystal-structure sense, is important in any discussion of dolomitization of algae. Chave (1952) believed that X-ray and chemical studies demonstrated a partial solid solution between the minerals calcite, $CaCO_3$, and dolomite, $CaMg(CO_3)_2$. However, Goldsmith, Graf, and Joensuu (1955, p. 212) stated that the use of the expression "solid solution between calcite and dolomite" by Chave (1952) is permissible compositionally but fails structurally to take into account the ordered nature of dolomite with respect to the calcium and magnesium ion positions. The dolomite structure involves the ordered substitution of magnesium ions into approximately 50 percent of the calcium ion positions in the lattice. The magnesium and calcium ions occupy separate and alternate cation planes. Thus, the random addition of more magnesium ions from sea water to a magnesian calcite would not result in a true dolomite phase inasmuch as an ordering process must also take place.

Based on the above information and the well crystallized dolomite in the Eniwetok material, the writer suggests the following line of reasoning in an attempt to explain the dolomite crystals in the *Corallina:*

1. There is no reason to assume that the magnesium ions in the algal solid solution are distributed in equal concentration throughout. There may be regions within the algal fragment in which the magnesium-ion concentration is in excess of the "average" for the fragment that is shown by a chemical analysis. Chave (1954a) showed that a considerable variation exists within a single algal colony, possibly because of seasonal temperature variation. Other factors may influence the metabolism of the algae and induce short-term high uptake of magnesium. Some statistical fluctuation of cation distribution within a solid solution would also be expectable, and thus there would be a few centers within high magnesium regions where the calcium and magnesium ions are in the ordered condition which defines true dolomite structure.
2. Thus, the alga, as it grows, may contain scattered dolomite nuclei, perhaps only a few unit cells in size. These nuclei, at this stage, would be too small to be detected by X-rays.
3. Through time, the dolomite nuclei, evidently more stable than the surrounding calcium-magnesium solid solution under existing conditions, enlarge by diffusion of the magnesium ions in the structure, by the ordering of magnesium ions originally only adsorbed, and by the addition of magnesium ions from the sea water.

Chave (1954b) considered that the magnesium in solid solution within calcite is unstable and that eventually a new form should develop. He believed that as one of three possible processes by which equilibrium may be reached, the magnesian calcite could reorganize crystallographically into two stable phases: low-magnesian calcite and dolomite. He considered this type of dolomitization of little importance. In giving examples of fossil evidence of crystallographic reorganization, Chave (1954b) failed to make clear whether the dolomite phase is inferred from the $MgCO_3$ content or whether it is present in the true dolomite structural sense.

D. L. Graf and J. R. Goldsmith (p. 1098–1053) used single-crystal and powder-diffraction techniques to determine the structure and composition of the dolomite from Eniwetok submitted by the writer. They found that the dolomite deviated some 5 mol percent from the theoretically ideal 1:1 calcium-magnesium ratio in the direction of excess $CaCO_3$. The partial filling of some magnesium ion positions by calcium ions is indicated. Goldsmith also reported that the dolomite crystals contain very small calcite particles in random orientation.

The writer believes that the addition of large amounts of magnesium ions from the surrounding sea water need not be a requirement for dolomitization of coralline algae because (1) perhaps as much as 20 to 25 percent of the cation positions (not considering high values found by Chave, 1954a) in growing algae may be initially filled with magnesium ions; (2) ordered dolomite crystals can form with only 45 percent of the cation positions filled by magnesium ions; and (3) calcite particles may account for several percent of the volume of the crystal.

Graf and Goldsmith (1956) pointed out the difficulty of crystallizing dolomite at low temperatures and attribute this difficulty to the decrease of the probability, at low temperatures or during rapid crystallization, that ideal cation sorting into ordered positions can take place. They (p. 185) also pointed out that "Ultimately, an understanding of dolomite formation at earth-surface temperatures must include the mechanisms by which ordered dolomite nuclei are formed * * *."

The writer suggests that (1) the effect of time—the algae in the Eniwetok core are from 40 to 60 million years old—may be greater than generally assumed in low temperature environments, and that (2) the nuclei of dolomite may be inherent in the original algal precipitate as the result of environmental conditions, such as occasional water temperatures of more than 30° C, under which crystallographically local high magnesium-ion concentrations may build up. The dolomitized coralline algae figured and described in this report demonstrate the extent to which dolomite growth in high-magnesian calcite can proceed.

Petrographic evidence indicates that the final stage of dolomitization includes the complete obliteration of all organic remains and original textures. The amount of magnesium needed for this complete alteration precludes a solely algal source for all the dolomite. In massive dolomite, the sea water must act as the supplier of magnesium. Thus the high-magnesian algal calcite may merely serve as a trigger to initiate dolomite growth.

This hypothesis of dolomitization explains only a minor percentage of the dolomite in these atolls. Conditions under which the nonmagnesian calcite around the algae can be replaced by dolomite remain unknown.

FUTURE WORK

Any general theory on atoll dolomitization must take into account the seeming lack of influence of original texture, porosity, and fossil composition on the formation of dolomite. Examination of many thin sections of dolomitized limestone from atolls shows that original porosity does not correlate with intensity of dolomitization. Either dense muds or porous sands may be dolomitized. The original fossil composition likewise appears to have little influence on the dolomitization process. The tendency of algae to be early hosts to dolomite at Eniwetok contrasts with the persistence of the same fossils at Funafuti and Kita-daitō-jima. The behavior of tests of large Foraminifera shows similar variation; at Eniwetok they resist dolomitization, whereas at Funafuti they are dolomitized in some cores and relict in others.

A second point is that nowhere in these atolls has dolomite been found in association with aragonite. If dolomitization takes place at depth, then an aragonite-rich sediment, such as most atoll sediments, might undergo dolomitization. Therefore, some dolomite could be expected in the thick intervals of aragonitic sediments below Bikini and Eniwetok. As pointed out elsewhere, these aragonitic sediments do not appear to have been subjected to subaerial solution. The relationship between persistence of aragonite, lack of dolomite, and lack of subaerial solution indicates that the conversion of primary aragonite to secondary calcite is a possible prerequisite to dolomitization. At Eniwetok, core E-1-2, which correlates precisely with core F-1-11, is made up of aragonite and calcite, whereas core F-1-11 is dolomitic. The aragonitic core has not been subject to prolonged subaerial solution, but the dolomitic core has. Because both these cores are the same age, time alone cannot be a limiting factor in dolomitization.

The lack of coexisting dolomite and aragonite does suggest that rate of subsidence may be a factor in dolomitization. Skeats (1903, p. 125) considered this and stated:

> Whatever the conditions for the introduction of magnesium carbonate into coral limestone may be, it seems probable, from the distribution of magesium carbonate in upraised coral islands, that the introduction takes place at or near the surface of the water, and that a limestone exposed to suitable conditions for a sufficiently long time will become dolomitic. * * * An ordinary non-magnesian limestone might result from a somewhat rapid subsidence or elevation, while a constant and slow subsidence or upheaval might result in the formation of a completely dolomitized island.

In a subsiding atoll the aragonite-rich sediments pass downward into a region where physicochemical conditions are fairly constant in comparison to the upper water layers. Evidently the aragonite is stable enough to persist indefinitely without recrystallizing to calcite, much less to dolomite. However, if these sediments remain near the surface long, perhaps in the intertidal zone, or are moved in and out of sea water, they will lose all aragonite and become calcite. If conversion of aragonite to calcite is a prerequisite to dolomitization, then most dolomitization may well be a shallow-water phenomenon.

Any attempt to explain the formation of dolomite in these atolls must take the following into account:

1. The vertical distribution of dolomite in all drilled atolls. Undue emphasis on the pattern of dolomitization below Funafuti has led to the acceptance, by many geologists, of Reuling's pressure hypothesis which is obviously inapplicable to Kita-daitō-jima and Eniwetok.
2. The presence of dolomite as a distinct mineral phase in limestones that contain as little as 2 to 3 percent $MgCO_3$. Leaching of originally magnesium-rich rocks could not account for these traces of dolomite. Further, the lack of dolomite in magnesium-rich limestones, such as those in the upper 50 feet of the Funafuti section, indicate that a high initial magnesium content does not necessarily foster dolomitization. The magnesium in these oft-discussed limestones below Funafuti is due to an abundance of algal calcite.
3. The differing susceptibility of any single fossil group to dolomitization. In hole E–1 coralline algae are preferentially dolomitized, although at Funafuti and Kita-daitō-jima these same fossils resist dolomitization.
4. The apparent lack of effect of primary porosity on dolomitization. Evidently, both dense fine-grained and porous coarse-grained limestones are equally liable to dolomitization.
5. The lack of coexistent dolomite and aragonite, which suggests that atoll limestones may have to be leached and recrystallized to secondary calcite before they can be dolomitized. This view is in opposition to that held by some workers who believe that aragonitic limestones are more easily dolomitized than calcitic ones.
6. The lack of correlation between length of immersion in sea water and intensity of dolomitization suggests that mere prolonged soaking in magnesium-rich water does not by itself cause dolomitization.
7. The wide variety of secondary textures seen in limestone from these atolls suggests that emplacement of dolomite takes place in several ways with differing paragenetic sequences.
8. The fact that the dolomite from these atolls is structurally calcium rich.
9. The fact that most of the limestone from both atolls and high islands in the Pacific is not dolomitized. Therefore one must look at dolomitization as an "abnormal" rather than a "normal" diagenetic effect.
10. That the three-dimensional distribution of dolomite in the subsurface of any atoll is unknown. Future drilling may show that dolomite forms a sheath around the outside of the limestone column; perhaps it is present only in a central plug or is scattered randomly throughout. A knowledge of whatever pattern exists is vital to any general hypothesis of atoll dolomitization.

CONCLUSIONS

This discussion stresses the fact that there is actually more than one "dolomite problem." Even within the restricted conditions that prevail during deposition and diagenesis of atoll limestones, dolomite apparently may form in at least the following three ways:

1. From metastable high-magnesian calcite, as illustrated by the growth of dolomite crystals in coralline algae, which possibly may take place at any depth.
2. By reaction of sea water with low-magnesian calcite to form the massive coarsely crystalline dolomite in hole F–1 at Eniwetok and most of the fine-grained dolomite at Funafuti and Kita-daitō-jima.
3. By direct precipitation of dolomite, with alternate layers of calcite, in vugs as the chemistry of the interstitial water or the pressure and temperature vary cyclically, probably in shallow water.

DETAILED DESCRIPTIONS OF CORES AND CUTTINGS

The information given below supplements that of Ladd and Schlanger (1960, table 3). It includes detailed descriptions of thin sections from the 15 cored intervals of hole F–1 and the 3 cored limestone intervals of hole E–1. Cuttings from those intervals that appear to have been exposed to subaerial solution, as shown by fossil molds and casts and the replacement of primary aragonite skeletal material by secondary calcite, are given particular attention. Paleoecological interpretations based on depth are made for each hole; the geologic implications of the solution intervals and faunal and floral changes are discussed in the body of the text.

The recovered cores were in pieces that ranged in

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size from irregular lumps less than 1 inch across to perfect cylinders more than 1 foot long. Each piece from each core was numbered consecutively from the top of the core downward. Thus F–1–1–1 designates the uppermost piece from core run number 1 in hole F–1. The aggregate length of these pieces is given as the recovered footage in the descriptions below.

Cuttings were bottled, prior to the writer's work, by 10-foot intervals and later examined for evidence of lithologic and faunal breaks.

DRILL HOLE E–1

Interval (feet)	*Drilling method*	*Recovery*	*Remarks*
10–30	Rock bit	Cuttings	Coarse, unconsolidated sand made up largely of worn and broken tests of *Calcarina* and *Marginopora* and subordinate worn and polished fragments of coral and coralline algae. Alcyonarian spicules and echinoid debris make up a trace in the samples. A small percentage of the cuttings are in the very fine sand and silt sizes and contain abundant delicate well-preserved miliolid Foraminifera. The sample, taken from 20 to 30 feet, contains pieces of several types of coral as much as 2 inches in length; some of these are well rounded, and all are unaltered. No recrystallization, lithification, or chemical deposits of calcite are present. *Interpretations.*—The abundant reef-type Foraminifera, now worn and broken, indicate that many of these sediments were deposited in a shallow-water environment. Well-preserved miliolids may have been indigenous lagoon forms that are now largely masked by transported material. Thus the sediment may have been deposited in a lagoon very close to a reef.
30–45	Rock bit	Cuttings	Unconsolidated coarse cuttings made up almost entirely of unaltered *Halimeda* segments between 3 and 6 mm across. A minor part of the cuttings consists of irregular pieces of unaltered coral and polished coralline algae as much as 10 mm in length. Also present are tests of *Calcarina, Marginopora,* and *Amphistegina,* and a few echinoid spines. No recrystallization, lithification, or chemical deposits of calcite are seen. *Interpretations.*—The overwhelming abundance of small *Halimeda* segments indicates deposition in a lagoon.
45–70	Rock bit	Cuttings	Heterogeneous mixture of coarse fossil debris that includes angular to worn rounded, and polished pieces of several types of coral as much as 1 inch in length, crusts and nodules of coralline algae, *Halimeda* segments, tests of *Calcarina* and *Marginopora,* and other sand-size fossil debris. Among the corals, delicate branches of *Seriatopora* are common. Well-rounded and worn pieces of purple "slate-pencil urchin" spines as much as 1 inch in length are present. A trace of unaltered molluscan shells is also present. No recrystallization, lithification, or chemical deposition of calcite took place. *Interpretations.*—The rounding and polishing of much of the coarse material is similar to that seen in many beach deposits on atolls. The fossils were probably all derived either from a reef or the shallow water behind a reef and deposited, after considerable movement, in shallow water—possibly within a lagoon or other back-reef area—or on a beach.
70–140	Rock bit	Cuttings	Cuttings from 70 to 90 feet are largely unconsolidated fossil debris dominated by whole and broken segments of *Halimeda* as much as 4 mm across. Angular chips of massive coral and pieces of delicate branching types are abundant, as well as pieces of coralline algae. Approximately 5 percent of the cuttings are worn individual tests of reef-type Foraminifera such as *Marginopora* and *Calcarina.* Fragments of mollusk shells and small well-preserved gastropods are common. The only consolidated materials are clusters of *Halimeda* segments as much as ½ inch across that are cemented by thin films of calcite, and a few irregular chips of lithified foraminiferal sand. The loose fossils are all unaltered. From 90 to 140 feet rock chips become more abundant, and the fossil debris is still unaltered. Most of the rock consists of weakly cemented aggregates of Foraminifera and algae. *Halimeda* and mollusks in the rock fragments remain unaltered. Below 100 feet many rock chips are made up of finely crystalline calcite that is secondary after original fine carbonate matrix. *Interpretations.*—The appearance of the recrystallized rock shows that these sediments had been exposed to subaerial solution for a short time; the top of the recrystallized zone is placed between 80 and 90 feet. The fossil assemblage indicates lagoonal deposition.

DRILL HOLE E-1—Continued

Interval (feet)	*Drilling method*	*Recovery*	*Remarks*
140–300	Rock bit	Cuttings	The cuttings are coarse; most of the limestone recovered is in the form of angular rock chips and pieces of coral between ¼ and ½ inch across. The rock chips are well-lithified aggregates of coral and foraminiferal sand but include small pieces of coralline algae that have evidently broken from larger pieces. Stained samples of cuttings from 140 to 150 feet and 230 to 240 feet show that most of the original aragonite remains. Many rock chips, however, contain finely disseminated crystalline calcite that is evidently in the process of replacing original matrix. In some samples, such as cuttings from 220 to 230 feet, there are abundant angular chips of massive coral that are still aragonite and which appear to have come from a single large head. *Interpretations.*—The most striking characteristic is the intimate mixing of recrystallized rock and unaltered fossils. This indicates that the section drilled was partly recrystallized and probably had been exposed to some solution. The high content of coral and encrusting algae suggests deposition of these limestones on or near a reef.
300–430	Rock bit	Cuttings	The cuttings are all angular rock chips as much as 1 inch in length of dense recrystallized limestone. Solution cavities due to the removal of fossils are abundant. Most of the rock is made up of coarsely granular secondary calcite, but it also includes large clusters of yellow sparry calcite. Corals, mollusks, and Foraminifera are the most abundant fossils. The fossil debris is poorly sorted, and most megafossils are fragments. In the lower part of the section mollusks are represented only by molds. Despite intense recrystallization, stained cuttings from 340 to 350 feet and 410 to 420 feet show a few percent of primary aragonite. *Interpretations.*—From 140 to 300 feet the degree of recrystallization gradually increases, but there is a definite strong increase in rock alteration at 300 feet. Evidently this whole section has undergone some solution. Recrystallized zones begin at approximately 300 feet in holes E-1 and F-1 and indicate a solution unconformity. The abundant corals and mollusks in these cuttings suggest that the sediments may have been deposited in shallow water, possibly within a lagoon.
430–590	Rock bit	Cuttings	A gradation from rock chips with fossil molds to abundant unaltered fossils is seen in this interval. From 430 to 540 feet the cuttings are all angular chips of highly recrystallized limestone. Many pieces show one or more sides coated with drusy calcite that was probably deposited on the walls of solution channels. Abundant clusters of euhedral yellow and colorless calcite crystals are present and some individual crystals are between ⅛ and ¼ inch long. Stained cuttings from 510 to 520 feet show no aragonite. Few recognizable fossils are present, but coral was abundant, as evinced by molds. Some crusts of coralline algae are also present. From 540 to 590 feet fragments of partly altered to unaltered fossils that include coral, mollusks, and *Halimeda* become more abundant. Stained cuttings from 570 to 580 feet are mostly primary aragonite. At 590 feet the cuttings are approximately 50 percent recrystallized rock chips and 50 percent unaltered fossil debris. *Interpretations.*—This interval covers the lower part of the recrystallized zone that started at 300 feet and demonstrates the gradual downward decrease in the effects of recrystallization and solution associated with subaerial exposure. The fossil assemblage indicates deposition in shallow water, possibly a lagoon.
590–1,070	Rock bit	Cuttings	Cuttings are all characterized by an abundance of primary aragonite skeletal material; the interval is comparable to the 650- to 970-foot interval in hole F-1. There are variations in color and size of cuttings throughout the interval. From 590 through 650 feet angular pieces of both branching and massive coral dominate the fauna, and these are as much as 1 inch in length. The interseptal openings are clear, and the coralla are formed of aragonite. Abundant fragments of large pelecypod shells still retain their nacreous luster. The finer fraction, which is largely coarse sand, contains mostly coral and mollusk fragments and lesser amounts of benthonic Foraminifera tests. In addition, a few chips of recrystallized limestone are present. Most of these rock chips are lithified aggregates of coral, mollusks, and Foraminifera in a fine-grained calcite matrix. Staining shows, however, that almost all the primary aragonite still persists. From 650 through 830 feet, cuttings are less than one-quarter inch in diameter, and coral and mollusks still predominate. Some of the pelecypod shell fragments indicate that the original shells were as long as 2 inches. Worn tests of *Heterostegina* and whole shells of gastropods are common in the 1- and 2-mm size fraction. Below 760 feet the cuttings have a brownish tan color similar to that seen in the 650- to 970-foot interval in hole F-1.

DRILL HOLE E-1—Continued

Interval (feet)	*Drilling method*	*Recovery*	*Remarks*
590–1,070	Rock bit	Cuttings	Stained samples from 650 to 660 feet and 740 to 750 feet show that about 80 percent of the cuttings are composed of original aragonite. From 830 to 900 feet the cuttings are again coarse and are composed mainly of fragments of several types of branching coral; the finer fraction still contains abundant unaltered pelecypod fragments. Between 900 feet and 1,070 feet the cuttings become finer again but remain similar in color and fossil content to those above. *Interpretations.*—Cuttings from above 670 feet probably came from rock that was partly recrystallized and represent the gradational zone below the solution unconformity at 300 feet. Below 650 feet the sediments have not been subjected to subaerial solution. The abundant branching corals and large mollusks indicate that these sediments were deposited in shallow sheltered waters, probably in a lagoon.
1,070–1,658	Rock bit	Cuttings	From 1,070 to 1,150 feet, cuttings show a brownish-tan color like that of the unaltered sediments above. At 1,070 feet, however, the cuttings are largely angular chips of tan recrystallized limestone, that is permeated by coarsely granluar calcite mosaics. Many chips are from miliolid-rich limestones made up of tightly packed tests of Foraminifera, algae, and coral debris in a fine-grained matrix. Corals are completely recrystallized, and the interseptal spaces are filled with recrystallized mud. Stained rock chips from 1,090 feet show no aragonite. Clear calcite casts of small gastropods are present, and many chips have molds owing to the removal of aragonite fossils by solution. Much unaltered debris is present, but this is thought to be contamination from above. The cuttings from 1,170 to 1,190 feet contain, in addition to rock chips, many fresh-looking tests of *Calcarina*, *Marginopora*, and pieces of bright pink *Homotrema*; these are very like tests from Recent sediments and are apparently the result of contamination. Below 1,200 feet rock chips become more abundant and unaltered fossils less so. At 1,310 feet the cuttings are almost all angular flakes and chips of recrystallized white-yellow dense limestone. *Interpretations.*—The top of a solution unconformity is placed at approximately 1,070 feet in this hole because of the flood of recrystallized rock chips that appears at this depth. On the basis of larger Foraminifera, Cole (1957, p. 746) places the top of the Miocene *e* at 1,080 feet in this hole. Todd and Low (1960, p. 802), on the basis of smaller Foraminifera, place the Tertiary *e* boundary between 1,020 and 1,100 feet. Thus the top of the recrystallized zone is a faunal boundary that suggests emergence following deposition of the Miocene *e* sediments. During later submergence, sediments containing a new post-Miocene *e* fauna were deposited, but the small size of the chips makes paleoecological interpretations difficult. However, the abundance of bentonic smaller Foraminifera and the presence of coral indicate a shallow-water deposit.
1,658–2,003	Rock bit	Cuttings	Cuttings from this interval are a mixture of partly recrystallized-rock chips and fragments of slightly altered to unaltered fossils, largely pelecypods, gastropods, corals, and Foraminifera. In the upper part of the interval, tests of larger Foraminifera including *Lepidocyclina*, *Spiroclypeus*, and *Heterostegina* are abundant and make up the bulk of the 1- to 4-mm fraction. These tests are generally chipped and worn. Most of the rock chips are made up of sand-size fossils, largely Foraminifera, packed in a fine-grained matrix. Granular mosaics of sparry calcite are common in these chips. At 1,860 feet the number of included larger Foraminifera diminishes, and the cuttings contain abundant tests of smaller Foraminifera, including miliolids and amphisteginids. Stained cuttings from the 1,776- to 1,805-foot interval show that approximately 50 percent of the material is aragonite, in the form of coral and molluscan debris. The lower part of the interval, below 1,860 feet, is characterised by an abundance of soft limestone chips that are made up of foraminiferal, coral, and molluscan debris. Although these rocks contain patches of secondary calcite, solution channels were not seen, and much of the limestone is aragonite. Mollusk shells in these limestones are generally chalky, but many still show a nacreous luster. Individual stained chips contain between 20 and 25 percent aragonite. *Interpretations.*—This interval lies below intensely recrystallized limestone and shows the effect of solution decreasing downward; the chips from the upper part of the interval show more recrystallization than those from the lower part. The lower part was probably not subjected to more than slight exposure to subaerial conditions, if at all. The abundance of larger Foraminifera in the upper part is suggestive of fore-reef or open shoal water conditions. The abundant miliolids and

DRILL HOLE E-1—Continued

Interval (feet)	*Drilling method*	*Recovery*	*Remarks*
			amphisteginids in the lower part also are suggestive of shallow-water deposits. Todd and Low (1960, p. 815), on the basis of smaller Foraminifera, interpret the sediments in this interval as of shallow-water origin.
2,003–2,028	Core barrel	4½ ft (core 1), 13 pieces	Rocks recovered in this run are gray friable poorly sorted soft limestones rich in disarticulated pelecypod valves, mostly *Cardium.* These well-preserved valves are randomly oriented in a matrix of sand-size fossil debris and fine carbonate. Most of the valves are approximately one-fourth inch across and many are broken. No bedding is seen. Echinoid spines, rods of articulate coralline algae, and rounded fragments of coral are also present. Some core pieces are single fragments of massive *Porites.* Although only 13 pieces are numbered, there are many small pieces because the rock breaks easily and tends to disintegrate in water. No molds or solution channels are present. A bulk X-ray analysis of E-1-1-4, a pelecypod-rich piece, showed 55 percent calcite and 45 percent aragonite (table 2). E-1-1-6, a piece of *Porites,* showed less than 2 percent calcite and more than 98 percent aragonite (table 2). Chemical and spectrographic analyses of these samples are given in tables 1 and 3, respectively. These rocks are unaltered and show no megascopic sign of calcite cement. Detailed descriptions of representative thin sections are given below. *E-1-1-1.*—A thin section shows the matrix to be a packed aggregate of rounded carbonate grains that are between 0.05 and 0.1 mm in diameter. Set in this porous matrix are abundant tests of well-preserved benthonic smaller Foraminifera. Many of these are miliolid types. Most have empty tests and still show a brown color in transmitted light; they appear isotropic in plane polarized light. Pelecypod shells show their original fibrous and prismatic internal structure. Fragments of both articulate and encrusting coralline algae are common. Much of the fine-grained matrix is recognizable fossil debris; the brown color of many of these fragments suggests comminuted Foraminifera. Although the material is tightly packed, the rock lacks any kind of chemical calcite cement. No signs of recrystallization or solution are seen. *E-1-1-4.*—As above, except that the fine matrix particles average approximately 0.2 mm in diameter; many of these are rounded fragments of coralline algae. *E-1-1-6.*—A section cut through a piece of solid *Porites.* The corallum is unaltered aragonite, and there is no sign of recrystallization of the microcrystalline skeletal material. There is only a trace of chemically deposited calcite, and this is found as thin linings in the interseptal spaces. This calcite may account for the calcite detected in the X-ray analysis. In transmitted light the septae are light brown with darker lines through their centers; in plane polarized light the aragonite shows even birefringence and no extinction, which indicates a microcrystalline aggregate. Traces of calcite show as microgranular aggregates. *E-1-1-9* and *-11.*—These sections show randomly oriented, scattered tests of thick-walled benthonic smaller Foraminifera and coralline algal debris in a fine-grained matrix of comminuted fossil debris. In reflected light the thin sections appear cloudy owing to irregular areas of white against a tan background. In transmitted light these white areas are opaque black. A few larger Foraminifera tests are present. The miliolid tests show their characteristic brown color. *Interpretations.*—The high content of original aragonite and the lack of solution, recrystallization, and calcite cement indicate that this interval has not been subjected to subaerial solution. The fossil assemblage, which is rich in miliolid Foraminifera and pelecypods, is suggestive of a lagoonal deposit. The lack of sorting and bedding indicate deposition in quiet water. However, the disarticulation and breaking of most mollusk shells evidence some movement of sediment before final deposition.
2, 028–2, 290	Rock bit	Cuttings	All cuttings from this interval are sand and granule sizes. Toward the upper part the material is dominantly sand size, and toward the bottom the cuttings are as much as 4 mm in diameter. More than 90 percent of the cuttings are discrete fragments of fossils or whole fossils. Rod-shaped fragments of coralline algae are very abundant,[4] as are angular fragments of unaltered mollusk shells. Foraminifera make up much of the cuttings; the fine sand fraction contains abundant well-preserved tests of delicate benthonic smaller types including miliolid, coiled, and serial forms. Angular fragments of unaltered coral and echinoid spines form only a minor part of the cuttings. The coarse cuttings from below 2,100 feet contain

[4] Tracey, *in* Emery, Tracey, and Ladd (1954, p. 253), reports that rod-shaped pieces of *Lithophyllum* make up from 50 to 75 percent of the cuttings from 2,288 to 2,327.5 ft in hole 2B at Bikini. The algae found here at Eniwetok probably are the same type as those found at Bikini.

DRILL HOLE E-1—Continued

Interval (feet)	*Drilling method*	*Recovery*	*Remarks*
2, 028–2, 290	Rock bit____	Cuttings____	numerous tests of larger Foraminifera as much as 4 mm in diameter. Also, the coralline algal debris is coarser. In the lower part of the interval particularly, many of the fossils have coatings of fine-grained white limestone. Rare chips of hard limestone are present, and a few pieces show extensive recrystallization. Stained cuttings from 2,110 to 2,120 feet and 2,230 to 2,240 feet show that much primary aragonite is present as molluscan and coral debris. *Interpretations.*—The coating of white limestone on the fossils indicates that the drill penetrated soft, friable limestone made up of sand- and granule-size algal and molluscan debris and tests of Foraminifera packed in a fine-grained matrix. The general agreement in size between the various fossil fragments and whole tests suggests that the debris underwent some sorting before final deposition. The abundant algae suggest deposition in shallow sheltered water.
2, 290–2, 410	Rock bit____	Cuttings____	Cuttings are a mixture of angular light-tan rock chips and discrete fossil fragments. The chips range from ⅛ to ½ inch across. The proportion of rock chips to fossils varies throughout the interval, but the rock chips generally make up the bulk of the material. These chips are partly recrystallized chalky limestones composed of randomly oriented foraminiferal, algal, and molluscan debris. The mollusk shells are chalky but still aragonitic. These fossils are packed in a fine-grained matrix which locally has recrystallized to granular mosaics of calcite. Stained chips from 2,370 to 2,380 feet show that the rock contains 10 to 20 percent aragonite. Pelecypod shell fragments are aragonitic. The sand fraction of the cuttings is dominated by cylindrical, rod-shaped fragments of *Lithophyllum*, similar to those in the interval described above, and angular fragments of pelecypod shells. In some samples, such as that from 2,330 to 2,340 feet angular chips of well-preserved coral as much as one-half inch in length are common. *Interpretations.*—This interval was probably soft limestone that yielded many fossil fragments on drilling. The high aragonitic content and lack of solution features indicate that this interval, like the one above, underwent little, if any, subaerial exposure. The abundance of mollusks and *Lithophyllum* and local concentrations of coral suggest a lagoonal environment, or at least shallow-water conditions.
2, 410–2, 540	Rock bit____	Cuttings____	Cuttings are largely coarse rock chips. In the upper part of the interval these chips are composed of light-tan porous and soft limestone made up of well-sorted medium-sand-size fossil debris dominated by fragments of mollusks, tests of benthonic smaller Foraminifera, and unidentifiable fossils. In the central part of the interval the rock chips are mixed with a small percentage of granule-size algal rods and angular fragments of pelecypods. A few of the rock chips contain unaltered shells of small pelecypods and gastropods. Most of the rock appears unaltered, but there are fine seams and patches of crystalline calcite scattered throughout the interval. From 2,440 to 2,450 feet the cuttings are flat chips of soft tan mudstone without recongizable fossils. Many of these chips show laminar structure similar to that seen in finely bedded shales and tend to part into flakes. Along some partings are films of flexible black carbonaceous(?) material. In transmitted light these show up as deep brown to red translucent structureless films; they probably are plant remains. *Interpretations.*—The rock chips are well lithified but show no solution features; the presence of aragonitic shell material indicates no prolonged exposure to subaerial conditions. The laminated mudstones may have accumulated in the deeper quiet water of a lagoon. The drilling record notes that the mudstones and sandy limestones may be interbedded. These well-sorted sands may represent periodic deposits of sediment on a muddy lagoon bottom.
2, 540–2, 780	Rock bit____	Cuttings____	The upper 20 feet of cuttings are coarse sand size and are made up mainly of rod-shaped fragments of algae along with a few tests of larger Foraminifera, molluscan debris, and angular chips of slightly recrystallized rock. Many of the algal rods are coated with fine-grained white limestone; others are coated with finely crystalline calcite. It appears as though these rods were broken from a partly recrystallized rock. Below 2,560 feet the cuttings are coarser; they are mixtures of tan rock fragments like those described from the interval above and angular fragments of unaltered coral and mollusks. A stained sample from 2,580 to 2,590 feet shows that both rock chips and fossils are highly aragonitic. Most of the pelecypod remains retain their original porcelaneous appearance. In many samples, angular chips of pelecypod shells as much as one-half inch in length and one-fourth inch in thickness are prominent; these must have been broken from

DRILL HOLE E–1—Continued

Interval (feet)	*Drilling method*	*Recovery*	*Remarks*
			large valves. Several genera of coral are represented and include both delicate branching and massive types. The coral is slightly chalky, but the structure is well preserved and the interseptal spaces are open. Proportions of the fossil types vary; some 10-foot intervals are rich in coral and molluscan remains, and some are high in rodlike algal debris.
			Interpretations.—This interval is transitional from the one described above. The main change is the downward increase in content of unaltered coral and large pelecypod fragments. Evidently the drill penetrated a section of soft limestone that is only slightly if at all recrystallized, and it contains fossils that are easily broken out of their matrix. The lack of alteration of the corals and mollusks indicates little or no exposure to subaerial conditions. The high percentage of coral and molluscan remains suggests deposition under quiet-water, probably lagoonal, conditions.
2, 780–2, 802	Rock bit	Cuttings	Cuttings are much like those described above except for the appearance of angular chips of white dense crystalline limestone at this depth. These chips are rare in the 2,780- to 2,790-foot sample but become abundant below 2,790 feet. Through the upper 20 feet of this interval the cuttings take on a white color as opposed to the tan of the overlying sediments. The white rock chips are composed largely of foraminiferal limestone with some mollusk molds. Stained cuttings from 2,790 to 2,800 feet show that the rock is all calcite except for a trace of aragonite. Some of the rock chips are made up of packed tests of miliolids and fragments of coralline algae cemented by acicular and granular calcite. These rocks strongly resemble those described from core run 2, taken directly below this interval.
			Interpretations.—Cole (1957, p. 749) places the top of the Eocene at 2,780 feet on the basis of the first appearance of a diagnostic smaller Foraminifera, *Pseudochrysalidina.* Todd and Low (1960, p. 807) place the top of the Eocene at 2,770 feet. The writer accepts 2,780 feet as the top because of the appearance of a different lithology. Chips that appear at this depth show strong solution features, such as molds, which indicate that a solution unconformity separates the rocks of Eocene and Miocene age, just as the Miocene *e* sediments are separated from younger rocks by a similar but better developed unconformity. The faunal and lithologic resemblance of these cuttings to the cores below suggest that this interval represents shallow-water sediments like those found in the cores.
2, 802–2, 808	Core barrel	6 ft (core 2), 9 pieces.	Core pieces are gray porous to dense irregularly cemented to friable limestones rich in molluscan fossils. Generally disarticulated pelecypod valves and gastropod shells, many of which are broken, are randomly oriented in a matrix of sand-sized foraminiferal and algal debris. The fossils have been partly dissolved, leaving molds, but much original shell material remains. The mollusks are as much as 2 inches in length and include broken shells which may have been as long as 3 inches. A striking feature is the irregularity of cementation; areas of the matrix, particularly around molds, are well-cemented by hard white calcite that fills the interstices between the sand-size fossils. Much of the matrix is friable porous sand. The boundaries between the dense white patches and the porous patches are fairly sharp; a complete transition takes place in a few millimeters. About half the rock is cemented, and the other half is friable; the two types are intimately mixed so that the pieces are coherent. There are a few irregular areas as much as one-half inch across where the opaque white calcite grades into clear yellow calcite. Other fossils seen megascopically include echinoid and algal debris. Dasycladacean algae are common as molds; these have diameters as large as 3 mm. In piece E–1–2–8 they are especially abundant; more than a dozen molds are seen on a sawed surface of about 10 square inches. Some of these algae are broken. Piece E–1–2–9 is especially rich in large gastropod molds; eight of these, all between 1 and 2 inches in length, are in an irregular piece of core 4 inches long. Bulk X-ray analysis of E–1–2–1 showed 100 percent calcite, but picked molluscan fragments from E–1–2–5 showed 20 percent aragonite and 80 percent calcite. Chemical and spectographic analyses of E–1–2–1 are given in tables 1 and 3, respectively. Thin section descriptions are given below.
			E–1–2–1, –3, and –8.—Sections show that the sand-size matrix contains abundant well-preserved tests of *Triloculina*, a miliolid Foraminifera. Tests of these, other benthonic smaller Foraminifera, and rounded fragments of coralline algae are closely packed. In places these are cemented only by thin films of granular calcite and correspond to the friable parts of the rock. Other areas show the inter-

