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Petrology of the Limestones of Guam

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Schlanger—PETROLOGY OF THE LIMESTONES OF GUAM—Geological Survey Professional Paper 403-D

Petrology of the Limestones of Guam

By SEYMOUR O. SCHLANGER

With a section on PETROGRAPHY OF THE INSOLUBLE RESIDUES

By J. C. HATHAWAY *and* DOROTHY CARROLL

GEOLOGY AND HYDROLOGY OF GUAM, MARIANA ISLANDS

GEOLOGICAL SURVEY PROFESSIONAL PAPER 403-D

Field and laboratory study of reef-associated limestones of Pleistocene and Tertiary age

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UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1964

UNITED STATES DEPARTMENT OF THE INTERIOR

STEWART L. UDALL, *Secretary*

GEOLOGICAL SURVEY

Thomas B. Nolan, *Director*

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C. 20402

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PETROLOGY OF THE LIMESTONES OF GUAM

By Seymour O. Schlanger

ABSTRACT

Limestones characteristic of the so-called reef facies are found in all the formations that crop out on the island of Guam. The mountainous central part of the island is underlain by the Alutom Formation of Eocene and Oligocene age—a succession of more than 2,000 feet of marine tuffaceous sandstone, shale, pillow lava containing beds of Eocene limestone, and breccia of Oligocene age containing fragments of the Eocene limestone. The Mahlac Member of the Alutom Formation is a marine calcareous shale of Oligocene age. The northern part of the island is a limestone cap that rests unconformably on the Alutom Formation and is made up of the Bonya Limestone of Miocene age; the Alifan Limestone, the Barrigada Limestone, and the Janum Formation, all of Miocene or Pliocene age; and the Mariana Limestone of Pliocene and Pleistocene age. The southern part of the island is underlain by the Umatac Formation of Miocene age, a succession of volcanic rocks and limestone approximately 2,200 feet thick. This formation is made up of four members: the Facpi Volcanic, the Bolanos Pyroclastic, the Maemong Limestone, and the Dandan Flow Members.

All the limestone on the island had, as primary constituents, various combinations of coral, coralline algae, *Halimeda*, Foraminifera, mollusks, echinoids, minor amounts of worm tubes and bryozoans, fine limemud, and volcanic material in the form of clay, single crystals of various minerals, and rock fragments. The limestones are classified into two main groups: incrustate and particulate. Incrustate limestones are those that have been built by incrusting or attached organisms such as colonial corals, coralline algae, or incrusting Foraminifera. Particulate limestones are those that have been formed by the accumulation of individual foraminiferal tests or fragmental skeletal debris. The particulate limestones are subdivided by considering four rock attributes: (1) the amount of intergranular mud matrix, (2) degree of wear of the fossils, (3) degree of sorting of the fossils, and (4) size of the fossils. A third, minor group of metasomatic limestones includes those in which replacement of the original carbonate has taken place.

Although these limestones occur in the reef facies—as used in the stratigraphically unrestricted sense—it was possible to distinguish rock assemblages characteristic of subdivisions within this blanket term. Evidence bearing on the assignment of any given rock type or rock association to a facies includes: (1) Comparison of the rocks in question with modern sediments by the use of individual faunal and floral elements as ecologic indicators and by matching lateral lithologic changes in the rocks with areal distribution patterns of modern reef complexes; (2) comparison of individual formations with other well-known fossil reef complexes; (3) reconstruction of the original configuration of partly destroyed reef complexes, on structural and stratigraphic evidence; and (4) comparison of thin-section attributes of rocks from a known facies with those of the rock in question.

Systematic study of the limestone on a formational basis showed that rock associations characteristic of individual facies are present throughout the geologic column on Guam. The limestone of the island was formed as a series of reef complexes intermittently destroyed or buried by outbreaks of volcanic activity. Comparison of rocks from several facies of the Maemong Limestone Member with lower Tertiary limestones from Louisiana and Iraq shows that striking textural similarities exist from one area to another. Lower Tertiary limestones throughout much of the world show similar microfacies attributes.

Secondary features of the limestones include: extensive recrystallization of the original constituents in all formations; silicification as the result of burial by lava flows, in the Alutom Formation and in the Maemong Limestone Member of the Umatac Formation; replacement by several manganese minerals in the Bonya Limestone; local dolomitization in the Alifan Limestone; and phosphatization in the Mariana Limestone. Microstylolites are well formed in the argillaceous parts of the Alifan Limestone. The microstylolites formed under loads of less than 300 feet of superincumbent limestone. Inspection of similar limestone from cores taken at depths below 4,000 feet in Eniwetok reveals only minor pressure-solution effects. It is concluded that pressure alone may not cause the formation of microstylolites.

Analyses of 29 samples for $CaCO_3$, $MgCO_3$, and $SrCO_3$ content show ranges of 52.7 to 99.2 percent $CaCO_3$, 0.52 to 2.72 percent $MgCO_3$ (no dolomitic limestones were analyzed), and 0.01 to 0.36 percent $SrCO_3$. The low $SrCO_3$ content correlates with the generally highly recrystallized condition of the limestones.

In addition to calcite—the dominant mineral—aragonite, and dolomite, many minerals were identified in insoluble residues from the various formations by X-ray, microscopic, and chemical tests. In the clay and silt fractions are montmorillonite, chlorite, mixed-layer montmorillonite-chlorite, mica, kaolinite, halloysite, quartz, cristobalite, plagioclase, zeolites, gibbsite, nordstrandite, magnetite, hematite, goethite, lithiophorite, pyrolusite, apatite, and a woodhouseitelike mineral. In the sand fraction are magnetite, ilmenite?, augite, hypersthene, greenish-brown amphibole, basaltic hornblende, blue-green amphibole, sphene, zircon, apatite, plagioclase, quartz, beta-cristobalite, and zeolites. These minerals show a wide range of relative abundances in the various formations. Most of the samples, however, are characterized by either a feldspar-zeolite-montmorillonite assemblage indicative of contributions by ash falls, or an iron oxide-nordstrandite-halloysite assemblage indicative of contributions by subaerial erosion of volcanic terrain. Tabulation of these assemblages by stratigraphic succession shows that ash falls contributed to limestones in the Alutom Formation, the Umatac Formation, and the Bonya Limestone. The Janum formation and the Alifan Limestone received argillaceous material mainly from subaerial erosion. The Mariana Limestone contains the ashfall assemblage. The classification of insoluble residues by this grouping shows that periods of active volcanism can be differentiated from periods of subaerial erosion.

Two dominant geologic processes, reef growth and volcanic activity, combined to build up the island of Guam. This study shows that characteristic limestone facies recur through time in the various formations. A comparison of the fossil content of the formations shows that the same groups of organisms contributed rock-making material from Eocene through Pleistocene time.

INTRODUCTION

PURPOSE AND SCOPE OF STUDY

Field study of reef and associated limestones of Recent and Tertiary age on the island of Guam (July 1951 through July 1953) led to a supplementary thin-section study of the limestones of Tertiary age. The main purpose was to augment field data. As work progressed, it became evident that certain lithologic attributes, apparent in thin section only, were diagnostic in rock and facies classification. Thus, the subject was approached somewhat after the fashion of Henson (1950), in his regional study of limestones in the Middle East. Limestones of Miocene (*e*) age from Guam already have been compared to reef and associated limestones from the *Heterostegina* zone of southern Louisiana (Forman and Schlanger, 1957).

Chapter A of this series (Tracey and others, 1963) covers the general geology of Guam; the field relations and gross lithologic aspects of the limestones are fully treated in the section on stratigraphy in chapter A, and are discussed in the present chapter only where necessary to augment the laboratory investigation. The Recent calcareous deposits on and around Guam, such as those of present-day beaches, reefs, and lagoons, are discussed in chapter B (Emery, 1962), and in less detail in chapter A.

Age designations used in this report are based on diagnostic larger Foraminifera identified by Cole (1963) and correlated with the standard section of the Indonesian region (van Bemmelen, 1949, p. 79–108). In the Indonesian region letter designations are used to differentiate faunal zones. The relationship between these Indonesian faunal zones and the standard Tertiary series subdivisions of the United States is shown on figure 1. In this paper the age of a limestone under discussion is designated by two terms, the standard Tertiary series name followed by the Indonesian zonal letter in parenthesis; that is, Eocene (b), Miocene (e), and so forth.

GEOLOGIC SETTING

Limestone of Eocene (*b*), Oligocene (*c*), Miocene (*e, f*, and *g*), and Pliocene to Pleistocene age are known on Guam (fig. 1; Tracey and others, 1963, pl. 1). Limestone of Eocene (*b*) age is found interbedded within marine tuffs and pillow lavas and as fragments in beds of breccia of Oligocene (*c*) age within a succession of more than 2,000 feet of folded and faulted volcanics. This succession—the Alutom Formation—forms the mountainous central core of the island. It includes a marine calcareous shale, the Mahlac Member of Oligocene (*c*) age. The northern plateau of the island is a limestone cap that rests unformably on the Alutom Formation and is made up of the relatively flat-lying Bonya Limestone of Miocene (*f*) age, Alifan Limestone, Barrigada Limestone, and Janum Formation, all of Miocene (*f* to *g*) and Pliocene ages, and the Mariana Limestone of Pliocene and Pleistocene age. The southern third of the island is made up of a succession of volcanic rocks and limestones of Miocene (*e*) age approximately 2,200 feet thick, named the Umatac Formation. This formation is composed of four members: (1) the Facpi Volcanic Member; (2) the Bolanos Pyroclastic Member, which contains limestone fragments from (3) the Maemong Limestone Member; and (4) the Dandan Flow Member. The field relations of each formation are discussed in the unit descriptions.

METHODS

Limestone samples collected during the fieldwork and used for the laboratory studies are listed in table 11 and locations are shown in figure 2. Laboratory study consisted largely of examination of thin sections under a binocular microscope fitted with a polarizing attachment, at magnifications ranging from ×9 to ×45. Details were studied at higher magnification with a standard petrographic microscope. A few specimens were ground, polished, and stained with Meigen's solution to distinguish aragonite from calcite, and chemical and mineralogical analyses were made (p. 8–10).

The percentages of fossils were determined by visual estimation in thin section. The visual-estimation percentage charts of Folk (1951), Allen (1956), and Terry and Chilingar (1955) were used, and the writer also prepared a set of charts that showed percentages of shapes within the field that were characteristic of fossils common in the limestones of Guam.

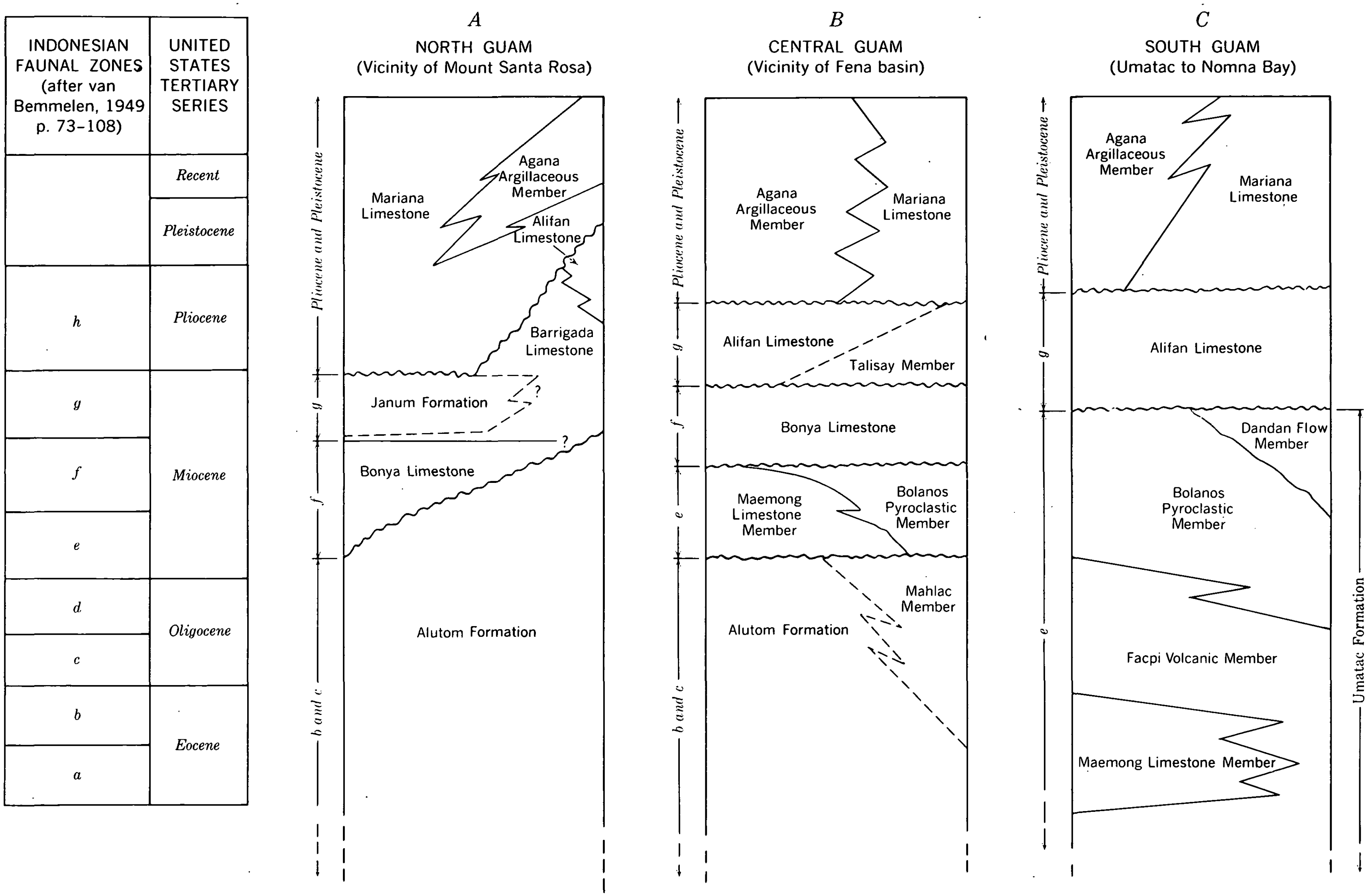


Figure 1.—Columnar stratigraphic sections from north, central, and south Guam. Each diagrammatic section is a local composite of strata arranged to illustrate formational relationships and is not to true vertical scale.