DRILL HOLE E–1—Continued

Interval (feet)	*Drilling method*	*Recovery*	*Remarks*
2, 802–2, 808	Core barrel	6ft (core 2), 9 pieces.	stices between fossils to be filled with finely granular mosaics of calcite that correspond to the indurated part of the rock. In places the granular mosaics contain patches of dark, cloudy original mud. Many of the miliolid tests retain a brown color as in core 1; most of the tests are filled with calcite similar in texture to the cement. *Interpretations.*—Abundant pelecypods and gastropods, miliolid Foraminifera, and dasycladacean algae make up an assemblage characteristic of shallow-water, probably lagoonal, deposits. The algae, particularly, flourish in water only a few feet deep. However, these may have been carried downward into a lagoon several fathoms or more deep, as indicated by broken algal fragments. The large mollusks were probably indigenous, although breakage and disarticulation suggest movement before final deposition. The development of molds points to a period of subaerial solution. However, the persistence of aragonite suggests that the exposure was of comparatively short duration.
2, 808–3, 130	Rock Bit	Cuttings	Cuttings from this interval are all sand- and granule-size angular chips of hard white limestone, although the upper few feet contain some unaltered fossils that are probably contamination from above the solution unconformity at 2,780 feet. Stained cuttings from 2,840 to 2,850 feet, 2,940 to 2,950 feet, 2,990 to 3,000 feet, and 3,020 to 3,030 feet show these chips to be entirely calcite. There are clusters of clear yellow calcite crystals. The limestone is predominantly well cemented and recrystallized and is made up of abundant tests of benthonic smaller Foraminifera, including miliolids that are closely packed to floating in a fine-grained crystalline calcite matrix. Some chips are made of recrystallized coral. *Interpretations.*—Todd and Low (1960, p. 812) found three foraminiferal zones in the 2,770- to 3,120-foot intervals; they are as follows: a *Peneroplis-Trioculina* assemblage, 2,770–2,940 feet; a *Ornatonomalina* assemblage, 2,940–2,960 feet; and a *Asterigina rotula* assemblage, 3,010–3,120 feet. Todd and Low interpret these sediments as shallow-water deposits. The comparable zones in hole F–1 range from 4,200 to 4,550 feet, and the sediments there are interpreted as outer slope equivalents of the 2,770- to 3,120-foot interval in E–1. The recrystallization and solution molds in this interval show that it is still within the strongly affected zone below the solution unconformity at 2,780 feet.
3, 130–4, 078	Rock bit	No recovery.	
4, 078–4, 100	Core barrel	13 ft (core 3), 42 pieces.	The lithology through this interval remains constant. The rocks are all white dense very hard and well-cemented, highly recrystallized dolomitic limestones containing numerous molds of massive corals as much as several inches in length and mollusks, dominantly disarticulated pelecypod valves. The larger fossils are randomly oriented and no bedding is evident. The bulk of the rock is made up of sand-size fossil debris that includes abundant articulate coralline algae in a fine hard mud matrix. Laminae of encrusting algae are common. In addition to the fossil molds there are irregular solution voids lined with drusy calcite and dolomite. Dolomite is easily seen megascopically by sparkles of light from the euhedral crystal faces. The dolomite is evenly distributed, as all pieces have some dolomite, but none of the rocks are as intensely dolomitized as some of the pieces in core 12 from hole F–1. Bulk X-ray analyses of pieces E–1–3–10 and E–1–3–42 showed 5 percent and 14 percent dolomite, respectively; the remainder of the rock was calcite. Chemical analyses of these samples are given in table 1. The following descriptions include features seen in sections from pieces E–1–3–1, –2, –5, –8, –10, –20, –23, –26, –31, –33, –36, –40, and –42. Almost all these pieces contain some coral. All the interseptal spaces are filled with semiopaque lithified mud. Plate 283*D* shows the state of preservation of coral in this interval. The corallum itself has either been dissolved out or replaced by granular calcite. The mud filling is the host for numerous dolomite euhedra. Of interest is the fact that in no thin section was the originally aragonite corallum itself dolomitized. Mollusk shells are generally replaced by finely granular mosaics of dolomite that show sharp boundaries against the dark matrix (pl. 283*E*). However, some valves still show traces of an original fibrous and prismatic internal structure and appear yellow in transmitted light. The fine-grained matrix appears to be rich in coralline algae, although intense recrystallization makes positive identification difficult. Pockets of packed rounded dark particles that average 0.04 mm in size are common between larger fos-

DRILL HOLE E-1—Continued

Interval (feet)	*Drilling method*	*Recovery*	*Remarks*
			sils. Irregular solution channels are present but are completely filled by laminar deposits of fibrous calcite. Much of the dolomite is restricted to rod-shaped segments of articulate coralline algae (pl. 283*C*). These algal rods, where not too greatly recrystallized, are identifiable as *Corallina*. The rods appear in thin section as dark circles, ellipses, or rectangles according to the orientation of their long axes with respect to the plane of the thin section. Plate 283*C* shows a typical dolomitized algal rod, cut parallel to its long axis, that is 0.3 mm wide by 1.7 mm long. The original algal rod is almost completely replaced by clear dolomite across its width and is recognizable only by a small amount of algal material at each end. The dolomite crystals are definitely restricted to the algae, and their growth seems to be controlled by the shape of the rod. The area near the axis of the rod is occupied by a fine-grained mosaic of anhedral dolomite that grades outward into coarser crystals. Under crossed nicols the rhombic habit of some of these crystals is clearer due to separate extinction. In a section cut perpendicular to the long rod axis, the dolomite forms a rosette of subhedral crystals that radiate from a center of fine-grained anhedra (pl. 283*B*). Many algal rods contain separate, euhedral dolomite rhombs that apparently are not so closely controlled by the shape of the algal fragment. Plate 283*B* shows one such rod cut parallel to its long axis. In this view three dolomite rhombs are well developed. The crystal on the left has a cloudy, dark center that is typical of many of these euhedra. In any given thin section, some rods may be completely dolomitized, whereas a few millimeters away, a similar rod may bear no trace of dolomite. In general, however, most of the rods are partly replaced by dolomite. Thin sections may show circular, ellipsoidal, and rectangular areas of dolomite that have apparently obliterated the original algal rods and spread into the matrix. Dolomite is scattered through the matrix and in the mud fillings. Part or all of this dolomite may have originated in small algal fragments in this mud. In some slides, later solution has removed parts of the undolomitized algae and has left only clusters of dolomite rhombs within algae-shaped voids.
			Interpretations.—The high content of large massive corals, mollusks, and abundant coralline algae suggest a shallow-water deposit. The poor sorting and the ubiquitous mud fillings, both within the fossils and as a rock matrix, are common attributes of reef and near-reef limestones. This interval was probably deposited on a reef or within a shallow lagoon. The degree of recrystallization shown by these limestones indicates at least one period of subaerial solution; the laminar calcite deposits show that chemical deposition of calcite was cyclic. Further, the solution of algal rods from around their dolomitized cores shows that some rock was removed following dolomitization.

DRILL HOLE F-1

Interval (feet)	*Drilling method*	*Recovery*	*Remarks*
20–55	Rock bit....	Cuttings....	Unconsolidated sand, from 20 to 45 feet, dominated by worn tests of *Calcarina* and *Baculogypsina*. Tests of *Marginopora* and other benthonic shallow-water types are present. Shells of high-spired gastropods as much as 3 mm long are common. Broken fragments of unaltered *Halimeda* segments as much as 4 mm in length are also present. Fragments of red *Homotrema* and *Tubipora* speckle the cuttings, and rounded fragments of coral are common. Most of the material is between ½ and 2 mm in diameter. The fragments of larger organisms such as coral and *Halimeda* are roughly the same size as the whole tests of Foraminifera and gastropod shells. This size relationship indicates sorting; the abraded state of much of the material supports the interpretation of sorting. The sample from 45 to 55 feet is coarse and is dominated by fragments and whole segments of *Halimeda* as much as 6 mm across. Coarse *Tubipora* debris is common. Only a small percentage of the sample consists of foraminiferal tests. The entire interval is unaltered; primary aragonite is abundant, and no signs of recrystallization or cementation is seen.
			Interpretations.—The abundant reef-type Foraminifera, now worn, indicate that these sediments were largely of shallow-water origin, and that they underwent some transport. They were finally deposited off the reef, either in a lagoon or a fore-reef area.

DRILL HOLE F-1—Continued

Interval (feet)	*Drilling method*	*Recovery*	*Remarks*
55–70	Rock bit	Cuttings	Samples are unconsolidated and are made up almost entirely of whole and broken unaltered *Halimeda* segments as much as 10 mm in length. There are two types of *Halimeda* present: large fan-shaped and twisted segments; and smaller ones in the form of three distinct tubes, in a plane, fused at one common juncture and radiating at an angle of from 60 to 90 degrees. These segments average approximately 5 mm long. A small percentage of *Tubipora* fragments and foraminiferal sand accompany the algal segments. No recrystallization or deposition of chemical calcite is seem. *Interpretations:* The high content of *Halimeda* indicates deposition in a lagoon, possibly at depths of from 10 to 30 fathoms.
70–110	Rock bit	Cuttings	Cuttings are a mixture of discrete unaltered whole and broken fossils including *Halimeda*, Foraminifera, *Tubipora*, gastropods, and angular rock chips. The unaltered fossil material is similar to that described in the above interval. The rock chips include poorly lithified partly recrystallized foraminiferal sands and dense, well-cemented crystalline limestone. Many chips are aggregates of sparry calcite. Fragments of partly to wholly recrystallized coral are common. The upper 10 feet of the interval contains a high percentage of large *Halimeda* segments, similar to those in the 55- to 70-foot interval, and fewer rock chips than the rest of the run. Evidently the drill passed from wholly unconsolidated and unaltered material into a zone of lithified and recrystallized sediment in this interval. The drilling time record shows a sharp increase in drilling time per 10 feet between 60 and 70 feet in hole F–1; this may indicate the top of the recrystallized zone. *Interpretations.*—The mixture of unaltered fossils, which may be contamination from above, makes interpretation difficult; however, the common fragments of coral indicate a shallow-water deposit.
110–170	Rock bit	Cuttings	Coarse cuttings made of angular to subrounded rocks and individual fossil fragments, almost all of which are between ¼ and ½ inch in diameter. Among the fossil fragments, angular chips of massive coral are common and several genera are represented. Delicate branching coral fragments are also present. Rods and fragments of branching coralline algae are common, and molluscan debris is prominent. A few *Halimeda* segments are present. Most of the rock chips are partly recrystallized, and fossils are obscured. However, much of the rock evidently was coralliferous. Small solution molds are common. Cuttings from the 110- to 120-foot interval were stained with Meigen's solution, and this revealed that most of the coral, molluscan, and *Halimeda* debris is unaltered aragonite. Many of the rock chips show abundant sand-size fragments of aragonite in a partly recrystallized calcite matrix. *Interpretations.*—This interval underwent some subaerial solution, but much of the primary aragonite remains. The abundant coral, algal, and molluscan remains suggest deposition in a lagoonal environment.
170–190	Core barrel	1 foot (core 1), 3 pieces.	*F–1–1–1 and F–1–1–2.*—White and tan porous, friable limestone made up of unsorted randomly oriented fragments of coral as much as 1 inch long, *Halimeda* segments one-half an inch long, pelecypod and gastropod debris, and irregular fragments of encrusting algae. These fossils are white, but the rock matrix has a large proportion of tan finely filamentous encrusting Foraminifera (Ladd and Schlanger, 1960, pl. 7 fig. 2). The rest of the matrix is porous, slightly lithified carbonate of spongy texture. Thin sections of F–1–1–1 show that the *Halimeda* segments are largely unaltered coffee-colored microcrystalline aggregates of aragonite. A few segments show originally open tubes now filled with clear microgranular calcite. The corals are also largely unaltered but fibrous aragonite. Some of the interseptal spaces are filled with dark carbonate mud rich in small spherulitic bodies identified as tunicate ascidian spicules. Minor parts of the coral have been replaced by finely granular calcite. Encrusting Foraminifera and mollusk shells both show a fibrous structure: the former, calcite; and the latter, aragonite. Encrusting algae show irregular, blotchy coloration; some parts are black and semiopaque, and others are light tan. The matrix is a fine open fretwork of unidentifiable carbonate. Parts of it are dominated by a network of subcircular links resembling a soap-bubble pattern; other parts appear to be relict after laminar encrustations. A bulk X-ray analysis of F–1–1–2 showed 60 percent aragonite and 40 percent calcite (table 2). Chemical spectrographic analyses are given in tables 1 and 3, respectively.

DRILL HOLE F-1—Continued

Interval (feet)	*Drilling method*	*Recovery*	*Remarks*
			F-1-1-3.—As above, but better cemented by masses of laminar encrusting algae. This core shows a denser, more lithified matrix than other samples from this run. *Interpretations.*—The fretted appearance of the matrix and the minor amounts of calcite in the *Halimeda* and the coral suggest that the material of this core has undergone only a minor amount of aragonite solution and calcite deposition; subaerial exposure for any significant time has not taken place. Cole (1957, p. 745) reports no diagnostic larger Foraminifera from this run. Todd and Low (1960, p. 805; table 3) report *Heterostegina, Homotrema, Calcarina, Marginopora, Amphistegina, Carpenteria,* and two species of *Triloculina* from this interval. This foraminiferal assemblage, the abundant small *Halimeda* segments, the coral debris, the mollusk shells, and the lack of sorting suggest deposition in a lagoonal environment.
190–280	Rock bit____	Cuttings____	Very coarse cuttings made up largely of unaltered and porous angular chips of massive coral as long as 1 inch, broken and whole unaltered shells of both gastropods and pelecypods as long as three-fourths of an inch, and finger-shaped fragments of branching coral as long as 1½ inches. Abundant angular rock fragments are present and include slightly recrystallized but still aragonitic foraminiferal sands and dense partly crystalline limestone. Proportions of various fossil types change throughout the interval. Cuttings from the 240- to 250-foot section are almost all angular chips of a single type of massive coral; apparently a single large coral head was broken by the drill. From 250 to 260 feet, fragments of branching coral are prominent; many of these are coated with white crustose coralline algae. Only a small percentage of material finer than one-quarter inch in diameter is present. Worn tests of *Amphistegina*, fragments of pelecypod shells, and whole shells of gastropods make up most of this finer fraction. Cuttings from the 200- to 210-foot section were stained with Meigen's solution and showed that recrystallization, although evident, is not as strong as that shown by the 110- to 170-foot interval. Many rock chips show only slight lithification and little recrystallization; no solution molds were seen. Rock chips include *Halimeda*-rich limestone; the algal segments are still aragonite, but the rock matrix is fine-grained calcite. *Interpretations.*—This interval has undergone only minor solution and recrystallization. Replacement of aragonite by calcite and chemical deposition of calcite is rare. Thus there seems to be some diminishing of the effects of subaerial exposure downward from the above interval. These sediments were probably deposited in a lagoon.
280–330	Rock bit____	Cuttings____	Cuttings are very similar in fossil content to those from the 190– to 280-foot interval. However, from 280 to 330 feet the cuttings have a higher percentage, approximately 10 to 20 percent, of material between 2 and 4 mm in diameter. Most of this finer fraction is made up of worn tests of benthonic Foraminifera such as *Amphistegina*, angular fragments of unaltered mollusk shells, and coral and algal debris. Many partly recrystallized rock chips are present, but many of the aragonitic fossils, such as coral and *Halimeda*, are unaltered. Staining of cuttings from the 290- to 300-foot and 320- to 330-foot intervals reveals abundant primary aragonite. From 310 feet to 330 feet angular chips of unaltered and massive coral are again abundant. This interval should probably be grouped with the 190- to 280-foot interval, but the change in cuttings size warranted the split. *Interpretations.*—The degree of recrystallization and the fossil content indicate that the interval records a history of deposition under shallow-water conditions, probably lagoonal, followed by a slight exposure to solution and concomitant recrystallization.
330–600	Rock bit____	Cuttings____	Cuttings from this interval are made up almost entirely of angular chips of buff-colored well-cemented, recrystallized limestone. Thus, there is a marked change in degree of recrystallization and loss of primary aragonite in comparison to the above aragonitic intervals. Stained cuttings from 330 to 340 feet, 430 to 440 feet, 520 to 530 feet, and 550 to 560 feet show that only a small percentage of the original aragonite remains; most of the coral has been recrystallized and replaced by secondary calcite. The angularity of most of the chips indicates that hard, dense rock was penetrated. In many chips the rock matrix is now a finely granular mosaic of anhedral calcite, and the original texture is obliterated. Many chips show solution cavities. A few chips still show original textures, such as foraminferal sands rich in small benthonic types. On a few chips, fragments of large pelecypod shells are evident; some of these are still partly aragonitic. A few unrecrystallized chips of massive coral are present, but these are similar to those in higher intervals and may be contamination. Clusters of sparry light-yellow calcite are common.

DRILL HOLE F–1—Continued

Interval (feet)	*Drilling method*	*Recovery*	*Remarks*
330–600	Rock bit	Cuttings	Some of these crystal aggregates show a curving flat side in the form of an impression of a pelecypod shell; some shell material still clings to the impression. Thus chemical deposition of calcite in empty mollusk shells has evidently taken place. In some samples (each of a 10-foot interval), fine cuttings are abundant; these are made up of discrete tests of benthonic Foraminifera such as *Amphistegina* and *Marginopora* and small rock chips. Although Todd and Low (1960, p. 805) placed the Miocene-post-Miocene boundary at 560 to 570 feet, no change in lithology, degree of recrystallization, or fossil content was apparent in the cuttings. The most abundant fossils in this interval are corals, Foraminifera—dominantly shallow-water types—and mollusks; echinoid spines are scattered throughout and rare *Halimeda* are present. *Interpretations.*—The degree of recrystallization and loss of primary aragonite indicates that this interval was subjected to prolonged subaerial solution. The marked increase in these characteristics at 330 feet evidences the top of a leached zone at that depth (fig. 308). The fossil assemblage suggests deposition under shallow-water, probably lagoonal, conditions.
600–625	Core barrel	2 ft (core 2), 10 pieces.	*F–1–2–1 through –10.*—Core run is homogeneous buff well-indurated vuggy limestone. Original rock was highly coralliferous, as cores contain abundant randomly oriented molds of finger coral as much as 1 inch in diameter and 4 inches in length. Many smaller molds of delicate *Seriatopora* are present. Much coral shows thick encrustations of laminar algae. Molds of broken and whole gastropods and pelecypods as much as 1 inch in length are common. This fossil debris is embedded in a hard fine-grained matrix. Many original voids, such as the interior chambers of gastropods, are entirely filled with coarse granular calcite. Drusy coatings of light yellow calcite occur throughout the rock. Thin sections of F–1–2–1 show the matrix to be a dense sandy mud that contains abundant tests of *Amphistegina* with lesser amounts of benthonic Foraminifera, fragments of encrusting Foraminifera, rare echinoid spines, articulate coralline algae, and other unidentifiable organic debris. Coral is shown only by virtue of the persistence of mud-filled interseptal spaces, because the original aragonite corallum has been dissolved. Irregular patches of calcite mosaic spread through the original mud matrix and impart a grainy texture. The matrix of F–1–2–9, as seen in thin section, is an *Amphistegina* sand. These originally calcitic tests retain a fine fibrous structure that shows pseudonuiaxial crosses in plane polarized light; original aragonitic shell material is represented only by molds or granular secondary calcite. Bulk X-ray analyses of both F–1–2–1 and F–1–2–9 showed 100 percent calcite (table 2). Chemical analyses of these two samples are given in table 1. *Interpretations.*—The large amounts of drusy calcite and the recrystallization of the mud matrix coupled with the solution of all the aragonite fossils indicate that this interval underwent a prolonged period of subaerial solution and redeposition of carbonate. Cole (1957, p. 745) reported no diagnostic larger Foraminifera from this core run, but Todd and Low (1960, p. 805; table 3) reported several genera of miliolids, two species of *Elphidium*, and one genera each of *Homotrema*, *Planorbulina*, *Calcarina*, *Marginopora*, and *Amphistegina*. These smaller Foraminifera were found immediately above and below the cored interval in cuttings. The foraminiferal assemblage, the abundance of branching coral and mollusks, and the poor sorting indicate a lagoonal environment unaffected by strong currents.
625–650	Rock bit	Cuttings	Cuttings are composed entirely of irregular fragments of soft moderately lithified, buff-colored limestone as much as 1 inch in length. Most of the pieces are rich in sand-size fossil remains. The rock chips contain disseminated irregularly distributed anhedral finely granular calcite. Clusters of sparry calcite are common. Some chips show pieces of pelecypod shells, and pieces of coral are present. Staining by Meigen's solution of cuttings from 630 to 640 feet reveals a few percent of primary aragonite. *Interpretations.*—As in the cored interval directly above, the 625- to 650-foot interval appears to have undergone considerable solution of primary aragonite and chemical deposition of calcite. However, this 25-foot interval grades downward into little altered aragonitic sediments, which start at 650 feet (see description below).

DRILL HOLE F–1—Continued

Interval (feet)	*Drilling method*	*Recovery*	*Remarks*
650–970	Rock bit	Cuttings	Cuttings from 650 feet to about 700 feet are transitional between the above described interval and the cuttings below 700 feet. This 50-foot section is made up of angular rock chips, like those found in the 630- to 650-foot interval, and large pieces of coral. The coral is unaltered, and several genera are represented, including massive types that are present only as angular chips, delicate branches of *Seriatopora*, and thick finger-shaped pieces as much as 1½ inches in length of other branching types. Some are encrusted with coralline algae. Unaltered angular fragments of both large and small mollusk shells are present but form only a minor part of the sediment. Approximately 80 percent of the material is identifiable as coral. The interseptal spaces of these are open, and little deposition of calcite has taken place. From 700 to 720 feet the percentage of rock chips diminishes rapidly, and below this depth the cuttings are coarse fragments of coral and mollusks. The content of molluscan debris varies throughout this part of the interval, but shells never make up more than 15 to 20 percent of the cuttings. Single pieces of finger-shaped coral fragments attain lengths of 2 inches and diameters of one-half inch. The color of the cuttings gradually darkens from a light gray to a brownish tan at 810 feet and from there down remains constant. Chips of blue *Heliopora* are scattered throughout the section. No significant alteration of the fossils beyond darkening in color nor recrystallization or calcite deposition was noted. Many of the samples contain a small percentage of fine cuttings that range from fine sand to fragments one-quarter inch in diameter. Much of this is broken coral and molluscan debris, but individual well-preserved tests of benthonic Foraminifera are common. Also present are chips and flakes of soft black carbonaceous material; these are porous, and some look like burned pieces of wood. When split, the black chips show a brown color on fresh surfaces. The drilling time chart shows a uniform high rate of penetration through this whole interval. *Interpretations.*—The lack of lithification, of chemical calcite, and of alteration of aragonite indicate that these sediments were never subjected to subaerial solution. The transition downward to unaltered material from the thoroughly recrystallized core (no. 2) taken between 600 and 625 feet shows that the effect of subaerial exposure diminishes gradually, rather than abruptly, below the exposed section. The very high content of coral, including the delicate branching types, indicates that this entire interval was deposited in shallow water, probably in a lagoon.
970–1,040	Rock bit	No recovery.	
1,040–1,230	Rock bit	Cuttings	There are marked differences between cuttings from this interval and those of the 650- to 970-foot interval. From 1,040 to 1,230 feet the cuttings are white and fine; most of the material is sand and granule size. Large pieces of coral are lacking. From 1,040 to 1,060 feet the cuttings contain approximately equal amounts of recrystallized dense limestone chips and unaltered fossils debris including abundant *Halimeda* fragments, small gastropods and pelecypods, miliolid and other bethonic Foraminifera, and coral. A stained sample from 1,040 to 1,050 feet showed abundant primary aragonite. From 1,080 feet downward the ratio of rock chips to unaltered fossils increases, and below 1,100 feet the cuttings are all rock chips. Many rock chips show abundant Foraminifera in a finely crystalline matrix. Aggregates of sparry calcite are common, as are drusy coatings of calcite. Most of the chips are angular, which indicates that solid limestone was penetrated by the drill. *Interpretations:* Circulation was lost from 975 to 1,045 feet, and no cuttings were recovered in this 70-foot interval. Evidently there was a change in lithology from unconsolidated sediments composed of large coral fragments to sediments rich in *Halimeda*, small mollusks, and miliolid Foraminifera. Further, the abundant chips of recrystallized limestone in the 1,040- to 1,050-foot interval show that by this depth the drill had struck recrystallized rock. Therefore, there is a solution unconformity within the 975- to 1,040-foot interval. Cuttings from the 1,040- to 1,230-foot interval are evidently contaminated by postunconformity unaltered sediments for some distance below 1,040 feet. It is possible that the unaltered sediments in the 1,040- to 1,060-foot interval were laid down on and filtered into a base of rock that had been previously uplifted above sea level and recrystallized. Limestones thus exposed characteristically develop a rough and porous upper surface. Therefore, drilling through the top of the recrystallized zone might recover

DRILL HOLE F-1—Continued

Interval (feet)	*Drilling method*	*Recovery*	*Remarks*
1,040–1,230	Rock bit	Cuttings	younger sediments within the older rock. Upon resubmergence, the younger sediments, including those from the 630- to 970-foot interval have remained below sea level. The abundance of *Halimeda*, mollusks, and miliolid Foraminifera in the 1,040- to 1,050-foot interval indicates that these sediments deposited directly on the recrystallized base were lagoonal in origin. The site of deposition of the older rock is difficult to interpret because of the small size of chips. However, Todd and Low (1960, p. 815) believe that this section of hole F-1 is of shallow-water origin.
1230–1248	Core barrel	11 ft (core 3), 26 pieces	The 26 pieces of core range in length from 2 to 8 inches. The most striking megascopic feature is the variation in porosity through the run. Pieces 1 through 4 show only small unconnected vugs with a few coral molds. From piece 5 through piece 16 the pore spaces become more numerous, fretted, and interconnected. Many of these features are due to solution of corals, rotted impressions of which are still visible. From piece 17 through piece 26 the pores are again more regular openings as much as 1 inch across. They appear to be solution channels rather than molds. Representative pieces are described below. *F-1-3-3.*—White dense slightly vuggy limestone. Sawed faces show abundant *Halimeda* segments and other fossil debris solidly set in a hard-mud matrix. Vugs show thin coatings of drusy calcite. A small part of the rock is finely porous owing to coral molds now represented by interseptal spaces partly filled with calcite. Sawed surfaces show a splotchy pattern of gray, white, and light buff because of differences in skeletal texture and in degree of crystallization of the matrix. Thin sections show a poorly sorted matrix of closely packed *Halimeda* segments; rare tests of miogypsinids; lepidocyclinids, common encrusting Foraminifera; articulate coralline algae; and unidentifiable fossil debris. The spaces between the fossil fragments is in part filled with "mud" and in part with microgranular calcite. Between the fossils and the final void-filling calcite are two fine laminar encrustations of calcite. *F-1-3-4.*—As above, except at bottom of piece where most primary voids between the packed fossil debris are open. Here the fossils are cemented by a thin layer of calcite that laps over from one fragment to another and gives the rock a pellet-like texture. Thin sections show thick laminae of encrusting algae and completely recrystallized coral that shows foraminiferal encrustations in addition to debris similar to that in F-1-3-3. A bulk X-ray analysis (table 2) of this piece showed 98 percent calcite and a trace of dolomite. No dolomite was identified in thin sections. A chemical analysis is given in table 1. F-1-3-10.—Extremely porous and vuggy owing to many molds of coral and smaller fossils and incomplete filling of interstitial spaces by matrix. Thin sections show that the high porosity is in part due to the removal by solution of originally abundant *Halimeda* segments. Ghosts of *Halimeda* show up as dark fine outlines of original segments that are now partly packed by microgranular calcite and fringed by acicular calcite. The ragged and patchy appearance of the calcite fillings indicates further solution subsequent to initial solution of original aragonite and recrystallization. The acicular fringes of calcite on and in the *Halimeda* and other fossils are postsolution deposits. The matrix of this sample is a miliolid and coralline-algal fine sand in a partly recrystallized mud. The miliolids are well preserved and generally have fillings of granular calcite. Coral in these sections shows up as mud-filled interseptal spaces, now recrystallized into dark granular calcite, fringed by acicular and granular calcite. A bulk X-ray analysis showed 100 percent calcite; no dolomite was seen in the thin section. A chemical analysis is given in table 1. F-1-3-18.—Large vugs, as much as 2 inches in length and irregular in outline, are well developed in this piece. Vugs are lined with botryoidal masses of laminated calcite. Three megascopically conspicuous layers, each a fraction of a millimeter thick are usual. Generally the layer nearest the matrix is clear, the central layer is white, and the final layer is clear light-yellow sparry calcite. The vugs ramify through the rock and are solution channels rather than fossil molds. F-1-3-20.—Hand specimen as above. A thin section through a vug shows six distinct laminae of calcite (pl. 282*A*) that vary in thickness and degree of "dustiness." In plane polarized light the laminae are seen to cut across sheaflike calcite crystals that are oriented perpendicular to the bands; these crystals show optical continuity from the fossil base out through the sixth layer. Thus the bands merely represent interrupted crystal growth. The matrix of this piece, like F-1-3-10, has

DRILL HOLE F-1—Continued

Interval (feet)	*Drilling method*	*Recovery*	*Remarks*
			abundant miliolid tests, although fragments of encrusting algae are the most prominent constituent. Bulk X-ray analysis showed 100 percent calcite. However, a thin section etched and stained with copper nitrate revealed rare dolomite crystals in one of the vug linings. The dolomite is concentrated in the central layers of the set of calcite laminae. The dolomite has a tendency to form a band, but some of it is in the form of disconnected clusters of rhombs. The writer is unable to tell whether the dolomite is a primary precipitate, such as that described by Cullis (1904, p. 392–420) from Funafuti, or has developed by replacement of calcite. A chemical analysis of the specimen is given in table 1. *F-1-3-26.*—This lowermost piece is like those above it but has fewer well-developed vugs and calcite fillings. No dolomite was seen in thin sections. *Interpretations.*—The distribution of solution vugs through this interval indicates that these rocks have undergone prolonged subaerial solution. The repeatedly interrupted deposition of calcite in the vugs suggests that the rock was in a cyclically changing environment, possibly at or near sea level. The traces of dolomite within enclosing calcite laminae suggests that either primary dolomite deposition or conversion of calcite to dolomite took place. Whichever of these processes occurred, the dolomite formation was probably a submarine, or at least intertidal, phenomenon. The miliolid-rich matrix, the abundance of *Halimeda*, coralline algae, and the coral content point to deposition in a lagoonal environment. The presence of *Miogypsinoides dehaartii* (Cole, 1957, p. 747) suggests a shallow-water deposit. On Guam, the writer (Schlanger, 1963) found that in limestones of comparable age this foraminifer was largely restricted to reef and shallow water limestones.
1, 248–1, 718	Rock bit	No recovery.	
1, 718–1, 740	Core barrel	10 ft. 6 in. (core 4), 24 pieces.	Cores taken in this run exhibit striking differences in texture and fossil content. Representative pieces are described below. *F-1-4-2.*—Tan porous well-cemented and sorted limestone composed of tests of Foraminifera as much as 4 mm across but averaging about 1 mm; a coarse-grained calcarenite. Thin sections show that the rock is almost completely an aggregate of *Rotalia* tests (pl. 286*A*) with subordinate amounts of articulate coralline algae, a few large test of *Lepidocyclina* and *Heterostegina*, and rare pebbles of rounded coral fragments; a few miliolids are present. This fossil debris is cemented by a single thin layer of granular to acicular calcite. The texture is strikingly similar to beach rock. The primary voids between fossils are open; mud matrix is completely lacking. The internal chambers of the Foraminifera are open but lightly lined with acicular calcite perpendicular to the chamber walls. The algal debris is the same size as the dominant *Rotalia* tests. A bulk X-ray analysis of this piece showed 100 percent calcite. Spectrographic and chemical analysis are given in tables 1 and 3, respectively. *F-1-4-3 through -24.*—The foraminiferal limestone described above grades through piece 3 into dense coral-rich rock that makes up most of the interval. Instead of being finely porous, these lower pieces are dense owing to a large amount of lithified "mud" that forms the matrix; and large voids are numerous owing to the solution of abundant delicate branching corals, many of which appear to be in growth position. Some of these molds have been lined with drusy calcite since the solution of the coral. Irregular vugs are also common. Pieces 4 and 5 have parted along a steeply dipping fissure that is largely lined with a fine film of drusy calcite. Thin sections show the matrix of the rock to be a foraminiferal sand, as in piece 2, but with the addition of interstitial "mud" and thicker clear calcite. A thin section of piece 10 shows the matrix to be irregularly distributed; small patches as much as 5 mm across lack a mud fill and are cemented only by calcite films. The mud itself has been partly recrystallized to a calcite mosaic. Corals are generally coated with algae. In a few places the coral has been crosscut by irregular solution voids; some of these voids in pieces 10 and 20 show extremely fine laminae of alternating clear and dusty calcite. Tests of *Heterostegina* and *Lepidocyclina* become more abundant in deeper cores, and the grain size shows a general increase to where much of the rock is made up of particles 2 mm or more in diameter. A thin section of piece 24 shows abundant randomly oriented tests of *Lepidocyclina* as much as 5 mm in diameter; these make up about 5 percent of the rock. As above, the interstices between the still abundant *Rotalia* tests are irregularly choked with recrystallized mud. Chemical and mineralogical analyses of piece 10 are given in tables 1 and 2, respectively.

DRILL HOLE F-1—Continued

Interval (feet)	*Drilling method*	*Recovery*	*Remarks*
1, 718–1, 740	Core barrel..	10 ft. 6 in. (core 4), 24 pieces.	*Interpretations.*—The solution voids and the laminar calcite in the coral indicate that this interval, like that from which core 3 was taken, underwent a period of subaerial solution and cyclic calcite deposition. The sorting and lack of mud matrix in the upper pieces suggest that these foraminiferal sands were laid down under the influence of a strong current. The abundance of *Rotalia* tests leads the writer to compare these pieces to the equally *Rotalia*-rich limestone of Miocene age from Guam (Schlanger, 1963) which were closely associated with reef and shallow-water limestone. The delicate branching coral associated with the foraminiferal rock in the lower part of the interval suggests quiet-water conditions; the abundant mud matrix in these coralliferous cores corroborates this. Thus the lower part of the interval was probably deposited in shallow water that was generally quiet but which was influenced by currents that bore sorted debris into the possibly reef-protected area.
1, 740–1, 978	Rock bit....	No recovery.	
1, 978–2, 003	Core barrel..	20 ft 6 in. (core 5), 41 pieces.	Cores from this interval are all very dense white limestones that, taken as a whole consist of a framework of large reef-type corals, between which is packed a formainiferal-algal sand in a fine matrix. Several cores are composed entirely of completely recrystallized massive coral, much of which still shows open interseptal spaces that give the rock a locally high porosity. Much of the coral is coated with thick winding laminae of encrusting algae that are strikingly well developed in this interval. Algal coatings also serve as a cement for a large part of the rock. Many foraminiferal tests and other fossil debris are enveloped by algal laminae. Gravel-size fossils, such as tests of larger Foraminifera, echinoid spines, mollusk shells, and algal debris, are randomly packed between algal nodules and coral; primary voids between this coarse debris are largely open, as the fossils are cemented by drusy calcite. Large sections of core consist of irregular pockets of well-sorted foraminiferal-algal sand; the majority of particles range from 1 to 2 mm in diameter. Intergranular porosity in this material is low owing to the abundant fine matrix. Striking features of this interval are the well-developed solution channels that commonly pierce the core and show openings as much as 3 inches in diameter at the core surface. These ramify through the rock and are invariably lined by thin coatings of yellow drusy calcite; the surfaces of the vugs show a botryoidal structure. Bulk X-ray analyses of pieces F-1-5-3, F-1-5-9, F-1-5-26, and F-1-5-41 all showed 100 percent calcite. Chemical analyses of F-1-5-3, F-1-5-26, and F-1-5-41 and a spectrographic analysis of F-1-5-26 are given in tables 1 and 3, respectively. Descriptions of selected thin sections are given below. *F-1-5-3.*—Composed largely of subrounded fragments, mostly 1 to 2 mm in diameter, of both articulate and encrusting coralline algae, in a matrix of dark mud and fine-sand- to silt-size fossil debris. A small percentage of broken and whole tests of *Lepidocyclina* as much as 6 mm in diameter are present. However, one thin section is made up entirely of a single piece of recrystallized, massive coral. The algal-rich section shows numerous irregular voids lined with calcite. Some of these have the shape of pelecypod shells but may represent solution channels. *F-1-5-6.*—This section was cut from a pocket of matrix between coral and algal deposits. It is dominated by closely packed whole tests of *Rotalia;* minor amounts of subrounded coralline algal debris, a few broken tests of *Lepidocyclina* and *Heterostegina,* and echinoid spines are present. The *Rotalia* tests, coralline algae, and spines are almost all between 1 and 2 mm in diameter; the fossils are well sorted and the rock has an intact framework. Many of the original intertest voids are filled with dark "mud." This matrix is partly recrystallized owing to the growth of rims of acicular calcite on the outer surfaces of the Foraminifera tests. In places these acicular rims have coalesced completely and replaced the dark "mud." The calcite overgrowths are in optical continuity with the original tests; in plane polarized light very irregular pseudouniaxial crosses extend from the test wall out through the overgrown rim. In some places the "mud" has recrystallized to a granular mosaic. In a few places a mud matrix is lacking, and the cement consists only of acicular calcite rims on fossils. In these areas interfossil voids are present. The chambers of the Foraminifera, however, are filled with granular calcite that is clearer and coarser than the recrystallized matrix. The writer thinks that these tests were empty of sediment when deposited and were later filled with a chemical deposit of calcite. The intact framework suggests that the tests were deposited as a coquina that was later filled by fine mud, possibly after some cementing calcite

DRILL HOLE F-1—Continued

Interval (feet)	Drilling method	Recovery	Remarks
			was deposited; the mud fill has been partly recrystallized. This rock strongly resembles F-1-4-2. *F-1-5-9.*—Sections from this piece are largely recrystallized coral that shows well-developed partly recrystallized dark sandy mud as interseptal fillings. The edges of the coral have encrustations of both Foraminifera and algae. One section (pl. 286*B*) shows what appears to be a worm boring through a coral. The tube is filled with two types of deposits; a thin outer shell, adjacent to the coral, of fine sand and mud containing abundant angular fossil fragments, and a final filling of coarse sand made up largely of *Rotalia* tests and subrounded coralline algal debris in a mud matrix. *F-1-5-16.*—Section cut through a coral and enclosing foraminiferal-algal sand. Half the section is well cemented closely packed tests of *Rotalia* and rounded fragments of coralline algae. This debris is very well sorted; almost all fragments are about 1 mm in diameter. Much of the algae is in the form of slightly elongated rods. These show a tendency toward preferred orientation (pl. 286*C*); the section illustrated is cut perpendicular to the core axis. The matrix consists of cementing laminae of alternate dark and clear calcite which culminate in a final pore-filling deposit of granular calcite. In some interfossil voids the cloudy appearance of the matrix suggests that some "mud" may have been present. The coral, which is completely recrystallized, shows irregular solution channels that are now lined with five layers of alternate clear and dark calcite. The sequence of laminae is identical in each channel; from the coral base out there is a thick layer of clear coarse calcite, a thin very dusty layer, a very thin clear layer, a second dusty layer, and a final clear layer. All the layers are in optical continuity. In addition to the definite laminae, there are several fine lines parallel to the laminae that indicate short hiatuses in crystal growth. *F-1-5-23.*—Although not strictly representative, this section is used (pl. 286*D*) to illustrate the complex sequence of solution and recrystallization that affect both the corallum and the interseptal fillings of a coral. A description is given in the figure caption. *F-1-5-35.*—Poorly sorted conglomerate composed of whole and broken tests of randomly oriented *Lepidocyclina,* gravel-size coralline-algal debris, and rounded pebbles of coral in a matrix of sand-size foraminiferal-algal debris and dark mud (pl. 287*A*). *F-1-5-41.*—This section shows an unusual association of larger Foraminifera, chiefly *Lepidocyclina,* in a matrix of laminar encrusting algae (pl. 287*B*). Individual tests are enveloped in a complex net of the algae, which show that these tests evidently once lay on an algal mat long enough to be cemented by further algal growth. The algae also cement fine fossil debris and mud. Lesser numbers of encrusting Foraminifera are present. *Interpretations.*—As in cores 2, 3, and 4, solution, recrystallization, and chemical deposition of calcite have been operative in this interval and indicate a period of subaerial solution and movement of material through the rock. Limestones from core 5 bear a strong resemblance, with regard to fossil composition, texture, and postdepositional changes, to limestones of Miocene *e* age from Guam (Schlanger, 1963). The Guam rocks are reef and fore-reef limestones that have been exposed to subaerial solution at least once in their history. The rounding of the algal debris, the good sorting, and the intact framework of the foraminiferal-algal sand between the coral indicate that currents played a part in deposition of much of the rock. The massive coral framework is indicative of reef or near-reef conditions. Some pieces of core, such as F-1-5-35, show poor sorting and a conglomeratic texture suggestive of rapid deposition or trapping of sediment by the coral. The algae-enmeshed *Lepidocyclina* of F-1-5-41 show rapid growth of these plants. Thus this interval was probably deposited in a shallow reef or near-reef environment influenced by strong currents.
2,003-2,130	Rock bit	Cuttings	Cuttings from the 2,000- to 2,020-foot interval are heterogeneous granule-size debris containing fresh wood chips, flakes of iron, unaltered *Halimeda* fragments, gastropod shells, and tests of benthonic Foraminifera, as well as recrystallized rock chips. The two samples appear to be heavily contaminated because of caving. They are not considered representative of the interval and are disregarded. Below 2,020 feet the cuttings are all very angular flakes and chips of dense cream-colored recrystallized limestone. The size of the cuttings varies, but the lithology

DRILL HOLE F-1—Continued

Interval (feet)	*Drilling method*	*Recovery*	*Remarks*
2, 003–2, 130	Rock bit	Cuttings	appears uniform. From 2,020 feet through 2,050 feet most of the chips range from ¼ to ½ inch across; below 2,050 feet the cuttings become finer, and at 2,130 feet most are between ⅛ and ¼ inch across. By looking at the large chips while they are under water in a shallow dish, the original textures are clearly seen. Many chips are from massive completely recrystallized coral; interseptal spaces are filled with dense recrystallized mud. Other chips show laminar deposits of calcite lining old solution channels. A split of cuttings from 2,110 to 2,120 feet was stained with Meigen's solution, but no trace of aragonite was seen. *Interpretations.*—These cuttings strongly resemble those described from the 1,978- to 2,003-foot interval (core 5), and there is probably no significant change in sediment type or postdepositional history from the top of the cored interval to 2,130 feet.
2, 130–2, 662	Rock bit	No recovery.	
2, 662–2, 687	Core barrel	16 ft 5 in. (core 6), 30 pieces.	The lithology of this interval of rock is fairly constant throughout. The rocks are white very dense and well-cemented slightly vuggy limestones rich in coral, encrusting algae, and tests of larger Foraminifera. Some of the coral shows open interseptal spaces and small pockets of larger Foraminifera tests that lack a matrix; these give the rock local porosity. Large irregular vugs lined with botryoidal layers of calcite are present but are not as well developed as those in core 5. Most of the rock has very low porosity owing to the well-lithified mud matrix and the closing of many small solution channels by chemical calcite deposits. In general the interval is conglomeratic and poorly sorted. Sawed faces show pebble size irregular fragments of algae-encrusted coral, encrusting algae, and echinoid spines and plates in a matrix of foraminiferal sand and mud. The bulk of the rock is coarse-sand- and gravel-size tests of Foraminifera and other fossil debris. Todd and Low (1960, p. 806) report that smaller Foraminifera from this core are abundant and varied; they include bolivinids, globigerinids, amphisteginids, and biserial and uniserial arenaceous benthonic types. Cole (1957, p. 748) reported *Borelis*, *Heterostegina*, and two species of *Lepidocyclina* from this interval. Bulk, X-ray analyses of samples F–1–6–1, F–1–6–9, F–1–6–23, and F–1–6–30 all showed 100 percent calcite. Material scraped from a vug lining in piece F–1–6–9 was reported to contain less than 2 percent dolomite. A spectrographic analysis of F–1–6–30 and chemical analyses of F–1–6–1 and F–1–6–9 are given in tables 1 and 3, respectively. Descriptions of representative thin sections are given below. *F–1–6–1.*—Abundant broken and whole tests of *Heterostegina* packed in a poorly sorted matrix of partly recrystallized mud and sand. The sand-size fraction is rich in tests of smaller Foraminifera, which include very well preserved globigerinids and benthonic types, rounded fragments of coralline algae, pieces broken from tests of larger Foraminifera, fragments of encrusting Foraminifera, and unidentifiable fossil debris. Pebbles of recrystallized coral are present. Irregular solution channels that truncate fossils are almost entirely blocked with laminar deposits of clear and dark calcite. In one vug, at least nine distinct layers are visible. The biconvex tests of the larger Foraminifera show a high degree of parallelism. This type of orientation was also noticed in fore-reef limestones from Guam (Schlanger, 1963). *F–1–6–9.*—In this section, subparallel tests of *Heterostegina* dominate and are packed in a matrix similar to that described in F–1–6–1. Coral pebbles here are distinctly rounded. One solution channel (pl. 287*C*) evidently formed by solution of the matrix around the tests of larger Foraminifera. A few of the tests have been almost freed from the original matrix. Following the solution, the void was completely filled with chemical deposits of varying thickness, opacity, and grain size. It was material scraped from a void like this in F–1–6–9 that showed dolomite in the X-ray analysis. No dolomite was identified in thin section so it is not known whether any single lamina is dolomitic or whether the dolomite is scattered through the void filling. *F–1–6–23.*—The most prominent fossils here are well-preserved tests of *Lepidocyclina*. These large tests are randomly oriented in a matrix of fine sand and mud made up of smaller Foraminifera that include some globigerinids, amphisteginids, and serial types; fragments of coralline algae are abundant, as are pieces of encrusting Foraminifera. Tests of *Heterostegina*, so abundant directly above, are lacking. Pebbles of mud-filled coral are common; the mud in these pebbles is similar to the matrix of the rock. As in the above pieces, irregular calcite-filled solution channels are present.

DRILL HOLE F-1—Continued

Interval (feet)	Drilling method	Recovery	Remarks
			F-1-6-30.—The lower part of this piece is a solid mass of completely recrystallized coral that is recognizable in thin section only by virtue of fine dark dust lines (pl. 287*D*) which form a jigsaw pattern that represents the original interseptal spaces. The corallum has been dissolved, and the resultant space has been filled with fine granular calcite. Thin crooked partly open veins traverse the coral; these are lined with acicular calcite. *Interpretations.*—As in cores 3 through 5, evidence for subaerial solution is abundant in this interval. The presence of relatively abundant tests of well-preserved globigerinids suggests that these limestones accumulated in water deeper than that associated with reef limestones. The rounded pebbles of coral and the broken condition of many of the larger Foraminifera are suggestive of transported material. These are features also found in fore-reef limestones of Miocene *e* age from Guam (Schlanger, 1963). Thus much material from shallow water was probably swept down into deeper, fore-reef areas before final deposition.
2, 687-3, 052	Rock bit	No recovery.	
3, 052-3, 055	Core barrel	3 ft (core 7), many small pieces.	Cores from this interval are irregular pieces of chalky white friable limestone composed of sand-size fossil debris packed in a soft chalky matrix. Pieces from the upper part of the run, such as F-1-7-3, when wetted, and only after hard rubbing, break down into a coarse sand with some gravel-size pieces of coral. The pieces from the lower part of the run disintegrate easily, when wetted, into a gritty mixture of sand, gravel, and greasy white mud. No solution channels are present, and, on megascopic inspection, no chemical deposits of calcite cement were seen. On a broken surface, rounded sand-size grains, most of which are tests of smaller Foraminifera, project from the matrix; the rocks break around the fossils rather than through them. This core represents a distinct lithologic change from the well-cemented rocks recovered in core runs 3 through 6. Todd and Low (1960, p. 806) reported a rich assemblage of globigerinids with minor amounts of small benthonic types from this interval; Cole (1957, p. 749, table 4) reported only abundant tests of *Heterostegina saipanensis* Cole. Bulk X-ray analysis of piece F-1-7-3 and a combined sample of pieces F-1-7-6 and F-1-7-7 showed 100 percent calcite. Chemical and spectrographic analyses of these samples are given in tables 1 and 3, respectively. Description of thin sections follow. *F-1-7-3.*—The slight degree of cementation shown by this piece facilitated the making of a good thin section. This shows sand-size fragments of coralline algae, worn and broken tests of larger Foraminifera, and well-preserved tests of globigerinids in a sandy mud matrix. Echinoid debris is also present. A small percent of the algal and foraminiferal particles reach a size of 4 to 6 mm. The mud matrix shows a slight degree of alteration to finely granular calcite. Some of the fossils that project into irregular pores are coated with thin films of granular and acicular calcite that form the cementing material (pl. 287*E*). No vugs filled or lined with laminar calcite deposits are present. This is in sharp contrast to such features seen in cores 3 through 6. *F-1-7-6 and -7.*—This material broke down during cutting, and only small chips could be mounted for sectioning. Most of these pieces appear as masses of unrecrystallized dark mud containing scattered tests of larger Foraminifera and algal debris as well as tests of globigerinids. This mud is largely unlithified, as shown by the smearing out of many pieces and the rapid disintegration in water. A few pieces are made up of coral pebbles. This coral is comparatively well-preserved; the original corallum still shows as a light-brown finely fibrous structure. The interseptal spaces are open but lightly lined with clear granular calcite. The coral appears unaltered; however, staining of other coral pebbles with Meigen's solution shows the coralla to be calcite. Also the bulk X-ray analysis of this piece of core showed 100 percent calcite. Rounded and broken tests of *Heterostegina* are common. The chambers and edges of these have thin films of granular calcite. *Interpretations.*—The unconsolidated nature of much of this material suggests that the rocks were not subjected to any prolonged period of subaerial solution. However, the change of the originally aragonite corals to calcite shows that some alteration took place. The appearance of these corals in thin section suggests that the original aragonite was dissolved prior to the deposition of calcite. These actions did not reach completion inasmuch as the original skeletal structure is still distinct. The abundant globigerinids in the cores indicate, according to Todd and Low (1960, p. 815), a depth of deposition of not less than 100 fathoms. The abundant rounded coralline-algae debris and the coral pebbles show that material from

DRILL HOLE F–1—Continued

Interval (feet)	*Drilling method*	*Recovery*	*Remarks*
3, 052–3, 055	Core barrel	3 ft (core 7), many small pieces.	shallow-water, possibly reef, environments was carried down into deeper water, where it mixed with planktonic tests that were also being deposited there.
3, 055–3, 350	Rock bit	No recovery.	
3, 350–3, 353	Core barrel	3 inch (core 8) 1 piece.	One piece of core was recovered in this interval. The limestone is a white porous friable poorly sorted conglomerate. The single core contains an irregular piece of massive coral 2 inches in diameter. The rock has a chalky appearance and resembles pieces from the 170- to 190-foot interval of core 1. The dense lithified mud and solution channels common in cores from runs 3 through 6 are lacking here. Spaces between fossil fragments are largely open; drusy calcite cement is lacking. The bulk of the rock is coarse sand- and pebble-size foraminiferal and algal debris. In thin section the rock has a fretted appearance; much of the coral has been dissolved and replaced by a lacework of finely granular calcite (and dolomite?). In one slide a coral fragment still shows a trace of its original brown fibrous structure. The foraminiferal-algal debris, which includes many worn and broken tests of *Heterostegina*, is lightly cemented by very thin films of granular calcite. Patches of recrystallized dark mud partly fill some interstices between fossils. Well-preserved tests of globigerinids are common. The chambers of the Foraminifera and interseptal spaces in the coral are largely open but lined with granular calcite (and dolomite?). No dolomite could be positively identified in this thin section, but a bulk X-ray analysis of F–1–8–1 showed 98 percent calcite and a trace of dolomite. Chemical and spectrographic analyses are given in tables 1 and 3. *Interpretations.*—The solution and replacement of corals in this interval and the minor calcite cement suggests a period of subaerial solution and chemical deposition of calcite. As in core 7, solution effects are minor compared to those seen in cores 3 through 6. Todd and Low (1960, p. 815) interpret the abundant globigerinids in this interval as indicating deposition at a depth of not less than 100 fathoms. The coarse coral and algal debris is probably shallow-water or reef-derived material that was swept down to greater depths, where it mixed with deeper sediments represented by the planktonic Foraminifera.
3, 353–3, 655	Rock bit	No recovery.	
3, 655–3, 665	Core barrel	3 ft. 3 in. (core 9), 10 pieces.	Cores from the upper part of this interval differ markedly from those recovered in the lower part with regard to texture, degree of cementation, and fossil content. *F–1–9–2 and –3.*—These pieces are representative of the upper part of the interval and strongly resemble the piece recovered in core 8. They are white chalky friable porous foraminiferal-algal conglomerates that contain a few pieces of rounded coral as much as one-half inch across; most of the fossils are from 1 to 4 mm in diameter. The size of the fossil debris varies, and there is one lens in which the dominant size is approximately 4 to 6 mm. Surrounding this illdefined lens is rock composed of dominantly sand-size fossils. Solution channels and drusy calcite cement are lacking. Individual Foraminifera are easily picked out of the soft matrix. The rock disintegrates readily in running water. A bulk X-ray analysis of F–1–9–2 showed 100 percent calcite. A chemical analysis is given in table 1. A thin section of F–1–9–2 shows the dominant fossils to be broken and worn tests of *Heterostegina*, rounded fragments of coralline algae, and well-preserved tests of globigerinids. Minor amounts of echinoid debris, fragments of mollusk shells, recrystallized coral, and tests of benthonic Foraminifera are present. Most of the interstices between the fossils are open and the cement is a fine layer of dusty granular calcite. In addition to the individual fossils, there are numerous subrounded pebbles of dense well-cemented recrystallized rock containing coral, laminar encrusting algae, and foraminiferal debris in a dense mud matrix. *F–1–9–6, 8 and –10.*—These pieces are typical of the lower part of the interval. They are white dense but vuggy well-cemented poorly sorted conglomerates containing fragments of coral as much as 1 inch across and a single *Pecten* valve 2 inches long. Molds of small fossils are abundant, and the coral has been replaced by calcite. The *Pecten* shell, made of calcite, appears to be relatively unaltered. Much of the cementing material is white drusy calcite; this material also lines some of the vugs and fossil molds. Thin sections of pieces F–1–9–6 and F–1–9–8 show abundant molds of *Halimeda* segments, corals, mollusks, and even coralline algae (pl. 288*A*). These molds are responsible for the fine porosity shown in these pieces. Undissolved and recognizable fossil remains include fragments of coralline algae, tests of smaller Foraminifera including globigerinids and benthonic types, and echinoid debris. The fossils and molds are randomly oriented in a recrystallized

DRILL HOLE F–1—Continued

Interval (feet)	*Drilling method*	*Recovery*	*Remarks*
			mud matrix. In places the matrix has recrystallized to a clear mosaic of calcite. Around many fossils the original mud has recrystallized into fibrous calcite that extends from the fossil edges perpendicularly into the mud. A bulk X-ray analysis of F–1–9–6 showed 100 percent calcite. *Interpretations.*—The lithologic break in this interval resulted from a change in type of sedimentation. The globigerinid- and coral-bearing conglomerate in the lower part of the interval may have formed by mass slumping of material such as *Halimeda* and coral downslope from shallow water into a fine "mud" containing globigerinids in deeper water. The comparatively good sorting shown by the sediments in the upper part of the interval, the high percentage of broken and worn *Heterostegina* tests, and the lack of mud matrix suggest deposition by moving water. Both rock types were probably deposited seaward from a reef or shoal, as evidenced by the abundant well-preserved globigerinids. Todd and Low (1960, p. 815) interpreted these rocks as having been deposited in no less than 100 fathoms of water. The abundant fossil molds in the lower part indicate that this interval underwent some subaerial solution. The pebbles of rock seen in F–1–9–2 and F–1–9–3 indicate that some breaking up of previously lithified older sediment was going on during deposition of this interval.
3, 669–3, 963	Rock bit----	No recovery.	
3, 963–3, 988	Core barrel--	3 ft, (core 10) 11 pieces.	*F–1–10–1.*—Four small pieces are included. White, friable to cemented, porous limestone composed of coarse-sand-size tests of Foraminifera and rod-shaped algal debris containing irregular fragments of encrusting algae and recrystallized coral. A few mollusk shells are present. In a few places the encrusting algae forms a cement for the smaller fossils. A thin section through the foraminiferal-algal sand shows it to be a coquina of well-preserved globigerinid tests, rounded fragments of coralline algae, broken and worn tests of both larger and smaller benthonic Foraminifera, and echinoid debris (pl. 288*B*). The globigerinid tests show up as pseudo-uniaxial crosses in plane-polarized light. The echinoid spines and plates show well-developed optically continuous overgrowths of clear clacite that extend completely across original interstices and form local cement. The rock has high porosity owing to lack of a mud matrix. The fossils are lightly cemented by thin films of dusty granular calcite. *F–1–10–3 through –6.* These pieces are all white porous slightly friable limestone composed of tightly packed tests of both larger and smaller Foraminifera and coralline algae. The great bulk of the material ranges from 1 to 4 mm across; a small percentage of the algal fragments reach lengths of 6 to 8 mm. The biconvex lens-shaped tests of larger Foraminifera and the rod-shaped fragments of coralline algae show a preferred orientation such that their long axes tend to lie perpendicular to the core axis. On a sawed surface cut perpendicular to the core axis the elongate fragments show no preferred orientation. Thin sections of piece F–1–10–5 show, in addition to the fossils mentioned above, abundant well-preserved globigerinids. The framework of the rock is intact, and a mud matrix is lacking. The fossils are cemented by thin films of granular calcite; primary voids are open. A bulk X-ray analysis of F–1–10–5 showed 100 percent calcite; a chemical analysis is given in table 1. *F–1–10–8 through –11.* In these lower pieces, large fragments and, in places, cementing crusts of coralline algae reappear. A few molds of pebble-size coral fragnents are also present. The bulk of the rock is similar to pieces F–1–10–3 through –6. In addition to the algal cement, the sand-size foraminiferal-algal debris is well cemented although still porous. Locally however, patches of this sand have a dense, lithified mud matrix. Thin sections of piece F–1–10–11 show that in addition to the usual globigerinids and other fossils similar to those in the rest of the interval, completely recrystallized mud-filled coral fragments are common. The encrusting algae is evidently in place and binds a lot of slightly recrystallized mud. Irregular patches of the rock show a dark mud matrix. This piece is well cemented by thick intergrown rims of granular and acicular calcite. *Interpretations.*—The coral molds in pieces from this interval indicate some exposure to subaerial solution. Cole (1957, p. 749, table 4) identified *Asterocyclina, Operculina, Gypsina,* and *Pellatispira* from this interval and concluded that the rocks were deposited in about 70 fathoms of water. On the basis of the planktonic foraminiferal assemblage Todd and Low (1960, p. 215) conclude that the depth of deposition was at least 100 fathoms. The degree of sorting, the general lack of

DRILL HOLE F-1—Continued

Interval (feet)	*Drilling method*	*Recovery*	*Remarks*
3,963–3,988	Core barrel__	3 ft. (core 10), 11 pieces.	fine matrix, and the numerous broken tests of larger Foraminifera all combine to show that the sediment underwent considerable transport prior to final deposition. The abundant rounded fragments of coralline algae and the coral pebbles were probably shallow water contributions that were swept by currents into deeper water.
3,988–4,197	Rock bit____	No recovery.	
4,197–4,222	Core barrel__	11 ft., 2 in. (core 11), 37 pieces.	Pieces from this interval are all white porous friable limestones that are composed almost entirely of tests of both larger and smaller Foraminifera and fragments of coralline algae; no coral or molluscan remains were seen megascopically. The fossils are closely packed and the interstices between them are largely open. The only lithologic variation, on a megascopic scale, is a gradual change in grain size from the top of the interval downward. This is due to an increase in abundance of test of larger Foraminifera that reach diameters of 8 mm. The lower pieces are composed largely of coarse-sand-size foraminiferal and algal debris that contains about 10 percent of larger tests. The upper pieces are almost entirely coarse-sand-size fossil debris. On freshly broken surfaces scattered dolomite crystals are recognized by virtue of sharp reflections of light from well-developed crystal faces. Bulk X-ray analyses of F–1–11–1, F–1–11–9, and F–1–11–37 showed less than 2 percent dolomite; F–1–11–18 and F–1–11–29 showed less than 8 percent. Chemical analyses of these same pieces are given in table 1. Cole (1957, p. 749, table 4) identified *Asterocyclina, Fabiana,* and *Biplanispira* from this interval. Todd and Low (1960, p. 807; table 3) identified abundant *Triloculina, Peneroplis,* and globorotalids. Thin-section descriptions of representative pieces are given below. *F–1–11–5.*—The section shows an intact framework of sorted sand-size fossils dominated by rounded fragments of articulate coralline algae and a few fragments of encrusting coralline algae. Tests of *Triloculina* and other benthonic smaller Foraminifera are also abundant; the foraminiferal and algal debris make up at least 90 percent of the rock. A few broken and worn tests of larger Foraminifera and rare pieces of echinoid spines and plates are present. Almost all the voids between fossils are open, but there are rare patches of a microgranular calcite matrix. The coralline algae shows light-brown rims and black cores. Euhedral rhombs of dolomite are scattered throughout, and many of these are within or projecting from the rim of a piece of coralline algae. The fossils are cemented by thin coatings of acicular and granular calcite. *F–1–11–9.*—This section is similar to F–1–11–5 except for the presence of a recrystallized mud matrix that fills about one-third of the interstices between fossils. Also much of the algal and foraminiferal debris appears to have been broken following deposition. Many fossils are cracked, and the adjoining pieces are slightly offset. There is a slight degree of interpenetration of fossils with the development of stylolitelike contacts. No thin sections from cores taken above this interval show such interpenetration and breakage. *F–1–11–18.*—This piece is similar to F–1–11–5 and F–1–11–9 except for the presence of crude bedding caused by variation in grain size. The core piece is approximately 2 inches long. The upper inch and the lower half inch are made up of fossils approximately 1 mm in diameter. These layers are porous. The near-central half inch of the piece is finer grained and less porous. The thin section, cut perpendicular to the bedding, shows the finer layer to contain much mud and abundant small globigerinids (pl. 288*c*). The coarser layers are rich in *Triloculina,* which are rare to lacking in the finer layer. Further, elongate algal rods in the coarser layers tend to lie parallel to the bedding. Euhedral rhombs of dolomite are more abundant in this piece than in those taken above. *F–1–11–26.*—Well-sorted porous limestone much like F–1–11–5 but showing abundant dolomite crystals. Most of the dolomite is in the form of scattered rhombs, but local patches of intergrown crystals form irregular mosaics. Some pieces of algae are almost entirely replaced by these mosaics. Tests of Foraminifera are almost entirely free of dolomite crystals except where these crystals encroach on the tests from adjacent algal fragments. However, a few tests do contain euhedral rhombs, and some algal fragments are free of dolomite. *F–1–11–30.*—This piece differs from the above in that it contains abundant tests of *Biplanispira* and *Asterocyclina.* A few rounded pieces of recrystallized coral the same size as the larger Foraminifera tests are present. These tests show a preferred orientation parallel to the bedding. Dolomite is abundant and not partic-

DRILL HOLE F–1—Continued

Interval (feet)	Drilling method	Recovery	Remarks
			ularly associated with algal debris. Much of the dolomite is in a fretted microgranular matrix which looks like a recrystallized sandy mud. Patches of this matrix close many interfossil areas. Tests of the larger Foraminifera are generally free of dolomite. *F–1–11–34.*—The texture of this piece is basically similar to F–1–11–30 except that broken and worn oriented tests of larger Foraminifera are the dominant fossil (pl. 288*D*). Mud matrix is almost completely lacking, and the fossil debris is in close contact. The chambers of the Foraminifera are entirely open. Dolomite crystals form only a trace of this piece, and they are small and scattered. *Interpretations.*—The most striking characteristics of this interval are the vertical variations in grain size, matrix content, and obvious fossil orientation. These features give parts of the interval crude bedding. The rounding and sorting of the fossils and the high degree of breakage shown by the larger Foraminifera combine with the bedding to indicate deposition under the influence of currents of varying competence. Most of the material probably underwent some transport before burial. Association of abundant planktonic Foraminifera with the fine-grained bed in F–1–11–18 suggests that this thin bed represents untransported material. On the basis of the smaller Foraminifera, Todd and Low (1960, p. 815) interpreted this interval as an outer-slope deposit. The abundant algal debris and the rare rounded coral fragments are shallow water contributions. The origin of the dolomite in this and other intervals is discussed in the body of the text.
4, 222–4, 316	Rock bit	No recovery.	
4, 316–4, 341	Core barrel	8 ft. (core 12), 24 pieces.	The chief feature of this section is the high content and vertical variation of dolomite. Bulk X-ray analyses show a range from 11 to more than 98 percent dolomite. Analyses of pieces F–1–12–(1, 2, 3) composite, –4 top, –4 bottom, –5 top and bottom composite, –7 top, –7 bottom, –10, –12, and –23 are given in table 2. Chemical and spectrographic analyses of these same pieces are given in tables 1 and 3 respectively. To study the distribution of dolomite better, 10 individual pieces were stained with copper nitrate, which coats calcite with a blue precipitate and does not affect the dolomite. Descriptions of individual pieces and thin sections are given below, and a brief discussion of relations between pieces follows. *F–1–12(1–2–3).*—These are white porous friable limestones made up of tests of larger Foraminifera from 2 to 6 mms in diameter; coarse-sand-size debris of coralline algae, rare rounded pebbles of coral, rare echinoid spines, and megascopically unidentifiable fossil debris. Voids between fossils are largely open, although irregular patches and streaks in the rock have a fine matrix. Slight variations in grain size and preferred orientation of the biconvex discoidal tests of the Foraminifera impart a crude layering. The layers dip at about 22°. Clear euhedral rhombs of dolomite several tenths of a millimeter in diameter are scattered through the rock. Some of the dolomite forms irregular solid patches composed of clusters of crystals. A bulk X-ray analysis of a composite sample of pieces –1, –2, and –3 showed 11 percent dolomite. Thin sections show most of the fossils to be worn, broken, and subangular. Much of the rock is cemented by a fretted and patchy matrix of recrystallized mud and granular calcite. Some of the fossils are slightly interpenetrating and show fractures and slight offsets indicative of breakage by compaction after deposition. The coral pebbles are barely recognizable owing to intense recrystallization, but dolomite crystals are abundant in the coralline algae and scattered through the matrix. The tests of larger Foraminifera are particularly resistant to dolomitization. Most dolomite crystals are from 0.1 to 0.5 mms in diameter, but there are rounded pebbles(?) of lithified mud that are hosts to very small dolomite crystals which float in this mud. Much of the fossil debris shows corroded edges where it projects into interstices, and many dolomite crystals show rounded and corroded faces in the same situation. Many voids cut across fossils, and this suggests that some solution and removal of matrix and fossil material took place after formation of the dolomite. *F–1–12–4.*—This is a 5-inch piece of highly dolomitized limestone whose upper end is largely a well-indurated mixture of tan sugary dolomite and white chalky calcite. The relict calcite is present both as fine matrix packed between touching dolomite crystals and as scattered irregular patches up to 4 mm across. This part of the core is finely porous. Down from the upper end, the rock becomes more dolomitic

DRILL HOLE F-1—Continued

Interval (feet)	*Drilling method*	*Recovery*	*Remarks*
4, 316–4, 341	Core barrel	8 ft. (core 12), 24 pieces.	as the white calcite thins and disappears toward the bottom. At the lower end the core is a solid mass of tan sugary dolomite. Voids as much as 10 mm across are common. These are lined with perfect euhedral rhombs of dolomite. Many of these voids have the shape of larger Foraminifera and are oriented with their long axes parallel to the diameter of the core. The voids probably resulted from the solution of tests that lay in the bedding planes. Many of the dolomite crystals show white cloudy centers. Bulk X-ray analyses of a chip from the top of the piece showed 65 percent dolomite and 35 percent calcite; the bottom of the piece analysed at more than 98 percent dolomite and less than 2 percent calcite. A stained chip from the upper piece shows the dolomite to be irregularly concentrated; areas as much as 1 inch across are almost entirely clear, unstained dolomite. Irregular areas of calcite that stained blue reach lengths of one-half inch. A stained chip from the bottom of the piece showed no detectable calcite. A thin section of F-1-12-4*t* (top) shows a mosaic of dolomite rhombs that average about 0.3 mm in long dimension. In many places these are closely packed and largely subhedral to anhedral. Irregular voids bounded by crystal faces are common. Between many crystals are patches, bounded by crystal faces, of original rock. Some of these patches are relict mud matrix, others are relict pieces of fossils including coralline algae and larger Foraminifera. These are recognizable only by virtue of their internal structure; encroaching dolomite crystals have destroyed their outlines. This relict calcite forms the chalky spots seen megascopically. Most of the dolomite crystals show cloudy centers and good cleavage parallel to the crystal faces. Under high magnification (344×), using a petrographic microscope, the individual dolomite crystals show cloudy and patchy extinction owing to the presence of abundant shredlike bodies of calcite(?) that extinguish in various positions other than that of the host crystal. These inclusions make up 3 or more percent of the dolomite crystal. A thin section of F-1-12-4*b* (bottom) shows a mosaic of anhedral even-grained dolomite crystals from 0.1 to 0.3 mm across. Most crystals show cloudy centers and clear edges, but there are vague streaks through the thin section where the entire dolomite mosaic is cloudy. A photomicrograph of F-1-12-10 (pl. 282*c*), which is similar to F-1-12-4, illustrates this texture. Relict calcite is present as small angular areas, dark in thin section, between dolomite crystals. *F-1-12-5.*—This is a 5-inch core of massive tan sugary hard dolomite. Numerous disk-shaped voids less than 8 mm in diameter are present that result from solution of Foraminifera. A few larger voids as much as 1 by ½ inch in size are present. The long axes of these voids tend to parallel the diameters of the core. Clusters and strings of clear dolomite crystals lie in these voids. There are rare scattered flecks of chalk-white relict calcite. A bulk X-ray analysis of a composite sample composed of chips from both the upper and lower parts of the piece showed more than 98 percent dolomite and less than 2 percent calcite. The original texture of the rock has been completely destroyed except for the fossil-shaped solution voids that show preferred orientation. Thin sections of F-1-12-5*t* (top) show an even-gained mosaic of anhedral dolomite with an average grain size of 0.2 mm. The inner halves of the grains are charged with inclusions that give the rock a dusty look. In general the rims of the crystals are clear. There are streaks and pods of very dusty anhedral dolomite; in the interstices between crystals there is relict calcite that looks like mud matrix or relict fossils (pl. 282*B*). The section contains many Foraminifera-shaped and minute irregular voids. *F-1-12-7.*—This is an 8-inch-long piece of massive tan dolomite. The upper part is aphanitic dense dolomite that grades downward to sugary dolomite containing scattered flecks of chalky white calcite. Foraminiferal-shaped voids are scattered throughout and do not tend to lie in planes as do those in E-1-12-5. Irregular voids as much as 1½ inches by 1 inch in size are present; these show traces of coral impressions and result from solution of coral fragments. A conspicuous feature of this piece is a set of fine fractures that extends through the entire core and roughly parallel its axis. These fractures are paralleled by closely spaced hairline fractures that reach about one-quarter of an inch from the central fracture. En echelon fractures extend from the main fractures and make acute angles toward the top of the core of from 10° to 30°. The cracks are most distinct at the top of the piece and fade out toward the bottom. In a few places, small slivers that resemble structural horses and that are as much as one-half inch in length are enclosed where the main fracture splits in two and rejoins. No offsetting can be seen,

DRILL HOLE F-1—Continued

Interval (feet)	*Drilling method*	*Recovery*	*Remarks*
4, 316–4, 341	Core barrel	8 ft. (core 12), 24 pieces.	but the fracturing suggests that some movement took place along these cracks, probably after the rock had been dolomitized to its present dense well-lithified condition. Bulk X-ray analysis of the upper part showed more than 98 percent dolomite and a trace of calcite; the lower part contained 89 percent dolomite and 11 percent calcite. Thin sections of F-1-12-7*t* show a very fine grained mosaic of anhedral dusty dolomite with an average grain size of 0.04 mm. Many interstices between dolomite grains are filled with dark relict calcite. Certain areas, less than 1 inch in width, are characterized by regularly spaced voids about 0.5 mm in diameter surrounded by coarser clearer dolomite (pl. 282*D*). The size and shape of these areas and the void distribution within them suggest that they were once occupied by coral fragments, now completely replaced. Many irregular patches of microgranular very dusty dolomite as much as several millimeters in diameter are present; these may be fossil "ghosts." Thin sections from the lower part of the core show numerous sand-size relict fossils, many of which are coralline algae and echinoid debris. The dolomite matrix is coarser than that in the upper part and averages approximately 0.2 mm in grain diameter. *F-1-12-8 and -9.*—These two pieces of core, totaling 6 inches in length, are composed of white slightly porous slightly friable mixtures of sugary dolomite and chalky calcite. About 75 percent of the rock is dolomite in the form of evenly distributed crystals; the remainder is relict fossils, including tests of larger Foraminifera and coralline algae. The disclike tests have preferred orientation. Many tests have been dissolved and left platy voids. Thin sections of F-1-12-8 and -9 illustrate how the dolomite crystals have largely obliterated the original texture. However, enough parts of the tests and coralline algae persist to show that the rock was a coarse-grained mixture of packed Foraminifera and coralline algae; echinoid debris that resisted dolomitization is common. The original rock must have closely resembled core pieces 1 through 3. *F-1-12-10.*—The upper part of this 3-inch piece is solid tan dolomite that is sugary in texture and contains abundant platy voids. The lower inch, however, contains abundant calcitized fossils, including larger Foraminifera, which parallel the voids in the upper part. A bulk X-ray analysis of the upper part showed 93 percent dolomite and 7 percent calcite. The lower part contains about 85 percent dolomite and 15 percent calcite. A thin section of F-1-12-10 shows a typical void in a matrix of solid dolomite (pl. 282*C*); no recognizable fossils remain except rare echinoid debris. *F-1-12-12.*—This piece is very similar to pieces 8 and 9; however, it contains 45 percent dolomite by X-ray diffraction method, and the original texture and fossil content is easily seen. Abundant tests of larger Foraminifera, coralline algae fragments and echinoid debris are closely packed and well oriented. Many of the interstices between fossils are open but, in places, original fine matrix is present. Some fossils have been slightly attacked by solution. The dolomite is evenly scattered throughout. It shows corroded edges that project into irregular voids and suggest some solution following dolomitization. *F-1-12-14.*—In this piece, which is similar to F-1-12-12, the resistance of larger Foraminifera to dolomitization is evident (pl. 288*E*). Growth of secondary dolomite has effaced original texture, and these tests remain unaffected except for the encroachment of automorphic dolomite around their edges. Solution of these tests would produce voids. *F-1-12-16.*—This piece shows a variation in dolomite crystal size in a plane perpendicular to the crude bedding. Where the rock is composed of coarse fossil debris, such as larger Foraminifera, the dolomite crystals average about 0.2 mm in diameter and almost completely fill the interfossil spaces. In a crude bed of sand-size fossils packed in a dense mud matrix, the dolomite crystals are more widely scattered and average approximately 0.1 mm in diameter. *F-1-12-23 and -24.*—These lower most pieces are dolomitic conglomerates made up of coral fragments, tests of larger Foraminifera, and corollain algae. Bedding is lacking. Piece 23 showed 42 percent dolomite by X-ray diffraction. *Interpretations.*—Todd and Low (1960, p. 807) state that the fauna of core 12, like that of core 11, represents a transitional foraminiferal assemblage between a largely planktonic one in cores 7 through 10 and a largely benthonic one in cores 13 through 15. Todd and Low interpreted this assemblage as indicating deposition on an outer slope subject to contamination by shallow-water sediments swept downward.