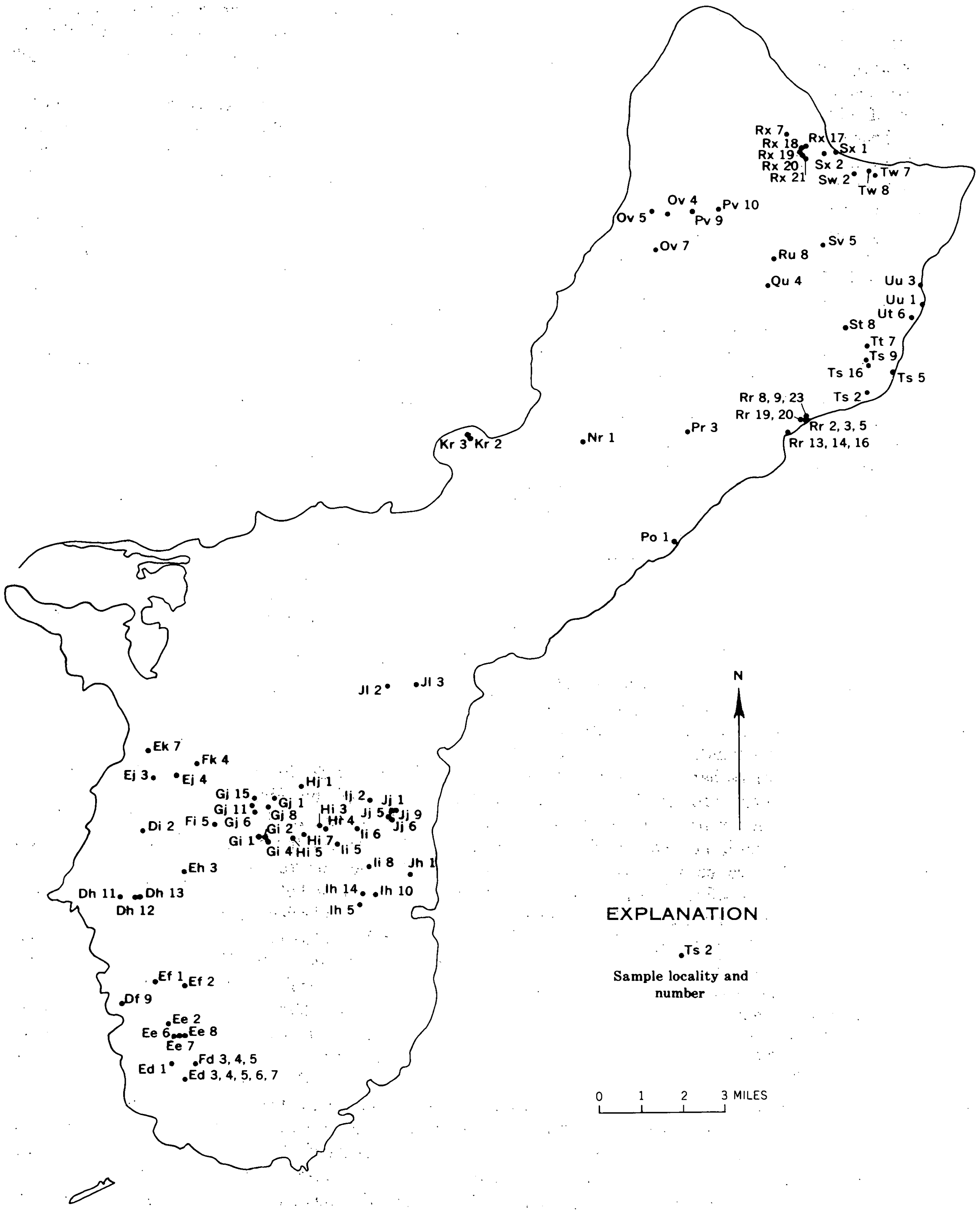


FIGURE 2.—Sample locality map. (See table 11.)

ACKNOWLEDGMENTS

Much of the information relating to field occurrence, stratigraphy, and gross lithology of the Guam limestones has come from the fieldwork and preliminary reports of other members of the Guam field party: J. I. Tracey, Jr., David B. Doan, Harold G. May, and John T. Stark. Discussion of the paleoecology of the Guam limestones and the ecology of extant forms with the above mentioned coworkers and the cooperating paleontologists, W. S. Cole, Ruth Todd, and J. Harlan Johnson, has been invaluable. Norman D. Newell, Francis J. Pettijohn, and David M. Raup read the manuscript critically. F. R. S. Henson of the Iraq Petroleum Co., Ltd., loaned the writer thin sections of limestones from representative Middle East formations for comparative purposes. M. J. Forman of Atwater, Cowan, and Associates, cooperated in a study of the *Heterostegina* zone of southern Louisiana. James A. Denson of the U.S. Geological Survey made some of the photomicrographs. Work done by Schlanger on the limestones was used in a dissertation submitted to the Faculty of Philosophy of the Johns Hopkins University in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

LIMESTONE PETROLOGY

CLASSIFICATION

In establishing the classification and terminology to cover the pre-Recent limestones of Guam, an attempt has been made to keep rock names distinct from facies names, to coin as few new terms as possible, and to use terms that have textural rather than genetic connotations. Thus in this report, "reef," "lagoon," and other terms connoting specific environments of deposition are reserved for facies designations. Rock terms defined in standard works are used where possible. The philosophy behind the classification of limestones used in this paper might well be described, perhaps somewhat hopefully, by quoting Pettijohn's description (1957, p. 293) of his classification of sandstones:

> Although the classification here presented is based on what are believed to be genetically significant properties, the classification is not genetic. A knowledge of the origin is not necessary to name or classify the sandstone. The classification is based upon simple observable characters.

Table 1 lists the main limestone classes defined and their various subgroups. All these rocks are limestones. Such terms as "lime-mudstone" (Rodgers, 1954, p. 230) are redundant in a paper dealing with limestone petrology. These limestones may contain admixtures of volcanically produced material. Where the noncarbonate fraction is dominantly clay, the modifier "argillaceous" is added to the rock name. Where the volcanic fraction consists of silt-size or coarser mineral and rock grains, the term "volcanic" is used.

Any discussion of limestones from a reef complex involves the differentiation of the class of deposits made up of whole remains of sessile organisms, such as crustose coralline algae, incrusting Foraminifera, and hermatypic (reef-building) corals, from the class made up of discrete but aggregated tests of Foraminifera, mollusk shells, disarticulated or fragmented algal debris, and broken corals. The terms "incrustate" and "particulate" are proposed to denote, respectively, these two main classes.

TABLE 1.—*Classification of the pre-Recent limestone of Guam*

Class	*Limestone type*
I	Incrustate:
	A, algal
	B, foraminiferal
	C, algal-coral
	D, E, and so forth, combinations of A–C
II	Particulate:
	A, coquinite (and microcoquinite)
	B, paracoquinite
	C, breccia (and microbreccia)
	D, coquinoid (and microcoquinoid)
	E, mudstone
III	Metasomatic:
	A, dolomitic
	B, siliceous
	C, manganiferous
	D, phosphatic

Class I, incrustate limestones.—Incrustate, an adjective, is defined by Merriam-Webster as "formed into or like a crust; having a crust." Rocks of this class are texturally dominated by extensive *in situ* deposits of either crustose coralline algae or incrusting Foraminifera, or both. The algae are members of the subfamily Melobesieae (Johnson, J. H., 1954, p. 12), which includes the genera *Lithothamnium*, *Lithophyllum*, and others. The Foraminifera are represented by various species of such genera as *Carpenteria*, *Homotrema*, *Gypsina*, and others. Skeletal crusts of these organisms coat and bind coral heads in position of growth, and thus form the framework that traps tests of Foraminifera, coral debris, mollusk shells, and fragments of the crustose forms. In outcrop the structure of the rock is distinctive: The limestone is unstratified. In thin section the binding nature of the crustose forms is obvious also.

This class of limestones is considered equivalent to the reef limestone of Hatch and Rastall (1923, p. 30): "Reef limestone differs from the majority of fragmental and organic deposits in the fact that it is largely built up in a solid coherent form from the first, and therefore constitutes a rock mass in the strict sense, without any process of cementation." Subclasses of the incrustate limestones are based on the relative abundance of the main fossil contributors. Where algae is dominant, the rock is termed an "algal incrustate limestone"; the term "algal-coral incrustate limestone" indicates the presence of coral heads *in situ* in the algal matrix.

Class II, particulate limestones.—Particulate, an adjective, is defined by Merriam-Webster as "of, or pertaining or relating to, distinct particles; existing as minute separate particles." This class includes limestones made up of lithified aggregates of discrete particles. These particles are whole and broken tests of benthonic and planktonic Foraminifera, fragments of tests of encrusting Foraminifera, disarticulated segments of articulate coralline algae and *Halimeda*, fragments of crustose coralline algae, whole and fragmental mollusk shells, coral debris broken from sessile colonies, echinoid spines and plates, other minor fossil constituents, and fine-grained carbonate mud. These limestones lack the laminar crustose framework of the incrustate limestones. This strictly textural difference, based on simple observable characters, is a more valid criterion for classifying limestones of the reef facies than inferred genesis implied by such word pairs as "mechanical versus nonmechanical" (Rodgers, 1954, p. 231). Subclasses of the particulate limestones shown on table 1 are based on the following rock attributes: (1) amount of the intergranular mud matrix, (2) condition of the recognizable fossil fraction, (3) degree of sorting of the fossil fraction, and (4) size of the fossil fraction.

1. Amount of the intergranular mud matrix: The term "mud" denotes size (less than 0.125 mm) rather than composition, and covers the fine-sand-, silt-, and clay-sized carbonate material. This material is probably triturated or disaggregated skeletal debris. The volume of the mud matrix is important, for it determines whether the limestone has an intact or disrupted framework. The term "framework" is used in connection with particulate limestones to denote the fraction having grains greater than 0.125 mm in size, in contrast to the mud-matrix fraction. An intact framework is one in which each particle larger than 0.125 mm "is in contact with its neighbor so that the whole framework is a mechanically stable structure in the gravitational field" (Pettijohn, 1957, p. 283). A disrupted framework is defined as one in which particles larger than 0.125 mm float in the mud matrix. These observable relations have genetic implications: Where fossils or fragments float in mud, the assumption is that both were deposited together in the absence of currents; where packed fossils lack a mud matrix, the assumption is that washing by current action took place.
2. Condition of the recognizable fossil fraction: Breakage in the fossil fraction indicates possible transportation of the sediment. Actual fracturing of a skeletal element is differentiated from disarticulation of organisms.
3. Degree of sorting of the fossil fraction: The terminology used to describe sorting is taken from Pettijohn (1957, p. 284): "A well sorted sand has three or fewer Udden size classes, and the maximum diameter therefore is 8 or fewer times the smallest. Sands with 4 to 6 grades, inclusive, may be said to show fair sorting. In these, the diameter of the largest grain does not exceed that of the smallest by more than a factor of 64. Sands with a size range in excess of this have 7 or more grades and are poorly sorted." True current sorting must be distinguished from what is here termed "biologic" sorting that is due to the inherent size of dominant organisms. Thus, a *Calcarina*-rich reef-flat deposit may be well sorted even though the foraminiferal sand has not been moved at all. In the same general locality, however, coarse reef debris may be accumulating by entrapment along with mud in reef pools. This material has been subject to some current action but is unsorted. In distinguishing current sorting from biologic sorting, the natural growth form of the constituents must be considered.
4. Size of the recognizable fossil fraction: If most or all of the fossil fraction falls in the sand-size grades coarser than the mud fraction—0.125 to 2 mm—the prefix "micro" is added to the subclass name as shown on table 1.

Class II A, coquinite.—As defined by Rodgers (1954, p. 229), this term denotes "a fully cemented mass of mechanically deposited shells or shell fragments." In this report, the term "coquinite" refers to a lithified aggregate of moderately to well-sorted fossil debris of coarser than sand size. The fossils generally consist of whole shells and fragments of shells. The rock has an intact framework. The cement of some coquinites is clear, chemically precipitated calcite; this calcite may be accompanied by some mud matrix. Definition of any exact percentage limits on the amount of mud matrix in any subclass has been avoided. Rocks classed as coquinites and microcoquinites generally have less than 25 percent intergranular mud matrix. Emery, Tracey, and Ladd (1954, p. 65, table 10) have shown that sands of Recent age from Bikini Atoll have intergranular pore space of as much as 50 percent. Thus a current-sorted sand may later be infiltrated by mud to this extent. A matrix value of 50 percent might also indicate a disrupted framework. Therefore, approximately one-half the maximum observed intergranular pore space of modern atoll sands is taken as the rough limit for the mud matrix of coquinites. This procedure follows that of Pettijohn (1957, p. 284, table 48) in the classification of terrigenous sandstones; the normal porosity of a quartz sand is 30 to 35 percent, and the division between graywackes as distinguished from arkosic and lithic sandstones is taken at 15 percent detrital matrix—a significant percentage. Varietal names for coquinites depend on the dominant fossil types; for example, foraminiferal, algal, and molluscan coquinites.

Class II B, paracoquinite.—This term refers to rocks that are texturally close to coquinite. Here the prefix "para" denotes a rock that is near to—almost, but not quite—a coquinite. The distinguishing characteristic of this subclass is an intact fossil framework of whole and fragmental shells that generally show only a fair degree of sorting and are imbedded in a conspicuous mud matrix generally greater than 25 percent. The matrix may run as high as 60 percent. Emery, Tracey, and Ladd (1954, p. 65, table 10) have shown that packed *Halimeda* debris has an intergranular porosity of as much as 57 percent. Paracoquinites are somewhat anomalous rocks; the matrix may be due in part to postdepositional mud infiltration of a current-deposited sand. Some specimens show an obviously packed fossil framework in which mud clogs every intergranular and intercellular interstice. The somewhat clumsy but descriptive term "microparacoquinite" may be used to describe rocks having predominant sand-size fossil debris. Varieties of the paracoquinites are named in the same fashion as those in the coquinite subclass.

Class II C, breccia.—Rocks of this subclass are lithified aggregates of poorly sorted fossil debris in a prominent mud matrix. The fossils are largely fragmental. It would be difficult to separate accurately the rocks of this subclass into breccias and conglomerates on the basis of rounding of the debris; the initial shapes of the fossils precludes this division. These limestones display both intact and disrupted frameworks. Breccias are much more common than microbreccias. The paracoquinites, which contain two distinct orders of size fractions (the framework, and the mud matrix), and the breccias, which commonly show a complete gradation from mud through cobble-size fragments, may be likened to graywackes in texture. These limestones, therefore, may be thought of as limewackes or calcwackes, just as some of the microquinites may be calcarenites as defined in the strict sense by Pettijohn (1957, p. 401).

Class II D, coquinoid limestones.—This subclass refers to limestones having a prominent to dominant mud matrix in which are imbedded generally whole, unsorted fossils. These fossils may form either an intact or a disrupted framework; the latter is more common. Thus the characteristics of these limestones are in accord with those of coquinoid limestones as defined by Pettijohn (1957, p. 402): "coquinoid limestones are autochthonous deposits consisting of coarse shelly materials which have accumulated in place and generally with a fine-grained matrix." The upper limit of mud matrix for coquinoid limestones is taken at 75 percent. This arbitrary limit follows the classification of terrigenous sediments, 75 percent marking the line between graywacke and mudstone (Pettijohn, 1957, p. 284).

Class II E, mudstone.—Limestones in this subclass consist of approximately 75 percent or more mud containing generally whole fossils; some samples, owing possibly to compaction, show postdepositional fragmentation of fossils. No size division based on the fossil fraction is made in this subclass. Varieties are named after the dominant fossil type, such as foraminiferal mudstone.

Use of this classification of particulate limestones implies the possibility of differentiating a recrystallized mud matrix from a clear, chemically precipitated calcite cement. Study of the limestones of Guam has shown that an original mud matrix can recrystallize into a deceptively clear granular calcite mosaic. Study of a number of thin sections from a single sample often revealed slight traces of original mud in otherwise generally clear cements. Not all clear cements were entirely due either to recrystallized mud or to a primary precipitate.

Crystalline matrices that have formed from original mud matrices generally show some relict mud scattered throughout; the contact between the granular calcite crystals and the mud is usually gradational. In some rocks the mud has only partly recrystallized owing to the growth of clear calcite around the perimeters of the fossil framework. Thus the centers of interstices between fossils are still occupied by semiopaque mud. Some rocks show a disrupted framework now packed in a clear calcite matrix, and these fossils probably were originally held apart by mud before recrystallization obliterated this original matrix. Rocks having crystalline calcite matrices that precipitated from interstitial solutions all show intact frameworks. The cement generally fails to fill completely the original interstices, and the rocks show euhedral crystals that project from the fossil walls into the interstices. Chemical cements commonly show a laminar structure, concentric with the fossils; recrystallized muds show no such structure. Table 2 summarizes the characteristics of the particulate limestones.

TABLE 2.—*Attributes of particulate limestone*

Type	Condition of fossils	Size of fossils (millimeters)	Sorting of fossils	Type of cement or matrix and abundance relative to fossils	Condition of framework	Faunal and floral varieties
Microcoquinite	Fragmental and whole	<2	Good to fair	Chemical and little or no mud	Intact	Foraminiferal, algal, and so forth.
Coquinite	do	>2	do	do	do	Coral, algal, and so forth.
Paracoquinite	do	$< >2$	Generally fair	Conspicuous mud	do	Coral, foraminiferal, algal, and so forth.
Microbreccia	Fragmental	<2	Generally poor	do	Intact to disrupted	Coral, foraminiferal, and so forth.
Breccia	do	>2	do	do	do	Do.
Microcoquinoid	Whole	<2	Unsorted	do	do	Foraminiferal, and so forth.
Coquinoid	do	>2	do	do	do	Molluscan, and so forth.
Mudstone	do	$< >2$	do	do	Disrupted	Foraminiferal, molluscan, and so forth.