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DRILL HOLE F-1—Continued

Interval (feet)	*Drilling method*	*Recovery*	*Remarks*
4, 316–4, 341	Core barrel__	8 ft. (core 12), 24 pieces.	The writer agrees inasmuch as the bedding, the larger Foraminifera-coralline algae-coral fragment assemblage, and the wearing of the fossils are reminiscent of these same features in fore-reef limestones of both Miocene and Eocene age on Guam (Schlanger, 1963). The interpenetration of fossils and the offsets along fractures in the fossils are indicators of compaction following deposition. The lithology of the interval of rock was evidently fairly homogeneous prior to dolomitization; the rocks were largely foraminiferal-algal aggregates. The variation in intensity of dolomitization was probably not controlled, therefore, by initial differences in texture. Piece F-1-12-16 however, shows that original texture may have had some effect. Following dolomitization the rock was subjected to some solution, as evidenced by the numerous platy voids relict after Foraminifera tests. Plate 288*E* shows how these tests resist dolomitization but do allow dolomite crystals to penetrate their edges. Upon solution the resultant voids appear to be lined by euhedral crystals much like a drusy calcite vug lining. If it were not for the few remaining tests, one might interpret the euhedral dolomite that lines the voids as having grown into open spaces.
4,341–4,406	Rock bit____	No recovery.	
4,406–4,431	Core barrel__	1 foot (core 13), 5 pieces.	*F-1-13-2.*—Porous white slightly friable conglomerate composed of tests of larger Foraminifera from 4 to 8 mm in diameter, rounded fragments of coralline algae, irregular masses of encrusting algae and Foraminifera, and pebbles of dense rock set in a matrix of sand-size foraminiferal and algal debris. Interstices between fossils are largely open. The larger Foraminifera show a tendency to preferred orientation parallel to the diameters of the core. Most of the tests are chipped and worn. Some have been broken in place following burial. Bulk X-ray analysis of F-1-13-2 showed 100 percent calcite; however, etching with dilute hydrochloric acid and staining with copper nitrate revealed the presence of scattered rare dolomite crystals. These amount to perhaps 0.1 to 0.2 percent of the rock by volume and average 0.08 mm across. Large parts of the piece have no dolomite; the chip submitted for analysis may have been from one of these parts. The dolomite is not associated with any particular fossil group. Thin sections of F-1-13-2 and -3 reveal the presence of well-preserved tests of planktonic Foraminifera, rounded echinoid debris, and tests of small benthonic Foraminifera. Some of the rounded pebbles are seen to be pieces of fine-grained, recrystallized rock. Also present are irregular masses of encrusting algae and intergrown Foraminifera, whose convolutions contain mud and fossil debris finer than the coarse sediment of the surrounding rock. Contacts between the pebbles and algal-foraminiferal masses and the enclosing sediment are sharp. *F-1-13-4 and -5.*—These pieces contain abundant larger Foraminifera and algal debris like the pieces described above, but these are confined to irregular pockets separated by denser rock that contains much fine well-lithified matrix. Molds of small coral fragments and mollusks are present. Staining of these pieces reveals very rare small crystals of dolomite. *Interpretations.*—Cole (1957, p. 749, table 4)reports four species of *Asterocyclina* plus *Operculinoides* and *Camerina* from this interval. Todd and Low (1960, p. 815) identified many small benthonic types and some planktonics including globorotalids. Todd and Low interpreted this as an outer slope assemblage. In core 12 the texture of the rock and the fossil content allow comparison to similar features of fore-reef limestones from Guam (Schlanger, 1963). The rounded pebbles of "foreign" rock and the masses of encrusting algae and Foraminifera indicate that destruction of previously lithified rock was taking place during deposition of this interval. Perhaps a subaerially exposed area existed upslope at this time and contributed these fragments. The coral and mollusk molds in F-1-13-4 and -5 suggest some solution.
4, 431–4, 500	Rock bit_____	No recovery.	
4, 500–4, 525	Core barrel__	8 ft (core 14), 29 pieces.	The upper 24 pieces of core, aggregating about 7 feet, are almost identical lithologically. They are porous well-cemented well-sorted tan foraminiferal-algal limestones. The pieces are massive; no bedding, solution voids, or fractures are present. Except for rare scattered echinoid and mollusk fragments, which attain lengths of several millimeters, the foraminiferal and algal debris is between ¼ and ½ mm in diameter. Bulk X-ray analyses of F-1-14-8 and F-1-14-11 showed more than

DRILL HOLE F–1—Continued

Interval (feet)	Drilling method	Recovery	Remarks
			98 percent calcite and a trace of dolomite. A stained piece of F–1–14–11 revealed rare scattered euhedra of dolomite. Pieces 25 through 28 are somewhat coarser grained owing to: (1) the presence of tests of larger Foraminifera as much as 4 mm in diameter, fragments of various mollusk shells up to half an inch long, including *Pecten* and small gastropods, and fragments of coralline algae; and (2) a general increase in grain size of the bulk of the foraminiferal-algal debris to an average size of about half a millimeter. Rare crystals of dolomite are also present in these pieces. Piece 29 is radically different from the above pieces. It is well-cemented white limestone composed of thick encrusting algal laminae in which are enclosed coral molds and foraminiferal-algal debris packed in a lithified mud matrix. Bulk X-ray analysis of this piece showed 100 percent calcite, but a stained piece showed rare crystals of dolomite. Thin section descriptions are given below. *F–1–14–2.*—The bulk of the rock is randomly oriented thick-walled benthomic smaller Foraminifera. The chambers of these are largely open, and in plane polarized light the tests show a fibrous structure. Next most abundant are fragments of coralline algae, both articulate and encrusting, these are rounded and the same size as the Foraminifera. Also present, in minor amounts, are fragments of mollusk shells and echinoid debris as much as 2 mm in length. The mollusk shells still show their original fibrous structure. There is no evidence for strong recrystallization and solution. In many places the dark coralline algae have been squeezed between and penetrated by the tests of Foraminifera and appear at first glance to be a dark mud matrix, but cellular structure can be seen. There is some true fine-grained matrix present, however, between the intact framework. No dolomite was seen in thin section. *F–1–14–17.*—A very porous rock made up mostly (65 percent) of test of benthonic smaller Foraminifera. A small percentage is composed of fragments of coralline algae. The chambers of the tests are open and almost all the interstices between the fossils are open. These are cemented by thin films of granular and acicular calcite, and the chambers are lightly lined with the same material. Some of the fossils show postdepositional breakage. A few complete tests of *Asterocyclina* and many fragments of tests of *Operculinoides*(?) are present. The algal and operculiniod debris is the same size as the dominant tests of complete smaller Foraminifera, which indicates sorting. There are some ragged patches of microgranular calcite between tests that may be relict, recrystallized, and partly dissolved mud matrix. No dolomite was seen in thin section. *F–1–14–28.*—This piece shows a less sorted aggregate of foraminiferal and algal debris within a well-lithified patchy mud matrix. Foraminifera tests range from thin-walled planktonic types 0.1 mm in diameter to benthonic larger types as much as 6 mm in diameter. Even though mud matrix is common, the chambers of these tests are open. Scarce dolomite euhedra are scattered throughout. *F–1–14–29.*—This thin section shows sinuous laminae of encrusting coralline algae enveloping coral fragments and finer debris. The coral has been completely dissolved, leaving open space where the original septae were and granular mosaics of calcite in place of originally mud-filled interseptal openings. Also enclosed by the algae is poorly sorted sandy mud that contains coralline algae and well-preserved miliolid Foraminifera. These tests retain a light-brown color in transmitted light. The original mud matrix has recrystallized into microgranular calcite. *Interpretations.*—Both larger and smaller foraminiferal assemblages in the upper 28 pieces indicate deposition in a fore-reef, outer slope environment. Good sorting and largely open interstices suggest deposition from moving water. Piece 29 shows such a different lithology and fossil content that the writer regards it as a cored piece of a block that was swept downslope. Further, the bottom of piece 29 shows a coating of foraminiferal-algal sand like the rest of the core run. The high content of laminar algae and coral suggest that this lowermost piece is of reef origin.
4, 525–4, 528	Rock bit	No recovery.	

DRILL HOLE F-1—Continued

Interval (feet)	*Drilling method*	*Recovery*	*Remarks*
4, 528–4, 553	Core barrel__	2 ft 6 in. (core 15), 13 pieces	Pieces recovered in this interval show lithologic similarities to those from core 14; two distinct rock types are present. Pieces 1 and 2 are foraminiferal-algal limestones, and pieces 3 through 13 are dominated by laminar algae. Bulk X-ray analyses of F-1-15-2 and -13 showed 100 percent calcite; however, copper nitrate-stained pieces and thin sections showed that rare dolomite persists throughout the interval, amounting to perhaps 0.1 percent of the rock by volume. Representative pieces and thin sections are described below. *F-1-15-1 and -2.*—These are white porous slightly friable limestones made up largely of poorly oriented tests of Foraminifera and algal debris from ½ to 1 mm in diameter. Also present are angular to rounded fragments of encrusting algae, coral, and echinoid fragments as much as 6 mm in diameter. Staining with copper nitrate revealed rare euhedra of dolomite. Some of the fossils show postdepositional fracturing. A thin section of F-1-15-2 shows that many of the tests of benthonic larger and smaller Foraminifera are worn and broken, but tests of planktonic types are abundant and well preserved. Mollusk shell fragments are now calcite but retain their original fibrous structure. These fossils are packed—the rock has an intact framework—in an irregularly distributed mud matrix. In places the interstices between fossils are open. Dolomite is present both as widely scattered single crystals and as rare clusters of crystals. The thin section shows crude bedding due to subtle changes in grain size and rough orientation of lenticular fossils. *F-1-15-3 through -13.*—These are irregular pieces, some of which are roughly ellipsoidal and resemble rounded boulders. Lithologically they are identical with piece F-1-14-29. They are dominated by laminae of encrusting algae that encloses pockets of lithified poorly sorted sandy mud. Molds of coral and mollusk shells are common. Rare single crystals and clusters of dolomite are common. *Interpretations.*—As in the case of core run 14, the rocks rich in laminar algae are interpreted as blocks from previously lithified and partly dissolved limestones that were swept down into deeper water sediments represented by the foraminiferal-algal sand rich in planktonic Foraminifera. Thus, during the deposition of the rock in intervals 14 and 15, there was probably a mass of reef limestone, either subaerially exposed during deposition of the rock in this interval or prior to it, that was contributing detritus to an outer slope upon which foraminiferal-algal sands were being deposited. The amount and distribution of dolomite in both the foraminiferal-algal sands and the reef rock suggest that dolomitization took place after the reef limestone was deposited on the outer slope.
1, 553–4, 619	Rock bit____	No recovery.	
4, 619–4, 630	Core barrel__ Bottom of hole.	No recovery.	

PETROGRAPHY OF THE BASALT BENEATH THE LIMESTONE

By Gordon A. Macdonald

Hard basement rock was reached both in drill hole F-1, on Elugelab Island on the north-northwest side of Eniwetok Atoll, and in drill hole E-1, on Parry Island on the southeast side of the atoll. Although the basement rock in hole F-1 is presumed to be basaltic, no samples were recovered. Basaltic rock was found in hole E-1, and good samples were obtained.

In drilling the 4,170- to 4,190-foot interval, a brief return circulating drilling fluid brought to the surface a few small chips of basalt. The corrected depth from which these cuttings originated is 4,154 feet (Ladd and others, 1953, p. 2266). No samples were obtained in the 4,190- to 4,208-foot, interval, but between 4,208 feet and the bottom of the hole at 4,222 feet, 14 feet of basaltic core was obtained. The cuttings from 4,154 feet may have come from a boulder enclosed in the reef limestone, but there can be no question that the core obtained below 4,208 feet represents the volcanic base upon which the reef accumulated.

The basaltic core has been examined both megascopically and microscopically—62 thin sections were cut for the microscopic work. Through cores 4 and 5 (4,208 to 4,216 feet), in which recovery was respectively 97 and 100 percent, one horizontal and one vertical section were cut approximately every 4 inches. Through core 6 (4,216 to 4,222 feet), one approximately horizontal section was cut every 6 inches. These sections were studied to ascertain the variations in mineral composition and texture from one part of the core to another and the relation of alteration in the basalt to veins of calcite that cut it.

Refractive indices were determined in ordinary light by immersion in fluids of known index and are believed to have an accuracy of ± 0.003.

Because these are the only cores thus far obtained from a basaltic basement underlying an atoll, and because of the great difficulty and expense incurred in getting them, a more detailed megascopic description is given, in tabular form, than might otherwise be warranted. The description is summarized in the text. Microscopically, the rock is so uniform that a similar detailed description, piece by piece, is pointless.

Previous work and acknowledgments.—A preliminary study of the basaltic cores was made by Earl Ingerson (Ladd, and others, 1953, p. 2272–2276). For the most part, the present more detailed study confirms Ingerson's findings.

I wish to thank H. S. Ladd and Earl Ingerson for the privilege of studying the basaltic cores. The microscopic work was done in the laboratory of the Hawaii Institute of Geophysics. The chemical analysis was made by P. L. D. Elmore, I. H. Barlow, and S. D. Botts, of the U.S. Geological Survey, Washington, D.C., by rapid methods resembling those described by Shapiro and Brannock (1956).

MEGASCOPIC FEATURES

A detailed megascopic description of the cores is given in table 4. The nature of the materials produced by alteration is described more precisely on pages 1044–1045.

In measuring the amount of dip of the calcite veinlets, it was assumed that the hole is vertical. Thus, a dip of 20° means that the veinlet is inclined 70° to the long

TABLE 4.—*Megascopic description of cores from hole E–1, Parry Island, Eniwetok*

No.	Core				Section of core		Description
	Depth (feet)	Length		Recovery (percent)	Number	Length (inches)	Remarks
		feet	inches				
4	4, 208–4, 211	2	11	97	4–1	2. 3	Dense dark-gray basalt with partly altered olivine phenocrysts. Basalt is cut by two irregular compound calcite veinlets 2 to 8 mm thick that dip approximately 20° and 65°. Joint surfaces also dip approximately 20° and are covered with a film of green alteration products.
					–2	1. 2	Do.
					–3	8. 75	Top: very dense dark-gray basalt with brownish-green to grayish-green phenocrysts of olivine as much as 2 mm in length. Most of the phenocrysts are partly altered to saponite, but some appear fresh and glassy. Bottom: same, but with some acicular olivine phenocrysts as much as 3 mm in length and 0.8 to 1 mm wide. More commonlv the phenocrysts are more nearly equidimensional and blocky in outline. A few ovoid vesicles (amygdules) are as much as 5 mm in length and filled with calcite.
					–3A	0. 25	Compound veinlet, apparently dipping about 20°, that consists largely of calcite but includes thin irregular interleaves of altered basalt.
					–4	2. 3	Like section 4–3. Joints with green alteration material on their surfaces dip from 0° to 30°. One calcite veinlet is 4 to 6 mm thick, and one is 0.5 mm thick; both are very irregular; the smaller branches from the larger in both directions, and the two and connected by another small veinlet.
					–5	6. 5	Small piece at the top contains a 4-mm veinlet of calcite. Veinlet is irregular but dips approximately 20°. The joint surface along the side of the vein is altered to saponite and chlorite. The main piece of core, 6 inches long, is dense dark-gray basalt with many phenocrysts of olivine as much as 2 mm in length; most are less than 1 mm. A few irregularly ovoid cavities as much as 4 mm in length are filled with calcite. A very irregular veinlet of calcite, which is about 0.3 mm thick and dips about 30°, cuts the middle of the piece and dies out about two-thirds of the way through the core. The bottom of the core segment is truncated by an altered joint surface that dips about 50° and to which some fragments of calcite vein still adhere.
					–6	5. 8	Like section 4–3. Some tabular olivine phenocrysts appear very acicular in cross section; they are as much as 2 mm in length and only 0.3 mm wide. Sections includes some irregular spheroidal masses of calcite as much as 1 mm in length. The top is truncated by two intersecting joints that dip 45° and 60° in approximately the same direction; both are coated with calcite. Other very thin irregular calcite veinlets are less than 1 mm thick and occur in groups partly parallel to the bigger veins, partly roughly horizontal, and partly dipping about 90°.

TABLE 4.—*Megascopic description of cores from hole E–1, Parry Island, Eniwetok*—Continued

No.	Core				Section of core		Description
	Depth (feet)	Length		Recovery (percent)	Number	Length (inches)	Remarks
		feet	inches				
4	4, 208–4, 211	2	11	97	–7	4. 4	Like section 4–3. Includes two veinlets that strike approximately 30° from each other, average 1.5 mm thick, dip 45° and 30°, and have anastomosing branches that tend to be approximately at right angles to the larger veinlets. The veins and cross veins separate the rock into rough polygons. These polygons are joint blocks, not aa clinker or breccia from a block lava flow. Another irregular veinlet 0.5 mm thick dips 30° but passes only part way through the core. The bottom of the piece is truncated by a vein-coated joint surface that dips 10°.
					–8	3. 5	Like section 4–3. The bottom is truncated by a multiple vein that is 1 cm thick and dips 25°. Thin irregular laminae of altered basalt enclosed in calcite parallel vein walls. Other tiny veinlets less than 0.5 mm thick dip at approximately 90° to the larger vein. Near the top a veinlet 1 to 2 mm thick dips about 15° but strikes at a slightly different azimuth from the one at the bottom.
5	4, 211–4, 216	5	3	100	5–1	8	Like section 4–3. Core section includes very irregular veinlets that are from less than 1 mm to 2.5 mm thick and dip 30° to 60°; other veinlets are approximately at right angles to them. Joint surfaces adjacent to the veins are coated with serpentinous material. A few irregular spheroidal openings as much as 1 cm in length are filled with slightly greenish, argillaceous-appearing material.
					–2	6	Like section 4–3. A 5-mm multiple veinlet at the top dips 35°, and a less regular veinlet 1 mm thick dips 25° in nearly the opposite direction.
					–3	3. 5	Like section 4–3. At the top, an 8-mm multiple veinlet dips 45°. Another 1- to 2-mm veinlet dips 65°. A few irregular amygdules of saponite and chlorite are as much as 6 mm across.
					–4	3. 5	Like section 4–3. An irregular veinlet of calcite partly coats the top of the piece. One fairly regular ovoid amygdule of saponite and chlorite is about 5 mm long, and another very irregular mass of the same material 3.5 cm long, dip 30°, approximately parallel to the predominant veins.
					–5	5–5	Like section 4–3, very dense. Includes several irregular calcite veinlets less than 1 mm thick, and a few irregular cavity fillings of saponite and chlorite as much as 5 mm long; one cavity filling is 2.5 cm long.
					–6	5	Like section 4–3; abundance and size of phenocrysts is unchanged. The section contains several irregular veinlets of calcite that are from less than 1 mm to 8 mm thick and dip 15° to 65° and one irregular altered joint face that dips about 65°. The veins are multiple.
					–7	9	Like section 4–3. Includes amygdules of saponite and chlorite as much as 2.5 mm in length. One multiple veinlet, 1 cm thick, lies on a joint surface that splits the piece diagonally at a dip of 70°. Another 1- to 4-mm veinlet strikes at a slightly different angle and dips 20°. Another strikes at a considerable angle to the first and dips 50°, cutting the other veins. Other irregular veinlets less than 1 mm thick lie at various angles; one is nearly vertical.
					–8	7	Like section 4–3. A prominent multiple veinlet 5 to 10 mm thick dips 20°. The rock along the veinlet is much altered to saponite and chlorite. Other thin irregular veinlets cut the rock in all directions. One cuts sharply through an amygdule.
					–9	3	Like section 4–3. An 8-mm multiple veinlet cuts the core with a dip of 20°. Many other small irregular veinlets cut it at all angles.
					–10	2. 5	Like section 4–3. Contains a few vesicle fillings of saponite and chlorite as much as 2.5 mm in length.
					–11	4	Like section 4–3. Principal veinlets cross the core with dips of about 20°. Vesicles as much as 1 cm in length are flattened and roughly almond shaped and filled with greenish alteration products. The long direction of the amygdules and olivine phenocrysts are at almost right angles to the veins, some of which cut sharply across the amygdules.
					–12	2	Small fragments of rock, same as section 4–3.
					–13	------	Small chips of basalt and vein material.
					–14	1	Fragment of basalt like that of section 4–3.
					–15	2. 5	Rock like that of section 4–3. The core section contains a few amygdules of saponite and chlorite and small calcite veinlets.

TABLE 4.—*Megascopic description of cores from hole E-1, Parry Island, Eniwetok*—Continued

No.	Core: Depth (feet)	Core: Length, feet	Core: Length, inches	Core: Recovery (percent)	Section of core: Number	Section of core: Length (inches)	Description: Remarks
6	4, 216–4, 222	5	10	97	6–1	3	Fragments of dense dark-gray basalt, somewhat rounded by attrition during drilling and apparently identical with section 4–3, with a 2- to 4-mm veinlet of calcite, which dips about 30°, at the top.
					–2	12	Like section 4–3, with many anastomosing veinlets of calcite. The two largest veinlets, each averaging about 1 cm thick, dip 15° and 25° in nearly opposite directions. Near the top, two cavities about 3 cm long, one irregular and the other fairly regular, are filled with marly material.
					–3	4	Like section 4–3; several fragments.
					–4	4	Like section 4–3, but so broken up that detailed description cannot be made.
					–5	2. 5	Small fragments of basalt, same as above.
					–6	2. 5	Do.
					–7	4	Do.
					–8	6. 5	Like section 4–3, with many ovoid vesicles filled with greenish saponite and chlorite.
					–9	5	Like section 4–3, with a few small amygdules and several calcite veinlets.
					–10	2. 5	Several fragments of dense basalt.
					–11	1	A few very small fragments of basalt.
					–12	8	Dense basalt with some amygdules of saponite and chlorite and several calcite veins. A multiple vein 2 to 3 cm thick near the bottom of the piece dips about 20°.
					–13	4	Small fragments of dense basalt.
					–14	7	Dense dark-gray basalt with a few thin veinlets of calcite.
					–15	4	Do.

direction of the core. The greatest inclination of the hole shown in the drilling record is only 1°.

Throughout the core the rock is a dark-gray basalt with many phenocrysts of olivine. Some of the phenocrysts are as long as 3 mm, but most of them are less than 1 mm. Some appear fresh, but many are altered to saponite and chlorite.

A few vesicles are present, but for the most part the rock is very dense. Some of the vesicles are flattened and roughly almond shaped, but most are very irregular in shape and resemble the vesicles typical of aa lava flows (Macdonald, 1953 p. 179). Some are filled with greenish-brown saponite and chlorite, and others are filled with calcite. No aa clinker or block lava breccia are present.

Most of the olivine phenocrysts are nearly equidimensional, less than twice as long as they are wide. Some, however, are tabular parallel to the side pinacoid, and in cross sections perpendicular to that direction they appear highly acicular, the long dimension being as much as 8 times the width. Olivines of this sort were recognized in Hawaiian lavas long ago by Dana (1889, p. 445) and recently have been redescribed by Drever and Johnston (1957, p. 294–295).

The basalt core is cut by many veins of calcite (fig. 312) that range from less than 1 mm to 2 cm in thickness. Assuming that the hole is vertical, most of the veins dip at an angle of 20° to 30°. However, because the core is not oriented, it is not possible to give the direction of dip. It is also impossible to be sure that the dip is always in the same general direction; but in view of the prevalence of dips within a rather limited range, it is probable that the direction of dip in various parts of the core is fairly uniform. There is also a lesser tendency for the formation of veins at approximately right angles to the predominant direction—that is, with dips of 60° to 70° in roughly the opposite direction. There is no question that the veins formed along former joints in the lava. Not all the joints are filled with vein material, but all the joints, whether filled or not, are coated with greenish alteration products.

At several places in the core there was a distinct tendency for the olivine phenocrysts to be alined parallel to the predominant veinlets, and, at places in thin sections, eutaxitic structure is oriented similarly. This suggests that the joints that guided the predominant veins were flow planes in the molten lava along which at least incipient shear continued after the lava had congealed. The joints at right angles to them are tension fissures that resulted from the same tendency of continued flowage after consolidation of the lava. The first type is similar to platy joints parallel to flow planes that are very common in such andesitic rocks as the mugearites (Macdonald, 1949a, p. 54). However, at one place (core fragment 5–11) the long direction of

FIGURE 312.—Polished section of basalt core from drill hole E-1 on Parry Island, Eniwetok, showing calcite veins. The scale is in centimeters. From Ladd and others, 1953, plate 1, figure 2.

phenocrysts and amygdules are nearly at right angles to the trend of the principal veinlets.

Most of the larger calcite veinlets are multiple and enclose laminae of altered basalt. The disposition and shape of the laminae indicate repeated shearing and vein filling. Many of the calcite veinlets contain enough saponite and chlorite to give them a distinct pale-green or brownish-green color.

The outstanding characteristic of the rock is its overall denseness. This denseness is not, however, diagnostic of the depth in the ocean at which the flow was extruded, and indeed, the flow need not have been submarine. To be sure, the denseness might be the result of the weight of overlying water preventing the formation of gas bubbles in the molten lava. However, similarly dense lava is found in the State of Hawaii in flows that were erupted subaerially, particularly among the valley-filling flows belonging to the late groups (Honolulu and Koloa volcanic series). Scoriaceous character in a lava flow probably is good evidence that the flow was not extruded in very deep water, but denseness of the lava does not necessarily indicate the converse.

MICROSCOPIC FEATURES

Except for variations in the degree of alteration, the basaltic rock of the cores is uniform from top to bottom. The specimen chosen for chemical analysis (table 5), from the bottom of core fragment 4-3 at a depth of approximately 4,209 feet, is as fresh as any. It is described in detail below, and variations from it found in other sections are noted.

GENERAL DESCRIPTION

The analyzed specimen is an olivine basalt containing olivine phenocrysts as much as 3 mm in length. Strictly speaking, the texture is seriate rather than porphyritic; the large grains of olivine grade in size to small grains in the groundmass. The latter is intersertal, with an average grain size of approximately 0.1 mm, and has a moderately well developed eutaxitic structure. The primary magmatic minerals of the groundmass are olivine, augite, plagioclase feldspar, opaque iron oxides, apatite, alkali feldspar, and analcime.

The large grains of olivine are irregular, with an embayed appearance (fig. 313), and have islands of groundmass material enclosed within them. This seem to be the result of irregular crystal growth, as described by Drever (1956, p. 32–35) and Drever and Johnston (1957), rather than of resorption in the magma. There is a slight zonal difference in composition within the large grains: the centers have an optic axial angle of approximately 90°, which corresponds to a composition of about Fo_{90} Fa_{10}; and the outsides have an optic angle of (−) 80° to 85°, which corresponds to a composition of about Fo_{70}. There is also a small increase in the strength of birefringence in the outermost part of the grains. The small groundmass grains are similar in composition to the outsides of the large grains.

The olivine phenocrysts, and less commonly the groundmass of olivine, are partly altered to a yellowish-

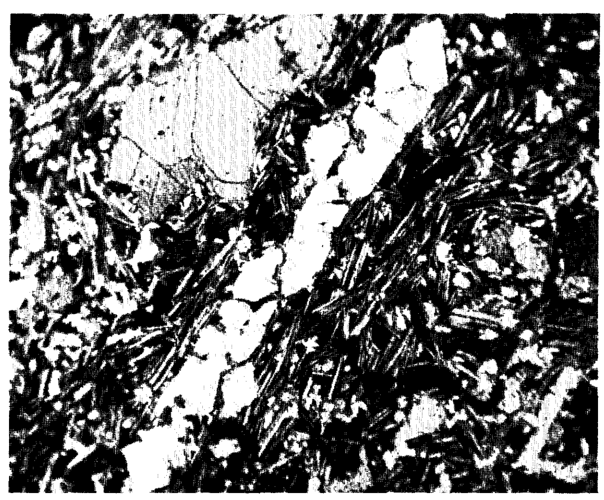

FIGURE 313.—Photomicrograph of a thin section of fresh basalt from drill hole E-1, Eniwetok, showing one of the acicular phenocrysts of olivine. Another large olivine crystal lies just to the left of it. Note the embayed outlines of the olivine, resulting from irregular growth of the crystals, not resorption. The groundmass is labradorite, augite, olivine, and opaque oxides. Crossed nicols, × 35.

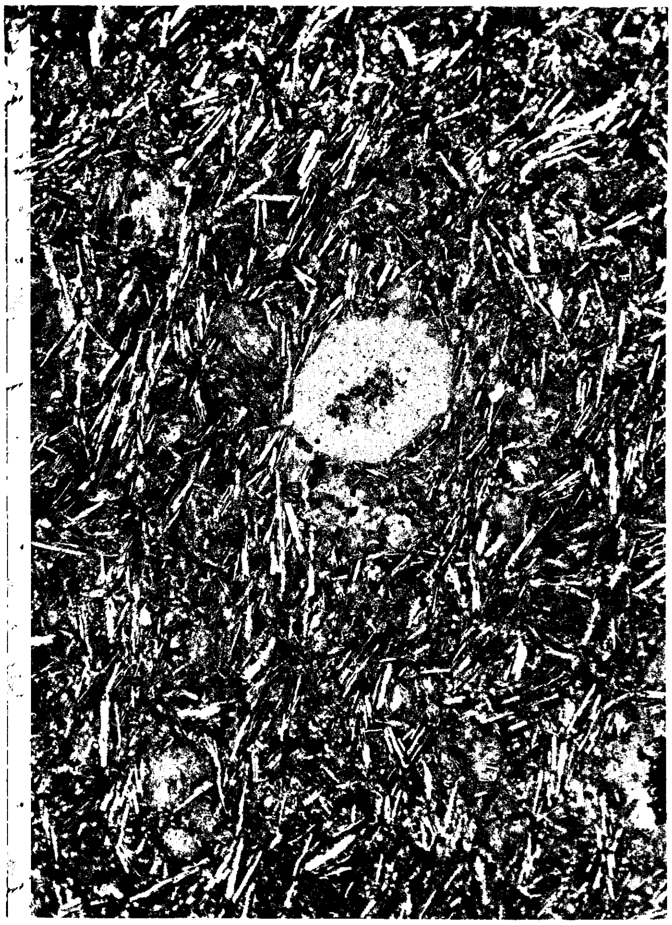

FIGURE 314.—Photomicrograph of a thin section of altered basalt from drill hole E-1, Eniwetok, showing an olivine phenocryst completely altered to saponite. Ordinary light, × 35. From Ladd and others, 1953, plate 2, figure 1.

brown to golden-yellow or greenish-yellow weakly pleochroic fibrous saponite (fig. 314) which is described in detail later. The saponite is in turn altered in part to chlorite.

A slide cut from core segment 4–4 contains a single inclusion of dunite, 1 mm across, composed of nearly equant anhedral to subhedral grains of olivine as much as 0.1 mm across; most are less than 0.05 mm across. The olivine grains in the dunite are partly altered to saponite and chlorite.

The monoclinic pyroxene in the basalt is augite, with $(+)2V=60°\pm$, and moderate dispersion with $\rho>\mu$. The grains are subhedral and typically slightly elongated with the length generally about twice the width. They are very pale brown to slightly purplish brown in color and probably contain some titanium. Some grains show poorly developed hourglass zoning, and others show a small decrease in extinction angle in the outermost parts.

In some other slides, some of the augite is distinctly purplish, with strong dispersion, and is almost certainly titanian. In those slides the augite varies in color, and probably in titanium content, from one part to another. Several instances were noted in which the augite in masses of groundmass material enclosed in large olivine crystals is distinctly more purplish than that in the surrounding rock. As suggested by Drever and Johnston (1957, p. 298), this seems to indicate an entrapment of volatile compounds, including titania, within the olivine crystal.

In a slide cut from the top of core fragment 5–8 a single composite phenocryst (glomerocryst) of augite 2 mm long, composed of half a dozen grains 0.25 to 1.5 mm across, shows pronounced zonal structure and very strong dispersion.

Most of the plagioclase is in subhedral lath-shaped grains with pronounced albite twinning. A few grains also show Carlsbad twinning. The center of the grains is medium labradorite ($\beta\doteq1.563$), and around the edge is a thin zone in which the composition changes abruptly to labradorite-andesine. A small amount of alkalic feldspar occurs in anhedral interstitial grains with a mean refractive index of about 1.524 and a maximum birefringence of about 0.007. It is probably sanidine, but it has not been possible to confirm this by other optical properties. The norm (table 5) contains 5 percent orthoclase and 44.7 percent plagioclase with average composition of Ab_{41}.

Most of the opaque grains are blocky or nearly square in cross section and are probably magnetite, but others have lathlike outlines and probably are ilmenite. In a few other slides, distinct skeletal shapes of magnetite crystals have been observed.

Minute acicular crystals of apatite are enclosed in the other minerals, particularly in the feldspar. Brown crystals of spinel, probably picotite, are enclosed in olivine grains in a few slides, but none were found in the analyzed specimen. The spinel crystals generally are less than 0.05 mm in diameter, but, in a slide cut from core section 4–4, one of them is 0.2 mm across.

Small interstitial patches consist of single grains or mosaics of very weakly birefringent analcime with a refractive index of about 1.490. The mosaics consist of several variously oriented anhedral but generally nearly equant grains. Associated with the analcime in a few places are tiny flakes of very pale green chlorite, but most of the surrounding constituents are the magmatic minerals, augite, olivine, and plagioclase, and are wholly unaltered. The analcime appears to be a very late magmatic primary mineral. Similarly, in lavas of the Honolulu volcanic series on the island of Oahu (Winchell, 1947, p. 25) and the Koloa volcanic series on the island of Kauai, Hawaii, the analcime is almost certainly of late magmatic origin and occurs interstitially or in pegmatoid segregations. Surrounding minerals are not altered, and there is no evidence to indicate that the analcime is secondary in the sense of being an alteration product of earlier crystallized minerals.

The estimated mineral composition of the analyzed rock, in volume percent, is:

Olivine	20
Augite	25
Plagioclase	44
Opaque oxides	7
Alkali feldspar	1
Analcime	2
Chlorite and saponite	2

Both the analcime and the chlorite and saponite are irregular and patchy in distribution. In lower sections of the core analcime is more abundant than in the analyzed specimen and becomes as much as 5 percent of the rock. This may represent an enrichment in late-crystallizing constituents within the central part of a thick flow.

In a few other slides, notably from core fragment 4–4, a few small irregular interstices, probably originally vesicles, contain radiating and divergent length-slow colorless fibers with a very low refractive index, a birefringence about 0.008, and parallel extinction. They probably are natrolite. The masses of natrolite are enclosed in thin layers of pale green chlorite. A slide cut from the bottom of core section 5–6 contains one vesicle filled with spheroidal bodies about 0.05 millimeter across and composed of radiating fibers of stilbite, associated with a little calcite. The rock immediately around it, through a radius of 0.5 to 1 mm, is thoroughly chloritized; both olivine and plagioclase are almost completely destroyed, although augite remains unaffected. The natrolite, stilbite, calcite, and chlorite are of secondary origin.