Class III, metasomatic limestones.—This class includes limestones that have been replaced, wholly or in part, by minerals other than calcite. "Dolomitic limestone" refers to rock that contains both calcite and dolomite, the dolomite being subordinate, as discrete mineral phases; the magnesium content of the rock is not considered in this classification. If dolomite is predominant, the rock is termed "calcitic dolomite." This terminology follows that suggested by Rodgers (1954). "Siliceous limestone" refers to limestone that contains silica introduced from solutions; replacement of the host rock and void filling are criteria for this subclass. "Manganiferous limestone" covers those rocks that show replacement by pyrolusite wad, and lithiophorite. "Phosphatic limestones" are also placed in this class. Metasomatic limestones are rare on Guam; they are described in detail in the section on postdepositional alteration.

MINERALOGY AND CHEMICAL COMPOSITION

PRIMARY AND SECONDARY CARBONATE MINERALS

The limestones of Guam are made up largely of skeletal carbonate produced mainly by calcareous algae, Foraminifera, echinoids, corals, and mollusks; some less important groups such as bryozoans and worms contributed traces of material. Originally this skeletal material was in the form of aragonite and calcite. The corals and one form of algae—the genus *Halimeda*—contribute aragonite containing generally less than 1 percent $MgCO_3$ and from 1 to 1.5 percent $SrCO_3$. Mollusk shells contain both aragonite and calcite in various proportions. Most Foraminifera, all the echinoids, and all the coralline algae precipitate magnesium-rich calcite. Chave (1954, table 1) lists $MgCO_3$ contents of as much as 15.9 percent for echinoids and Foraminifera and 28.6 percent for coralline algae. Thus the primary carbonate minerals of these limestones were magnesium-bearing calcite and aragonite low in magnesium but containing a significant amount of $SrCO_3$. Almost all the primary aragonite has been destroyed through solution and replacement by calcite. Dolomite in the Alifan Limestone has locally replaced calcite. Thus the rocks contain secondary calcite and dolomite, and chemically deposited calcite fills many interstices in all formations.

CALCIUM CARBONATE, MAGNESIUM CARBONATE, AND STRONTIUM CARBONATE CONTENT

Analyses to determine the $CaCO_3$, $MgCO_3$, and $SrCO_3$ content of a number of limestone samples representative of the Guam suite were made by members of the U.S. Geological Survey (table 3). One reason for making these analyses was to use the $MgCO_3$ content as a guide to dolomitic zones; another was to see if the $SrCO_3$ content varied significantly with age or recrystallization. The low $MgCO_3$ content of these limestones indicated a lack of widespread dolomitization; this lack was confirmed by the examination of thin sections from each analyzed sample. The present $MgCO_3$ content is probably a function of magnesium in the calcite structure. However, a low $MgCO_3$ content cannot be taken as a criterion for assuming complete lack of dolomite. By staining the calcite matrix with $2N$ copper nitrate, Schlanger (1956) found scattered dolomite euhedra in limestone from the subsurface of Kita-daito-jima that contained only 2.74 percent $MgCO_3$. Kulp and others (1952, p. 715) studied a large number of limestones of various ages and came to the conclusion that "Finally recrystallization always lowers the Sr/Ca ratio in varying amounts so that, after recrystallization, the strontium content cannot be used as an index of initial conditions."

TABLE 3.—*Carbonate contents of representative samples of Guam limestones*

[Analyses by J. I. Dinnin, P. W. Scott, and H. F. Phillips. $CaCO_3$ and $MgCO_3$ soluble in 1:3 acetic acid; $SrCO_3$ soluble in 1:3 nitric acid; residue insoluble in 1:3 acetic acid. In sample Df 9-1a the insoluble residue includes cristobalite in the form of internal casts of planktonic Foraminifera]

Formation or member sample	$CaCO_3$	$MgCO_3$	$SrCO_3$	Insoluble residue	Total
Mariana Limestone:					
Kr 2-1	98.3	0.96	0.14	0.9	100.3
Kr 2-2	98.8	.92	.11	.6	100.4
Qu 4-2	98.5	1.00	.17	.5	100.2
Sx 2-1	97.6	2.09	.03	1.2	100.9
Po 1-2	97.0	1.59	.36	2.2	101.1
Sw 2-4	65.8	1.36	.09	31.2	98.5
Ij 2-1	96.1	1.09	.04	3.5	100.7
Pr 3-3	98.5	1.05	.13	.9	100.6
Janum Formation:					
Ts 5-4	81.8	1.63	.11	14.2	97.7
Ts 5-9	97.6	1.51	.06	1.0	100.2
Rr 23-1	88.5	1.21	.04	9.8	99.6
Rr 5-1	95.0	.98	.09	3.6	99.7
Barrigada Limestone:					
Sv 5-1	98.8	1.05	.04	.5	100.4
Alifan Limestone:					
Di 2-1	98.2	1.05	.07	1.1	100.4
Di 2-2	91.8	1.74	.14	7.5	101.2
Jl 3-2	98.8	1.05	.01	.3	100.2
Ts 9-1	96.7	1.76	.04	1.9	100.4
Ru 8-3	88.9	1.05	.18	10.0	100.1
Bonya Limestone:					
Rr 13-1	97.6	1.38	.03	1.4	100.4
Gi 2-1	98.2	1.59	.11	.5	100.4
Ut 6-1	98.2	1.69	.04	.9	100.8
Maemong Limestone Member of Umatac Formation:					
Il 5-2	99.2	.86	.01	.7	100.8
Ef 1-1	98.2	1.80	.03	.3	100.3
Ed 1-1b	96.3	2.72	.03	1.6	100.6
Gi 1-2a	91.0	1.57	.01	7.4	100.0
Df 9-1a	78.3	1.27	.06	20.8	100.4
Eo 2-1	74.1	2.51	.16	23.8	100.6
Alutom Formation:					
Fk 4-11	97.8	1.84	.03	1.0	100.7
Mahlac Member:					
Gj 11-1	52.7	.52	.17	42.4	95.8

Kulp and others (1952, table 11) also give the average $SrCO_3$ content of 155 samples of limestones as being close to 0.1 percent. The 29 samples analyzed from Guam averaged 0.09 percent $SrCO_3$. Thus, the $SrCO_3$ content of the limestones of Guam is consistent with other limestones. The generally low $SrCO_3$ content of all the Guam samples indicates a high degree of recrystallization and replacement of primary aragonite by secondary calcite. In a few samples the degree of strontium expulsion or loss may be inferred because the rocks contain abundant fossils of a single group. Sample Po 1-2, for example, which contains 0.36 percent $SrCO_3$, contains 40 percent *Halimeda* segments. Pure, unaltered *Halimeda* segments carry approximately 1.27 percent $SrCO_3$ (Emery, Tracey, and Ladd, 1954, p. 67). If the non-*Halimeda* part (60 percent) of Po 1-2 contains 0.08 percent $SrCO_3$, which is the 29-sample average less the $SrCO_3$ in Po 1-2 the segments themselves contain approximately 0.76 percent $SrCO_3$ and the $SrCO_3$ loss in the partly recrystallized aragonitic segments amounts to approximately 40 percent.

NONCARBONATE MINERALS

Many different noncarbonate minerals have been identified in the limestones of Guam by Dorothy Carroll and J. C. Hathaway of the U.S. Geological Survey. These minerals are listed by formation and are discussed on pages 37–46.

Most of the minerals are traceable to the volcanic rocks exposed on the island, and they reached the areas of limestone deposition as airborne eruption products and as subaerial erosion products; some minerals are the result of alteration of volcanic material following its incorporation in the limestones. The insoluble-residue content of 23 samples ranges from 0.1 percent in parts of the Alifan Limestone to 42.1 percent in the Mahlac Member of the Alutom Formation. The residues, mainly silt and clay, consist of clay minerals and of nonclay-mineral groups. The clay minerals found are: montmorillonite, chlorite, mixed-layered montmorillonite-chlorite, mica, and minerals of the kaolinite group. The nonclay minerals are divided into two groups: a group of silicate minerals including quartz, cristobalite, plagioclase feldspar, and zeolites; and a nonsilicate group including gibbsite, nordstrandite, magnetite, hematite, goethite, lithiophorite and pyrolusite, apatite, and a woodhouseitelike mineral. Most of the samples studied contain either a nonclay group characterized by feldspar and zeolites, or a group characterized by iron oxide minerals and nordstrandite.

The relative instability of zeolites to weathering indicates that the noncarbonate fraction of limestones containing the feldspar-zeolite assemblage originated as ash falls. Montmorillonite, which accompanies this assemblage, also commonly occurs as the dominant mineral in bentonite, which is the product of volcanic ash devitrification. Those samples containing the iron oxide-nordstrandite assemblage received their noncarbonate fractions from erosion of soil formed on volcanic rocks. The formations containing the erosion assemblage are the Agana Argillaceous Member of the Mariana Limestone, the Alifan Limestone, and the Janum Formation. The Mahlac Member of the Alutom Formation, limestones of the Alutom Formation, the Maemong Limestone Member of the Umatac Formation, the Bonya Limestone, and parts of the Mariana Limestone contain the ash-fall assemblage.

Heavy minerals of sand-size grades make up only a trace of the limestones. They include magnetite, ilmenite?, augite, hypersthene, greenish-brown amphibole, basaltic hornblende, bluish-green amphibole, sphene, and zircon. Minerals of the light fraction include plagioclase feldspar, quartz, clay aggregates, opaline silica (beta-cristobalite), zeolites, and apatite.

Volcanic material easily identified in thin section, in hand specimens, and in outcrop is present mainly in three forms: (1) scattered angular fragments of single crystals of plagioclase and ferromagnesian minerals, (2) bands and lenses of fine detritus within calcareous interstitial fills or as pockets, and (3) well-rounded rock fragments. The rock fragments are now largely clay, but their shapes are suggestive of water-worn gravel formed during subaerial erosion of volcanic terrane. Many of the present-day beaches around south Guam are rich in this material. The angular single crystals are probably the result of ash falls. All three types of material are present in the Alutom Formation and the Maemong Limestone Member of the Umatac Formation. A few beds of the Maemong Member in the Geus River contain as much as 50 percent of volcanic detritus in the form of well-rounded pebbles, cobbles, and boulders of pyroclastic and crystalline rocks in a limestone matrix.

POSTDEPOSITIONAL ALTERATION

RECRYSTALLIZATION OF ORIGINAL MATRIX AND PRIMARY SKELETAL MATERIAL

Both matrix and fossils in the limestones have been greatly altered. In the matrix the main change has been the conversion of much of the ubiquitous dark semiopaque mud to clearly transparent fine- to coarse-grained mosaics of calcite. This recrystallization follows two patterns. In some places, the mud first crystallized to clear calcite around the enclosed fragments. In the initial stages of this process each fragment is surrounded by a halo of clear calcite in which the crystals are perpendicular to the rim of the fragment. These halos coalesce to make the entire matrix crystalline. In other places, the fragments had no effect on the recrystallization of the mud; patches of clear calcite grade outward into dark mud. One effect of this second type of recrystallization is a spotted appearance strikingly similar to a leopard-skin pattern. In such rocks small black specks occur in a clear calcite mosaic. Some of these patches are thought to be fine algal fragments that have resisted recrystallization. The sharpness of the contact between the recrystallized mud and the fossil depends on the type of organism; in some places the calcite crystals formed from the mud are continuous with recrystallized mollusk shells and coral remains. This occurrence is especially true in advanced stages of recrystallization. The Foraminifera tests and the articulate and encrusting algae, however, except for the fine algal material already mentioned, have sharp contacts with the calcite.

This mosaic-fossil relationship depends on the varying susceptibility to recrystallization of different fossil groups. Crickmay (1945) arranged the fossil remains in the limestones of Lau, Fiji, in the following order of decreasing susceptibility of recrystallization: corals, mollusks, pelagic Foraminifera, beach-type Foraminifera, larger Foraminifera, echinoids, and calcareous red algae. In this report *Halimeda* is added between coral and mollusks. Crickmay (1945, p. 239), in discussing this relative solubility, states:

> * * * The factors which determine solubility appear to be: (1) chemical composition—the presence of magnesium carbonate (calcareous red algae) reduces solubility; (2) form of calcium carbonate—aragonite shells (corals, most mollusks) are more soluble than calcite shells (Foraminifera); (3) shell structure—compact nearly opaque shells (larger Foraminifera, calcareous red algae) are much less soluble than prismatic transparent shells (pelagic and beach-type Foraminifera).

There is general agreement with Crickmay's order of susceptibility and the factors controlling it, but the stages and mode of recrystallization of shell material described by Crickmay differ in some respects from those seen in the Guam material. In discussing shell material, apparently molluscan, Crickmay (1945, p. 238) states:

> shell molds filled with granular calcite resemble shells which have undergone recrystallization, but can be distinguished by the following criteria: (a) filled molds (casts) have sharp margins; recrystallized shells have irregular and fuzzy margins; (b) a rock with casts generally contains some shells of the same species showing unaltered structure; in a recrystallized rock all shells of similar character are more or less equally altered; (c) insofar as the calcareous paste is generally more susceptible to alteration than calcite shells, coarsely granular shells in unaltered paste indicate casts and not recrystallization. Shells originally made up entirely or in part of aragonite (mollusks, corals) are much more commonly represented by molds or casts than calcite shells.

Crickmay (p. 240–41) further states: "The paste surrounding radially prismatic shells commonly recrystallizes in optic continuity with the shell fibers, and thus structurally there is a breakdown of the shell margin. * * * Further recrystallization leads to a replacement of prismatic structure by granular calcite, but before that occurs the shell margin has already been rendered obscure."

The slides studied, particularly those from sample Fk 4–5 (pl. 1*A*, *B*), contain fragments of molluscan shells showing a sequence of recrystallization that differs in process from Crickmay's generalizations but which yields the same final result. This sequence in the Guam rocks of Eocene age is:

1. Almost unaltered fibrous yellow-brown laminar shell fragments occur in sharp contact with the paste matrix.
2. Formation of a patchwork of coarse well-defined polygonal calcite crystals within the shell frag-

ment. These crystals are clearly apparent only under crossed nicols; they terminate sharply at the edge of the shell.

3. The crystal patchwork becomes easily visible in plain light; shell structure is still distinct.
4. The crystals become a clearer mosaic that partly obscures the original structure.
5. The crystals transcend the shell boundary and grow into the surrounding paste, but the original shell structure can still be vaguely seen as yellow-brown bands and fibers. In only a few fragments is all structure completely effaced.

Crickmay's criteria for distinguishing shell recrystallization from replacement and mold filling may not hold true in all coral limestones. In the material of Eocene age from Guam, numerous shell fragments show sharp edges even though internal recrystallization is in an advanced stage. The encroachment on the matrix by crystals in the shell may be a late stage of recrystallization. The distinction between shell recrystallization and solution and secondary filling is important because the solutional history of a limestone can sometimes be determined accurately only if this distinction is made.

Coral fragments, originally aragonite, have been completely recrystallized into fine- to coarse-grained calcite mosaics and are recognizable as coral remains by the following features: (1) original interseptal voids filled with dark-gray mud that has preserved the pattern of the coral structure (pl. 9*D*); (2) fine dark lines that preserve a coral pattern even when the dark fill is missing; and (3) algal coatings on the fragments that preserve the original outline of the corallum but prevent the recrystallization of the coral material from proceeding into the matrix.

Foraminifera are in general well preserved and show encroachment by crystalline calcite and then along cracks or as enlargments from calcite fillings in cells. The larger Foraminifera appear yellow and fibrous in section, but the small thin-walled types, such as miliolids, appear black.

Calcareous algae, except *Halimeda*, are well preserved and show calcite replacement in only a few places. The algae appear dark and have well-defined cellular structures in thin section.