The cuttings from a depth of 4,154 feet are dense black opaque basaltic glass containing microlites of labradorite and monoclinic pyroxene. They probably are fragments of quickly chilled explosive ejecta. They resemble some of the scoriaceous fragments dredged up at Bikini (Macdonald in Emery, Tracey, and Ladd, 1954, p. 120–124).

ALTERATION PRODUCTS

The basalt is moderately to highly altered. The commonest alteration product is a brownish yellow to golden yellow fibrous material with moderately high birefringence. The fibers are length-slow, the mean refractive index is about 1.56, and the maxium birefringence is 0.025 to 0.030. The mineral was called "saponite-like" by Ingerson (Ladd, and others, 1953, p. 2275), and it agrees reasonably well in properties with one variety of saponite listed by Larsen and Berman (1934, p. 158). It also resembles rather closely the yellow hydrothermal alteration product of olivine known as bowlingite, which is probably a member of the same group. The mineral grades imperceptibly into coarser material that bears a striking resemblance to pale biotite. This material forms micaceous grains as much as 0.2 mm long that are pleochroic from $X=$ very pale brownish yellow to $Z'=$ medium greenish brown or brownish green. The cleavage flakes have positive elongation and parallel extinction, with X sensibly normal to the cleavage. The optic axial angle ranges from sensibly 0° to about 20°, and the optic sign is negative. Birefringence is somewhat variable, as much as 0.040, with $\alpha=$ approximately 1.530 and β and $\gamma=$ approximately 1.570. The mineral resembles griffithite but has a lower birefringence and higher low index of refraction. In a slide cut from the top of core segment 5–1, similar material is pleochroic from bright orange-red to pale yellowish orange, and in a few other slides material of otherwise similar properties it is pleochroic from very pale yellow to clear green and resembles green biotite. The typical yellow fibrous alteration product also grades into a greenish-brown to brownish-green fibrous material with similar optical properties, and this in turn seems to grade toward typical chlorite.

All this material is conveniently included in the general term "saponite." Its variation in optical properties probably results from substitution of varying amounts of ferrous iron for magnesium.

Nearly as widespread as saponite is a typical chlorite that is pleochroic from very pale yellowish green to medium bluish green, has very low birefringence, and typically shows "ultra-blue" interference colors. Less widespread, but common, is a very bright grass-green to bluish-green chlorite resembling celadonite, with interference colors so weak that they are hidden by the very strong green body color. In some slides there appear to be intergradations between the two varieties of chlorite.

In all the slides the olivine is at least partly altered, but the degree of alteration ranges from slight, as in the analyzed specimen, to complete. Commonly the amount of alteration is obviously related to the proximity and size of calcite veins, with rock close to large veins showing a high degree of alteration. The precise pattern of alteration is irregular and differs considerably from grain to grain, even in the same thin section. In general, however, the sequence is: (1) formation of narrow borders of fibrous yellow-brown saponite and veinlets of similar material along fractures in the olivine; (2) alteration of the intervening olivine to fibrous saponite, with local development of large micaceous plates; (3) alteration of unaltered olivine or saponite to chlorite along fractures and in irregular patches; and (4) in extreme cases, further alteration of the material between the original saponite veinlets to chlorite or calcite, or both.

The first-formed veinlets of saponite are composed of moderately coarse fibers mostly oriented about normal to the edge of the olivine grain or to the fracture that guided the alteration. In the latter, the fibers form a double row which extends in both directions from a median line that marks the original fracture. Rarely, as in a slide cut from the bottom of core fragment 5–5, the fibers form a series of radiating groups on both sides of the medial fracture. Quite commonly, there is a film of hematite and limonite directly along the border of the fibers on the side away from the original fracture, and this apparently represents iron driven out as a miniature "iron front" during the alteration of olivine to saponite.

Later alteration of olivine between the network of original veinlets produces an irregular mat of fibers in which the fibers generally show little or no order or arrangement. The shape of the original olivine grain and its pattern of fractures are perfectly preserved. Commonly, the structure of the saponite pseudomorph at this stage strongly resembles the net structure in ordinary metamorphic serpentine. Within the mat between the veinlets, larger micaceous grains may form without any particular orientation with regard to each other or to the original veinlets.

Some saponite pseudomorphs after olivine are cut by veinlets or contain irregular patches of chlorite. There appears to have been an alteration of saponite to chlorite. Other pseudomorphs consist wholly of chlorite except for borders of saponite and veinlets of saponite along the fractures of the original olivine. This also may represent alteration of earlier saponite to chlorite, or it may be the result of direct alteration of olivine to chlorite under somewhat changed conditions. Some support for the latter suggestion is the occurrence of occasional patches of chlorite enclosed in fresh olivine without saponite. Similarly, the areas between saponite veins in pseudomorphs may be occupied wholly by calcite or by a mixture of calcite and chlorite. In some areas, brown grains of limonite are mixed with the calcite, and rarely the borders of the pseudomorphs are limonite enclosing calcite, or calcite and chlorite. The chlorite in the pseudomorphs is generally the ordinary chlorite, but in some places it is partly the very bright green variety.

Several different types of alteration of olivine may be present even within a small part of a single slide.

In a few places very small pale flakes of chlorite are associated with interstitial analcime, but whether it was formed directly with the analcime in a deuteric stage or is of secondary origin is uncertain.

At a few places along calcite veins, minerals other than olivine have been attacked, with plagioclase being partly or even largely chloritized, and rarely also the augite. Even where both plagioclase and augite have been partly altered to chlorite, the magnetite appears completely unaffected.

A slide cut from the bottom of core fragment 5–8 contains pseudomorphs of saponite, chlorite, and calcite after olivine, with which there is associated abundant brown limonite and red hematite. Several irregular openings are filled with radiating fibrous masses of chlorite and opaque to red hematite. The rock immediately surrounding these openings contains irregular patches of bright grass-green chlorite and bright purple titanaugite. The combination of these minerals with white laths of feldspar and black skeleton crystals of magnetite results in a rock with a spectacular appearance in thin section.

Alteration of the olivine to saponite and chlorite definitely is related to the same solutions that deposited the carbonate and formed the saponite and chlorite veins described below. The association with the carbonate veins seems to preclude the possibility that the alteration was brought about by hot water during and immediately following a submarine eruption. It is natural to think of the altering solutions as coming from, and deriving their dissolved carbonate from, the overlying reefs. This is to some extent confirmed by the formation along the same fissures of veins of collophane, the phosphate for which almost certainly must have been derived from organic debris in the reefs.

Solutions attacking the olivine and altering it to saponite must have introduced a little aluminum and removed a little iron. Some of the iron was driven ahead of the advancing wave of alteration and was deposited at the inner edge of the saponite. The aluminum may have been derived by alteration of aluminous minerals, particularly plagioclase, in the adjacent rock. The resemblance of the saponite in these rocks to bowlingite may indicate that there actually is very little aluminum present in it.

VEINS

The carbonate veins (fig. 312) range from less than 0.01 mm to more than 2 mm in thickness. In thin section most of them appear to be simple mosaics of anhedral grains of calcite. Some, however, show fairly well developed comb structure.

X-ray examination of a sample of carbonate from a vein in core 6–12 by Daphne R. Ross of the Geological Survey confirms the microscopic identification of the carbonate mineral as calcite; a partial chemical analysis by rapid methods run by P. L. D. Elmore and S. D. Botts of the Geological Survey shows the carbonate to contain 53.5 percent CaO and only 1.2 percent MgO. The abundance of trace elements in the sample is given in table 6.

Veins in core segment 4–1 are typical. They are as much as 3 mm in thickness and anastomose rather irregularly through the rock. Bands of irregular granules of limonite lie within the calcite, and the center of one 3-mm vein is almost wholly limonite. The principal vein has borders of saponite and chlorite; the chlorite lies directly against the wallrock, and the saponite is between the chlorite and the calcite. The fibers of saponite are normal to the wall of the vein. The calcite is at least partly later than the saponite-chlorite border, because angular fragments of the border enclosed in the calcite are detached and slightly shifted from their original positions, and small calcite veinlets cut sharply across the border and pass out into the wallrock without the development of similar borders. Narrow bands of saponite and chlorite, 0.01 to 0.03 mm wide, lie within the calcite parallel to the vein wall and appear to mark former vein boundaries.

In several slides, other thin veins of saponite and chlorite lie within the wallrock a few tenths of a millimeter from the main vein and parallel to it, separated from the vein by partly altered wallrock. They seem to represent subsidiary breaks roughly parallel to the main one. Projecting angles on one side of the vein commonly match well the re-entrants in the other wall, which suggests that the opening of the vein fissures has been by simple distension rather than by shearing.

Although minerals in the wallrock adjacent to the veins have been altered by the vein-forming solutions, room for the veins seems to have been made by simple opening of the fracture rather than by replacement. Evidence points to repeated opening of fractures and vein deposition, with the chlorite and saponite veins being formed first, and then those of calcite.

Veinlets of saponite and(or) chlorite unassociated with calcite are in some slides. Some veinlets composed almost wholly of saponite and chlorite have a little calcite in the very center.

Some calcite veinlets have borders of red hematite or brown limonite granules. The granules generally are rounded and at some places show botryoidal forms and concentric layering. Botryoidal masses as much as 1 mm across are enclosed in the veins. Roundish masses of chlorite coated with iron oxide also are enclosed in some veins. A calcite veinlet in the top of core fragment 5–5 contains strongly pleochroic plates of saponite, as much as 0.2 mm in length, arranged along the middle part of the vein and oriented normal to the vein walls.

Along one edge of the same vein is a band of collophane 0.1 to 0.3 mm thick. Across part of the slide the collophane band leaves the edge of the calcite vein and extends within the vein. Along the edges of the collophane, but within the calcite, are many roughly spherical to irregular bodies consisting of radiating fibers of yellowish-brown saponite. A veinlet only 0.1 mm thick of collophane without any associated calcite but with an irregular border of saponite diverges from the main vein and cuts the basalt wallrock. A calcite veinlet diverging in another direction is similarly bordered by saponite but has no collophane. The collophane appears to be later than most or all the calcite. Core fragment 6–12 also contains a veinlet of calcite cut by a smaller veinlet of collophane.

In the bottom of core fragment 6–2 a veinlet of zeolite about 0.1 mm wide has been partly broken up by a later veinlet of calcite that follows the same general line of fracture. In part, the zeolite enclosed in the calcite has recrystallized to euhedral rhombic crystals of nearly square cross section. Its index of refraction is approximately 1.490, and its birefringence ranges from 0 to about 0.005. The zeolite is probably chabazite.

In the top of core fragment 4–7 also, a calcite vein is bordered by what appears to be a remnant of an older vein of zeolite that encloses very thin wavy septa of chlorite.

The sequence of vein formation, probably with some overlapping, appears to be: (1) formation of veins of chlorite and saponite; (2) formation of veins of zeolite; (3) formation of veins of calcite, commonly with iron oxide borders, and some with borders and associated veins of the very bright green chlorite; and (4) formation of veinlets of collophane.

Evidence and conclusions bearing on the origin of the carbonate veins and the associated alteration of the basalt may be summarized as follows:

1. The carbonate veins contain no recognized fossils, not even Foraminifera, and therefore probably were formed by precipitation from solution, not by infiltration of calcareous ooze from the overlying sea bottom.
2. The alteration of the basalt is closely related spacially to the carbonate veins and decreases away from the veins. It is, therefore, definitely related genetically to the vein-filling fissures as channel ways for the altering solutions and probably to the same solutions that deposited the carbonate veins.
3. No similar veining has been found in the State of Hawaii or, to my knowledge, in any other of the mid-Pacific volcanic islands. It is, therefore, not a feature typically related to Pacific volcanism at levels commonly visible—that is, above sea level.

It may be concluded that it either resulted from solutions of nonvolcanic origin or formed below sea level, or both.

4. If the solutions were of nonvolcanic origin, were they of some other hydrothermal nature, or of epigene nature? The presence of collophane veinlets in and closely associated with the carbonate veins suggests strongly that they were of epigene origin and derived their calcium carbonate and phosphate from the overlying reefs. If this is true, the vein formation must have taken place long enough after the solidification of the lava for the top of the volcanic pile to have been planed off by wave erosion and covered by an unknown thickness of calcareous reef.
5. The alteration of the basalt resembles hydrothermal alteration in other parts of the world, rather than alteration by ordinary weathering. This may, however, simply be the result of alteration under nonoxidizing conditions, beneath the water table or below sea level.
6. There is no evidence, however, other than the lack of resemblance of the alteration to ordinary weathering, that the alteration and vein formation did not take place above sea level.
7. If the solutions were of epigene origin, as is likely, some condition must have existed that caused them to migrate downward from the reefs into the basalt, carrying with them dissolved calcium carbonate. In a static condition of reefs saturated with sea water resting on a relatively impermeable basalt platform beneath sea level, it is unlikely that much such vertical migration would occur. However, a condition involving downward migration of solutions from the reefs into the basalt might well result from an elevation of the reefs above sea level, such as is indicated by the solution unconformity at 2,780 feet in drill hole E–1 or the earlier elevation suggested by the absence of deposits of Oligocene age. Recent hydrologic investigations indicate that much of the ground water that sinks into an oceanic island does not move out laterally at the top of the Ghyben-Herzberg lens, but penetrates deeply into it before moving laterally. Thus meteoric water dissolving calcium carbonate from the elevated Eniwetok reefs might be expected to move downward into the basalt, provided the Ghyben-Herzberg lens extended deep enough into the island to reach the basalt. The thickness of the lens would depend on the abundance of rainfall and the permeability of the rocks above, and just below, sea level.
8. Reef limestone is highly permeable, and if the lens was thick enough to reach the basalt, as is strongly suggested by the evidence listed above, then, with low rainfall, the basalt platform at the base of the reef must have been above or very close to sea level in order to have been reached by a thin ground-water lens; or rainfall must have been high enough to produce a thick lens. However, high rainfall implies a high island, and this in turn would imply elevation of the island to a degree that would have brought the top of the basalt above, or close to, sea level. Thus, in either event the basalt platform must have been close to or above sea level, and the top of the limestone must have stood at least several hundred feet above sea level, possibly more than 1,400 feet (the thickness of the limestones between the basalt and the Miocene unconformity).
9. The carbonate veins are not dolomitized, although the overlying rocks less than 100 feet above contain some dolomite. This may be because, once formed, the veins are much less permeable than the overlying reef limestone.

In summary, the alteration of the basalt and formation of the veins appear to have been by epigene solutions that derived the carbonate and collophane by solution of the overlying reefs at a time when the top of the basalt stood close to sea level and part or all the limestone stood well above sea level.

CHEMICAL COMPOSITION

The rock chosen for analysis is from the bottom of core segment 4–3, one of the least altered parts of the core. The chemical composition and norm are given in table 5, column 1. The rock is undersaturated with

TABLE 5.—*Chemical analyses of basalt from Eniwetok and other similar rocks*

[1. Analcime-bearing alkali olivine basalt, from bottom of core fragment 4–3, at a depth of approximately 4,209 feet in drill hole E–1, Parry Island, Eniwetok Atoll. P. L. D. Elmore, I. H. Barlow, and S. D. Botts, analysts. 2. Analcime basanite, Koloa volcanic series, Kauai Island, Hawaii. F. A. Gonyer, analyst. (Macdonald, Davis, and Cox, 1960.) 3. Average normal alkali basalt (average of 96 analyses). Nockolds, 1954, p. 1021, col. IX]

	1	2	3		Norms 1	Norms 2	Norms 3
SiO_2	44.4	45.30	45.78	or	5.0	3.9	6.1
Al_2O_3	14.9	11.76	14.64	ab	18.3	16.8	18.3
Fe_2O_3	2.3	3.98	3.16	an	26.4	19.7	24.7
FeO	9.4	8.80	8.73	ne	2.0	1.7	2.3
MgO	10.7	12.88	9.39	di wo	7.0	13.2	10.8
CaO	9.4	10.72	10.74	di en	4.4	9.4	7.1
Na_2O	2.6	2.36	2.63	di fs	2.1	2.6	2.9
K_2O	.82	.72	.95	ol fo	15.6	16.0	11.5
H_2O+	2.4 (with H_2O-)	.67	.76	ol fa	8.3	5.0	5.0
H_2O-		.00	-----	mt	3.2	5.8	4.6
TiO_2	1.8	2.30	2.63	il	3.5	4.4	5.0
P_2O_5	.48	.31	.39	ap	1.3	.7	1.0
MnO	.20	.11	.20				
CO_2	.22	.00	-----				
Total	100.0	[1] 100.04	-----				

[1] Includes 0.13 percent BaO.

silica and contains a little normative nepheline. The content of trace elements is given in column 1 of table 6.

In chemical composition the rock closely resembles an analcime basanite from the Koloa volcanic series of the island of Kauai, Hawaii (table 5, column 2), except that it contains more alumina. It is also much like the average normal alkali basalt of Nockolds (table 5, column 3).

The average amount of modal analcime present is hardly enough to justify calling the rock an analcime basanite. Similar rocks in the Honolulu volcanic series on the island of Oahu, Hawaii, were called "linosaite" by Winchell (1947, p. 28), but the name "alkali basalt" now is in common use for these rocks. The most appropriate designation for the Eniwetok rock appears to be analcime-bearing alkali olivine basalt.

TABLE 6.—*Abundance of trace elements in samples of the basaltic cores from Eniwetok*

[The figures are reported in percent to the nearest number in the series 7, 3, 1.5, 0.7, 0.3, 0.15, and so on. These numbers represent midpoints of group data on a geometric scale. The letter "M" indicates that the element is a major constituent, the abundance of which is reported elsewhere. Katherine V. Hazel, analyst. Looked for but not found: As, Au, B, Bi, Cd, Ce, Cs, Dy, Er, Eu, Gd, Ge, Hf, Hg, Ho, In, Ir, Li, Nd, Os, Pd, Pr, Pt, Rb, Re, Rh, Ru, Sb, Sm, Ta, Tb, Te, Th, Tl, Tm, U, W, Yb, Zn]

	Basalt, core 4-3	Calcite veinlet, core 6-12		Basalt, core 4-3	Calcite veinlet, core 6-12
Si	M	0.015	Ga	0.0007	0
Al	M	.003	La	0	.003
Fe	M	.3	Mo	.0003	0
Na	M	.03	Nb	.0003	0
K	M	.3	Ni	.03	0
Ti	M	0	Pb	.07	0
Mn	M	.15	Sc	.0015	0
Ag	.00003	.00003	Sn	.003	0
Ba	.015	.0003	Sr	.03	.015
Be	.00015	0	V	.015	.003
Co	.03	0	Y	.0015	0
Cr	.015	0	Zr	.015	0
Cu	.015	.0007			

CONSANGUINITY OF THE ROCK

Alkali olivine basalts are widespread in the volcanic islands of the central Pacific Ocean. In the State of Hawaii some of them appear to be interbedded with tholeiitic basalts in the uppermost parts of the major volcanic shields. More typically, however, they are associated with picrite-basalts of ankaramite type, hawaiites, mugearites, and trachytes in later volcanic series that form thin cappings on the major shields (Macdonald, 1949b, p. 1566), or with nepheline basalts in volcanic series that were erupted much later, after a long period of erosion. In the titanium-bearing character of its augite, the Eniwetok rock resembles olivine basalts of the Honolulu volcanic series on the island of Oahu, Hawaii (Winchell, 1947, p. 23, 25), the Kiekie volcanic series of Niihau Island (Macdonald, 1947, p. 46), and the Koloa volcanic series of the island of Kauai. Analcime also is present in some of the lavas of the Honolulu and Koloa volcanic series, but not in earlier lavas in the Hawaiian group. These series were erupted as the last episode in the activity of the Hawaiian volcanoes, after a pause that permitted erosion of canyons several thousand feet deep into the flanks of the main volcanic mountains. By analogy, the Eniwetok rock probably represents a lava flow erupted very late in the history of the volcano that forms the volcanic pedestal of the island.

Specimens of volcanic rock dredged from the outer slopes of Bikini Atoll also appear to be partly, if not wholly, alkali olivine basalt (Macdonald *in* Emery, Tracey, and Ladd, 1954, p. 120–124).

CARBONATE MINERALOGY

By Donald L. Graf[5] and Julian R. Goldsmith[6]

The results of powder X-ray diffraction and emission spectrographic analyses of 16 carbonate rock samples from cores at Eniwetok, Funafuti, and Kita-daitō-jima are summarized in table 7. It should be emphasized that the natural samples studied were only small pieces of drill core, and that the values given in table 7 may not be valid even inches away.

The information upon which the determination of carbonate mineral abundances (table 7) is based is shown in figure 315.

X-RAY DIFFRACTION ANALYSIS OF CARBONATE MINERAL MIXTURES

The quantitative powder X-ray diffraction analysis of calcite, dolomite, and aragonite in mixtures presents unusual difficulties. The well-developed cleavage of the two rhombohedral carbonates is at the orientation of the uniquely strong $\{10\bar{1}4\}$ powder reflection for these materials. When, as in the present study, the strongest reflection is used to achieve maximum sensitivity, the elimination of preferred orientation is particularly important. On the other hand, a number of glide mechanisms are known for these minerals, the $\{01\bar{1}2\}$

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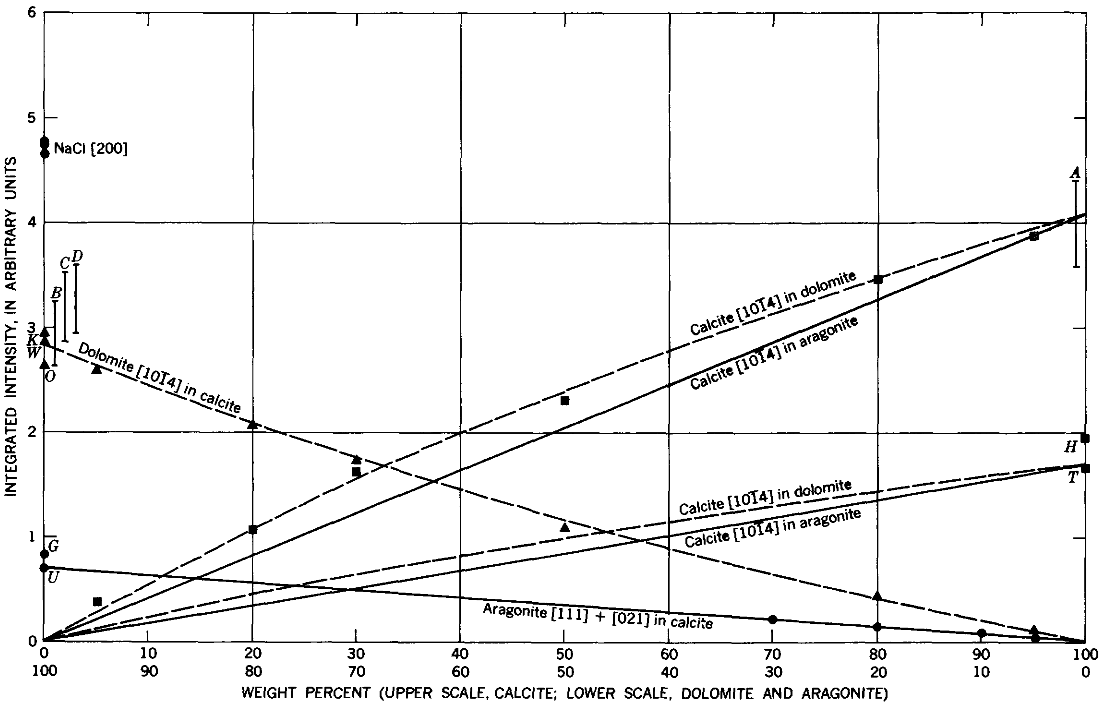

FIGURE 315.—The integrated intensities of selected powder X-ray diffraction maxima obtained from mixtures of calcite (Iceland spar, Taos, N. Mex.), aragonite (fresh-water *Unio* shell), and dolomite (Upper Eocene, Levy County, Fla.).

A, Expectable range for integrated intensity of calcite {10$\bar{1}$4}, based upon that of NaCl {200} and the data of Hanawalt, Rinn, and Frevel, 1938.
B, Expectable range for integrated intensity of aragonite {111}+{021}.
C, Expectable range for integrated intensity of dolomite {10$\bar{1}$4}, if dolomite contains 50 mole percent $CaCO_3$.
D, Expectable range for integrated intensity of dolomite {1014},.if dolomite contains 55 mole percent $CaCO_3$.
G, Aragonite crystals, Girgenti, Sicily.
H, Chalk, Dover, England, disaggregated but not further ground.
K, Dolomite, Kankakee, Ill., ball milled for 8 hours.
O, Dolomite, Carey, Ohio, ball milled for 8 hours.
T, Iceland spar, Taos, N. Mex., after prolonged hand grinding in mortar.
U, Aragonite, fresh water *Unio* shell.
W, Dolomite, Gabbs, Nev., after prolonged hand grinding in mortar.

TABLE 7.—*Carbonate mineral composition of selected samples*

[The minimum amounts of carbonates detectable by the X-ray diffraction method used are about 1 percent for calcite and dolomite and about 2 percent for aragonite. The quantities in parentheses were obtained by difference. The plus-minus ranges given for these mineralogical determinations indicate only the disagreement between values read from calcite and aragonite curves, or from calcite and dolomite curves, and are not necessarily equivalent to accuracy. The information on which the determination of carbonate mineral abundance is based is shown in figure 315]

Sample	Weight percent			Mol percent		Weight percent		Maximum possible mol percent	
	Aragonite	Calcite	Dolomite	$MgCO_3$ in calcite	$CaCO_3$ in dolomite	Mn in dolomite concentrate	Fe in dolomite concentrate	$MnCO_3$ in dolomite	$FeCO_3$ in dolomite
Eniwetok:									
F-1-12-7*b*	--------	2	(98)	3	55. 2	0. 012±. 004	0. 004±. 002	0. 026	0. 01
F-1-12-23	--------	63±3	37±3	2	55. 6	. 004±. 002	. 004±. 002	. 01	. 01
F-1-11-26	--------	89±3	11±3	0. 5	55. 2	. 004±. 002	. 029±. 006	. 01	. 058
F-1-12-12	--------	53±3	47±3	2-3	55. 2	. 005±. 003	. 027±. 008	. 015	. 058
F-1-3-20	--------	100	--------	[1]3. 5	--------	--------	--------	--------	--------
F-1-11-9	--------	97	3	2	55. 2	. 001- . 006	. 015±. 008	. 01	. 038
F-1-12-24	([2])	([2])	([2])	([2])	55. 6	--------	--------	[3]. 02	[3]. 17
Funafuti:									
15	12±1	88±1	--------	[1]15;14	--------	--------	--------	--------	--------
491A	--------	--------	100	--------	([4])	. 005±. 003	. 001- . 004	. 015	. 006
4A	--------	--------	100	--------	54. 2	. 005±. 003	. 015±. 005	. 015	. 033
224A	--------	66±1	34±1	2	56. 6	. 004±. 002	. 009±. 005	. 01	. 025
668A	--------	12±2	88±2	5-8	56. 2	. 004±. 002	. 005±. 003	. 01	. 015
Kita-daitō-jima:									
595	--------	1	(99)	3-4	54. 2	. 006±. 003	. 020±. 006	. 015	. 043
691	--------	76±2	24±2	[1]3;2	56. 0	. 005±. 003	. 011±. 006	. 015	. 028
557	--------	--------	100	--------	55. 2	. 005±. 003	. 005±. 003	. 015	. 015
737	--------	96±1	4±1	[1]4;3	55. 8	. 005±. 003	. 01-. 04	. 015	. 065

[1] Values obtained from back-reflection film measurements.
[2] Only dolomite concentrate available.
[3] Oiva I. Joensuu, spectrographer; these results were originally reported as weight percent MnO and weight percent Fe_2O_3. The other spectrographic determinations are by Juanita Witters.
[4] Range of compositions between typical $CaCO_3$-rich values and 1:1 molar $CaCO_3$:$MgCO_3$.

twin glide for calcite occurring most readily, and prolonged grinding decreases measurable diffracted intensity markedly as progressively larger percentages of the crystal volume are occupied by disturbed regions resultant from differential movement. When mixtures of these minerals are ground together, the components incur structural damage at unequal rates, both because of the different energies required for glides in different minerals and because the more easily deformable component yields preferentially and protects the others. The problem is thus one of grinding fine enough to eliminate preferred orientation and other effects such as extinction and microabsorption while introducing no significant structural damage, or at least a constant and reproducible amount. Procedures such as that of Tennant and Berger (1957), involving long periods of ball milling, are presumed to introduce a reproducible amount of damage, but do not disclose the level of damage.

The experimental procedure used in the present study is applicable to smaller samples than would be required for ball milling and has permitted some monitoring of the grinding procedure influence. Initially, batches of Iceland spar from Taos, N. Mex., upper Eocene dolomite from Levy County, Fla., and aragonite from a fresh-water *Unio* shell were prepared by hand grinding small portions to smoothness in a small mullite mortar. The Florida dolomite is calcium rich, similar in composition and structure to the dolomites found in the Pacific core samples (Goldsmith and Graf, 1958a). A number of 2-gram calcite-aragonite and calcite-dolomite mixtures were then weighed into vials, mixed by the prolonged mechanical rotation of these vials through an eccentric orbit, and X-rayed without further grinding. A General Electric diffractometer and filtered copper radiation were used. A sample well 52 by 13 by 1.5 mm in size and a slit width of 3° were chosen in order to irradiate a relatively large mass of sample and thus to make weighing, sampling, and mixing requirements somewhat less stringent. No X-radiation penetrated to the bottom of the sample holder for the compounds studied. The proportional counter moved 1° in 2θ per 5 minutes, and the digital printer recorded every 20 seconds (0.04° in 2θ). The results of 2θ scans from 25° to 33°, including the dolomite $\{10\bar{1}4\}$, calcite $\{10\bar{1}4\}$, and aragonite $\{111\}$ and $\{021\}$ reflections, were plotted, and integrated intensities for those reflections were obtained by planimetering. Such data are suitable for constructing two-component standard curves, as employed by Klug and Alexander (1954).

The potential accuracy of such quantitative determinations of calcite, dolomite, and aragonite in mixtures is reduced somewhat by interference among the rather large number of reflections involved, although this source of error proves to be much less important than those connected with grinding, as were discussed above. The integrated intensity for aragonite used in this study is actually the sum of those for the $\{111\}$ and $\{021\}$ reflections, which are both quite strong and are close enough together that resolution is incomplete. For calcite-aragonite mixtures, it is necessary to subtract from the integrated aragonite intensity the contribution of β radiation from the very strong $\{10\bar{1}4\}$ reflection of calcite. The amount of β radiation passed by the filter, which was about 0.6 percent of the integrated intensity of the α reflection, was determined for a calcite sample, and this percentage was then taken of the observed calcite $\{10\bar{1}4\}$ radiation from calcite-aragonite mixtures. For a calcite-aragonite mixture that contains 5 weight percent aragonite, the β correction reaches 30 percent of the aragonite integrated intensity.

Similarly, graphical approximations based upon assumed symmetrical profiles for reflections in the 2θ region involved between 25° and 33° were made to resolve slight overlapping between $\{10\bar{1}4\}$ of calcite and $\{10\bar{1}4\}$ of dolomite, and between $\{10\bar{1}4\}$ of dolomite $\{0006\}$ of calcite. The weak $\{002\}$ reflection of aragonite would interfere with $\{10\bar{1}4\}$ of dolomite in dolomite-aragonite mixtures, but such mixtures were not encountered in this study. For calcite-dolomite mixtures in which both minerals are present in considerable amount so that maximum sensitivity is not of paramount importance, other reflections that do not interfere, such as $\{11\bar{2}3\}$, might be used to advantage. The intensity of the dolomite $\{11\bar{2}3\}$ reflection, furthermore, would be relatively insensitive to ferrous iron substitution in ferroan dolomites, because this reflection owes its intensity primarily to contributions from oxygen atoms.

The integrated intensities derived from the mixtures are shown in figure 315 by the squares, triangles, and X's which do not have letter designations. The aragonite intensities fall accurately on a straight line that extends to the intensity for 100 percent aragonite (point U), as should be the case because of the identical mass absorption coefficients of calcite and aragonite. The intensities for calcite in dolomite and dolomite in calcite fall, with somewhat greater scatter, on gently curving arcs. The curves actually shown in figure 315 passing through these two sets of points are theoretical ones. They were computed using mass absorption coefficients for copper radiation of 75.63 for calcite and 52.81 for dolomite containing 55 mol percent $CaCO_3$, and the relation (Klug and Alexander, 1954, p. 415)

$$I_1=\frac{(I_1)_0 x_1 \mu_1^*}{x_1(\mu_1^*-\mu_2^*)+\mu_2^*}$$

where I_1 is the integrated intensity of a selected reflection of component 1 in a two-component mixture, $(I_1)_0$ is the integrated intensity of the reflection for a pure sample of component 1, X_1 is the weight percent of component 1 in the mixture, and μ_1^* is the mass absorption coefficient of component 1. The experimental points for synthetic mixtures fit the curves satisfactorily.

The requirement of comparable textures in analysis by comparison with a standard makes necessary some appraisal of textural influences.

One independent check of the relative intensities of the calcite, dolomite, and aragonite reflections used in figure 315 may be obtained from the published data of Hanawalt, Rinn, and Frevel (1938) for the intensities of the calcite and dolomite $\{10\bar{1}4\}$ reflections related to that of the NaCl $\{200\}$ reflection, and from similar data of the Hanawalt group for aragonite that appears in the first set of ASTM powder diffraction cards. The relationship obtained from the data of these authors, who used the Debye-Scherrer method and molybdenum radiation, is

$$I_{\mathrm{NaCl}\{200\}}:I_{\mathrm{Calcite}\{10\bar{1}4\}}:I_{\mathrm{Dolomite}\{10\bar{1}4\}}:I_{\mathrm{Aragonite}\{111\}+\{021\}}::150:125:100:92.$$

Samples of NaCl that have been hand ground to smoothness in a small mortar give a reasonably reproducible experimental value of

$$I_{\mathrm{NaCl}\{200\}}$$

(see fig. 315), although this value can be reduced at least 25 percent by moderately prolonged grinding. If a ± 5 percent accuracy is assigned to the Hanawalt values, because they are given by those authors only to the nearest five units, the predicted ranges A, B, and C of figure 315 are obtained for the integrated intensities of, respectively, the calcite, aragonite, and dolomite reflections being used. Range D, for dolomite containing 55 mol percent $CaCO_3$ instead of 50 mol percent, was obtained by shifting range C 10 percent of the distance toward range A. The difference between ranges C and D is an insignificant part of the total ranges. The predicted and observed intensities for calcite are in ideal agreement, and those for dolomite are quite satisfactory, especially in view of the structural and compositional irregularities shown by sedimentary dolomites (Goldsmith and Graf, 1958a). The Hanawalt aragonite value and that obtained from *Unio* shell material disagree by a factor of four. No explanation is apparent for this striking discrepancy; differences resulting from the use of molybdenum and copper radiations, respectively, for the two determinations are quite inadequate to explain the anomaly. The integrated intensities for powdered aragonite crystals from Herrengrund, Hungary, and Girgenti, Sicily (G in fig. 315) agree well with that for the *Unio* shell material, which does suggest that the textures and resultant integrated intensities obtained by processing natural rocks would be comparable.

The ratio $I_{\mathrm{Calcite}\{10\bar{1}4\}}/I_{\mathrm{Dolomite}\{10\bar{1}4\}}$, shown in figure 315, may be checked by a further computation. Using the variable parameters for calcite (Chessin and Post, 1958) and dolomite (Steinfink and Sans, 1959) accurately determined from single crystal studies, the scattering factors of Berghius and others (1955) for calcium, carbon, and oxygen, those of the same authors for Mg^{+2} but modified at low values of $\frac{\sin\theta}{\lambda}$ in the direction of the neutral Mg atom, and appropriate Lorenz and polarization corrections, the calculated intensities for the two reflections give a ratio of 1.47. The inclusion of absorption factors (for diffractometer mounts, the reciprocals of the linear absorption coefficients, see Klug and Alexander, 1954, p. 397) lowers the ratio to 1.03. It is possible that the additional inclusion of temperature factors would increase the ratio. It should also be remembered that the Hanawalt group used filled capillaries of uniform diameter, a procedure that would give a spuriously low intensity for a material of low absorption if the capillary diameter were such that X-radiation just reached the sample center for more highly absorbing materials.