Halimeda segments are recognizable by their characteristic outline and sparse remnants of internal structures. In one locality, the Mariana Limestone (sample Po 1–2) contains primary aragonite in the form of irregularly altered *Halimeda* segments. Almost unaltered segments in sample Po 1–2 appear as amber, yellow, and brown masses of cryptocrystalline aragonite that show peculiar low relief against the surrounding calcite. The central tubes are filled with clear granular calcite. In early stages of replacement the segment retains its yellow color but has been transformed into a fine-grained mosaic of anhedra that shows normal calcite relief. In the final stage of recrystallization the segment is completely occupied by clear calcite anhedra.

Solution has dissolved many of the segments and left *Halimeda*-shaped voids. Segments in all stages of recrystallization have been dissolved, but those having a high percentage of original aragonite are most affected. Parts of the rock have, in effect, undergone a textural reversal from what must have been a loosely packed *Halimeda* gravel to a porous network of banded aragonite and granular calcite.

The abundance of unaltered aragonite shells and skeletons in cores from Bikini Atoll has been assumed to indicate a history of nonemergence for the limestones containing them. Emery, Tracey, and Ladd (1954, p. 2) state: "Recrystallization of aragonitic shells and skeletons to calcite is limited to irregularly consolidated intervals, and is believed to be due to emergence of the rocks above sea level." Johnston and others (1916) make the point that impure aragonite (that which contains some lead, zinc, or strontium in solid solution) might be stable in contact with the "natural waters in which it formed." They further state, in connection with the transformation of aragonite to calcite (p. 509): "thus it may be that chemically precipitated aragonite, which apparently persists under some circumstances in saline waters, is soon transformed to calcite when exposed to the action of meteoric waters." The presence of aragonite in limestones of Miocene age in the subsurface of Bikini (Emery, Tracey, and Ladd, 1954, p. 2) certainly supports the idea of the stability of aragonite in normal marine saline waters over the period of some tens of millions of years. However, the aragonitic limestones from Guam indicate that the rate of change of aragonite to calcite under subaerial conditions may be slower than generally assumed. The persistance of small pockets of aragonite-rich limestone in the otherwise almost completely recrystallized mass of the Mariana Limestone, which is several hundreds of feet thick and several miles in lateral extent, indicates that the mere presence of aragonite in a core should not be taken as unequivocal evidence for a history of nonemergence.

FRACTURES

In thin section many of the limestone fragments from the Alutom Formation display intersecting sets of fine fractures, generally less than 0.25 mm wide, healed by finely granular calcite. These fractures are best developed in sample Hj 1–5 (pl. 1*D*). In slides from this sample, two distinct well-developed sets of fractures intersect at approximately 60°. The amount of offset along these fractures was determined by matching algal fragments across the cracks. Offsets in the plane of the slide were as much as 0.5 mm. Offsetting at an angle to the slide no doubt took place but could not be measured. In slides from sample Hj 1–7, a fracture system of two sets intersecting at approximately 70° was poorly developed. In this sample the calcite-filled veins were as much as 1 mm wide. These fractures are well-developed on Guam only in limestones of Eocene (*b*) age.

DEPOSITION OF CHEMICAL CALCITE

Chemically deposited calcite is in two forms. The dominant type is represented by coarse-grained clear calcite that fills cells in tests of Foraminifera and original interstices between large detrital fragments. Some of these original voids are incompletely filled and show geodelike incrustations of calcite. The second form of secondary calcite is represented by fine fibrous crystals perpendicular to the walls of large solution voids (pl. 1*C*). These bands of fibrous calcite reach a maximum thickness of 1 mm. The remaining interstices, some of which are 5 mm in diameter, are completely filled with gray mud.

SILICIFICATION

Limestones, interbedded with tuffs and flows of the Alutom Formation, show extensive silicification both as vein fillings and as metasomatic replacement (pl. 2*A–D*). In one sample (Ek 7–4), the silicified limestone is directly overlain by a pillow lava flow of considerable but undetermined thickness. Prior to the silicification, the limestone underwent a period of brecciation, subaerial solution, and deposition of calcite. However, inasmuch as the overlying pillow lava suggests a submarine flow, the limestone may have been silicified in a marine environment after becoming submerged following a period of subaerial erosion and solution. The flow was probably the source of the silica that gained access to the limestone through fractures and solution fissures. Evidently the cavity filling and the metasomatic replacement of limestone took place contemporaneously.

Limestones of Miocene (*e*) age interbedded with pillow lava near Umatac show silica filling of globigerinid tests by beta-cristobalite, probably a result of a postdepositional history similar to that of the Eocene (*b*) limestone just described.

MANGANESE MINERALS IN THE BONYA LIMESTONE

Large parts of the Bonya Limestone in the Ugum-Talofofo area show patchy replacement by earthy black manganese minerals. Lithiophorite, lithium-bearing manganese wad, and pyrolusite were identified in this formation by X-ray diffraction techniques. On Guam, replacement by manganese is apparently confined to the Bonya Limestone, though replacement is widespread within this formation. Sample Ut 6–1, a cobble of Bonya Limestone found in the underlying Janum Formation, contained lithiophorite. Thus the time of manganese replacement of the Bonya Limestone can be dated as pre-Janum in age. Evidently a small amount of these manganese minerals in a limestone can impart a dark color; sample Ut 6–1 contains less than 1 percent insoluble residue, yet it is dark slate gray in hand specimen.

Study of these manganiferous limestones in thin section reveals a characteristic mode of occurrence (pl. 13*C*, *D*). Most of the manganese occurs in the microcrystalline and fine-grained matrix. It is finely disseminated as small distinct flecks and blebs. In transmitted light as well as in reflected light the manganese is coffee brown to black. In scattered areas these flecks and blebs coalesce, becoming blacker and more opaque as they become more concentrated, and finally merge into black massive patches of pyrolusite that show a metallic luster in reflected light. Fossil debris serves as centers for deposition. Almost all the Foraminifera show fine coatings of black and brown minerals on both their internal and external surfaces. On these tests there is a tendency for the manganese minerals to take the form of stubby, tabular crystals oriented perpendicular to the test surface. In fragments of encrusting Foraminifera the perforations are filled with these minerals. Coralline algae are more resistant to replacement and are only locally infiltrated by manganese. Late-stage calcite mosaics fill, or almost fill, many secondary solution voids. In a few of these voids the final deposit is black massive manganese oxide that shows metallic lustre. Most of these late calcite mosaics lack manganese replacement minerals. However, small radiating and sheaflike clusters of stubby, acicular, and rhombohedral crystals have formed in some mosaics. These crystals are coffee colored and show weak pleochroism or absorption in shades of light yellow brown. Absorption is greater parallel to the long axis of the crystals. These crystals show high birefringence and indices of refraction greater than calcite; they have not been identified.

The source of the manganese just described was undoubtedly the pre-Bonya volcanic rocks of Guam.

Chemical analyses of fresh basalt from Guam show a range in MnO_2 content of 0.05 to 0.20 percent (Stark, 1963). Slightly acidic surface waters draining these volcanics during Bonya time probably carried the manganese (as manganous ions) to the sea, where slightly alkaline conditions caused its precipitation as manganese hydroxide $Mn(OH)_2$. According to Pauling (1953, p. 524), manganese hydroxide, a white precipitate, rapidly changes in the presence of oxygen to the brown manganic compound $MnO(OH)$. The presence of the finely disseminated dark-brown to black manganese minerals in the fine-grained matrix and the crusts of these minerals on and in tests of Foraminifera suggest that the manganese hydroxide may have been precipitated and oxidized soon after the deposition of the Bonya Limestone; possibly the precipitation was contemporaneous with the accumulation of the limestone. Later, further oxidation converted much of these compounds to black metallic manganese oxides such as pyrolusite. Subaerial solution of the limestone by percolating water may have resulted in the redistribution and concentration of the minerals.

The conditions that would cause transport and precipitation of manganese compounds would also operate for iron compounds. However, as Mason (1952, p. 147) and Clarke (1920, p. 553–554) point out, iron compounds tend to precipitate under weaker oxidizing conditions than equivalent manganese compounds. Thus the manganese may be transported longer distances, or into a different environment, which would effect a separation of manganese from iron. The presence of lithium in the manganese minerals may be due to the strong absorptive power of compounds such as manganese dioxide hydrate, which, according to Mason (1952, p. 154), causes oxidate sediments to be relatively rich in minor elements.

In summary, field and chemical data indicate that a period of subaerial erosion during which the streams were slightly acidic affected the pre-Bonya volcanic rocks during the deposition of the Bonya. That this erosion was island-wide is indicated by the lithiophorite in sample Ut 6–1 from north Guam.

In addition to the manganese replacement described, the Bonya Limestone carries earthy black coatings of manganese minerals that may be related to the concentration of manganese oxides in the nearby volcanic rocks during later erosion cycles. Abundant nodules and stringers of manganese minerals are found in the deeply weathered volcanic rocks throughout the island.

MICROSTYLOLITES IN THE ALIFAN LIMESTONE

Thin sections from samples Eh 3–5 (pl. 3*A*) and Di 2–1 (pl. 3*B*, *C*) show well-formed microstylolites. Closely spaced bands of subparallel, bifurcating, and intersecting seams produce reddish-brown streaks in the limestone that show up well in reflected light. In transmitted light these color streaks are resolved into individual microstylolite seams, each of which is marked by a film of reddish-brown clay. The seams range in width from 0.1 to 0.25 mm and are closely spaced; in sample Eh 3–5, 14 were counted over a distance of 10 mm. These truncate tests of Foraminifera as well as the fossil debris and the fine-grained material of the matrix. Some fossil debris, particularly sand-size echinoid fragments, are completely bounded by such seams and, in addition, have sutured contacts with adjacent fossil fragments. Many molluscan shell fragments show well-formed sawtooth contacts with the matrix (pl. 3*B*).

The limestones in which the microstylolites are found retain some primary porosity in the form of empty cells within tests of Foraminifera, and also show secondary voids due to solution. Interstitial residual primary porosity is low owing to the tight packing of the grains having concomittant suturing and to the dense microcrystalline matrix. The areas most affected by secondary porosity are those occupied by bands of microstylolites. The formation of secondary porosity post-dates the microstylolites, and the seams are cut and bounded by irregular solution voids.

The microstylolites discussed in this paper are similar to those described by Dunnington (1954) from subsurface rocks of north Iraq. Dunnington reviewed the evidence for and against the postlithification growth of stylolites and came to the conclusion that these seams postdate lithification of the enclosing sediments. Study of the meager Guam material may not resolve the prelithification verus postlithification controversy, and it is not intended here to attempt such a resolution. The Guam occurrence, however, may shed additional light on the importance of differential pressure as a factor in stylolite formation. Dunnington (1954, p. 47) studied thousands of thin sections from representative rock suites of Carboniferous to Miocene age and came to the following conclusion:

> * * * Other factors being equal, it would appear that there must be a critical rock pressure below which stylolites cannot form, and above which they must. This necessity is merely a vague and theoretical one, but it is supported by the finding that in the more recent or never deeply buried formations studied in the Middle East, stylolites are rare, whilst in sin-

gle formation stylolites are found in increasing abundance in rough proportion as they have been subjected to increasing overburden. Other factors, which must in fact vary, render difficult any investigation of the significance of overburden, and any attempt to determine the critical pressure value (if such exists).

Samples Eh 3–5 and Di 2–1 are from the base of the Alifan Limestone, which now forms a cap on the Mount Alifan-Mount Lamlam ridge. The site from which sample Eh 3–5 was collected is, at present, overlain by perhaps 200 feet of limestone. Sample Di 2–1, however, taken from the crest of the ridge, was overlain by only a few feet of limestone. No doubt the upper part of the Alifan Limestone has been removed by subaerial solution, but it is doubtful whether the site of sample Di 2–1 was ever buried below more than perhaps 300 feet of limestone. In connection with studies of the subsurface geology of Eniwetok (Schlanger, 1963), thin sections of limestone taken from a depth of 4,530 to 4,550 feet below the atoll have been examined. A coarse-grained foraminiferal-algal dolomitic limestone from this depth retains a porosity of approximately 5 to 10 percent and shows only slight signs of intergranular penetration; no well-formed microstylolites were seen. The limestone column below Eniwetok has not been subjected to any tectonic pressure; the differential pressure on the sample studied is due to simple static loading.

The presence of microstylolites in the lightly loaded Alifan Limestone contrasts with the lack of such pressure-solution features in the Eniwetok material. Dunnington (1954, p. 47) was careful to state that his critical pressure concept assumed "Other factors being equal * * *." One factor that is not equal in the Guam-Eniwetok comparison is argillaceous contamination; the basal part of the Alifan Limestone contains enough insoluble clay to color the limestone red, whereas the Eniwetok sample is pure. The solution histories of the two limestones are also different. The Alifan Limestone has been subject to considerable subaerial exposure and concomitant ground-water percolation. The basal part of the Alifan Limestone which directly overlies relatively impermeable volcanic rocks was and is subject to lateral ground-water movement at and above the limestone-volcanic contact. The Eniwetok material appears to have undergone some subaerial solution, but probably has a longer history of immersion in sea water. It is suggested that ground water movement along clay seams, rather than merely differential pressure, was the controlling factor in microstylolite development in the Alifan Limestone.

NORDSTRANDITE DEPOSITS IN THE ALIFAN LIMESTONE

Nordstrandite ($Al_2O_3 \cdot 3H_2O$), a polymorph of gibbsite-bayerite, is present in a number of widespread samples from the Alifan Limestone. The petrography of nordstrandite is discussed in the following paragraph; the chemistry of its deposition and theoretical considerations involved are discussed on page 44. Detailed chemical, physical, optical, crystallographic, and X-ray diffraction data are published elsewhere (Hathaway and Schlanger, 1962, p. 265–266; Hathaway and Schlanger, 1963). A simultaneous discovery of nordstrandite from Borneo is described by Wall and others (1962, p. 264–265); the Guam and Borneo nordstrandite finds are the first known natural occurrences of this mineral.

X-ray diffractometer study of the Alifan Limestone revealed nordstrandite in samples Di 2–1, Ts 9–1, and Ru 8–3. Thin-section study showed that the mineral is present in samples Dh 12–1, Eh 3–2, and Ts 16–13. Thus, nordstrandite is characteristic of the lower part of the Alifan Limestone from both north and south Guam. In all these samples, nordstrandite occurs in secondary solution voids. This mode of occurrence is best seen in sample Dh 12–1 (pl. 4*C*, *D*); the crystals of nordstrandite completely fill a former solution void approximately 0.5 mm in diameter. The nordstrandite fills spaces between previously deposited calcite; it does not replace the calcite.

In plane polarized light (pl. 4*C*), nordstrandite shows marked negative relief against abutting calcite; the crystals are clear and barely visible. Between crossed nicols the crystals are arranged radially from discrete points or areas on the wall of the original void (pl. 4*D*); from these centers the crystals fan out toward the opposite wall as bladed to flamboyant aggregates. In some filled voids, nordstrandite shows up as a mosaic of intricately intergrown twinned anhedra. Several crystals do not impinge on the void walls; these crystals are tabular in form and terminate in sharp, well-defined pyramidal(?) faces. Many of the crystals show polysynthetic twinning parallel to their length. The optical properties of the mineral are as follows (Hathaway and Schlanger, 1962): $\alpha=1.580\pm0.004$ colorless; $\beta=1.580\pm0.004$ colorless; $\gamma=1.596\pm0.004$ colorless; $\gamma-\alpha=0.016$. Optic sign=positive, 2V=low, elongation=negative, extinction=inclined, $2\wedge C\cong34°$.

The original voids appear to be the result of structurally controlled, probably subaerial solution of the limestone. The three converging linear areas of clear calcite leading into the central clear area, shown on plate 4*C*, *D*, are healed fractures that traverse the rock and connect with other former voids now filled by nordstrandite. The initial deposit, or residuum, on the walls of these solution openings is a thin film of reddish-brown clay. Similar-appearing argillaceous material is finely disseminated in the solid limestone around the voids. A few of these particles are clear and appear dark red to brown in transmitted light, showing extinction between crossed nicols. The argillaceous layer shows up as dark lines in the photomicrographs. Directly overlying this clay film over most of its area is a deposit of clear calcite, in the form of subhedral crystals, which fills smaller original voids and fractures but merely lines the larger openings. The final deposit is nordstrandite. The nordstrandite growth centers from which the crystals radiate, are commonly the places along the original void wall that lack a deposit of clear calcite. At these points the initial part of the nordstrandite crystals are in contact with the clay film and contain scattered, possibly residual, blebs of the reddish-brown clay. In connection with this nordstrandite clay contact, it is noted that the voids that are thickly and completely coated with calcite lack nordstrandite deposits.

These nordstrandite clay relations suggest that the growth of the clear nordstrandite was initiated by recrystallization of the clay. However, the volume of nordstrandite certainly exceeds that which could have been produced by recrystallization. Some deposition of nordstrandite from solution must have taken place. The time of deposition of the nordstrandite may be inferred from the textural relations seen in thin section. Emergence, lithification, and fracturing of the Alifan Limestone must have taken place before the subaerial solution that produced the original voids could have operated preferentially along fissures. A period of precipitation of calcite from solution followed; the precipitation produced the void linings and fracture-healing mosaics. The precipitation of nordstrandite was a late-stage event in the history of the limestone.

Nordstrandite occurs in the Janum Formation according to X-ray diffractometer data, but it was not recognized in thin sections. The nordstrandite in the Janum Formation may be entirely the result of recrystallization of detrital gibbsite. (See p. 44.)

DOLOMITE IN THE ALIFAN LIMESTONE

Dolomite was tentatively identified in thin sections from several samples of the Alifan Limestone on the basis of crystal habit and textural similarity to known dolomitic limestones from the Pacific area. A thin section of sample Tt 7–4, cover glass removed, was subjected to X-ray diffractometer testing that confirmed the preliminary identification. The occurrence of dolomite was not noted during fieldwork on Guam and, therefore, its distribution can only be inferred from its frequency of occurrence in sample suites. In 13 closely spaced samples of the Ts 16 set, only Ts 16–8 and possibly Ts 16–7 contain dolomite. In four samples of the Tt 7 set, collected within a distance of 100 yards along the volcanic-limestone contact northeast of Mount Santa Rosa, only Tt 7–4 contains dolomite. Other samples from south Guam lack even these scattered euhedra. Thus, dolomitic limestones are known to be sparsely distributed within a part of the Alifan Limestone on the north plateau.

Sample Ts 16–8 is an intensely recrystallized dolomitic limestone that contains relict ghost structures indicative of original texture and fossil content (pl. 5*A*, *B*, *C*). Recognizable fossil ghosts include fragments of coral, detrital coralline algae, whole and broken *Halimeda* segments, whole tests of *Rotalia* and smaller, thin-walled Foraminifera, fragments of encrusting Foraminifera, and echinoidal debris. These are packed in a fine-grained matrix. The fossil ghosts are invested, in many places, in a clear coarse-grained calcite mosaic. Under high magnification the outlines of these ghosts show up as very fine grained mixtures of microcrystalline calcite and barely visible dolomite rhombs. These now occupy what were original cell openings and perforations in Foraminifera, calcareous algae, and echinoids and line the septa of coralla. The small dolomite crystals show darker centers that indicate possible growth on nuclei of microcrystalline calcite. The form now preserved as darker material—the relative opacity of this type of deposit may be due to its fine grain—is the original void pattern of skeletons and tests. This reversal of fossil material, first described by Cullis (1904, p. 418) from Funafuti Limestone, is a common phenomenon in Pacific limestones and dolomitic limestones. The fine-grained calcite and dolomite that preserve the fossil outlines are coated throughout with deposits of larger euhedral crystals of clear dolomite (pl. 5*B*, *C*). Many of these larger crystals show one or more zones, generally near their outer edges. The clear background investing the coral ghost on plate 5*A* is a mosaic of calcite that forms the final cementing deposit in the rock. The deposition of this calcite evidently proceeded inward from the enclosing walls, inasmuch as a few voids show converging crystals that fail to merge. Calcite crystals within any single area bounded by dolomitic fossil ghosts generally show optical continuity; some of these crystals are continuous over several fossils. The matrix of the rock is a fine-grained mixture of dolomite crystals, which are euhedral to subhedral, and microcrystalline calcite. The matrix also is saturated with clear calcite that fills all former secondary solution voids. Sample Tt 7–4 has an original texture and postdolomitization aspect that differs somewhat from that in sample Ts 16–8. Although more intensely dolomitized, sample Tt 7–4 shows many fossils, particularly coralline algae, that are fairly well preserved. These fossil remains and jigsaw-shaped areas of dark microcrystalline mud are in a matrix of euhedral dolomite crystals, which are in turn loosely packed in microcrystalline calcite (pl. 5*D*, *E*). Dark mud areas are made up of scattered flecks of opaque material in a microcrystalline matrix; dolomite euhedra are not obvious in these areas.

Some of the large calcite crystals that saturate the rock show a peculiar texture. The originally optically continuous crystals have apparently undergone recrystallization or exsolution and a complementary set of crystals has been formed; the secondary crystals all show the same morphologic and crystallographic orientation. These are set in a single void-filling calcite crystal. In other areas marked by this type of secondary texture the rhombohedra are randomly oriented and show individual extinction against the still optically continuous background crystal. Many of these randomly oriented rhombohedra appear to be floating in the original calcite. These secondary crystals are interpreted as possible dolomite or incipient dolomite crystals on the basis of their crystal form and their evident alteration from original calcite.

The lithologic reversal shown by these rocks indicates that a period of intense solution preceded dolomitization. Following this solution, a deposit of dolomite euhedra was laid down on the fossil ghosts; and the calcite matrix was, possibly at the same time, the site of formation of floating and loosely packed dolomite crystals. These matrix crystals may be the result of replacement of calcite. The deposition of clear saturating calcite followed; this deposit then underwent recrystallization, and possibly dolomitization. The predolomite solution of the original limestone probably took place under subaerial conditions, and the rock became highly porous. The dolomite that coats the ghosts appears to have been deposited from solution in voids. The original algal content of the Alifan Limestone was not high enough to provide significant amounts of magnesium-rich carbonates by preferential leaching of the algal calcite. The algae do not serve as centers of dolomitization as they do in dolomitic limestones of Eocene age from below Eniwetok Atoll (Schlanger, 1957). The initial dolomitization of the Alifan Limestone probably took place below sea level or in the intertidal zone, where magnesium was available, after a period of subaerial exposure. The final cementation required a considerable volume of calcite. If this cementation took place subaerially, the limestone nearby was dissolved, then transported and reprecipitated in the porous dolomitic host rock. Skeats (1903, p. 115–118) described a virtually identical sequence of solution, dolomitization, and cementation in emergent dolomitic limestones from the islands of Ngillangillah and Mango in the Fiji group.

Dolomite from below sea level at Funafuti (Cullis, 1904, p. 407–408, figs. 41 and 42), however, is identical with the reversed dolomitic limestones from Guam except for the final cementing calcite deposit. If this deposit is a typical submarine phenomenon, it should be in the Funafuti material; its presence in the emerged Fiji and Guam material suggests a final subaerial stage. The recrystallization of the cement along with its possible conversion to dolomite, may then be a subaerial process.

This sequence of textural evolution suggests that the Alifan Limestone, which was originally a shallow-water deposit, underwent postdepositional uplift and solution, postsolution submergence and dolomitization, and finally, postdolomitization emergence and cementation. The depth at which dolomitization took place was not great. Skeats (1903) made a strong case for shallow-water dolomitization which he based on the study of many subaerial sections of dolomitic limestones exposed throughout the Pacific and Indian Oceans. Schlanger (1956) compared the vertical distribution of dolomite beneath Funafuti (Judd, 1904, p. 364–365) with that below Kita-daito–jima (Sugiyama, 1936) and came to the same conclusion as Skeats, that these atoll dolomites formed in shallow water. The textural similarity of the dolomitic limestone of Guam to those from Funafuti, the Fiji group, and Kita-daito-jima suggests a shallow-water origin for the Guam material.

PHOSPHATE DEPOSITS IN THE MARIANA LIMESTONE

A local veneer of phosphatic rock covers the Mariana Limestone in the Tarague embayment. This single outcrop is at an altitude of approximately 100 feet above sea level, bears E. 15°, and lies about 5,500 feet from the roadcut through the cliff edge overlooking Tarague Beach. The outcrop is on the east side of a box reentrant in the cliff, at the juncture between the marine terrace and the landward cliff. A relict sea nip is present 10 to 12 feet above the general level of the phosphate-veneered surface of the outcrop.

PETROGRAPHY

The phosphatic limestone is a dense, strongly cemented aggregate of hard coffee-brown spherical to discoidal biconvex pellets ranging from 1 to 5 mm and averaging 3 mm in diameter. On the weathered surface the pellets stand out in high relief owing to the extremely porous texture of the interstitial phosphatic limestone; they show no tendency toward preferred orientation and are loosely packed, some apparently floating in the matrix. The rock breaks across the pellets which are more brittle, denser, and harder than the matrix. On a broken or smoothly sawed surface the centers of the majority of the pellets are exposed as fragments of pelecypod shells and, rarely as tests of Foraminifera. The shape of the individual pellets is controlled by the shape of the nuclear fragment. The smaller, more spherical bivalve fragments are enclosed by spherical pellets, whereas larger tabular shell fragments are now within flattened disc-shaped, biconvex pellets. Some of these pelecypod fragments, after being boiled in Meigen's solution, were found to be aragonite and therefore probably were original shell material. Chemical analyses and mineralogical determinations were made on two pieces of sample Sw2–4 (see p. 9/38/40). One piece showed 31.2 percent insoluble residue after treatment in 1:3 acetic acid, and the second piece showed 16.4 percent after treatment in 1:4 acetic acid. Approximately 98 percent of the second residue was clay- and silt-size apatite.

The phosphatic pellets are seen in thin section (pl. 6*A*, *B*) to be lightly in contact with one another and cemented by a thin film of clear fibrous to granular calcite. Approximately 50 percent of the remaining interstitial void space is filled with light-brown microcrystalline phosphate. The internal structure of the pellets shows common pelecypod shell nuclei; most pellets contain fine- to medium-grained shell detritus. The more tabular of these fragments are usually oriented parallel to the edge of the pellet. In some pellets these fragments are concentrated into concentric zones that parallel color changes in the more phosphatic bands. These relations suggest intermittent accretion of both phosphate and shell material. Most of the pelletal phosphate is microcrystalline and does not change in appearance under polarized light. Some pellets, however, are partially or wholly amorphous and appear as light-yellow transparent colloform structures in which ghosts of fossil shell material are present. An apparent second generation of pellets is represented by a microcrystalline pellet that has a large nucleus consisting of an originally separate amorphous pellet.

COMPARISON WITH PHOSPHATIC LIMESTONE FROM ANGUAR, PALAU ISLANDS

Large deposits of oolitic phosphate ore on Anguar Island in the Palau group have been decribed by Irving (1950, p. 69), who writes:

> * * * One of the most typical occurrences is over karrenfeld topography on the 80-foot terrace within the amphitheater. Owing to the presence of a low saddle at the south end of the amphitheater, this terrace could never have been submerged beneath a lake. As the terrace apparently represents a former level of the sea, it is obvious that all lower areas were submerged beneath the sea. Nevertheless, it is believed that the deposits did not form in the sea, because stratification and organic remains would then be present. It is concluded that the oolites did not form in either a lacustrine or marine environment.
>
> The prevalence of amorphous phosphate, and the tendency towards colloform structures in the oolites, suggest that the oolites may be the product of intermittent colloidal precipitation.

The writer visited and saw these deposits during field work on Guam and nearby islands. Gilbert Corwin of the U.S. Geological Survey field party in the Palau Islands, supplied thin sections of the material (pl. 6*C*, *D*).

In thin section the phosphatic limestone of Anguar is seen to be a more advanced alteration of a rock originally like the pelletal limestone of Guam. In the Palau material all the pellets are now completely amorphous. These materials are the same size and shape as their Guam counterparts. Relict fossil structures in these pellets show that they originally had the structure and mechanical banding characteristic of the Guam pellets. As in the Guam material, phosphatized mollusk shells are common nuclei. The sequence of cementation and void filling in the Palau rock is different than that of the Guam phosphate. The Palau pellets are imbedded in: (1) a gray, microcrystalline calcite matrix that only partly fills the original primary voids; followed by (2) a thin deposit of clear granular calcite; followed by (3) a dark detrital mud fill (pl. 6*C*, *D*); and (4) a final layer of calcite.

GENESIS OF THE PELLETS

The field occurrence on terraces, and the similarity in the initial internal structure of the pellets—secondary solution and deposition effects notwithstanding—suggest a common mode of origin of the phosphatic limestones of Guam and Palau. The presence of the sea nip 10 to 12 feet above the flat on which the phosphate is found indicates that the local terrane in Guam is close to its original configuration, except for approximately 100 feet of relative emergence. Thus, if the nip represents the approximate sea level during the formation of the terrace, the site of deposition was in shallow water, 12 feet or less, directly below a steep cliff. The internal structures in the pellets are probably the result of mechanical accretion of finely divided phosphate and pelecypod shell fragments rather than of chemical precipitation of colloids. The ultimate source of the phosphate, on an island such as Guam, was probably bird excrement—guano; the size of the individual pellets is well within the fecal-pellet range. The high proportion of bivalve fragments present as nuclei is suggestive of an original sediment similar to the molluscan-rich coquinoid limestones described from the molluscan facies, which is a lagoonal deposit.

The preceding physiographic and petrographic evidence suggests the following interpretation of pellet origin. The local environment was one of a shallow back-reef flat or lagoon bounded to the landward by a steep cliff. The bottom fauna was dominated by pelecypods and mud-ingesting animals, possibly holothurians, living in and on a fine-grained carbonate bottom. Bird excrement, rich in phosphorous compounds, deposited from cliff rookeries was concentrated and molded by the mud-ingesters, which also ground up large amounts of pelecypod-shell material. The lack of a fine-grained carbonate matrix in the Guam material is possibly due to the washing out of fines and the concentration of pellets by water action. Evidently most of the Anguar pellets remained in the carbonate mud matrix.

Thus, the situation during the deposition of the Guam phosphate may have been much like the existing situation on the reef of Anao Point, where hundreds of sea birds congregate in a few acres on large limestone blocks that have fallen from the nearby landward cliffs and are lying in shallow back-reef waters.

Since the formation of the pellets, the Guam material has undergone cementation by calcite and some later solution that has resulted in the partial filling of primary interstices with phosphate. These processes were probably subaerial. The Anguar phosphate shows the effects of more than one period of calcite deposition. The gray microcrystalline deposit, closest to the pellets, is possibly the slightly altered original mud matrix. The second layer, of clear granular calcite, suggests a cycle of subaerial solution and deposition. The third layer, or filling, of calcite detritus, indicates a cycle of submarine deposition. The fourth and final layer, of clear calcite, may be a result of the present cycle of subaerial processes.