Continued hand grinding of several of the mixtures in a small mortar decreased calcite intensities markedly but had little effect upon those of dolomite and aragonite. Additional measurements were then made upon several calcite and dolomite samples in order to study the effect of grinding on the separate materials. Small parts of a sample of the Iceland spar from Taos, N. Mex. enough to fill the X-ray sample holder, were ground by hand in a small mortar for a total of 3 hours, and the integrated intensity indicated by point T in figure 315 was obtained. Aragonite can be formed from calcite by prolonged grinding (Burns and Bredig, 1956; Jamieson and Goldsmith, 1960), but none was detected, after the moderate degree of grinding described, in this Iceland spar sample. A sample of Dover chalk, disaggregated but not further ground, gave an integrated intensity ("H" of figure 315) similar to that of the Iceland spar at T; this material may contain a small amount of poorly crystallized silica. Sedimentary dolomites from Kankakee, Ill., and Carey, Ohio, ball milled for 8 hours, gave integrated intensities shown by points K and O, respectively, in figure 315. Parts of large cleavage pieces of dolomite from Gabbs, Nev., whose $CaCO_3$ and $MgCO_3$ contents are within 0.5 mol percent of the formula value (Goldsmith and Graf, 1958b), were hand ground in the same manner as the Iceland spar sample, but intensity was reduced only to point W in figure 315.

More severe structural damage could be produced in these compounds by extended grinding with motor-driven mortars (Bradley, Burst, and Graf, 1953), and there are unusual naturally occurring magnesian calcite and dolomite sediments (Alderman and Skinner, 1957) more poorly crystallized than any described here. On the whole, however, the materials examined and the grinding employed should be an indication of what to expect in attempting to determine proportions of these carbonates in powders using the diffractometer. The significant conclusion is that the observed integrated intensities for calcite will fall much farther below ideal values than those for aragonite and dolomite.

The Pacific samples are found to be very pure two-phase carbonate mixtures, and it is therefore possible to require that values read from the appropriate two curves must total 100 percent, that is, they must lie vertically above each other in figure 315. Although this requirement is a more stringent test of the experimental data than the alternative of reading percentages from a plot of intensity ratios versus composition (see Tennant and Berger, 1957), it is not rigorous. Poorly ground preferentially oriented calcite associated with fine-grained poorly crystallized dolomite could give a highly concordant analysis spuriously high in calcite; well crystallized preferentially oriented dolomite that was protected during the protracted grinding and serious damaging of calcite could, at least in theory, give a highly concordant analysis spuriously low in calcite. If the mineralogical analysis of such a two-phase rock gives a total greater than 100 percent, one can keep regrinding and reanalyzing until the total drops to 100 percent.

Initial examination of several of the Pacific core samples, however, using the calcite-in-dolomite and dolomite-in-calcite curves of figure 315 based upon standard mixtures, gave totals markedly below 100 percent and suggest that the calcite was already diffracting with substandard efficiency. The empirical calcite-in-dolomite and calcite-in-aragonite curves that end at point T of figure 315 were then tried, in conjunction with the aragonite-in-calcite and dolomite-in-calcite curves based upon standard mixtures, as representing a level of calcite structural quality that could be attained for all samples. It proved to be possible, using these curves and a single hand grinding, to get values agreeing to within ± 2 weight percent for the Kita-daitō-jima and Funafuti samples. The Eniwetok rocks, even after a second grinding, gave values agreeing only to within ± 3 weight percent; it is probable that they differ texturally from the other samples. In two samples where only 1 or 2 percent of one carbonate was indicated, and the integrated intensity for the other gave a value greater than 100 percent, the second value was obtained by difference. Even an error of 100 percent in the integrated intensity of the phase present in very small amount would still give results within ± 2 weight percent of the true value, the standard generally sought here.

CALCITE

Precision determinations of the magnesium content of the calcite in these samples, using back reflections, are frequently not possible. The calcite, derived from skeletal remains that originally contained a wide range of magnesium concentrations, sometimes still shows a compositional range. In other samples, the amount of calcite remaining after dolomitization is so small that the back reflections are not recorded.

The procedure used for those samples containing both calcite and dolomite involves measuring the positions of maximum intensity for the $\{10\bar{1}4\}$ reflections of calcite and dolomite by counting with the diffractometer at 0.01° intervals in 2θ across the maxima. The difference between the dolomite $\{10\bar{1}4\}$ spacing so obtained, and that computed from back-reflection measurements of the dolomite concentrate from the same rock, give a correction which is applied to the calcite $\{10\bar{1}4\}$ spacing. The procedure is less accurate when either of the two minerals is present in small amount and affords only a low gently sloping peak.

Back reflection film measurements were made for samples Eniwetok F-1-3-20 and Kita-daitō-jima 557, which contain no dolomite, and for samples Funafuti 15, Kita-daitō-jima 691, and Kita-daitō-jima 737 as a check on the diffractometer method described above.

Most of the calcite in these rocks contains a very low percentage of the magnesium in solid solution (table 7), which indicates that the magnesium has been lost extensively from inorganic skeletal remains. Where moderate amounts of magnesium are still present in the calcite (Funafuti 668A, Kita-daitō-jima 595), a range of composition is present and presumably indicates either a diversity of composition in the original mixed skeletal debris or a variation in the rate of magnesium loss from different particle sizes, or both.

DOLOMITE

Dolomite concentrates were obtained from these rocks by leaching with cold dilute (about 2 percent) acetic acid. The values given in table 7 for mol percent $CaCO_3$ in these dolomites are based upon measurements of the $\{40\bar{4}4\}$ and $\{31\bar{4}8\}$ back reflections on films taken with 114.59-mm diameter Straumanis-mount powder cameras, using manganese-filtered iron radiation. Changes of the *d*-spacings of these reflections with composition, for compositions near dolomite, are assumed to be linear (Goldsmith and Graf, 1958a). Spectrographic analyses of iron and maganese are also given in table 7, together with the corresponding mol percents of $MnCO_3$ and $FeCO_3$ that would result if the iron and manganese found were all in solid solution in the dolomite. The amounts of iron and manganese present are quite inadequate to produce significant changes in dolomite cell size, particularly in view of the fact that some of the iron is present as small particles of iron oxides that could not be completely removed during beneficiation.

All the dolomite fractions from these rocks contain $CaCO_3$ in solid solution in excess of the 50 mol percent value of ideal dolomite. The excess $CaCO_3$ is typically about 5 mol percent, as shown in table 7. No dolomite approaching the ideal molar ratio was observed.

The general characteristics of calcium-rich dolomites of this type are discussed by Goldsmith and Graf (1958a). In general, X-ray diffraction patterns of these materials have weakened order reflections, and reflections from basal planes that are broadened or diffuse relative to those reflections with little or no *c*-axis component. Heat treatment of the dolomite concentrate from Eniwetok sample F–1–12–24 clearly indicates that such a material which has excess $CaCO_3$ and a defective *c*-axis succession in the structure, is metastable at earth-surface temperatures.

Several observations on the Pacific samples should be made in addition to the general discussion by the above authors. X-ray powder patterns of the coarse and fine fractions of the dolomite crystals from sample F–1–12–24 showed significantly more occluded calcite in the coarse fraction. Little or no calcite could be detected in the powder patterns from the tiniest crystals, whereas the strongest reflection from calcite was of moderate intensity in the pattern made from the largest crystals. Several single-crystal X-ray photographs showed a weak Debye pattern of calcite superimposed on the single-crystal pattern of dolomite. This indicates that finely divided randomly oriented calcite was in these crystals. No compositional or structural difference in dolomite of the smallest and largest crystals could be detected. The calcite would thus seem to be relict from the original undolomitized rock and not an exsolution product from the calcium-rich dolomite.

Weissenberg photographs of several of the samples (Goldsmith and Graf, 1958a, plate 2*D*) show some interesting features. Moderately sharp reflections are apparent at positions appropriate for the calcium-rich dolomite and, in addition, all reflections show diffuse tails that extend to the positions characteristic of ideal dolomite. In addition, the strongest reflections have weak-intensity maxima in the diffuse regions. The fact that reflections both normal and parallel to the *c*-axis (including order reflections) show this bimodal character indicates that these crystals could be considered multiphase in nature. One intrepretation of this observation is that the calcium-rich dolomite has begun the reorganization, akin to exsolution, necessary to achieve the ideal dolomite composition and structure. The intensity distributions observed in X-ray photographs of the Pacific materials should not be confused with those of similar calcium-rich dolomites from other localities (Goldsmith and Graf, 1958a, fig. 2*c*) that have bimodal intensities only for reflections with strong *c*-axis components. We have suggested that the latter materials may have a disturbed succession of basal cation planes.

It is now apparent that many dolomites, at least in the early stages of their formation, are calcium rich and structurally imperfect. It has not yet been demonstrated however, that it is possible for calcium-rich dolomites existing in natural sedimentary environments to reorganize to ideal dolomite, but the process has been observed experimentally at somewhat elevated temperatures (Graf and Goldsmith, 1956).

ARAGONITE

Aragonite has not been observed in those rocks that contain dolomite (table 7, and discussion of petrology). It is apparent that the metastable aragonite (Jamieson, 1953; MacDonald, 1956; Clark, 1957) is destroyed by whatever diagenetic process is responsible for the formation of replacive dolomite. The tendency toward the development of an equilibrium assemblage is evinced by both changes in mineralogy. [7]

DATING OF CARBONATE ROCKS BY IONIUM-URANIUM RATIOS

By William M. Sackett and Herbert A. Potratz [8]

The extent of disequilibrium between certain members of the three naturally occurring radioactive families in ocean water and in marine calcium carbonates has been investigated. The Th^{230}/U^{238} ratios in these materials have been determined to ascertain the conditions under which this ratio may serve as a measure of geologic age.

The authors are indebted to the Aluminum Company of America and to the Van Blarcum fund of Washington University for support of this work through fellow-

[7] As discussed by Schlanger in a preceding section it is entirely possible that all the aragonite is converted to calcite prior to dolomitization. If so, the formation of dolomite may have nothing to do with the lack of aragonite.

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ships; to the U.S. Atomic Energy Commission for financial support under contract number AT(11-1)-581; to the Los Alamos Scientific Laboratory for samples and the loan of equipment; to Meyer Rubin and W. S. Broecker, U.S. Geological Survey, for readiocarbon dating of a number of the marine carbonates; to E. D. Goldberg and the Scripps Institution of Oceanography; to Thor N. V. Karlstrom, Harry S. Ladd, and J. I. Tracey, Jr., of the U.S. Geological Survey; and to J. C. Brice, R. P. Bullen, and C. R. McGimsey, who supplied the samples that formed the basis for this investigation. We are most grateful to Harry S. Ladd, S. O. Schlanger, and J. I. Tracey, Jr., for their helpful suggestions made during the course of the work and in the preparation of this report. Much of the material is taken from a dissertation presented by William M. Sackett to the Graduate Board of Washington University in partial fulfillment of the requirements for the degree of Doctor of Philosophy, June 1958.

PREVIOUS WORK

Barnes, Lang, and Potratz (1956), in work done at the Los Alamos Scientific Laboratory, found that coral limestone cuttings from the uppermost 200 feet of drill hole F-1 on Elugelab Island in Eniwetok Atoll exhibited an irregular increase of ionium to uranium with increasing depth (fig. 316). The possibility of making the disequilibrium of ionium and uranium the basis of a method for determining geologic age was mentioned (Potratz, Barnes, and Lang, 1955; Barnes, Lang and Potratz, 1956).

The work here described is a continuation of that done by the Los Alamos group. The object has been to study in general the disequilibria in the three radioactive families of some naturally occurring materials, with the ionium-uranium disequilibrium and its use in dating calcium carbonates as the prime interest.

The main modes of decay for the three families are illustrated in figure 316.

For undisturbed samples of very old materials, a situation is reached in which the rate of formation of any daughter is equal to its rate of decay, a situation known as secular equilibrium. In nature, however, processes may occur which separate parent from daughter. Parent or daughter elements may, moreover, be brought into a material from external sources. Such natural processes are usually slow, and, consequently, disruption of equilibrium in the radioactive families will be noticeable only if the separation or enrichment processes involve nuclides with relatively long half-lives.

The disequilibria that one may expect to observe in the three naturally occurring radioactive families usually arise because of gain or loss of one or more of the following nuclides:

1. Uranium series
   U^{238} (4.5×10^9yr), U^{234} (2.5×10^5yr), Th^{230} (80,000 yr), Ra^{226} (1622 yr), Pb^{210} (22 yr), Po^{210} (138 days)
2. Actinouranium series
   U^{235} (7.1×10^8 yr), Pa^{231} (34,000 yr), Ac^{227} 22 yr)
3. Thorium series
   Th^{232} (1.4×10^{10} yr), Ra^{228} (6.7 yr), Th^{228} (1.9 yr).

In the foregoing listing the figures in parentheses are the half-lives of the nuclides (Friedlander and Kennedy, 1955). The other radioactive daughters in the three families have half-lives of less than one month and should be generally in equilibrium with the long-lived parents listed above. The possibility of Rn^{222} loss should, however, be considered. This gaseous nuclide has a half-life of only 3.8 days. Uranium ores are nevertheless sometimes deficient in Rn^{222} and daughters because of continuous Rn^{222} loss. Because of the very short half-lives of Rn^{219} and Rn^{220}, loss of these nuclides is probably negligible.

The disequilibrium situations in the naturally occurring radioactive families may provide clues to the geologic history and age of various materails. The dating of marine sediments by means of U^{238}, Th^{230}, Ra^{226} disequilibrium was one of the first applications. Early

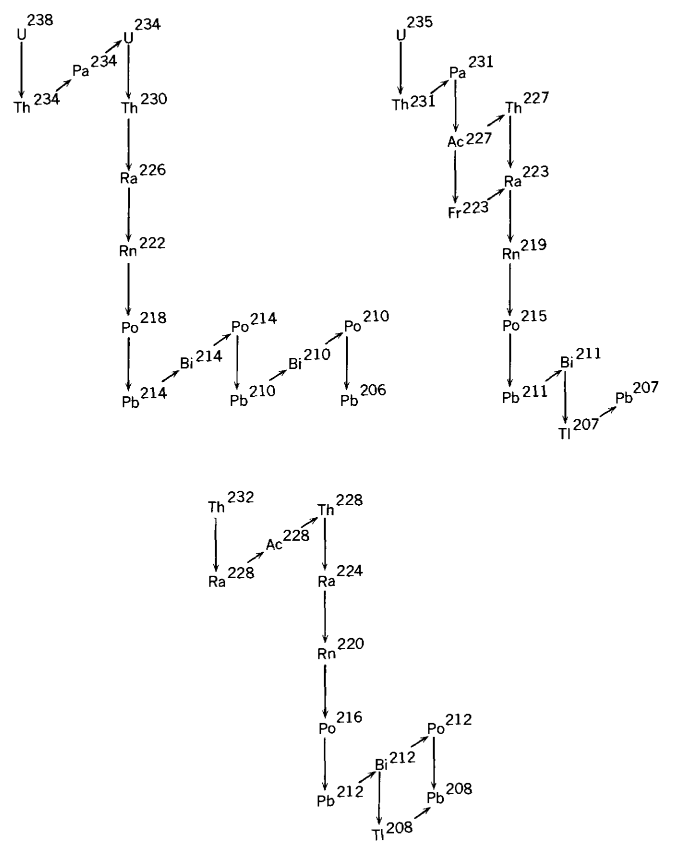

FIGURE 316.—Uranium, actinouranium, and thorium decay series.

workers had found a large amount of radium activity in marine sediments (Joly, 1908). To explain this phenomenon, Pettersson in 1937 proposed that ionium (Th^{230}) was coprecipitated on ferric hydroxide from the oceans, giving rise to ionium-supported radium on the ocean floor. Piggot and Urry (1939) a short time later found in successively deeper layers of cores of deep-sea sediments an increase of radium activity with depth until equilibration with ionium was attained. Below this point, the activity decreased exponentially with depth. Sedimentation rates were obtained from their work.

ISOTOPIC THORIUM CONTENT OF OCEAN WATER

The data complied by the Los Alamos group indicated that recently deposited limestones from Eniwetok contain several parts per million of uranium, but less than 1 percent of the equilibrium amount of ionium. When this work was begun in 1954, little was known about the ionium content of ocean water and it seemed that an experimental value was needed to answer the basic question: Does the calcium carbonate (aragonite and calcite) deposited by corals and other marine organisms contain no ionium because the organisms grow in an ionium-free environment, or do these organisms take up uranium and reject ionium?

Ocean water contains approximately 3×10^{-6} grams of uranium per liter (Nakanishi, 1951; Rona, Gilpatrick and Jeffy, 1956). This corresponds to an equilibrium ionium concentration of 5×10^{-11} grams per liter. The lack of information concerning ionium concentration in ocean water is related to experimental difficulties associated with determining the nuclide at this extremely low concentration. The precipitation of ionium as proposed by Pettersson (1937) suggests that the actual concentration may be considerably lower than the equilibrium value.

Other groups have been interested in determining the ionium content of ocean water in order to understand more completely the factors involved in the ionium method of dating marine sediments.

In 1954 Holland and Kulp attempted to calculate the ionium concentration by considering the four main factors that regulate the concentration of radium, one of which is its growth from ionium. By assuming no change of radium concentration with time, by knowing the decay constant and approximate concentration of radium, and by estimating its deposition rate on sediments and its rate of influx from rivers, they were able to calculate a value for the ionium concentration of ocean water (table 8).

Koczy, Picciotto, Poulaert, and Wilgain (1957) using concentration of thorium isotopes by coprecipitation on ferric hydroxide, purification by ion exchange and solvent extraction, and isotopic analysis by photographic emulsion techniques, obtained the first experimental values for the thorium isotopic content of ocean water. However, their water may not have been "typical" ocean water because it was collected in and around Scandinavian fjords (table 8).

TABLE 8.—*Calculated concentrations, in grams per liter, of thorium isotopes in ocean waters*

Nuclide	Deep ocean sample		Surface sample	
Th^{230}	[1] $<3\times10^{-13}$	[2] <0.6 percent	$<2.3\times10^{-12}$	[2] <5 percent
Th^{227}	$<2\times10^{-19}$	[2] <15 percent	3.8×10^{-19}	[2] 27 percent
Th^{232}	$<5\times10^{-8}$		$<4\times10^{-7}$	
Th^{228}	$<7\times10^{-18}$		2×10^{-17}	

[1] Holland and Kulp (1954, p. 210) give the value $3.1\pm1.0\times10^{-12}$ grams per liter. Koczy and others (1957, p. 103) give limit 6×10^{-13} grams per liter.
[2] Percentages represent the fraction of secular equilibrium for Th^{230} and Th^{227} in the deep ocean and surface samples.

The following work was done on two samples of Pacific Ocean water, one collected at the surface outside San Diego Bay in the summer of 1956 and the other at a depth of 3,500 meters from long 124°41.0′ W., lat 33°54.5′ N., on March 25, 1957 (Sackett, Potratz, and Goldberg, 1958). The procedure included the collection of the thorium isotopes on ferric hydroxide, purification by ion exchange techniques, and isotopic thorium determination by observing the growth and decay of total thorium alpha activity (Sackett, 1958 [9]).

Experimental values are listed in table 9. The fractions listed as S–2 and D–2 were obtained by reworking the resin washings. The listed thorium activities have been corrected for counter background, yield of thorium, 51 percent counter geometry, and reagent blank.

The initial activities of Th^{227}, Th^{228}, and $Th^{232}+Th^{230}$ in the surface-water sample are calculated from the growth and decay of the total alpha activity in the thorium that is separated from the sample. For the S–2 fraction of the surface water sample, the activities are:

$A_{Th}{}^{227}=1.6$ disintegrations per hour per liter
$A_{Th}{}^{228}=1.9$ disintegrations per hour per liter
$A_{Th}{}^{232}+A_{Th}{}^{230}=6.1$ disintegrations per hour per liter

Using these activities and the known half-lives of the isotopes, the concentrations of the individual thorium species in the surface sample are calculated. They are listed in table 8.

Also listed in table 8 are the results for the deep-water sample. The limits are arrived at by letting each thorium isotope have the maximum possible alpha activity listed (0.8 disintegrations per hour per liter).

[9] Sackett, W. M., 1958, Ionium-uranium ratios in marine deposited calcium carbonates and related materials: Ph. D. thesis, Washington University.

TABLE 9.—*Thorium alpha activity in Pacific Ocean water*

Sample designation	Percent Th^{234} tracer recovered	Thorium alpha activity in disintegrations per hour per liter at time of separation
Surface fraction		
S–1	10	9 (±2)
S–2	40	9.6 (±0.5)
Deep ocean fraction		
D–1	28	.3 (±0.3)
D–2	45	.4 (±0.4)

The activities of the individual thorium species in D–1 and D–2 could not be determined because of the extremely low counting rates (about 0.1 count per minute).

The percentages listed in table 8 for Th^{230} and Th^{227} represent the fraction of secular equilibrium for the two isotopes in the deep and the surface samples. They are based on a uranium concentration of 3.0×10^{-6} grams per liter (130 U^{238} disintegrations per hour per liter).

The 5 percent or less concentration of Th^{230} (table 8) found in the surface-water sample and the less than 1 percent found in the deep-water sample show that the Th^{230} content was far below the amount required for secular equilibrium with the U^{238} present in the water samples.

The sea water around Eniwetok Atoll, where the Los Alamos group obtained the coral they analyzed, should be devoid of contamination from continental land masses because of its location in the middle Pacific. It is thus probable that the deep ocean sample more nearly represents the Eniwetok area sea water than does the surface sample, which was collected near the coast and which contained sand and other solid particles. Making this assumption would mean that the organisms on the reefs grew in an environment that was very poor in ionium. Table 8 lists a conservative less than 0.6 percent of the equilibrium quantity, but it is probably less than 0.1 percent. Thus these organisms get little if any ionium. The question of whether or not marine organisms reject ionium cannot be ascertained.

The results shown in table 8 bring to light several other points of interest.

The equilibrium Th^{227} activity corresponding to a uranium content of 3.0×10^{-6} grams per liter is 6 disintegrations per hour per liter and gives the results listed in the table of less than 15 percent and 27 percent of the equilibrium amount of Th^{227} in the deep ocean and surface samples, respectively. This indicates that not only Th^{230} but apparently Pa^{231} and (or) Ac^{227} are precipitated with the sediments. It is probable that the limiting species is Pa^{231}, because it is so readily coprecipitated in neutral and basic solutions.[10] The larger amount of Th^{227} in the surface shore sample is most likely due to the moderate solubility of $Ac(OH)_3$, which may be either redissolved from the sediments or enriched in the shore waters from continental run-off water.

Development of techniques for determining very small amounts of protactinium might lead to a method for dating marine deposits.

If the Ra^{226} content of ocean water is taken as 1.3×10^{-13} grams per liter ($A_{Ra^{226}}=17$ disintegrations per hour per liter) (Faul, 1954, p. 116), then for the deep sample, $A_{Ra^{226}}/A_{Th^{230}}=20$.

Thus the radium content is far in excess of the amount that can be supported by the ionium which is present. Koczy and others (1957) report a similar situation in their samples and suggest that the excess radium may arise from a redissolution of the radium that originated in the sediments.

Marine organisms growing in this environment may possibly reflect this excess radium in their carbonate skeletons, a condition that could give rise to reports of concentration of radium by various organisms. Nonsupported radium in marine limestones might be used in geologic dating if the amount that was present at the time of deposition could be estimated, possibly from the amount present in limestone now being deposited in the same locality as the material under consideration.

Koczy and coworkers also report Th^{228} in excess of the amount that can be supported by the Th^{232} present in several of their samples and again account for this phenomenon by suggesting either a redissolution of Ra^{228} from the near-shore sediments or by introduction from rivers. Because of the relatively short half-lives of Ra^{228} and Th^{228}, this excess should be observed only near the shores or along the bottom.

Some preliminary work on river water has indicated that even at a pH=1, Th^{234} tracer is more than 90 percent adsorbed on the suspended material. With this information, the following conclusions may be stated:

1. Significant quantities of thorium isotopes probably do not enter the ocean in solution, because thorium seems to be completely adsorbed on the river sediments, which in turn are probably largely deposited on the continental shelves. Thus, it would expected that the only Th^{230} and Pa^{231} (which is also easily coprecipitated) that are deposited on the main body of the ocean floor result from the decay of the U^{238} and U^{235} in solution in the ocean.

[10] The pH of ocean water is between 7.5 and 8.4 (Sverdrup, Johnson, and Fleming, 1942, p. 194).

As most of the Th^{232} is also deposited on the continental shelves, practically none of it or its daughters should be found in deep-sea sediments.[11]

2. The more soluble, long-lived daughters—Ra^{226} in the uranium series, Ac^{227} in the actinouranium series, and Ra^{228} in the thorium series—may enter the oceans with the continental runoff waters or by a redissolution from the sediments.
3. The disequilibrium situations created by the excess of Ra^{226}, Ac^{227}, and Ra^{228} might be used to give time differentials in some marine processes.

IONIUM-URANIUM RATIOS IN MARINE LIMESTONES

If marine organisms deposit aragonite and calcite that (1) contains a measurable amount of uranium, (2) has very much less than the equilibrium amount of ionium (Th^{230}), and (3) does not gain or lose uranium or lose the ionium that grows into these minerals from the radioactive decay of uranium, then the time at which the calcium carbonate was deposited can be determined from the ionium-uranium ratio within the experimental error of the analyses for materials from approximately 1,000 to 300,000 years old.

Should the calcium carbonate fulfill only condition (1), clues to the geologic history of the material might still be obtained from the ionium-uranium ratio.

URANIUM CONTENT OF MARINE LIMESTONES

If the disequilibrium of uranium and ionium is to be used in the geologic dating of limestones, the usefulness of the method will depend to a large degree on the reliability of the analyses. The best analyses and age estimates should be obtained for the materials with the highest uranium contents, as the amount of ionium is also dependent upon the amount of uranium.

From the results shown in tables 10 and 11, it can be seen that the uranium contents of the materials listed vary by a factor of 30 or more. The reason for this wide spread is of some concern, because much time may be saved by the selection of only those materials for age determination whose uranium contents are likely to be high:

Several factors may influence the uranium content of marine limestones. One is the concentration of uranium in the ocean waters from which the limestones were deposited. However, during the time span for which the ionium-uranium ratio might be used (300,000 years), the uranium concentration in the oceans has probably changed very little. Holland and Kulp (1954) estimated that the uranium concentration has changed less than 20 percent in 10^7 years. For very old limestones, other factors, such as recrystallization, are more important in determining their present uranium content.

[11] Submarine volcanos, wind-blown and meteoric material, and possibly very finely divided colloidal material brought in by rivers may supply Th^{232} and other nuclides to the midocean areas.

TABLE 10.—*Uranium content versus crystal structure of marine-deposited calcium carbonates*

[Uranium content was determined by a sodium fluoride-fluorimetric precedure (Price, Ferretti, and Schwartz, 1953; Grimaldi and Levine, 1954; Sackett, 1958). As a check on the validity of this procedure some samples were also analyzed by a neutron activation method (Moore, 1957; Sackett, 1958). N.D., none detected]

Sample	Major crystal constituent	Minor crystal constituent	Uranium content (ppm)
Mu-7-4	Aragonite	Calcite	2.1
Mu-7-13	do	N.D	2.7
Mu-7-23	do	N.D	2.4
Mu-7-41	do	N.D	2.0
Ru-2-14	do	Calcite	2.5
En-6,-29	do	N.D	2.2
F-1-1-1	Aragonite and calcite.		3.1
F-1-5-37	Calcite	N.D	.34
F-1-6-10	do	N.D	.26
F-1-10-5	do	N.D	.19
F-1-12-8	Dolomite and calcite		.46
F-1-14-24	Calcite	N.D	.66
E-1-1-5	Aragonite	Calicte	1.05
E-1-2-5	Calcite	N.D	3.1
E-1-3-7	do	N.D	.17
E-1, 10-20[1]	do	Aragonite	.67
E-1, 30-40[1]	Aragonite	Calcite	3.46
E-1, 40-45[1]	Aragonite	≥Calcite	2.71

[1] Indicates cuttings. The others are cores. Crystal structures were determined by X-ray diffraction. The X-ray photographs of the cuttings were made by Donald Graf.

Another factor that seems to be related to the uranium content is the crystal structure of the calcium carbonate. Marine-deposited calcium carbonates may exist as either calcite (rhombohedral) or aragonite

TABLE 11.—*Uranium content of calcium carbonate deposited by some marine organisms*

Description	Sample No.	Crystal structure	Uranium (ppm)
Reef coral (*Porites australiensis* Vaughan).	JIT-1	(Aragonite) [1]	2.4
Clam (*Tridacna*):	JPEM-1		
inside portion of shell.		do	.1
outside portion of shell.		Aragonite, trace calcite.	
Modern shell (gastropod).	TNVK-1		.32
Algal deposit (*Porolithon craspedium*).	260A-67-6	Calcite	.37
Hydrocoralline deposit (*Millepora*) on coral listed next.	CKW-1	Aragonite	.42
Coral (*Favia*)	CKW-2	do	1.83
16 F-1 cuttings [2]		[1] do	[3] 3.89
21 E-1 cuttings [2]		[1] do	[3] 2.34

[1] Structures have not been determined experimentally.
[2] The F-1 uranium results were obtained by Los Alamos Scientific Laboratory. The cuttings contained coral, Foraminifera, mollusk shells, echinoid spines, *Halimeda* segments, and so on. (Ladd and others, 1953).
[3] Average.

(orthorhombic). Bragg (1937) mentions that bivalent ions smaller than calcium tend to form carbonates with the calcite structure, and ions larger than calcium tend to form carbonates of the aragonite type. Strontium, for example, whose bivalent ion is larger than the bivalent ion of calcium, tends to form a carbonate with the aragonite structure. Thompson and Chow (1955) and Kulp, Turkeian, and Boyd (1952) have found that, in general, aragonite deposited by marine organisms contain three to four times more strontium than does organically deposited calcite. Thompson and Chow have determined that the atomic ratio of strontium to calcium in sea water is 8.90×10^{-3} and that many of the aragonite skeletons of marine organisms have very nearly this same ratio. Thus for these carbonates there seems to have been an isomorphous replacement of calcium by strontium according to the homogeneous distribution law. Uranium seems to exhibit the same behavior as strontium. Uranyl ion the stable bivalent cation of uranium in ocean water, is large, and its mineral carbonate, rutherfordine, crystallizes in the orthorhombic form (Christ, Clark, and Evans, 1955). Therefore, one would expect aragonite to contain more uranium than calcite, which is shown generally to be so for the data in tables 10 and 11. The concentration of calcium in ocean water is 0.40 gram per liter (Rankama and Sahama, 1950, p. 287). Taking the concentration of uranium in ocean water as 3.0×10^{-6} grams per liter, one may calculate the atomic ratio of uranium to calcium to be 1.2×10^{-6}, which is about the ratio for a carbonate that contains 99 percent calcium carbonate and 2.7 ppm uranium. Most of the values for aragonite in table 10 are within ± 20 percent of this value.

Two coral specimens, JIT–1 and CKW–2 (table 11), and the F–1 and E–1 cuttings, which are mainly coral, all have a relatively high amount of uranium. The other aragonitic materials in table 11 have lower uranium contents. This evidence indicates that certain coral organisms may concentrate uranium to some extent or possibly cannot differentiate between calcium and uranium in ocean water, whereas other organisms may reject uranium.

The calcium required for the skeleton of marine organisms is believed to be obtained directly by adsorption from the sea water or indirectly by the ingestion of plant or animal food. The carbonate in both cases is thought to be derived from metabolic carbon dioxide (Robertson, 1941).

Uranium is present in ocean water in the sexivalent oxidation state, probably not as uranyl ion, but rather as the uranyl carbonate and double carbonate complex ions, whereas the calcium may be largely present as the dipositive ion. That is, the UO_2^{+2}/Ca^{+2} ratio is probably much less than the uranium-calcium ratio. Hence, if isomorphous replacement were the only factor that required consideration, the uranium-calcium ratio in calcium carbonate would probably be considerably less than the uranium-calcium ratio in ocean water. If an adsorption process is being used by an organism to obtain calcium, the different adsorption characteristics of the U(VI) and Ca(II) in ocean water should lead to a uranium-calcium ratio in the calcium carbonate which differs from the uranium-calcium ratio in ocean water.

Rao and Goldberg (1954) believe that specific enzyme systems in the gut may extract needed constituents that are adsorbed to the mucous. However, entry of ions directly into the mantle tissue from the adsorbing medium is sometimes indicated.

If the calcium is derived from the ingestion of plant and animal material, then the uranium-calcium ratio in the calcium carbonate produced by this mechanism might depend to a large extent upon the uranium-calcium ratio in the material being ingested. Thus, unless the uranium serves some biological need and is concentrated by biological processes of the organism, it is not likely that the calcium carbonate produced would have a high uranium content.

In conclusion, high uranium values for marine-deposited calcium carbonates seem to be directly associated with aragonitic calcium carbonate. This may possibly result from the fact that some uranium specie can substitute for calcium in the aragonite structure. The possibility of uranium uptake by organisms which derive calcium by an absorptive process should also be considered.

IONIUM-URANIUM RATIOS IN CUTTINGS FROM ENIWETOK ATOLL DRILL HOLES

Sixteen samples of cuttings from the uppermost 190 feet of the F–1 hole were analyzed for ionium and uranium by the Los Alamos Scientific Laboratory (Barnes, and others, 1956). An irregular increase in the ionium-uranium ratio with depth was observed (fig. 317 and table 12).

Twenty-one samples of cuttings from the first 200 feet of the E–1 hole were analyzed by the writers, and again an increase in the ionium-uranium ratio was observed with increasing depth (fig. 317 and table 13).

We must recognize at the outset that probability of sampling error during the drilling operations is significant. The exact depth from which cuttings come cannot generally be determined with high accuracy, and the cuttings from a given interval may be contaminated by material from above. However, the similarity of the ionium-uranium ratios at the same depths over much of the first 200 feet in the two holes indicates an expected parallel development of the coral reefs of the atoll

TABLE 12.—*Ratio of ionium to uranium in cuttings from drill hole F–1*

[Data from Barnes, Lang, and Potratz, 1956. The uranium results are average values and the estimated standard deviation was ±5 percent. The uncertainty in the ionium values is the expected standard deviation, calculated from the number of counts taken]

Sample depth (ft)	Uranium (ppm)	Ionium (10^{-5} ppm)	$\frac{N_{Th^{230}}\lambda_{Th^{230}}}{N_{U^{238}}\lambda_{U^{238}}}$
20–45	3.05	<0.2	<0.04
45–55	3.67	<.2	<.03
55–60	4.80	<.1	<.01
60–70	5.06	1.42(±0.08)	.16(±0.01)
70–80	5.35	2.5(±0.2)	.27(±0.03)
80–90	4.50	3.8(±0.1)	.49(±0.03)
90–100	4.14	3.5(±0.2)	.49(±0.04)
100–110	3.58	4.3(±0.2)	.70(±0.05)
110–120	4.08	2.7(±0.1)	.38(±0.03)
120–130	4.10	3.1(±0.2)	.44(±0.04)
130–140	4.04	2.9(±0.1)	.42(±0.03)
140–150	3.72	2.6(±0.1)	.41(±0.03)
150–160	3.12	3.4(±0.2)	.64(±0.05)
160–170	4.00	4.3(±0.1)	.63(±0.03)
170–180	3.08	3.7(±0.1)	.70(±0.04)
180–190	2.90	4.4(±0.2)	.88(±0.06)

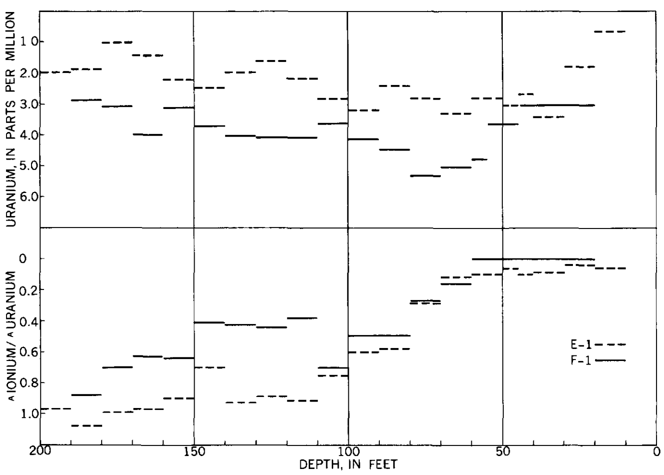

FIGURE 317.—Uranium content and ratio of ionium-uranium activities of cuttings from drill holes E–1 and F–1.

and gives some assurance that the ratios are truly representative of the depths sampled.

A comparison of the ionium-uranium ratios for the samples from drill holes E–1 and F–1 is given in table 14. The apparent ages were calculated for the E–1 samples for the depths indicated because the rock in this range was highly compact (Ladd and others, 1953). It is assumed to be, in part, unaltered aragonitic material.