LIMESTONE FACIES

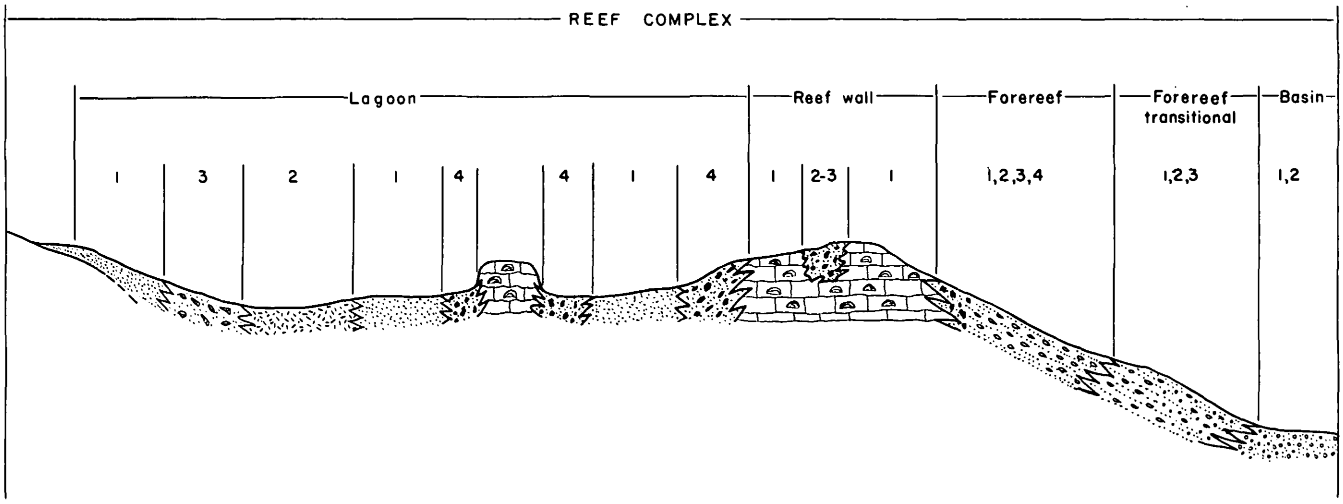
FACIES TERMINOLOGY AND CLASSIFICATION

In order to go beyond the definition and classification of these limestones as rock types and discuss their depositional histories, the genetic relationship of individual specimens both to contemporary, laterally contiguous limestones and to limestones of differing ages in the local column must be considered. This consideration involves the use of the term "facies." Pettijohn (1957, p.611) uses "facies" as equivalent to the term "consanguineous association," defined as "a natural group of sedimentary rocks related to one another by origin * * * Such an association is called a facies, such as the *black shale facies* * * *."

According to this definition however, the limestones discussed in this paper belong to the reef facies. The most striking attribute of the reef facies, is the short-range persistence, both laterally and vertically, of a given association of rock types. Detailed studies of well-exposed reef deposits led workers to divide the reef complex into a series of facies, or subfacies (Newell and others, 1953; Henson, 1950; Adams and Frenzel, 1950, p. 302–307). The term "reef complex" is used in the sense of Henson (1950, p. 215–216) and refers to an aggregate not only of reef limestone in the restricted sense—incrustate limestone of this paper—but of all "genetically associated sediments." In this report the "genetically associated sediments" are restricted to reef-derived and reef-influenced limestones. The entire limestone column that forms the base for Bikini Atoll (Emery, Tracey, and Ladd, 1954) may be thought of as the product of a series of reef complexes; reef, lagoons and forereef deposits are all part of the complex. Some limestones described in the foregoing rock classification may form independently of a reef; for example, globorotalid-rich mudstone, although not in the strict sense part of the reef complex, does grade into it directly and is considered a reef-complex rock in this paper.

The facies recognized in the Guam limestone section are listed in figure 3. The dominant limestone associations characteristic of each facies are given, and idealized facies relations in several types of reef complexes are shown. This terminology and classification of facies is derived from Henson (1950, table 1) for ancient reef complexes in the Middle East. Adams and Frenzel (1950, p. 302–307) used a four-part facies division: reef wall, back reef, forereef, and basinal, for the Capitan Barrier Reef. Not all the formations mapped exhibit all the facies listed, but all the facies are represented in more than one formation.

Because both a rock name and a facies name must be applied to fully describe these limestones, such names as "molluscan coquinoid limestone of the lagoon facies" and "foraminiferal-algal microcoquinite of the



Facies	*Typical rock associations*
Lagoon	1. Foraminiferal-algal microparacoquinite. 2. *Halimeda* paracoquinite. 3. Molluscan coquinoid and microcoquinoid limestone and mudstone. 4. Coral breccia.
Reef-wall	1. Incrustate limestone of all varieties. 2. Coral breccia (restricted to pockets). 3. Foraminiferal-algal paracoquinite and microparacoquinite (restricted to pockets).
Forereef	1. Foraminiferal and foraminiferal-algal coquinite and microcoquinite. 2. Foraminiferal and foraminiferal-algal paracoquinite and microparacoquinite. 3. Foraminiferal-algal breccia and microbreccia. 4. Coral breccia.
Forereef transitional	1. Foraminiferal (benthonic plus planktonic) microparacoquinite. 2. Foraminiferal microbreccia. 3. Foraminiferal (planktonic) mudstone.
Basin	1. Foraminiferal (benthonic plus planktonic) microparacoquinite. 2. Foraminiferal (planktonic) mudstone.
Off-reef (deep)	1. Foraminiferal (benthonic) paracoquinite and mudstone.
(shallow)	2. Foraminiferal-algal paracoquinite and microparacoquinite.

FIGURE 3.—Facies classification and typical rock associations in a reef complex. The off-reef facies, not shown, is also recognized in the limestone of Guam. It is not closely associated with limestone of the reef complex, but fossil content allows some ecologic interpretation.

forereef facies" are used in the description of individual specimens.

RECOGNITION OF FACIES

A specimen of limestone from Guam can be given a name from table 1. However, the assignment of a specimen, or outcrop, to one of the facies listed in figure 3, involves the use of one or more of the following four lines of evidence:

1. Comparison of pre-Recent rocks with modern sediments including:
   a. Use of individual faunal and floral elements as ecologic indicators, and
   b. matching lateral lithologic changes in ancient deposits with areal distribution patterns of modern reef complexes.
2. Comparison of individual formations with other well-known fossil-reef complexes.
3. Reconstruction of the original configuration of partly destroyed reef complexes on structural and stratigraphic evidence.
4. Matching thin-section attributes of rocks from a known facies with those of the rock in question.

FOSSILS AS FACIES INDICATORS

The first line of evidence is direct; it depends on the fact that many of the rock-forming organisms, at least on the generic level, range from Recent to Eocene. Where specific types do not have this range, extinct fossil groups of similar form, and perhaps habitat, make up a part of the older rocks. In order to take advantage of the numerous recognizable fossil remains in these limestones, the main rock-making fossil elements are arranged in groups that are easily identified and have well-known habitats in modern reef complexes. Other organisms such as bryozoans, echinoids, and worms also contribute to the limestones, but they are not major rock formers.

The main groups considered useful as ecologic indicators are discussed in the following paragraphs. The synopsis is taken from the extensive literature published on the subject, particularly from studies made since World War II in the Pacific Ocean area. Additional information on the ecology of these rockmakers is available in Emery, Tracey, and Ladd (1954, p. 79–80), Ladd and others (1950, p. 410–425), and Cloud (1952, p. 2125–2147).

CALCAREOUS ALGAE

Halimeda.—Taylor (1950, p. 77–78) figures and describes this genus in detail and states, concerning its habitat:

> * * * The *Halimeda* beds familiar in the Florida Keys and the West Indies were quite absent from the shallow reef area in the Marshall Islands. Occasionally similar species filled crevices, but the only really lusty *Halimeda* growth was on the sides of the deep holes and pools of the outer reef. The dredgings and bottom samplings, however, showed that the deeper parts of the lagoon floor were in some areas abundantly populated with *Halimeda*, and the segments from dead plants persisted and formed a substantial superficial layer on the bottom.

In general, substantial amounts of *Halimeda* segments are indicative of shallow or lagoonal sediments deposited as deep as 20 to 30 fathoms (Emery, Tracey, and Ladd, 1954, p. 79). Disjointed *Halimeda*, however, are often swept over the reef front into deeper waters. In addition, some species grow on the outer slopes and contribute to forereef deposits. Recent samples from as deep as 135 fathoms off Guam contain numerous *Halimeda* segments, (Emery, 1962). Emery, Tracey, and Ladd (1954, p. 79) describe samples rich in *Halimeda* debris from seaward slopes off Bikini Atoll.

Articulate coralline algae.—J. H. Johnson (1954, p. 45) describes these plants as "very abundant in the regions having tides of considerable amplitude where they usually occur in the lower part of the littoral stage and the upper part of the sublittoral zone, particularly on long, rocky coasts." These algae disarticulate easily and contribute fine rod-shaped detritus to the sediments formed at shallow depths. The fragments of both crustose and articulate coralline algae are also susceptible to transport down and the steep outer slope common around reefs.

Crustose coralline algae.—According to J. H. Johnson (1954, p. 12), this group of algae grows as crusts, as branching colonies, and as leaflike masses. Several genera are included under the term *Lithothamnium.* The crustose forms are particularly effective in forming much of the cement of reef rock. The branching colonies such as *Goniolithon*, which are brittle and fragment easily, contribute large amounts of detritus to shallow deposits. David, Edgeworth, Halligan, and Finckh (1904, p. 157) differentiate between laminar, encrusting *Lithothamnium* and nobby, branching *Lithothamnion*, stating: "the branching and knobby varieties of *Lithothamnium* are exclusively shallow water in habitat at Funafuti, whereas the encrusting form is both shallow and deep water in habitat." These algae have been dredged alive from depths as great as 156 meters in the tropical Pacific, but they reach their greatest abundance in the zone from low-tide level to depths of 30 to 70 feet. Below this depth they exhibit a marked decrease in size and abundance.

Dasycladacean algae.—According to Cloud (1952, p. 2134), these plants thrive only in water 3 to 5 meters deep. Thus, although they are rare, they are good ecologic indicators.

FORAMINIFERA

Large benthonic types such as Cycloclypeus *and* Heterostegina.—*Heterostegina*, where abundant, is indicative of off-reef deposits. In Bikini lagoon *Heterostegina* outnumbered, in some samples, the usually dominant *Amphistegina* (Cushman, Todd, and Post, 1954). Cole (1957, p. 750), in summarizing the depth ranges of living *Heterostegina*, gives average depths of 25 to 32 fathoms for their frequent or common occurrence. *Cycloclypeus*, which occupies a forereef habitat exclusively, occurs from 24 to 565 fathoms (common or frequent), and an average depth of 181 fathoms is given (Cole, 1957, p. 750). Myers (1943, p. 30), in a study of the habitat of large Foraminifera states:

> * * * Most Foraminifera provided with large planospiral, fusiform, or discoidal tests are limited to firm sand or sandy-mud bottoms within the sublittoral zone at depths that do not exceed that at which photosynthetic organisms thrive and are most numerous in areas adjacent to reefs. * * * Strong currents are required to transport these large tests and under these conditions one often finds them mixed with coarse detrital reef material including broken coral or even gravel from previous horizons.

Small, thin-walled benthonic types such as the miliolids.—These types, where abundant enough to show up significantly in thin sections, are considered indicative of shallow-water conditions, usually reef or backreef (Henson, 1950). Investigations of Recent Foraminifera from Pacific Ocean reefs confirm this habitat.

Small, thick-walled benthonic types such as Amphistegina.—Concerning the habitat of *Amphistegina* in the Marshall Islands, Cushman, Todd, and Post (1954, p. 362) state: "it occurs abundantly in the lagoons and down to moderate depths on the outer slopes of the reefs, comprising in some samples as much as 80 percent of the Foraminifera present. In the deep-water samples the species is present but much less abundantly and the specimens are very much smaller." Thus, *Amphistegina* alone might not be ecologically diagnostic, whereas *Amphistegina* plus miliolids would indicate shallow-water environments as opposed to deeper water conditions, which would be indicated by *Ampistegina* plus *Cycloclypeus* or globigerinid types. Tests of *Rotalia* are abundant in some Guam limestones. This genus thrives "only in rather stagnant, warm waters at the Tortugas" (Cushman, 1926, p. 76); according to Hedberg (1934), *Rotalia* is characteristic of brackish-water conditions.

Encrusting types such as Homotrema *and* Carpenteria.—In habitat and function these Foraminifera resemble encrusting calcareous algae. They are most abundant in shallow reef waters and serve to coat and bind detritus. Laminae of encrusting Foraminifera often alternate with algal layers on coral masses. Loose nodules and encrustations of Foraminifera are also found to considerable depths on the outer slopes of atolls (Emery, Tracey, and Ladd, 1954, p. 80). Chapman (1900) describes in detail the structure and habitat of these encrusting types at Funafuti Atoll.

Planktonic types such as Globigerina *and* Globorotalia.—The mass of evidence indicates that where tests of these types dominate a deposit, deep-water conditions prevailed. Studies by M. W. Johnson (1954, p. 306, fig. 107) in the Marshall Islands show that the concentration of *Globigerina* tests in lagoonal waters may actually exceed the concentration in parts of the surrounding open ocean. However, examination of lagoon-bottom samples reveals only rare *Globigerina* tests, for the high benthonic sedimentation rate in the lagoon masks the small planktonic contribution. *Globorotalia* do not form a significant part of bottom deposits above 4,000 feet in the Bikini area (Cushman, Todd, and Post, 1954, table 5).

CORALS

The use of corals in thin section as paleoecologic indicators is difficult. The growth form of a single species may differ greatly owing to its position with respect to the reef front. Also, very similar species, difficult to differentiate in thin section, have various ecologic niches. Outcrops and long cores, in which the size, shape, and orientation of the corals and their relations to the rest of the sediment can be seen, are necessary for reliable paleoecologic work. The recognizable sediment contributions of corals range from single massive heads 4 to 5 feet in diameter, to sand-size detritus.

MOLLUSKS

Well-preserved pelecypod and gastropod shells are found in varying amounts in deposits at all depths. This group, however, like corals, is best used for paleoecologic work when outcrops or large cores are available; their use in thin-section work is limited because of the difficulty of identification. Studies of the Florida reef tract by Ginsburg (1956) show that molluscan-rich muds are characteristic of back-reef or lagoonal areas. The distribution of the mapped molluscan facies in the Mariana Limestone also shows the back-reef nature of these deposits (Tracey and others, 1963, pl. 1.)

To summarize by example:

1. An incrustate limestone consisting of masses of matlike algae investing coral heads in growth position would be from the reef-wall facies.
2. A paracoquinite containing abundant *Halimeda* segments, miliolid Foraminifera, and dasycladacean algae would be from the lagoon facies.
3. A coquinoid limestone made up of mollusk shells and mud would also be from the lagoon facies.
4. A paracoquinite or breccia containing *Cycloclypeus* would be from the forereef facies.
5. A mudstone containing abundant globigerinid and globorotalid Foraminifera would be from the basin facies.
6. If the above limestone contained an admixture of benthonic larger Foraminifera and algal debris it would be from the forereef transitional facies.

Other examples and the reasoning behind their placement in a facies are discussed in the descriptions of the individual formations.

Table 4 summarizes the contributions of each ecologic fossil group to the limestone formations of Guam. The number of samples and the number of thin sections from each sample studied are given in table 11.

LIMESTONE FORMATIONS OF GUAM

LIMESTONE OF EOCENE (B) AGE FROM THE ALUTOM FORMATION

Limestones of Eocene (*b*) age are present on Guam mainly as fragments in volcanic breccias and, to a lesser extent, as discrete beds within the Alutom Formation. The following rock types have been recognized from the formation: molluscan-algal paracoquinite-molluscan and foraminiferal-algal microparacoquinite from the lagoon facies; algal incrustate limestone from the reef-wall facies; foraminiferal-algal coquinite, foraminiferal-algal micrococquinite, and foraminiferal paracoquinite from the forereef facies; foraminiferal-algal paracoquinite from the shallow off-reef facies; and foraminiferal mudstone from the basin facies.

TABLE 4.—*Summary of composition and fossil content, by volume percent, of limestone formations*

[Numbers represent estimated percentage of each group seen in thin sections. Tr. means less than 1 percent. Volcanics include only material seen in thin section. Matrix includes comminuted fossil debris too fine to be placed in a definite group but still recognizable as skeletal, carbonate mud, chemical deposits of calcite, and recrystallized mud]

	Alutom Formation	Maemong Limestone Member	Bonya Limestone	Janum Formation	Alifan Limestone	Barrigada Limestone	Mariana Limestone
Fossil group:							
Halimeda	Tr.	3	Tr.	--------	Tr.	Tr.	4
Encrusting algae	8	6	6	--------	5	Tr.	8
Articulate algae	14	5	4	--------	3	Tr.	2
Larger Foraminifera.	11	5	5	Tr.	15	2	1
Smaller Foraminifera.	2	2	9	Tr.	2	4	5
Encrusting Foraminifera.	6	1	7	--------	5	4	1
Miliolids, and so forth.	Tr.	Tr.	Tr.	--------	Tr.	Tr.	Tr.
Planktonic Foraminifera.	Tr.	4	Tr.	39	--------	Tr.	Tr.
Coral	8	6	2	--------	4	5	8
Pelecypods	Tr.	--------	Tr.	--------	5	Tr.	2
Gastropods	Tr.	--------	--------	--------	2	Tr.	1
Echinoids	Tr.	Tr.	1	--------	Tr.	Tr.	Tr.
Total (rounded)	50	32	34	40	43	17	33
Volcanics	Tr.	1	Tr.	7	Tr.	Tr.	Tr.
Matrix	47	64	60	53	51	75	57
Pore space	2	3	6	--------	5	8	10
Total	99	100	100	100	99	100	100

ROCK DESCRIPTIONS

Limestones from the reef-wall facies (*pl.* 7A).—These rocks are algal incrustate limestones. The incrusting organisms—incrusting algae and Foraminifera combined make up 49 percent of the organic remains—bind and coat much finer grained detritus as well as larger coral fragments. In some specimens, a single lamina of algae can be traced for over an inch along a convoluted course. The incrusting algae provide both a framework and detritus trap for two kinds of debris: a fine-grained dark mud, and scattered remains of *Halimeda*, Foraminifera, and articulate coralline algae. Coral-rich specimens present a different aspect, these rocks appear brighter in thin section owing to the large areas of clear calcite that are recrystallized coral. All the coral shows mud filling and algal-foraminiferal incrustations.

Limestones from the lagoon facies (*pl.* 7B, C).—Two rock types are represented: a miliolid-bearing foraminiferal-algal microparacoquinite and a molluscan-algal parocoquinite. The first type is characterized by numerous thin-walled tests of miliolid, uniserial, biserial, and coiled smaller Foraminifera and a flood of fine articulate algal debris. These fossil elements are in a matrix of finely crystalline clear calcite in which patches and clouds of the original mud matrix are visible. The rock is well-sorted, probably owing mostly to the inherent size of the detritus; the small tests are probably a life assemblage. The second type is characterized by significant amounts of molluscan remains (5 percent) in the form of whole and disarticulated pelecypod valves and fragments of gastropod shells set in algal debris.

Limestones from the off-reef shallow-water facies (*pl.* 7D).—Limestones of this type are dense algal-foraminiferal paracoquinite. Fine debris of articulate coralline algae, most of which is less than 1 mm in long dimension, makes up 42 percent of the organic remains. The next dominant group, the larger Foraminifera, are mainly *Fabiana*, *Biplanispira*, and *Pellatispira*. Together these forms make up as much as 50 percent of the rock. In some places in the slides studied, this detrital material is closely packed, whereas in other areas organic detritus floats in a dark mud matrix. In sample Hj 1–6 this mud has largely recrystallized into cloudy calcite. Framework organisms like encrusting algae are lacking except as fine detritus. The abundance of algal detritus suggests a reef or near-reef source for much of the detritus. On negative evidence it might be said that these limestones are not from the reef-wall or lagoon facies. Texturally and in organic content they most closely resemble limestones from the forereef facies.

Limestones from the forereef facies (*pl.* 8A, B, D).—Limestones from this facies are foraminiferal-algal coquinites, microcoquinites, and paracoquinites. A typical coquinite is dominated by broken tests of larger discoidal Foraminifera, some of which are as much as 6 mm in diameter (sample Ek 7–2). Subrounded fragments of fine-grained pre-extant limestones are present. However, the algal and foraminiferal debris is striking in its angularity. These organic remains are in a porous matrix of crystalline calcite. In a finer grained microcoquinite there is little fine-grained matrix; the rock is a tightly packed mass of angular and well-sorted algal-foraminiferal debris (sample Ek 7–3, pl. 8*B*). A trace of well-preserved globigerinid tests and some tests of smaller discoidal Foraminifera distinguish this type from the coarser coquinite. A limestone fragment from the Bolanos Pyroclastic Member of the Umatac Formation shows the effect of intense water-wearing of its components, mainly tests of *Biplanispira* (sample Ii 8–1, pl. 8*D*). These normally papillate tests have been worn smooth and deposited with well-rounded pebbles of finer grained limestone; they show a high degree of orientation. The abundance of larger Foraminifera, the tendency to preferred orientation and sorting, and the evident strong influence of transport and wear indicate a site of deposition on a forereef slope. The globigerinid tests in the microcoquinite suggest deeper water conditions than those which obtained during the deposition of the coquinite.

Limestones from the basin facies (*pl. 8*C).—These limestones are fine-grained globigerinid-bearing mudstones. The exceptionally well-preserved fragile Foraminifera tests are set in a matrix of fine mud that shows no signs of recrystallization and appears dark brown in transmitted light and chalky white in reflected light. Volcanic material is present as angular fragments of crystals of magnetite, plagioclase, and ferromagnesian minerals. Some of the globigerinid tests are filled with fine matrix; others are empty or filled with silica. The fine-grained mud matrix, the well-preserved tests, and the angular volcanic crystals points to a deposition in a quiet water far from the reach of reef detritus.

ENVIRONMENTAL RECONSTRUCTION

The presence, as fragments and bedded limestones, of a complete array of limestones from several facies within the Alutom Formation shows that during Eocene (*b*) time a widespread and highly evolved reef complex probably existed. Included volcanic material in the form of well-rounded gravel and single crystals indicates that a volcanic island existed and was subject to erosion, at least temporarily, during late Eocene time and that some volcanic activity may have produced ash falls.

The few remaining beds of limestone of the forereef and basin facies near Santa Rita are the relics of a larger reef destroyed by post-Eocene (*b*) volcanism; much of this former reef complex is now incorporated as limestone fragments in beds of volcanic breccias over central Guam. The structural geology of central Guam (Tracey and others, 1963) and the northeastward dip of the forereef talus and basin limestone remnants suggests that the Eocene (*b*) reef complex was mostly west of the present site of central Guam.

MAHLAC MEMBER OF THE ALUTOM FORMATION

The Mahlac Member is made up of buff, friable to chalky, fine-grained, argillaceous mudstone that fractures both conchoidally and around conspicuous sand-size tests of Foraminifera. Because of its fossil content and the lithologic similarity to planktonic mudstones from the Janum Formation and the Maemong Limestone Member of the Umatac Formation, it is placed in the basin facies. The small Foraminifera from the Mahlac Member indicate that it is of Oligocene (*c*) age, younger than the limestone of Eocene (*b*) age near Santa Rita.

Thin sections of this member appear dark in transmitted light owing to the fine-grained calcareous clay matrix. Floating or loosely packed in irregular patches in this matrix are well-preserved tests of Foraminifera, largely globigerinids, that are as much as 0.5 mm in diameter. Some of these tests are filled with opaline silica; others are empty. These organic remains account for perhaps 1 percent of the rock. The volcanic material, greater than silt size, is dominated by clear euhedral tabular crystals of plagioclase that are as much as 0.25 mm in length. Black opaque minerals and several species of ferromagnesian minerals are present in various stages of weathering; most of this material is angular.

Mechanical analysis of an insoluble residue, which constituted 42 percent of the sample by weight, showed 1.8, 42.1, and 56.1 percent in the sand-, silt-, and clay-size grades, respectively. Thus the Mahlac Member may be considered to be more nearly an argillaceous limestone than a calcareous shale.

M. R. Todd (written communication, 1955) interpreted the Mahlac Member of the Alutom Formation as being a moderately deep marine deposit, probably around 100 fathoms, as suggested by the composition of the foraminiferal fauna. There is a preponderance of planktonic specimens over benthonic specimens, and an abundance of species in the Lagenidae, Ellipsoidinidae, Cassidulinidae, and Chilostomellidae.

The presence of angular fine-grained—all less than 0.25 mm in length—volcanic contamination in the form of single crystals suggests ash-fall contributions rather than subaerial erosion of volcanic terrane.

MAEMONG LIMESTONE MEMBER OF THE UMATAC FORMATION

The Maemong Limestone Member is exposed in two distinct geologic situations in central and southern Guam. In the Fena-Mapao area, massive residual outliers of this member unconformably overlie the Alutom Formation. Along the west side of the Mount Bolanos-Mount Sasalaguan ridge, eastward-dipping limestones of this member, interbedded with the Facpi Volcanic Member, crop out in stream beds. The erosional outliers in the Fena-Mapao area are made up of white to pink-white hard massive, partly recrystallized limestone in which coral heads in growth position are coated with encrusting algae and Foraminifera. These heads are packed in particulate reef detritus; volcanic contamination is lackin. This sections of these shallow-water limestones reveal *Halimeda*-rich paracoquinite of the lagoon facies. Limestone fragments from the overlying Bolanos Pyroclastic Member in this area are shown in thin section to be miliolid-rich microparacoquinite of the lagoon facies. One outcrop of the basal Maemong Limestone Member in the Fena-Mapao area is well-bedded globigerinid mudstones of the basin facies. The particulate limestones within the Facpi Volcanic Member show a wide range of structures and textures indicative of forereef deposits. In the Geus River section, volcanically contaminated coral breccias and foraminiferal-algal breccias are interbedded with foraminiferal-algal coquinites and microcoquinites. Elsewhere in the Facpi Volcanic Member, microbreccias containing abundant tests of Foraminifera and algal debris are interbedded with mudstones carrying globigerinid Foraminifera only. In general the decrease in grain size is correlated with decrease in the thickness of bedding.

ROCK DESCRIPTIONS

Limestones of the reef-wall facies.—Fossil remains make up more than half the limestone in this facies. Coral, encrusting algae, and incrusting Foraminifera form the rock framework. The coral invariably shows some incrustation by algae or Foraminifera, or both (pl. 10*A*). These incrustations are not limited to coatings on the framework organisms but wind through the particulate matrix. In many places the laminae show bulges that enclose detritus; fragments of incrusting algae, segments of *Halimeda*, and tests of Foraminifera are loosely packed in between the coralla. This fossil debris is packed in a carbonate mud matrix that fills in almost all the interstices between particulate elements and much of the original void spaces within the incrustate organisms. The interseptal spaces in the originally porous coral are choked with dark fine-grained carbonate. Some of the larger original voids are only partly filled with mud and are coated with a later deposit of clear granular calcite. Much of the mud matrix has recrystallized, starting from the surface of fossil material and proceeding inward, into a mosaic of medium-grained anhedral calcite (pl. 10*C*). In addition, much originally void space has been filled by clear, coarse-grained calcite, probably directly precipitated. The present porosity is approximately 10 percent, it is almost all secondary and due to solution.

Limestones of the lagoon facies.—Two types of limestone are present: *Halimeda*-rich paracoquinite (pl. 10*B*) and miliolid-rich microparacoquinite (pl. 10*D*). The *Halimeda*-bearing limestone was collected a few feet from the reef-wall limestone just described. The miliolid limestone is from a boulder in the Bolanos Pyroclastic Member in the Fena-Mapao area. In both limestones the size of the fossil remains determines the texture. The *Halimeda* segments range from 1 to 3 mm in length and are associated with fragments of both articulate and encrusting algae as much as 2 mm in diameter. The thin-walled tests of miliolids and other small benthonic types range from less than 0.25 mm to, rarely, 1 mm in size; they average approximately 0.5 mm in maximum dimension. The large majority of these delicate tests are well preserved. Also present in this limestone are dark rodlike segments contributed by articulate coralline algae.

The matrix of both rock types is a recrystallized mud. Fossil elements in the *Halimeda* limestone are invested in coatings of fine dusty calcite having crystals oriented perpendicular to the fossil surface, which grades into clear subhedral mosaic toward the centers of interstices. Porosity is residual after these incomplete void fillings. The miliolid tests are filled with fine-grained calcite identical to the rest of the matrix indicating that the test fillings were originally fine mud rather than a later precipitate. The *Halimeda* segments probably represent a local accumulation in close association with the reef wall. The miliolid limestone is interpreted as being a lagoonal limestone by virtue of its high miliolid-peneroplid content, which is characteristic of lagoonal deposits (Henson, 1950). The well-preserved tests suggest a life assemblage.

Limestones of the forereef facies.—Limestones of this facies are coral breccia (pl. 11*A*), foraminiferal-breccia (pl. 11*B*), and foraminiferal-algal microcoquinite (pl. 11*C*). The breccias are poorly sorted and contain tests of larger discoidal Foraminifera as much as 13 mm in diameter, as well as fragmental fossils approximately 0.1 mm in diameter. These broken, chipped, and worn tests are randomly oriented, along with better preserved smaller discoidal tests and an accumulation of fragmental encrusting and articulate algae, in a dense fine-grained mud matrix. Rare subrounded fragments of coral are present. A trace of small, delicate planktonic tests of globigerinid Foraminifera is in the fine matrix. The fossils have evidently undergone considerable transport before deposition in an environment also capable of retaining the fine carbonate mud that forms the present matrix. The microcoquinites, by contrast, are better sorted and are characterized by an abundance of angular fragments of coralline algae, which dominate the fossil remains, evenly interspersed with tests of both thick-walled benthonic and thin-walled planktonic Foraminifera; the benthonic types are dominant. Volcanic contamination is present as sand-size fragments of fine-grained rocks and as single crystals of angular plagioclase.

Limestones of the forereef transitional facies.—Foraminiferal microbreccia and foraminiferal mudstone make up the limestone suite of this facies. Thin sections (pl. 11*D*) of the microbreccia show lenses and strings of packed tests of discoidal benthonic Foraminifera and algal debris alternating with fine-grained carbonate mud in which scattered tests of globigerinid Foraminifera float. The benthonic fossil elements are commonly fragmental; the planktonic contributions are well preserved despite the extreme fragility of the tests. Fragments of the benthonic material rarely exceed 1 mm in long dimension; most are less than 0.5 mm. Lenses of this detritus are as narrow as 2 mm. The fine matrix is dense; pore space as seen in thin section is less than 1 percent. The lenses of benthonic debris probably represent detritus swept downslope into a normally quiet water environment in which fine mud and planktonic tests were slowly accumulating. Where these two rock types are interbedded, the outcrop is assigned to the forereef transition facies. Where thick sequences of globigerinid-globorotalid mudstones occur, the outcrop is assigned to the basin facies.

Limestones of the basin facies.—Limestones of this facies contain tests only of planktonic Foraminifera (pl. 11*E*) scattered through a carbonate mud matrix. Both globigerinids and globorotalids are represented. The tests are crudely concentrated in vague bands. The orientation of the slightly discoidal tests of the globorotalids is random. A few large globigerinid tests, have diameters of 1.5 mm, but the average test size is close to 0.5 mm, and some individuals are as small as 0.1 mm. The tests are perfectly preserved and, in polarized light, show pseudo uniaxial crosses indicative of unrecrystallized shell material. The tests are largely free of any infillings of the fine-grained matrix. Some tests, however, have been filled with clear silica in the form of beta-cristobalite which displays undulatory extinction in polarized light. (See p. 42.) This limestone is directly overlain by submarine lava beds.

The presence of *Globorotalia* tests in places (sample Df 9–1a) makes possible an interpretation of the depth at which the limestone containing them was deposited. According to Todd (written communication, 1956), the *Globorotalia* tests are probably *G. menardii* and *G. tumida.* While clear-cut specific identifications were not made, the possibility is strong that these tests are *G. menardii* and *G. tumida*, inasmuch as both species are abundant in beds of the Donni Sandstone Member of Miocene (*e*) age on Saipan, 100 miles north of Guam (Todd, 1957). Study of Recent Foraminifera in the Bikini area by Cushman, Todd, and Post (1954) showed that only two specimens of *G. menardii* and none of *G. tumida* were found in 59 lagoon samples. *Globorotalia*, however, is abundant in the deep outer slopes around Bikini at depths of several thousands of feet. These rocks, therefore, were probably deposited in water deeper than 1,000 feet.