The data for the 200 feet of limestone in table 14 indicate that a vertical growth of 60 feet has occurred during the last 12,000 years. Comparing this with the growth of about 100 feet during the previous 250,000 years, one would assume that there were only

TABLE 13.—*Ratio of ionium to uranium in cuttings from drill hole E–1*

[Los Alamos results (Potratz, Barnes and Lang, 1955), where given, are listed directly underneath the Eniwetok results. To determine ionium (Th^{230}) in sample solutions, the total thorium was first concentrated by coprecipitation on ferric hydroxide. Pure carrier-free thorium was isolated from this concentrate by ion exchange techniques. The growth and decay of the total alpha activity in the carrier-free thorium which had been isolated was followed for a period of several months. From the data obtained the ionium content of the samples could be calculated. In making the calculation it was assumed that Th^{232} and Th^{228} activities in the original materials were equal. The beta particle emitter, Th^{234}, was used as a tracer to determine the chemical yield (Sackett, Potratz and Goldberg, 1958; Sackett, 1958).

Through the kind cooperation of D. J. Henderson of the Argonne National Laboratory, alpha pulse analyses were obtained on the thorium that had been isolated from E–1 samples 70–80, 110–120, 130–140 and 160–170. Only Th^{230}, Th^{228} and Ra^{224} alpha activities were observed in the 4.5 to 5.8 MEV range that was covered. Although it appeared that activity had been lost in transporting two of the samples to and from Argonne, the fraction of nonionium activity could be calculated and applied to previous counting data. Generally the nonionium activity was less than 5 percent of the total activity]

Sample depth (ft)	Uranium (ppm) (estimated standard deviation ±5 percent)	Ionium (10^{-5} ppm)	$\frac{N_{Th^{230}}\lambda_{Th^{230}}}{N_{U^{238}}\lambda_{U^{238}}}$
10–20 [1]	0.67	0.07(±0.02)	0.06(±0.02)
	.64		
20–30	1.82	.12(±0.03)	.04(±0.01)
	2.03		
30–40 [1]	3.46	.56(±0.14)	.09(±0.03)
	3.92		
35–40	3.10	.30(±0.06)	.06(±0.01)
	2.98	.30(±0.02)	.06(±0.01)
40–45 [1]	2.71	.44(±0.15)	.10(±0.03)
	2.73		
45–50	3.06	≤.33(±0.04)	≤.06(±0.01)
	3.07	.34(±0.03)	.06(±0.01)
50–60	2.82	≤.49(±0.03)	≤.10(±0.01)
	2.84		
60–70	3.31	.60(±0.04)	.11(±0.01)
	3.33		
70–80	2.86	1.34(±0.09)	.28(±0.03)
	2.95		
80–90	2.46	2.5(±0.2)	.58(±0.05)
	2.73	2.3(±0.1)	.48(±0.03)
90–100	3.21	------	.60(±0.04)
	2.94	3.3(±0.1)	.66(±0.04)
100–110	2.86	3.7(±0.2)	.75(±0.06)
	3.14	3.5(±0.1)	.65(±0.04)
110–120	2.20	3.4(±0.2)	.91(±0.07)
	2.26	3.2(±0.1)	.84(±0.05)
120–130	1.64	2.5(±0.2)	.89(±0.07)
	1.68	2.2(±0.1)	.77(±0.04)
130–140	1.98	3.2(±0.2)	.93(±0.07)
	1.91		
140–150	2.48	3.0(±0.2)	.70(±0.06)
	2.54	2.7(±0.1)	.63(±0.04)
150–160	2.24	3.5(±0.2)	.90(±0.07)
	2.18		
160–170	1.46	2.4(±0.2)	.97(±0.08)
	1.44		
170–180	1.02	1.7(±0.2)	.99(±0.09)
	1.04		
180–190	1.90	3.5(±0.2)	1.08(±0.09)
	1.96		
190–200	1.98	3.1(±0.2)	.97(±0.07)
	2.13	3.2(±0.1)	.89(±0.05)

[1] These samples were obtained in solid form and the others as nitric acid solutions from Los Alamos.

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TABLE 14.—*Comparison of ionium-uranium ratios and indicated ages*

[The age can be calculated from the following formula: age (years) = -2.66×10^5 log $(1-A_{Th^{230}}/A_{U^{238}})$]

Sample depth (ft)	Ionium-uranium ratios		Apparent ages for drill hole E-1 ratios (years before present)
	F-1	E-1	
20-60	<0.1	<0.1	<12,000
60-70	.16	.11	13,000(±1000)
70-80	.27	.28	38,000(±4000)
80-90	.49	.58	100,000(±7000)
90-100	.49	.60	106,000(±12,000)
100-110	.70	.75	160,000(±12,000)
110-120	.38	.91	280,000(±20,000)
120-130	.44	.89	
130-140	.42	.93	
140-150	.41	.70	----------
150-160	.64	.90	----------
160-170	.63	.97	----------
170-180	.70	.99	----------
180-190	.88	1.08	----------
190-200	----------	.92	----------

a few select periods during the late Pleistocene when conditions were appropriate for the vertical growth of the coral atoll. These times of growth possibly coincided with the interglacial periods.

Several explanations might be offered for the reversals in the ionium-uranium ratios observed in material from both the F-1 and E-1 drill holes. The deep cuttings may have been contaminated with cuttings from a higher level. The one reversal in the E-1 hole that is not due to any experimental error is in the 140- to 150-foot interval. Ladd and others (1953) indicate that the drill hole was cased at 146 feet, and it is possible that the cuttings obtained on the resumption of drilling were contaminated with shallow cuttings that had fallen down during the casing operation. Contamination may be responsible for the reversals in the F-1 hole, but this is very unlikely because there is such a large range with low readings. Other possible explanations for the reversals are the growth of young reef among the older cavernous unconsolidated material during periods of changing sea level or the migration of ionium or uranium into or from the calcium carbonate.

Using the Th^{230}/U^{238} ratio as a measure, it appears that the material from the first 60 feet of these holes was deposited since the last glacial stage, and that the material at the 200-foot level is approximately 300,000 ±100,000 years old.

Future analyses of short sections of a core taken from the first 200 feet of a coral reef may give detailed information about the times of sea level changes during the Pleistocene epoch.

Because all the marine limestones analyzed have a measurable amount of uranium, the first condition for age determination by the ionium-uranium ratio is generally fulfilled.

TABLE 15.—*Ionium-uranium ratios in Recent materials*

Description	Sample No.	Uranium (ppm)	$A_{Th^{230}}/A_{U^{238}}$
Reef coral collected live (*Porites australiensis* Vaughan).	JIT-1	2.4(±0.2)	<0.01
Clam collected live (*Tridacna*).	JPEM-1	0.10(±0.02)	<0.1
Modern shell (gastropod).	TNVK-1	0.32(±0.03)	<0.01
Algal deposit (*Porolithon craspedium*).	260A-67-6	0.37(±0.04)	<0.01

The very low ionium contents for the recently deposited E-1 and F-1 cuttings and the materials listed in table 15 indicate fulfillment of the second condition.

The third condition for the determination of the geologic age of limestones by use of the ionium-uranium ratio is that there should be no gain or loss of uranium, or of the ionium that grows from the radioactive decay of uranium. Unlike the first two conditions, it seems possible that nonadherence may be the rule rather than the exception.

By comparing the uranium and crystal structure results for the shallow cores with those of the deep cores, as given in table 16, it is seen that, in general, the shallow material has high uranium with the aragonite structure, and that the deep material has low uranium with either the calcite or dolomite structure.

Cuttings from a depth of 10 to 20 feet in hole E-1 (table 13) may possibly represent material which has only recently been transformed. This sample has the calcite structure and contains only 0.67 ppm uranium, whereas material in the next 20 feet has the aragonite structure and a higher uranium content.

On the basis of the previous discussion concerning the relationship of uranium content to crystal structure, and from a consideration of the fact that samples E-1, 10-20 feet; E-1, 40-45 feet; and F-1-1-1, 170-191 feet, contain much calcite, one might conclude that the rise and fall of uranium (table 17) with depth in holes F-1 and E-1, result from variation in the amount of transformed material present. However, a similar variation of uranium content with depth appears in the series of Mu-7 core samples that are essentially pure aragonite. This distribution of uranium in the core may be purely coincidental, and the distribution of readings for the cuttings may indeed be related to the presence of varying amounts of transformed calcium carbonates.

Then the question that naturally arises is this—if there is a loss of uranium by the calcium carbonate, what happens to the ionium-uranium ratio? If the aragonite-calcite transition proceeds at a first order rate with a half-time much larger than the half-life of ionium,

TABLE 16.—*Ionium-uranium ratios in cores taken from drill holes on Eniwetok Atoll*

[Crystal types are: *A*, aragonite; *C*, calcite; *D*, dolomite. The standard deviation for uranium is ±5 percent in the 2 ppm range and ± 10 percent in the 0.5 ppm. range. The ionium values were calculated from the total thorium alpha count after TH^{227} and daughters had decayed. The Th^{232} content for a typical pair E-1-3-7 and Mu-7-41 determined by a neutron activation procedure (Potratz and Bonner, 1954; Sackett, 1958), was about 0.1 ppm, an amount which would not contribute appreciable alpha activity]

Hole and core	Depth (ft)	Major crystal type	Uranium (ppm)	$\frac{A_{Th^{230}}}{A_{U^{238}}}$	Apparent age×1,000 years
Mu-7-4	13-24	*A*	2. 1	0. 067 (±0. 01)	8. 4(±1. 2)
				. 074 (±0. 01)	
Mu-7-13	34-46	*A*	2. 7	. 66 (±0. 05)	132(±12)
				. 71 (±0. 05)	
Mu-7-23	64. 5-69. 5	*A*	2. 4	. 73 (±0. 05)	152(±11)
				. 73 (±0. 05)	
Mu-7-41	90-97. 5	*A*	2. 0	1. 00 (±0. 07)	>300
				1. 05 (±0. 07)	
Ru-2-14	47-52	*A*	2. 5	. 77 (±0. 05)	160(±13)
				. 74 (±0. 05)	
En-6-29	96-101	*A*	2. 2	. 91 (±0. 07)	>300
				. 98 (±0. 07)	
F-1-1-1	170-191	*A* and *C*	3. 1	1. 00 (±0. 07)	>300
F-1-5-37	1978-2003	*C*	0. 34	1. 04 (±0. 10)	>300
F-1-6-10	2662-2687	*C*	0. 25	. 90 (±0. 10)	>300
F-1-10-5	3963-3988	*C*	0. 19	1. 00 (±0. 10)	>300
F-1-12-8	4316-4341	*C* and *D*	0. 46	1. 00 (±0. 10)	>300
F-1-14-24	4500-4525	*C*	0. 66	. 96 (±0. 10)	>300
E-1-5	2003-2028	*A*	1. 05	1. 01 (±0. 10)	>300
E-1-2-5	2802-2808	*C*	3. 1	. 87 (±0. 07)	>300
				. 98 (±0. 07)	
E-1-3-7	4078-4100	*C*	0. 17	1. 08 (±0. 10)	>300

TABLE 17.—*Uranium content versus depth for cuttings*

Depth (ft)	Average uranium (ppm)	
	Drill hole F-1	Drill hole E-1
20-60	3. 7	2. 7
60-110	4. 5	3. 0
110-150	4. 0	2. 1
150-190	3. 3	1. 6

the ratio will still give very nearly the correct age of the material. However, if the loss of uranium proceeds at a rate that is rapid compared to the rate of ionium decay and if such loss occurs in a material already containing a measurable quantity of ionium, then future determinations of the ionium-uranium ratio in the altered material will give erroneous ages the magnitude of the error varying with the amount of uranium which was lost. By assuming that ionium is retained, a correction might be applied by considering the uranium content of the surrounding unaltered material.

The thorium ion, with very nearly the same radius as that of the calcium ion, 1.10A° and 1.06A°, respectively (Moeller, 1952, p. 140), and with its additional bonding ability, is assumed to be largely retained when the calcium carbonate recrystallizes. Some evidence in table 18 indicates that the large change in uranium concentration that apparently occurs with recrystallization is not accompanied by a corresponding change in thorium concentration. It is seen in the first few samples

TABLE 18.—*Thorium²³² versus uranium in some calcium carbonates*

[The Th^{232} contents, other than those footnoted, were calculated from data obtained in following the growth and decay of the total alpha activity in the carrier-free thorium which had been isolated from the sample. Th^{232} and Th^{228} activities in the original sample were assumed to be equal. The values obtained by these last two methods may be in error by a factor of two]

Sample	Th^{232} (ppm)	U^{238} (ppm)	Crystal structure	$\frac{Th^{232}}{U^{238}}$
E-1, 10-20	0. 04	0. 67	calcite	0. 060
E-1, 30-40	. 06	3. 46	aragonite	. 017
	. 060			
E-1, 40-45	. 07	2. 71	aragonite and calcite.	. 026
E-1-3-7	[1] . 010	. 17	calcite	. 059
Mu-7-41	[1] . 0084	2. 0	aragonite	. 0042
E-1, 20-30	. 02	1. 82	Not determined.	. 01
E-1, 35-40	. 07	3. 10	do	. 02
E-1, 45-50	<. 1	3. 06	do	<. 03
E-1, 50-60	<. 1	2. 82	do	<. 03
E-1, 60-70	. 006	3. 31	do	. 002
E-1, 70-80	[2] . 06	2. 86	do	. 02
E-1, 80-90	. 03	2. 46	do	. 01
E-1, 100-110	. 03	2. 86	do	. 01
E-1, 110-120	[2] . 05	2. 20	do	. 02
E-1, 120-130	. 009	1. 64	do	. 006
E-1, 130-140	[2] . 06	1. 98	do	. 03
E-1, 140-150	. 09	2. 48	do	. 04
E-1, 150-160	. 07	2. 24	do	. 03
E-1, 160-170	[2] . 04	1. 46	do	. 03
E-1, 170-180	. 05	1. 02	do	. 05
E-1, 180-190	. 01	1. 90	do	. 005
E-1, 190-200	. 13	1. 98	do	. 07
Average				0. 02

[1] Th^{232} content determined by neutron activation analysis. Estimated standard deviation is ±10 percent.

[2] Th^{232} content determined from alpha pulse analysis data for Th^{228} and daughters. $A_{Th^{228}}$ at t_0 was assumed equal to $A_{Th^{232}}$.

TABLE 19.—*Ionium-uranium ages for some marine shells*

[A complete description of the marine shells is given on page 1064–1065. All samples appeared to be well consolidated and not appreciably altered. The shells were washed and scrubbed with distilled water before the analyses. For the first four samples, the total alpha activity at the time of separation was assumed to be entirely ionium. Therefore, the ionium-uranium ages may be on the high side. In sample TNVK-2, from the growth and decay of total thorium alpha activity, the activity of Th^{228} was calculated to be 0.019 disintegrations per minute per gram. The upper limit, ≤48,000 years, was obtained by assuming Th^{232} to be absent. The lower limit, ≥33,000 years, was obtained by assuming Th^{232} and Th^{228} activities in the sample to be equal]

Sample	Uranium (ppm)	$A_{Th^{230}}$ dis/min/g	$A_{Th^{230}}/A_{U^{238}}$	Apparent age (yr)	Age estimated by submitter (yr)
V67–61	0. 11 (±. 01)	0. 002 (±. 002)	0. 025 (±. 025)	3, 000 (±3, 000)	4, 000
V67–70	0. 14 (±. 01)	0. 0035 (±. 0035)	0. 035 (±. 035)	4, 000 (±4, 000)	4, 000–5, 000
V67–74	0. 24 (±. 02)	0. 010 (±. 005)	0. 056 (±. 028)	6, 700 (±3, 300)	5, 000
Co–40A	0. 044 (±. 005)	0. 005 (±. 005)	0. 15 (±. 15)	18, 000 (±18, 000)	7, 000–9, 000
TNVK–2	0. 26 (±. 03)	0. 066 (±. 013)	≤0. 34	≤48, 000	40, 000–60, 000
		0. 047 (±. 009)	≥0. 25	≥33, 000	

that the thorium-uranium ratio for the calcite material is about a factor of 3 greater than the ratio for the aragonitic material.

The ages given by the ionium-uranium ratios in the shallow core material help to substantiate the results obtained for the E–1 and F–1 drill holes. For the material from the Mu–7, En–6 and Ru–2 holes, very little if any transformation of aragonite to calcite has occurred, and thus there apparently has been little loss of uranium.

IONIUM-URANIUM VERSUS RADIOCARBON AND OTHER AGES

Through the cooperation of Wallace Broecker of the Lamont Geological Observatory and Meyer Rubin of the Geological Survey, four of the aforementioned samples of Eniwetok calcium carbonate have been dated by the C^{14} method. In addition, a number of marine shells, the ages of which had been estimated by other means, were dated by the ionium-uranium procedure. The results, shown in table 19, indicate relatively good agreement between the ionium-uranium age and the estimated age for these samples. The low uranium contents and the very low ionium activities in these relatively young materials are responsible for the high uncertainties in the ionium-uranium ages.

A comparison of the ionium-uranium and radiocarbon ages obtained on the four Eniwetok samples is given in table 20. There are wide disagreements here that cannot be attributed to experimental error.

It was proposed that the emergence of the coral atolls with lowered sea levels resulted in the solution of the calcium carbonate by fresh rainwater and a recrystallization upon evaporation of the water, a process that is greatly decelerated in the saturated ocean waters. This phenomenon suggests two mechanisms by which radiocarbon ages might be made smaller. First, the atmospheric carbon dioxide that is naturally present in rainwater could exchange with the carbon dioxide in the calcium carbonate when it temporarily enters solution. Secondly, the calcium carbonate in solution is deposited at a lower level, contaminating the surrounding older carbonate material.

It seems that the recrystallization process not only lowers the radiocarbon age but also raises the ionium-uranium age because of the loss of uranium.

Another process that apparently lowers the radiocarbon age is the filling of the primary cavities of the reef with young chemically precipitated or detrital calcium carbonate (Newell, 1955). If this secondary material contains a small amount of uranium and no ionium (such as the algal calcium carbonate in table 11), the ionium-uranium age will be lowered by a much smaller percentage than will be the C^{14} age. This can be illustrated by the following calculation.

If a calcium carbonate contains 2.0 disintegrations per minute per gram of uranium and 0.184 disintegration per minute per gram of ionium, then $A_{Th^{230}}/A_{U^{238}} = 0.092$, and it has an apparent age of 11,200 years. The C^{14} will have undergone two half-lives decay, and,

TABLE 20.—*Ionium-uranium versus radiocarbon ages for Eniwetok Atoll calcium carbonates*

Sample	Laboratory No.	Uranium (ppm)	$A_{Th^{230}}$	$A_{Th^{230}}/A_{U^{238}}$	Apparent age (yr)	C^{14} age (yr)
Engebi Island, beach rock 13–3	W–620	1. 35 (±. 07)	0. 05 (±. 01)	0. 05 (±. 01)	6, 300 (±1200)	[1] 2, 700 (±250)
Mu–7–4	W–619	2. 1 (±. 1)	0. 11 (±. 01)	0. 07 (±. 0)	8, 400 (±1200)	[1] 3, 840 (±300)
Mu–7–13	L–423B	2. 7 (±. 1)	1. 37 (±. 07)	0. 68 (±. 06)	132, 000 (±10, 000)	[2] 23, 500 (±1, 000)
E–1, 40–45	L–423B	2. 7 (±. 1)	0. 44 (±. 15)	0. 10 (±. 03)	12, 200 (±4000)	[2] 4, 900 (±150)

[1] Rubin, Meyer, and Alexander, Corrinne, 1960, Geological Survey radiocarbon dates V: Am. Jour. Sci. Radiocarbon Supp., v. 2, p. 1–57.
[2] Olson, E. A., and Broecker, W. S., 1959, Lamont natural radiocarbon measurements V: Am. Jour. Sci. Radiocarbon Supp., v. 1, p. 1–18.

assuming 1.82 disintegrations C^{14} per minute per gram for the original material, it has now decayed to 0.46 disintegration per minute per gram.

If this material is diluted 25 percent with a young material that contains 1.82 disintegrations C^{14} per minute per gram, 0.2 disintegration uranium per minute per gram and no ionium, the resulting material will have $A_{Th^{230}}/A_{U^{238}}=0.089$, or an apparent age of 10,800 years, as compared to 11,200 for the undiluted material. The $A_{C^{14}}=0.79$ disintegration per minute per gram and gives an apparent age of 6,800 years. Thus the apparent ionium-uranium age has been lowered 3.5 percent and the apparent C^{14} age has been lowered 39 percent.

The ionium-uranium age will be lowered 25 percent, to 8,400 years, if the young material has the same uranium content as the older calcium carbonate.

The discrepancy between apparent ionium-uranium age and apparent C^{14} age will be even more pronounced if contamination by newly formed carbonate occurs in still older materials.

Samples E–1, 40–45 and Mu–7–4 have apparently not been subjected to the emergence and recrystallization effect, because they were deposited in recent times in a period of rising sea levels. Sample Mu–7–13 has probably not been recrystallized either, as it is very pure aragonite. Thus the discrepancy in ages must be attributed to the contamination factor. This is supported by the increasing difference between the ionium-uranium and C^{14} apparent ages with increasing age for the above three samples.

Unquestionably, the ionium-uranium ratio will give the age for a material that does not violate any one of the three previously mentioned conditions. It has been extremely difficult, however, to obtain samples in which these conditions are completely satisfied. It is apparent from the preceding discussion that C^{14} ages for the marine calcium carbonates cannot be correlated with ionium-uranium ages.

OTHER POSSIBLE METHODS FOR DATING MARINE-DEPOSITED CALCIUM CARBONATES

The results obtained in analysis of sea water indicate that not only ionium but also Th^{227} in the U^{235} chain is present in the water in an amount that is very much less than the equilibrium quantity. It was suggested that Pa^{231} is the limiting specie in the U^{235} family because of its tendency to be coprecipitated. This apparent absence of Pa^{231} in sea water and also in newly deposited calcium carbonate can make two additional dating methods possible.

The first method is similar to the ionium-uranium method, except that it makes use of the disequilibrium between Pa^{231} and U^{235}. A modification of the protactinium procedure (Potratz and Bonner, 1954) could be used along with the fluorimetric method for the determination of uranium. Because the U^{235}/U^{238} ratio is fixed and is very well known, the amount of U^{235} is obtained from the total uranium.

The protactinium-uranium method seems to offer certain advantages. There is only one naturally occurring alpha emitter of protactinium, and this eliminates the need of either an expensive pulse analyzer or periodic counting. Also, the protactinium will grow in at a faster rate than ionium, thus making the protactinium-uranium method more applicable than the ionium-uranium method for materials less than 10,000 years old. The theoretical growth rates for the two methods are indicated in figure 318.

The second dating method made possible by the disequilibrium of Pa^{231} and U^{235} is a combination of the two previous methods. Because protactinium and ionium grow at different rates from their respective parents, the ratio of their activities changes with time, and if we begin with a material containing uranium but no Pa^{231} or Th^{230}, a determination of the Pa^{231}/Th^{230} ratio at subsequent times will tell us how much time

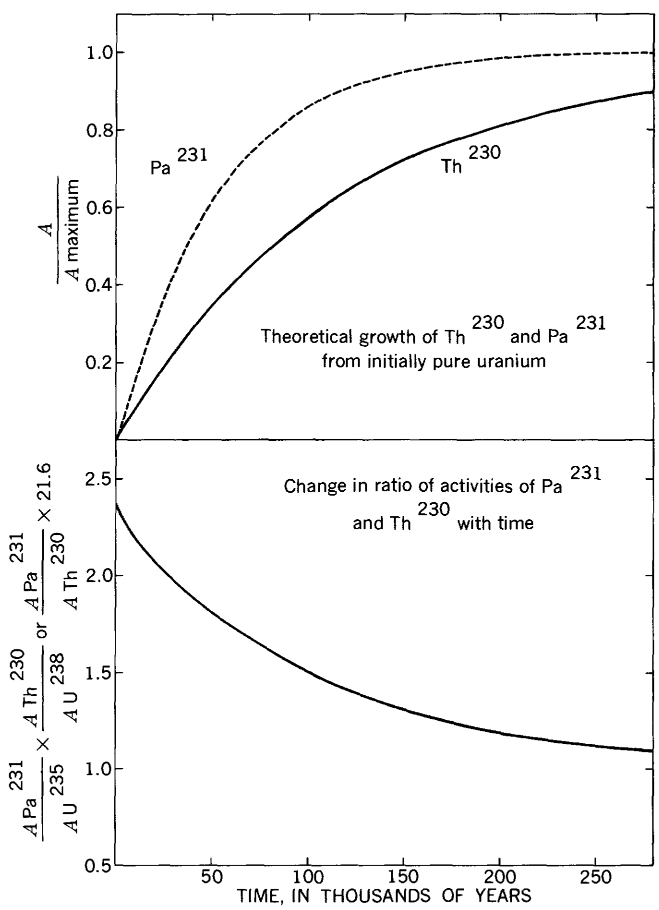

FIGURE 318.—Theoretical growth of Th^{230} and Pa^{231} from initially pure uranium and change in ratio of activities of Pa^{231} and Th^{230} with time.

has elapsed since the Pa^{231} and Th^{230} growth began. As can be seen from figure 318, which shows the theoretical change in ratio with time, the largest difference in activities would be observed in the most recently deposited materials.

As Ac^{227} ($t\frac{1}{2}$=22.0 years) and Th^{227} ($t\frac{1}{2}$=18.6 days) are probably in equilibrium with Pa^{231} in calcium carbonates, a procedure that involves separation of thorium followed by alpha pulse analysis for Th^{230} (4.68 MEV) and Th^{227} (5.7 and 6.0 MEV) would probably produce an age for the material.

The actual operation of these procedures would present difficulties because of the minute activities involved. These small activities are not only easily contaminated but must also be counted for extremely long periods to obtain good statistics.

DESCRIPTION OF MATERIALS STUDIED

1. Core samples received from H. S. Ladd, U.S. Geological Survey

[For exact location of drill holes see figures 260 and 261 in Ladd and Schlanger, 1960]

Hole	Core No.	Depth (ft)	Description
Mu-7	4 13 23 41	13–24 48–51 64. 5–69. 5 90–97. 5	Pure coral core splits from a drill hole in the northeast part of Mujinkarikku, Eniwetok. Altitude of drill hole, 8.5 feet.
Ru-2	14	47–52	Runit, pure coral core split.
En-6	29	96–101	Engebi, pure coral core split.
13-3	--------	9–10. 5	Core sample from foundation test hole near center of Engebi, Eniwetok. Sample is bedded rock similar to beach rock and a little below sea level.
F-1	[1] 1–1	170–191	Elugelab, coral-algal detritus.
	5–37	1978–2003	Recrystallized coral.
	6–10	2662–2687	Detrital limestone.
	10–5	3963–3988	Do.
	12–8	4316–4341	Dolomitic limestone.
	14–24	4500–4525	Detrital limestone.
E-1	1–5	2003–2028	Parry Island, pure coral split.
	2–5	2802–2808	Detrital limestone.
	3–7	4078–4100	Dolomitized coral.

[1] First number is that of core run, second is number of core piece below top of core

2. Cuttings from drill hole E–1 on Parry Island, Eniwetok, received from Los Alamos Scientific Laboratory (Ladd and others, 1953).

Depth (feet)	*Description*
10–30	Uncemented sand made up largely of worn tests of beach-type Foraminifera such as *Calcarina* and *Marginopora*, mixed with coral pebbles, mollusk shells, echinoid spines, and worn segments of *Halimeda*. Hard beach rock 18 to 21 feet.
30–90	Coarse, platy debris with numerous fresh and worn segments of *Halimeda*, some of which are cemented, and many small mollusks and Foraminifera. Larger fragments include worn corals and branching *Lithothamnium* and mollusks (*Arca, Cypracea*).
90–145	Worn coral and sand; some coral recrystallized to yellow calcite. Some mollusks well preserved; others occur as molds.
145–300	Coral limestone; white friable limestone recrystallized in places to yellow calcite. Mollusks abundant, some preserved as molds.

3. Cuttings from drill hole F–1 on Elugelab, Eniwetok (Ladd and others, 1953).

Depth (feet)	*Description*
0–45	Uncemented sand made up largely of beach-type Foraminifera such as *Calcarina* and *Marginopora*, mixed with fragments of larger forms, including corals (*Tubipora*) echinoid spines, mollusk shells, and segments of *Halimeda*. Hard beach rock from 12 feet 6 inches to 14 feet 6 inches.
45–110	Uncemented coarse, platy debris. Poorly sorted mixture of *Halimeda* segments and worn coral, algae, mollusks, and Foraminifera.
110–190	Worn, massive coral and delicate unworn branching coral. Large fragments of yellow calcite; some mollusks preserved as molds.

4. Sea-water samples from E. D. Goldberg, Scripps Institution of Oceanography.

Depth (feet)	*Description*
Sample *A*	Surface water from outside San Diego Bay, collected in the summer of 1956.
Sample *B*	Water collected at 3,500 meters depth from long 124°41.0′ W., lat 33°54.5′. N. on March 25, 1957.

5. Miscellaneous materials

Reef coral (*Porites australiensis Vaughan*), from lagoon channel reef off west side of Bogen, collected alive by J. I. Tracey, Jr., May 21, 1946. (Sample JIT–1, tables 11 and 15.)

Coral head (*Favia*) encrusted by hydrocoralline growth (*Millepora*). Sample was collected April 15, 1930, from Christmas Island by C. K. Wentworth. (Samples CKW–1 and CKW–2, table 11.)

Algal calcium carbonate (*Porolithon craspedium*), from Ourukaen island, Bikini, collected May 3, 1946. Sample submitted by J. I. Tracey, Jr. Chemical analyses of this sample are published by Emery, Tracey, and Ladd (1954, p. 67, sample 6). An X-ray analysis showed that the sample is calcite with a unit cell about 1.8 percent short. (Sample 260–A–67–6, tables 11 and 15.)

Clam (*Tridacna*), from Lidilbut, collected alive by J. P. E. Morrison, June 1, 1946. (Sample JPEM–1, tables 11 and 15.)

Marine shells (gastropods), submitted by T. N. V. Karlstrom, U.S. Geological Survey. (Sample TNVK–1, tables 11 and 15; modern shells from Cook Inlet area, Alaska. Sample TNVK–2, table 19; shells from Bootlegger Cove, Alaska, estimated to be 40,000 to 60,000 years old.)

Shells from Sq. A–3 at depths of 6½ to 7, 12 to 12½, and 15 to 15½ feet with ages of approximately 4,000 to 5,000 years. These are three fragments of Busycon gouges from Indian shell midden, Bluffton site, Volusia County, Florida. (Samples V67–61, V67–70, V67–74, table 19.) (Bullen, R. P., 1955, The Florida Anthropologist, v. 8, p. 1.)

Shell material 7,000–9,000 years old. (Sample Co–40A, table 19.) (McGimsey, C. R., 1956, Am. Antiquity, v. 22, p. 151.)

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PLATES 282–288

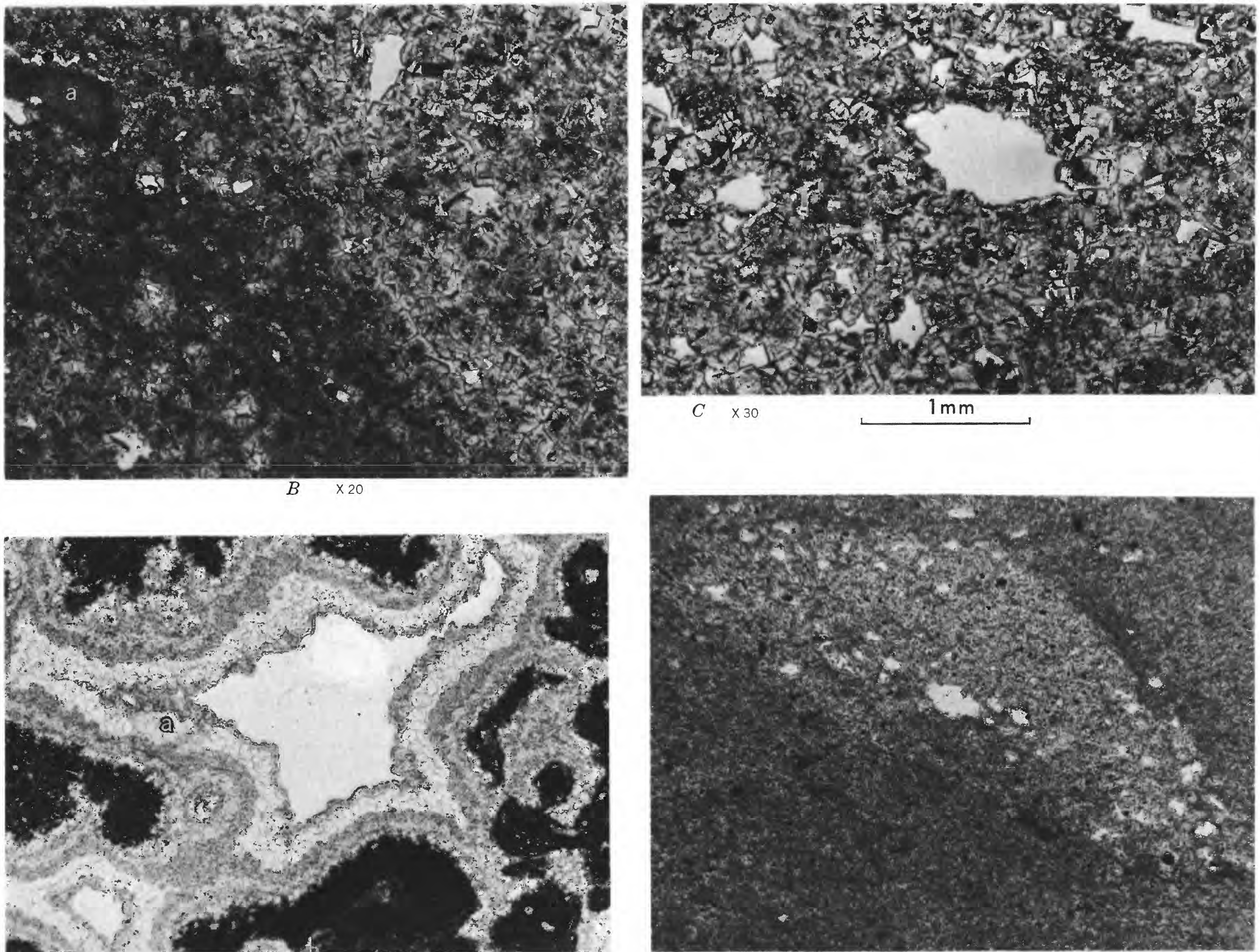
PLATE 282

A. Core F–1–3–20, × 12. Section across vug in limestone of Tertiary *e* age. Chemical analysis showed 2.8 percent $MgCO_3$ for bulk sample, and a bulk X-ray analysis showed no dolomite. Staining of another thin section from this core showed that the clear layer (*a*) contains a few strings of dolomite crystals.

B. Core F–1–12–5*t*, × 20. Relict dark areas in almost completely dolomitized rock of Tertiary *b* age. A composite sample from the top and bottom of this core piece showed 38 percent $MgCO_3$; X-ray analysis showed more than 98 percent dolomite. In this core piece, algae (*a*) are most resistant to the encroaching dolomite; most of the rock is a saccharoidal mass of subhedral dolomite grains. Dark areas are the only remains of the original coarse-grained foraminiferal-algal limestone.

C. Core F–1–12–10, × 30. Slightly calcitic dolomite of Tertiary *b* age. Chemical analysis showed 35.9 percent $MgCO_3$; X-ray analysis showed 93 percent dolomite. Lens-shaped void in the center was formed by the removal by solution of a Foraminifera test after dolomitization of the original foraminiferal-algal limestone.

D. Core F–1–12–7*t*, × 8. Dolomite of Tertiary *b* age. Chemical analysis showed 38.8 percent $MgCO_3$; X-ray analysis showed more than 98 percent dolomite, with only a trace of calcite. Some original texture is reflected in the patches of coarse-grained dolomite that have more and larger pore spaces than the surrounding fine-grained dolomite.



B X 20

C X 30

A X 12

D X 8

DOLOMITIZED LIMESTONES FROM HOLE F-1, ENIWETOK ATOLL

PLATE 283

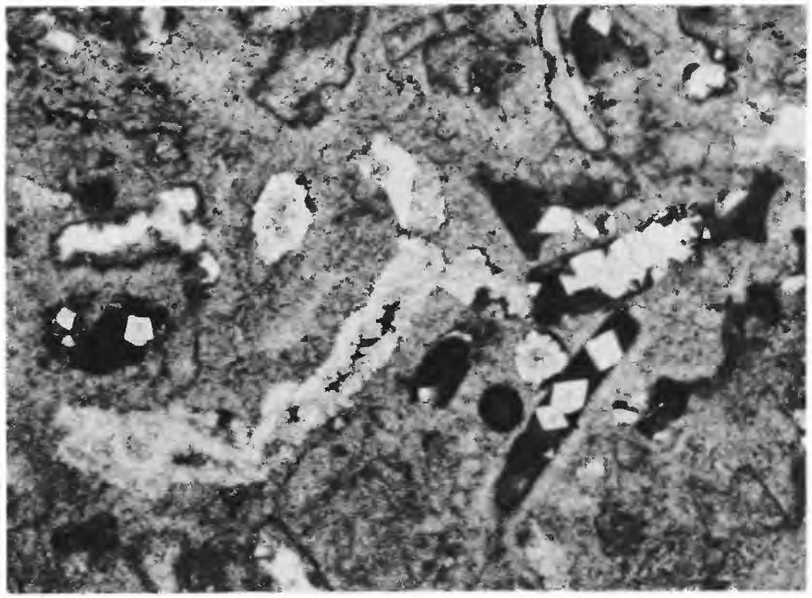
A. Core E–1–3–9, × 30. Dolomitized coralline algae. Most of the dolomite in this section is restricted to rod-shaped segments of *Corallina*.

B. Core E–1–3–9, × 180. Closeup of single algal segment partly replaced by 3 euhedra of dolomite. The dark centers of the dolomite crystals appear white and cloudy in reflected light and are possibly calcite-rich central zones.

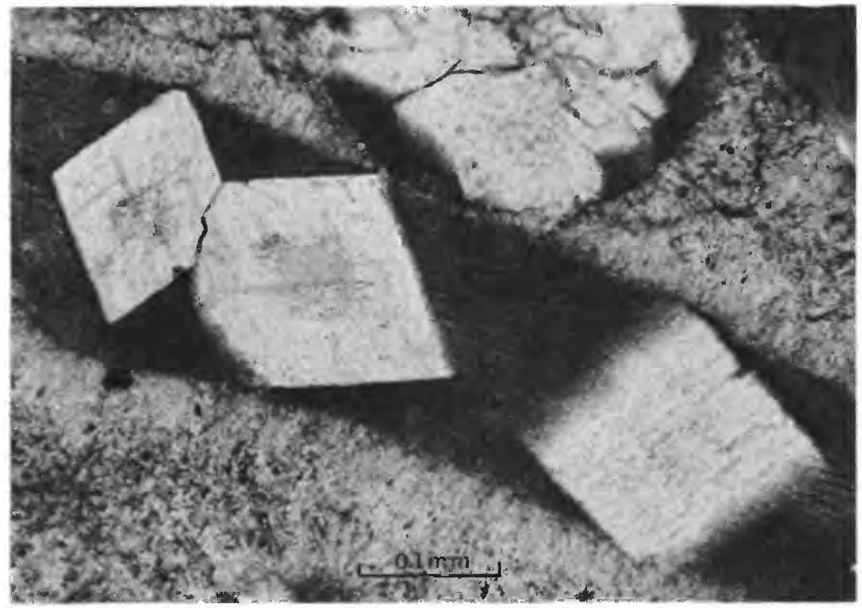
C. Core E–1–3–9, × 30. Algal segment almost completely replaced by a mosaic of dolomite. The dolomite is restricted to the algae and closely follows the outlines of the original segment.

D. Core E–1–3–10, × 20. Scattered dolomite crystals that occupy the mud-filled interseptal spaces in coral. All the original corallum has either been replaced by calcite or removed by solution. This sample showed an $MgCO_3$ content of only 4.5 percent; X-ray analysis showed 5 percent dolomite and 95 percent calcite.

E. Core E–1–3–40, × 10. Dolomite occupying a mollusk shell and coralline algae. Dolomite has faithfully followed the original shell of the mollusk.

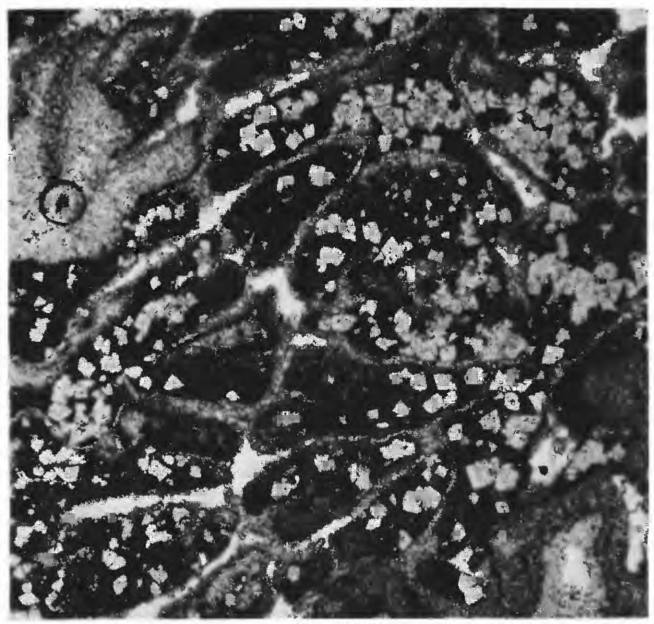


A X 30



B X 180

C X 30



D X 20

E X 10

DOLOMITIZED LIMESTONES OF TERTIARY *b* AGE FROM HOLE E-1, ENIWETOK ATOLL

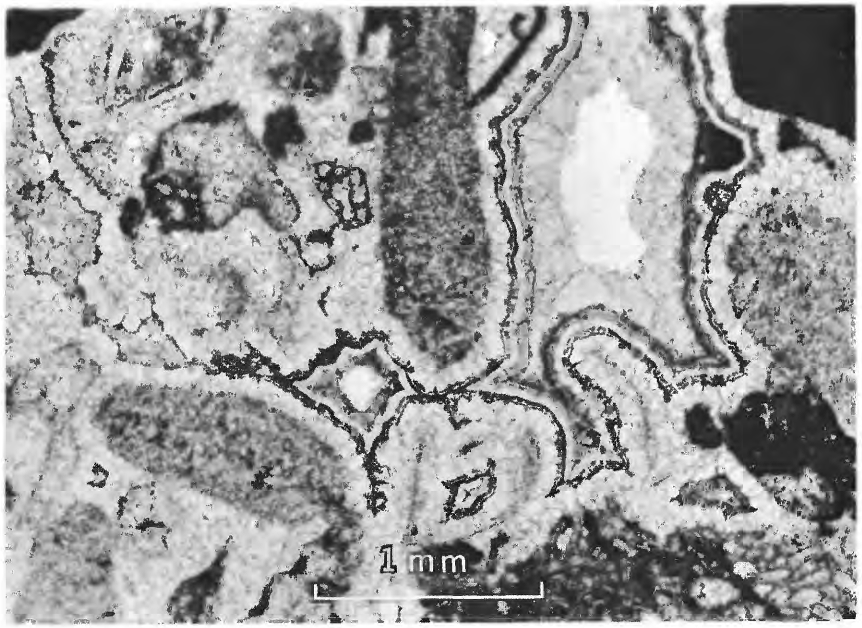
PLATE 284

A. Funafuti core 341A, × 30. Completely dolomitized limestone from a depth of 900 feet. This core contains about 40 percent $MgCO_3$.

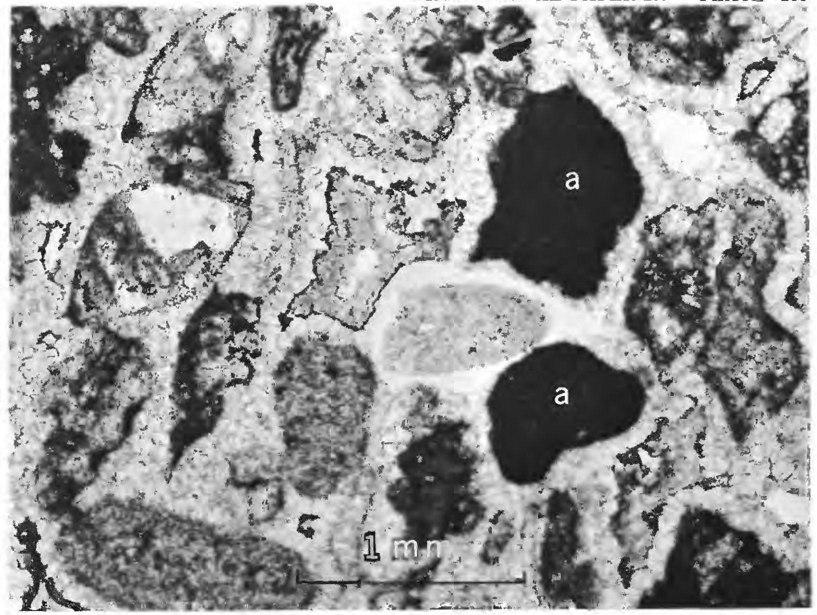
B. Funafuti core 634A, × 30. Completely dolomitized limestone from a depth of 1,070 feet. This core contains 39.4 percent $MgCO_3$. Note that although the rock is completely dolomitized, coralline algae (*a*) have not been texturally destroyed. This is in direct contrast to the state of algae in dolomitized cores from hole E–1 at Eniwetok Atoll (pl. 283C).

C. Funafuti core 205A, × 20. Dolomite laminae in rock from a depth of about 830 feet. The $MgCO_3$ content of this core is between 5 and 11 percent. According to Cullis (1904, p. 410, fig. 44) the layer of clear dolomite crystals (*a*) formed before depositions of the three bands of laminar deposits. Of these three laminae, the central one (*b*) is dolomite, the other two are calcite.

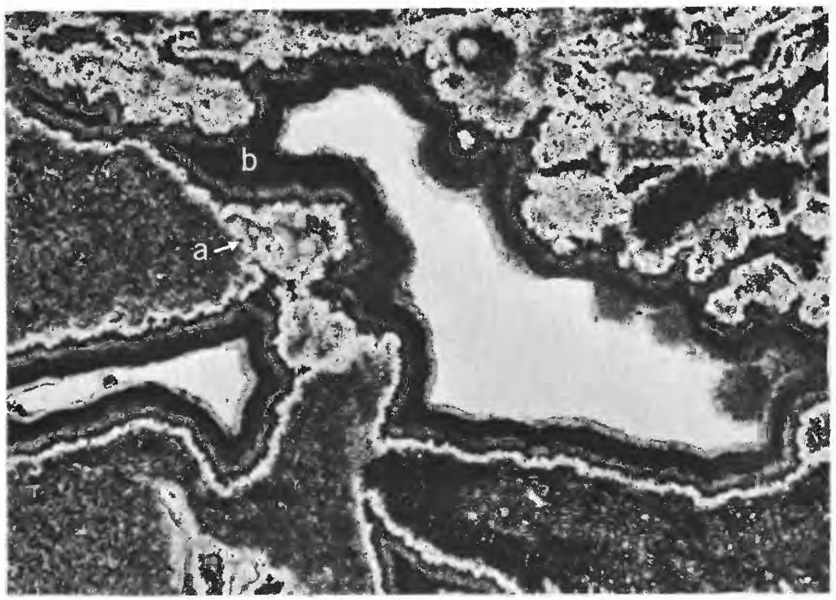
D. Funafuti core 203A, × 2.5. Dolomite in low-magnesium rock. $MgCO_3$ content is only 4.83 percent but dolomite (*a*) is widespread.



A X 30



B X 30



C X 20

D X 2.5

DOLOMITIZED LIMESTONES FROM FUNAFUTI ATOLL

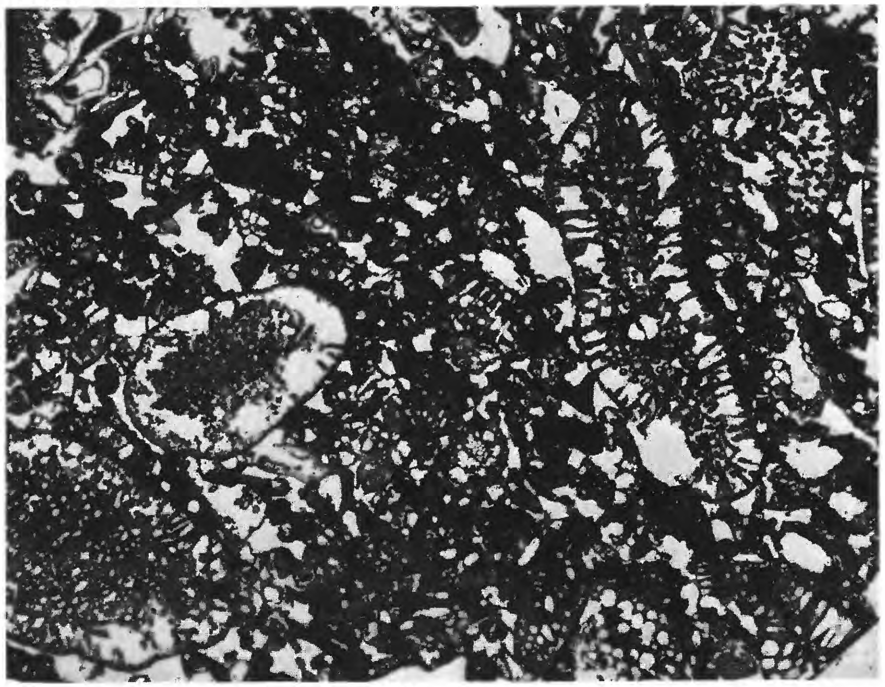
PLATE 285

A. Funafuti core 342, × 12. Porous dolomite from a depth of 659 feet. The rock contains about 40 percent $MgCO_3$. Most of the originally aragonite parts of the abundant *Halimeda* segments have been removed through solution. Those parts, such as tubes, normally occupied by calcite in fossil *Halimeda* are now fine-grained dolomite.

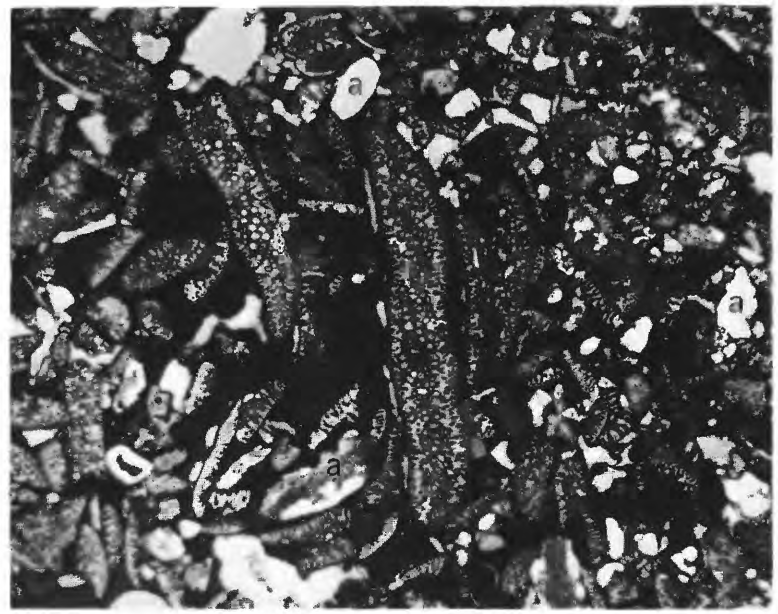
B. Kita-daitō-jima core 551, × 12. Dolomite from a depth of 300 feet. The *Halimeda* in this rock, which contains 40.1 percent $MgCO_3$, are completely dolomitized but well preserved. Evidently dolomitization affected both the original aragonite—after it recrystallized to calcite—and the calcite filling of the *Halimeda*. Note that fragments of coralline algae (*a*) have been partly removed through solution whereas the *Halimeda* are entire.

C. Funafuti core 320, × 20. Dolomitized coral from a depth of 643 feet; the core analyzed at 31.9 percent $MgCO_3$. Much of the dolomite is in the form of a film of anhedral crystals on ghosts of the original corallum (*a*).

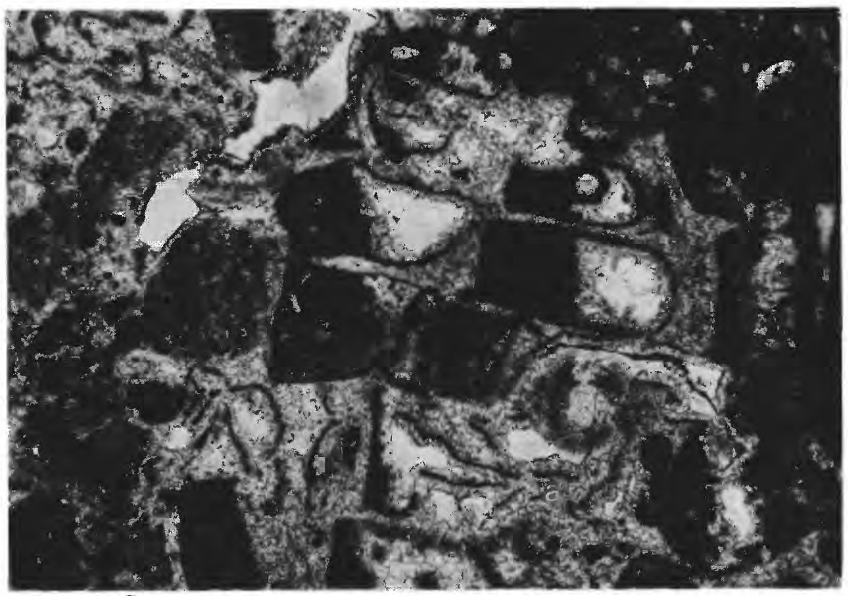
D. Funafuti core 578A, × 25. Dolomitized foraminiferal-algal limestone; this core contains about 40 percent $MgCO_3$. Although entirely dolomitized, the fossils are well preserved and show all fine skeletal details. Note contrast between this dolomite and the dolomite from core F–1–12–10 (pl. 282*c*); the latter was also originally a foraminiferal-algal limestone, but all original textures have been destroyed.



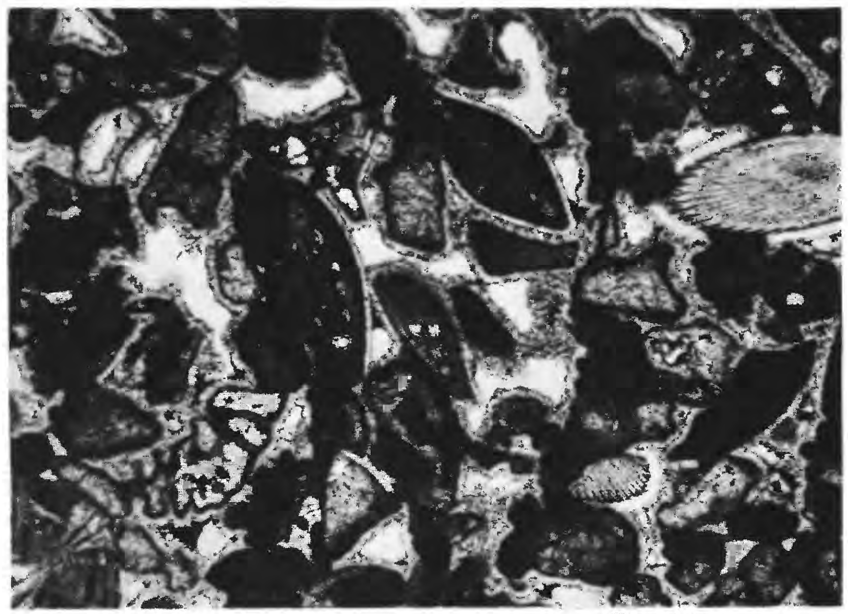
A X 12



B X 12



C X 20



D X 25

DOLOMITIZED LIMESTONES FROM FUNAFUTI AND KITA-DAITŌ-JIMA ATOLLS

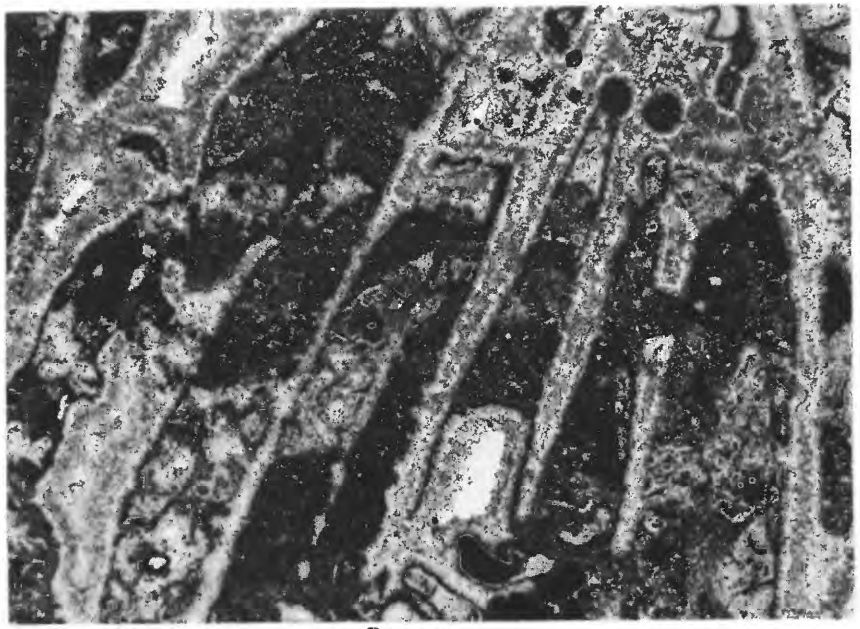
PLATE 286

A. Core F–1–4–2, × 8. Porous well-cemented foraminiferal limestone. Cement is a single layer of acicular and granular calcite.

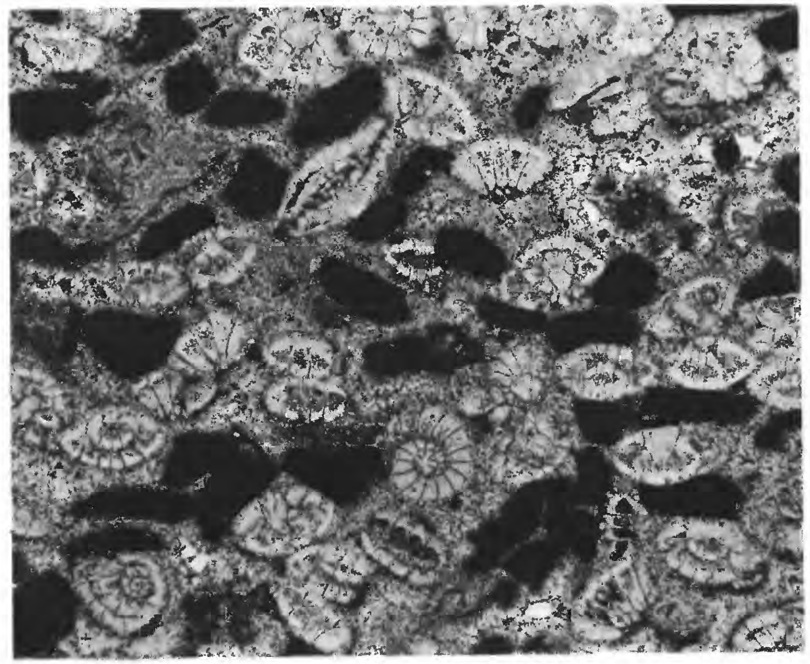
B. Core F–1–5–9, × 8. Section through a large piece of recrystallized mud-filled coral. Packed debris of Foraminifera tests and algae fill a cylindrical hole that is probably a worm burrowing.

C. Core F–1–5–16, × 8. Foraminiferal-algal sand that forms the matrix around corals in this core.

D. Core F–1–5–23, × 8. Recrystallized coral showing intricate pattern developed in secondary calcite.

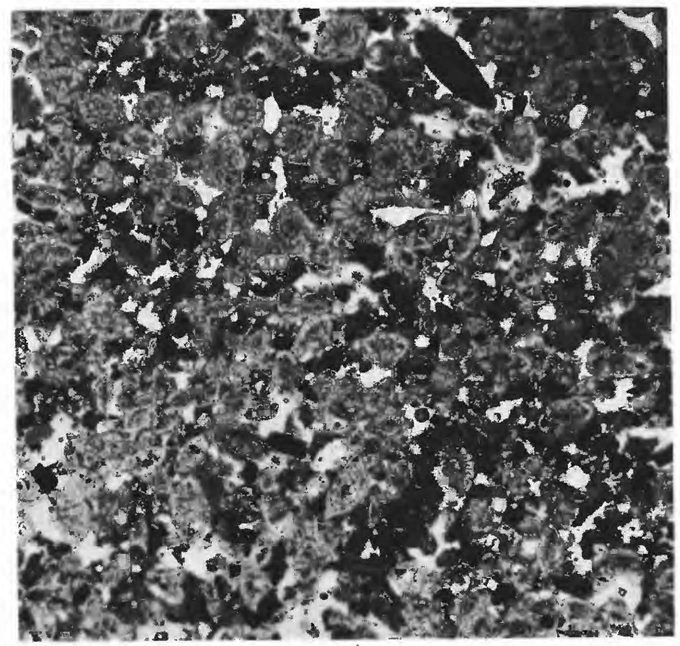


D ×8



C ×8

B ×8

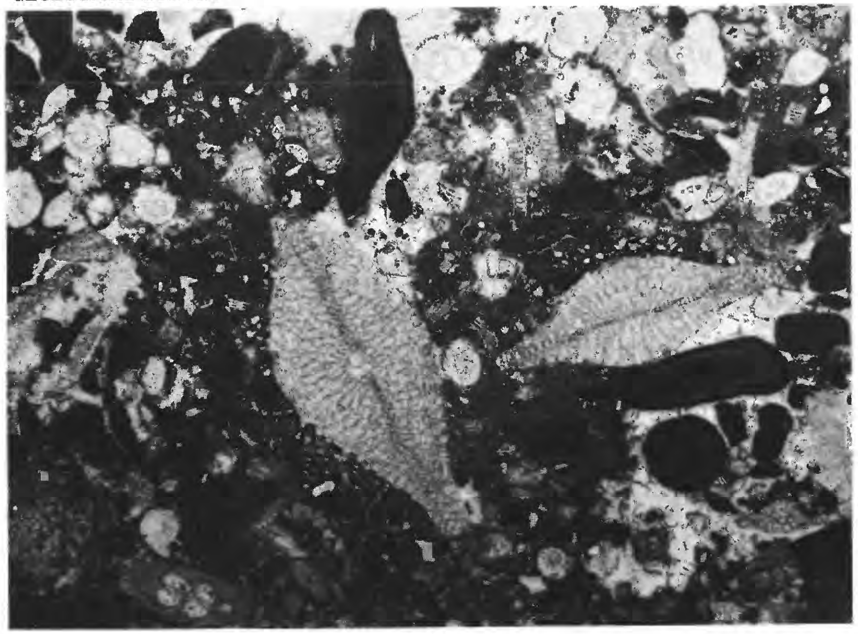


A ×8

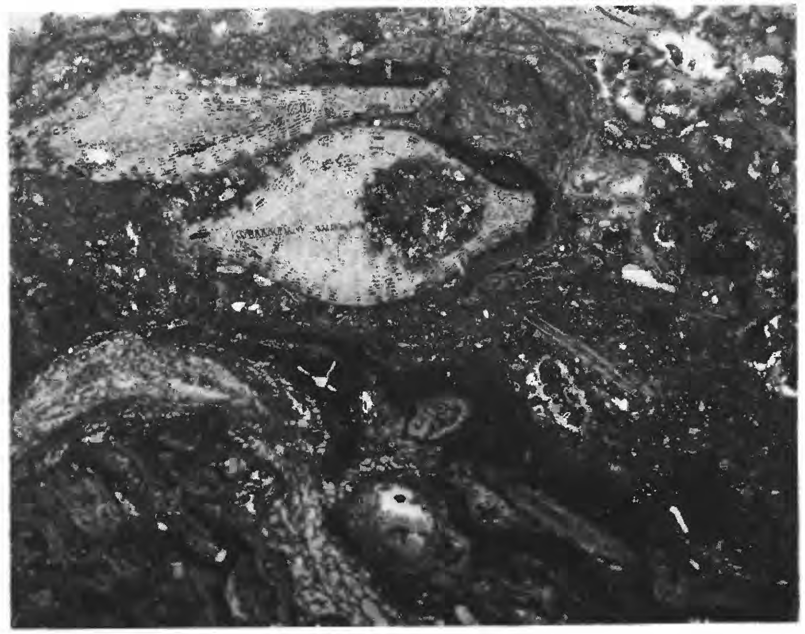
PHOTOMICROGRAPHS OF LIMESTONES FROM CORES F-1-4 AND F-1-5

PLATE 287

A. Core F–1–5–35, × 8. Conglomeratic limestone made up of tests of larger Foraminifera, coralline algae, and pebbles of coral.
B. Core F–1–5–41, × 8. Tests of larger Foraminifera in an unusual matrix of laminar encrusting algae and Foraminifera.
C. Core F–1–6–9, × 8. Solution channel into which project tests of large rForaminifera. Material scraped from filled channels such as this showed a trace of dolomite on X-ray testing.
D. Core F–1–6–30, × 12. Completely recrystallized coral.
E. Core F–1–7–3, × 8. Poorly sorted foraminiferal-algal limestone with a cement of granular calcite.



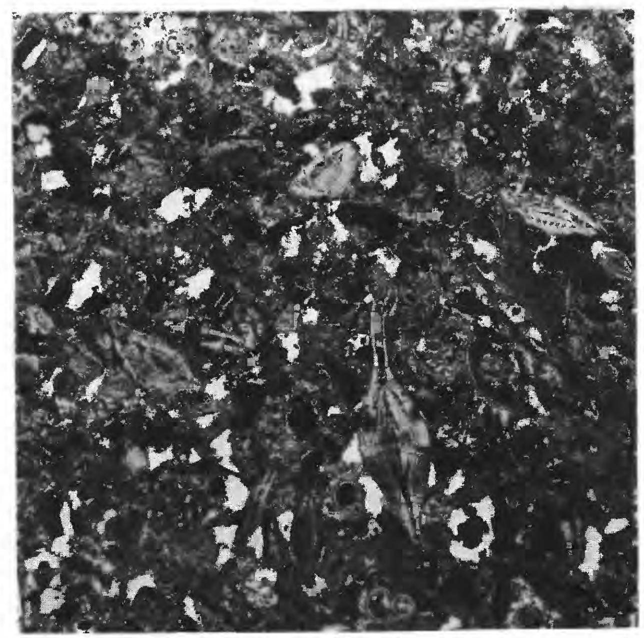
A ×8



B ×8

C ×8

D ×12



E ×8

PHOTOMICROGRAPHS OF LIMESTONES FROM CORES F-1-5, F-1-6, AND F-1-7

PLATE 288

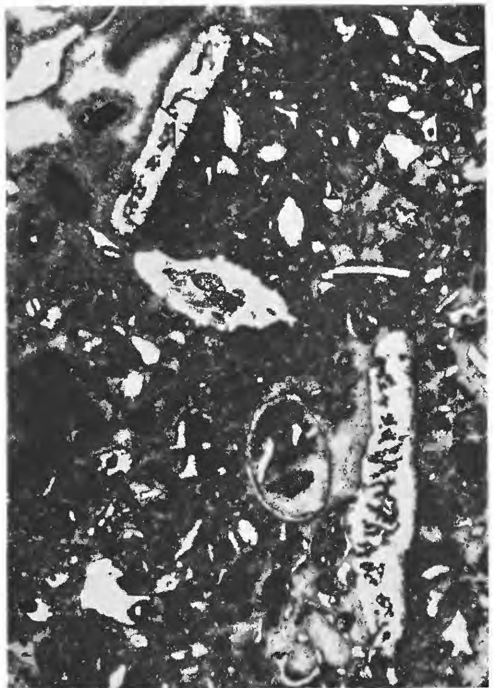
A. Core F–1–9–8, × 8. Molds of *Halimeda* in completely recrystallized limestone. All aragonitic skeletal material has been dissolved and removed.

B. Core F–1–10–1, × 12. Well-sorted, porous, foraminiferal-algal limestone containing well-preserved tests of planktonic Foraminifera.

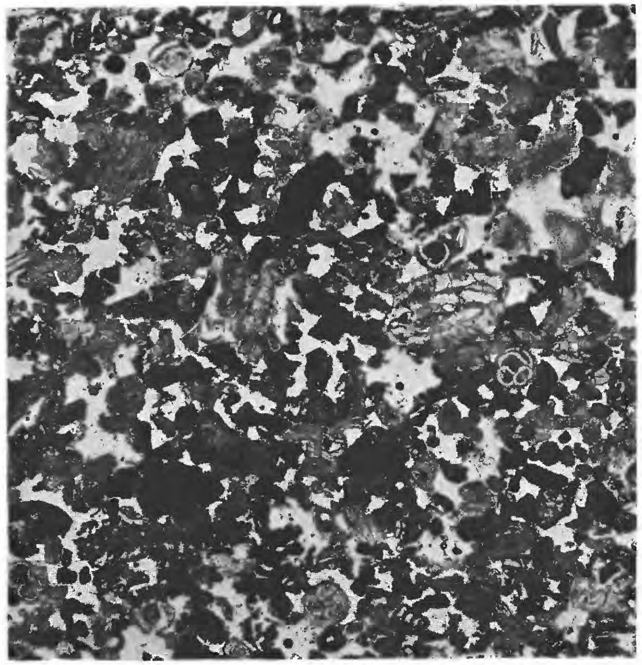
C. Core F–1–11–18, × 4. Bedding in foraminiferal-algal limestone (bedding planes run from lower left to upper right hand side of photo) deposited under outer slope conditions.

D. Core F–1–11–34, × 8. Porous coarse-grained foraminiferal limestone showing high degree of orientation of disc-shaped and biconvex tests of larger Foraminifera.

E. Core F–1–12–14, × 30. Unaltered tests of larger Foraminifera in a dolomitized matrix.

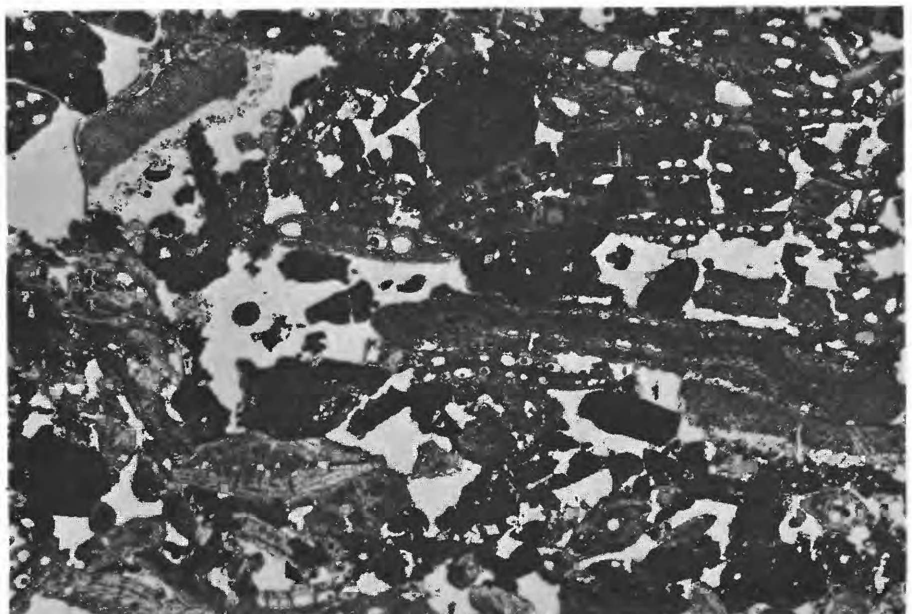


A X 8

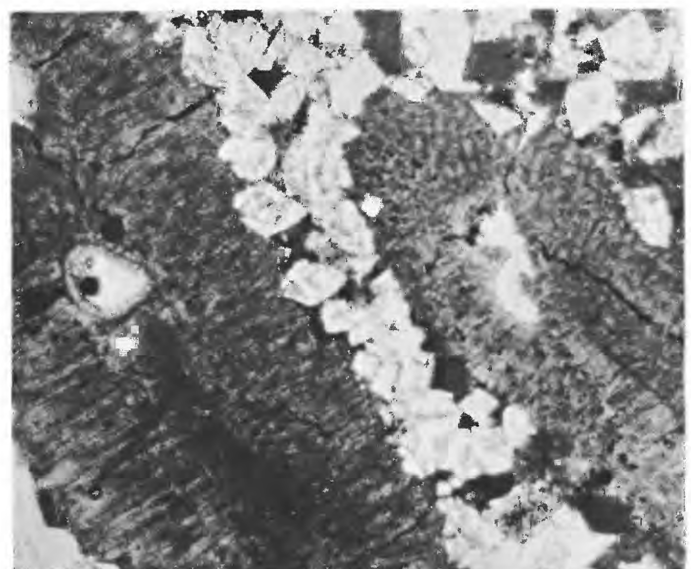


B X 12

C X 4



D X 8



E X 30

PHOTOMICROGRAPHS OF LIMESTONES FROM CORES F-1-9 F-1-10 F-1-11 AND F-1-12

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