ENVIRONMENTAL RECONSTRUCTION

The conditions under which the various facies of the Maemong Limestone Member were deposited were mainly controlled by uplift of the preexisting deformed Alutom Formation and the growth of a submarine volcano in early Miocene time to the southwest of the older volcanic ridge. The structure of south Guam (Tracey, and others, 1963) indicates that the Umatac Formation, as presently exposed, is the northeastern sector of a remnant of the Miocene volcano. This formation was deposited, from a southwestern source, against the Alutom Formation in central Guam. The oldest limestones of Maemong age are the deep-water, globorotalid-bearing mudstones. The presence of these rocks in both the south Guam section and in the Fena-Mapao area suggests that the south and central parts of Guam were deeply submerged in early Miocene time. Uplift followed and massive reef-wall growth was initiated on the deformed Alutom Formation in central Guam, which by then formed a shallow submarine ridge. The thick section of forereef limestones in the Geus River exposure indicates a lull in volcanic activity, during which a reef, probably of the fringing variety, formed on the flanks of the cone. This reef fed debris into a forereef basin between the present site of Umatac and the Fena-Mapao area. Deeper water planktonic limestones interbedded with forereef transitional limestones in the caldera wall section also accumulated in this basin. These forereef deposits were later covered by lava flows. A later explosive phase of volcanism gave rise to the Bolanos Pyroclastic Member and probably was followed by caldera collapse that destroyed the shallow-water reef-wall facies west of the present forereef outcrops.

Fragments of reef-wall limestone, however, are found in the Bolanos Pyroclastic Member along the Mount Bolanos-Mount Sasalaguan ridge line. This occurrence confirms the presence of a shallow-water reef-wall updip from the forereef limestones found in the Facpi Volcanic Member. Thus, during early Miocene time there existed two independent centers of reef-wall formation, one on a submarine ridge and one on a volcanic cone, separated by a basin receiving reef debris and accumulating planktonic tests of Foraminifera to form forereef and basin limestones.

PRESENT-DAY ANALOGUE

The early Miocene paleogeology of south Guam may be compared to the present-day configuration and geology of the island of Borabora in the Society Islands as described by Stark and Howland (1941). The geologic map of Borabora shows it to be a volcanic cone, greatly dissected, that rises to a height of 2,380 feet above sea level. The center of the cone has collapsed, the crater forming part of the present lagoon. The island and lagoon are almost completely surrounded by a roughly circular barrier reef 6 to 8 miles in diameter. Stark and Howland (1941) describe the growth of a lava cone approximately 5 miles in diameter in late Pliocene or early Pleistocene time, followed by caldera collapse, erosion, subsidence, and reef growth. The present conditions at Borabora probably resemble conditions that existed during the early Miocene lull in volcanism in the area around and to the southwest of the present caldera-wall section on south Guam. A second growth cycle at Borabora, including large-scale volcanism, would result in the destruction of the barrier reef and its reef-wall and lagoonal limestones, and in the burial of the forereef limestones under lava flows and conglomerates. Collapse, uplift, and erosion would produce a caldera-wall section such as the one on Guam. Borabora, however, lacks a nearby ridge of older volcanic rocks such as the submarine ridge of deformed Alutom Formation on Guam.

BONYA LIMESTONE

The Bonya Limestone crops out extensively in the low areas of Fena basin, the Mapao-Maagas River area, and along the Talofofo, Ugum, and Togcha River scarps. Smaller scattered outcrops of the formation are exposed on terraces and in coastal reentrants from Lujuna Point to Anao Point. Between these two widely separated areas no Bonya Limestone has been found. In the Fena basin-Ugum-Togcha area the formation is exposed principally as a series of eroded outliers and, to a smaller extent, interstratified between other formations. In this area the Bonya Limestone is generally unconformable on the Bolanos Pyroclastic Member of the Umatac Formation; the Bonya Limestone locally appears to grade down into the Bolanos Pyroclastic Member of the Umatac Formation. The basal part of the Bonya Limestone carries pebbles and cobbles of the Maemong Limestone Member eroded from the Bolanos Pyroclastic Member. One outcrop of the Bonya Limestone in Fena basin directly overlies the Maemong Limestone Member of the Umatac Formation. Near the east coast of south Guam the Barrigada Limestone conformably overlies the Bonya Limestone. The thickness of the Bonya Limestone in outcrop in south Guam ranges from less than 40 feet to 120 feet. In north Guam the Bonya Limestone overlies, with angular unconformity, the Alutom Formation. The Janum Formation generally overlies the Bonya Limestone in this area. The Janum Formation carries pebbles and cobbles of the Bonya Limestone in the same fashion as the Bonya carries material from the Maemong Limestone Member. Where the Janum Formation is missing, the Mariana Limestone lies unconformably on the Bonya Limestone.

The bulk of the Bonya Limestone is well bedded. In south Guam, porous to dense friable to indurated foraminiferal-algal coquinites and paracoquinites (and their micro-varieties) predominate. Dips, probably initial, as much as 15° have been observed. Significant concentrations of coral, mollusks, and coarse algal debris are only locally present as massive breccia. Volcanic contamination, in the form of rounded grains of clay, and interlayered fine-grained crystalline rocks, is widespread. The limestones range from buff white and white to brown, gray, and gray black in color. The gray and black shades are caused by replacement of the limestone by manganese oxides. This replaced limestone is mottled in shades of gray and black. In north Guam the Bonya Limestone is uniformly a dense, massively bedded pure foraminiferal mudstone. The amount of algal and coral detritus ranges from a trace to none; the main bulk of the rock is a fine-grained lithified mud in which the fossil remains float. The overlying Janum Formation, however, carries cobbles of manganiferous foraminiferal limestone strikingly similar to samples of Bonya Limestone from the Togcha River area. Apart from these cobbles, the limestones from north Guam are lithologically unlike those from the Bonya Limestone of south Guam.

ROCK DESCRIPTIONS

Limestones from the forereef facies.—These deposits include moderately well sorted to well-sorted foraminiferal-algal coquinites, paracoquinites, and their micro-equivalents. Worn tests of Foraminifera are predominant, mostly small thick-walled types like amphisteginids. Fragments of both incrusting and articulate algae are abundant. The size range of the originally incrustate algal material approximates that of the other primary particulate debris in the slides studied. Fragments of incrusting Foraminifera, also sorted in accordance with the other debris, are conspicuous contributors to some samples. This sorting relationship among material of different original size and shape indicates considerable sorting of heterogeneous elements before their final incorporation into the sediment. Fragments of echinoids, largely spines, also occur in unusual abundance, locally up to 5 percent. These fragments show optically continuous overgrowths of calcite. The debris is locally closely packed in a mud matrix. Recrystallization of the original matrix is seen in all stages including clear mosaics of calcite, from which all traces of the dark mud have disappeared. Packing appears to be closer than normal; many of the fossil fragments show sutured contacts against adjacent grains. This contact suturing is more evident in finer grained deposits. In many samples the long algal rods and discoidal Foraminifera show distinct alinement parallel to the bedding.

Breccias are also included in this facies. These are typically poorly sorted and carry a wide size range of fossil debris, mainly coral, algae, and Foraminifera, randomly packed in a mud matrix. All the fossil material is fragmental, except wear-resistant tests of thick-walled Foraminifera and some thin-walled globigerinid tests. Both the flat laminar and knobby types of encrusting algae are present; continuous laminae of encrusting algae are rare to lacking. Many of the larger fragments, such as stems of coral, have coatings of encrusting Foraminifera, which grew prior to the breaking and transporting of the host. Interseptal spaces of coralla are mud filled, and the original skeletons have recrystallized to mosaics of calcite. The trace of well-preserved tests of globigerinid Foraminifera and angular fragments of *Cycloclypeus* is an off-reef, deeper water contribution. Thus, these breccias were probably deposited in front of a reef rather than within it. A large part of the mud matrix has recrystallized, imparting a grumose texture to the rock. Solution cavities represent secondary porosity; the primary porosity of these limestones was low. The walls of many secondary voids are lined with clear calcite deposited from solution. Rounded pebbles of pre-Bonya limestone are present (pl. 13*B*).

Limestones from the forereef transitional facies.—These limestones are foraminiferal-algal microparacoquinites (pl. 12*C*). Planktonic tests are evenly scattered throughout, as are the other fossil constituents, rounded fragments of articulate and encrusting algae, worn tests of small thick-walled Foraminifera, fragments of encrusting Foraminifera, and echinoidal debris. Although these organic remains had, originally, a wide range of inherent growth sizes and shapes, their fragments are present now in approximately the same size grades. This sorted debris loosely packed in a mud matrix. In places (sample, Jj 9–1) the dark mud has recrystallized to finely granular clear calcite. Various fossil types show different contact relations to the matrix. The globigerinid tests show pseudouniaxial crosses and both internal and external overgrowths in the cell walls; the crosses pass undisturbed through all three layers. These optically oriented overgrowths are at least as thick as the cell wall. Amphisteginids, which also show a fibrous calcite test, have similar, but relatively thinner, overgrowths. The calcareous algae lack these recrystallized halos and have sharp contacts with the matrix. Echinoidal debris shows clear single-crystal overgrowths. The original structure of the fossil shell influences the type of recrystallization in the matrix adjacent to the fossils themselves.

Limestones from the off-reef deep-water facies.—Representatives from this facies in south Guam are foraminiferal-algal paracoquinites (pl. 12*D*). Flat tests of large Foraminifera are characteristic. Operculinid and amphisteginid tests are common, and miliolids and globigerinids are rare. Fragments of coralline algae and encrusting Foraminifera are ubiquitous. This heterogeneous mixture is in a matrix that varies from one thin section to another, fine-grained sand and mud dominating. Recrystallization has produced grumose texture in most specimens. The organic debris locally shows some degree of preferred orientation. Volcanic material is present as fine-grained angular detrital quartz and disseminated clay.

The off-reef facies in north Guam is represented by dense, massively bedded foraminiferal mudstones in which fragments of *Cycloclypeus* tests are common. In a typical specimen, these tests, and amphisteginid and operculinid Foraminifera, rare *Lepidocyclina* tests, and a trace of fragmental pelecypod shells make up the fauna and show a tendency toward a preferred orientation parallel to the bedding (pl. 13*A*). Those fossils and common nodules of encrusting Foriminifera, probably *Gypsina*, are in a dense mud matrix. Thin beds of this matrix lack fossils. In some specimens, fragments of recrystallized and reversed coral are seen. Some thin sections show irregular patches of matrix that are, in themselves, lithologically similar to limestones from the off-reef facies of south Guam. These patches show irregular blending contacts—or schlieren—with the surrounding mud. This type of contact suggests deposition of poorly lithified or semisolid sediment bodies into the mud host. In the specimen figured (pl. 13*A*), the *Cycloclypeus* tests commonly show breakage but only slight separation of the resultant fragments; fracturing after burial is suggested. Parts of the mud matrix also show smeared structures and inclusions of darker matrix that appear to have been originally a matrix. These relationships indicate periodic shifting of semilithified sediments.

A cobble (sample Ut 6–1) from the overlying Janum Formation is lithologically identical with the off-reef facies (sample Jj 9–1) from south Guam, except for some minor replacement by manganese oxides in the cobble. The westernmost and highest part of the Bonya Limestone mapped in the window at Lujuna Point is very dolomitic. Here the Bonya directly underlies nondolomitic beds of the Janum Formation. The texture of the dolomitic limestone is virtually identical with that described from the flanks of Mount Santa Rosa in the Alifan Limestone. These relations suggest that the dolomitization took place before the deposition of the Janum Formation.

ENVIRONMENTAL RECONSTRUCTION

During Bonya time the Fena basin-Ugum River-Togcha River area must have been an embayment bordered by exposed volcanic rocks. Local concentrations of coral-algal breccia, such as that found on the south bank of the Talofofo River just west of its confluence with the Ugum River (locality Ih 5), indicate that small reefs flourished in the shallow peripheral waters of the embayment. Volcanic contamination of these limestones and the associated limestones of the forereef facies shows subaerial erosion of the volcanic rocks. These reefs fed detritus into the embayment in which the forereef facies was being deposited. The sorting displayed by many samples from the Bonya limestone reflects a high degree of current action and consequent movement and winnowing of material. In north Guam, reefs appear to have been subordinate or lacking. The situation is interpreted as dominantly shoal to deep-water deposition on a bottom of sufficient relief to allow movement of coarse fossil debris. The abundant mud that now makes up the matrix in this area suggests deposition in quiet water of sufficient depth to allow the growth of *Cycloclypeus* in abundance.

ALIFAN LIMESTONE

The Alifan Limestone crops out on the Mount Alifan-Mount Lamlam ridge, where it forms a cap on older volcanics, in scattered small exposures in central Guam, and in the vicinity of Mount Santa Rosa in north Guam. This formation is best exposed in the Alifan quarry. There the basal part of the Alifan Limestone is a dense pink-red fine-grained mudstone recrystallized to a sedimentary marble that shows luster mottling on a fresh fracture (pl. 4*A*, *B*). It is pierced by numerous crooked and nearly vertical tubes, an inch or so in diameter and 1 to 3 feet long, produced by boring mollusks or worms. The upper part of the limestone is crudely bedded, white to buff, porous, and fossiliferous. A typical specimen is made up of randomly oriented pencil-like sticks of *Porites* and *Acropora* as much as 3 inches long and 1 inch in diameter, casts of articulate bivalves as much as 2 inches across, and finer molluscan debris floating in a matrix of sand- and granule-size skeletal debris and fine-grained carbonate mud. Original aragonite shell material has been partly removed by solution or recrystallized to calcite. Casts and molds of coral predominate; mollusks are subordinate. The rock may be classified as coral-molluscan coquinoid limestone. The section exposed in the Alifan quarry is part of the lagoon facies.

The Alifan Limestone near Yona is a dense white foraminiferal microparacoquinite made up almost entirely of tests of *Rotalia* in a matrix of fine-grained carbonate and that has largely recrystallized to clear crystalline calcite. On a fractured surface the tests appear chalk white against the light-tan calcite matrix. The tests are normally packed and range from 1 to 2 mm in diameter. Owing to preferential solution of the tests, weathered surfaces of the rock have a honeycombed appearance and a raised matrix.

In the vicinity of Mount Santa Rosa, the basal part of the Alifan Limestone, which directly overlies the Alutom Formation, is a mottle pink, yellow and orange dense massive *Rotalia*-rich paracoquinite (pl. 4*B*) and coral breccia containing some small included masses of algal incrustate reef-wall rock (pl. 14*A*). Within a few feet of the limestone-volcanic contact, this colored limestone grades up into white limestone that lacks volcanic contamination. In this area the Alifan Limestone is locally dolomitic. Limestone of the reef-wall facies forms only a small part of the Alifan in this vicinity. *Rotalia*-rich microparacoquinites are here classed as off-reef shallow-water limestone.

ROCK DESCRIPTIONS

Limestones from the reef-wall facies.—This facies (sample Tt 7–3, pl. 14*A*) is characterized by thick intergrown laminae of encrusting algae and Foraminifera. The limestone is directly comparable to those from the reef-wall facies in the Alutom Formation (pl. 7*A*), the Maemong Limestone Member of the Umatac Formation (pl. 10*A*), and the Mariana Limestone (pl. 18*B*). The encrusting Foraminifera are the thick-walled punctate type and the thin-walled type. These encrusting elements coat coral and bind finer grained debris, which is composed largely of foraminiferal and algal fragments, within a mud matrix. Fragments of a nodular form of encrusting algae are also present. The fine-grained matrix contains disseminated clay of red-brown color that sets it apart from the pure white algal and foraminiferal calcite. Branching and pinching fractures that break and separate originally continuous algal laminae are numerous. These show separations of as much as several millimeters in the plane of the thin section. The fractures are filled with fine-sand-size foraminiferal-algal debris. Walls of the separate algal masses are coated with a thin film of red clay. The fracturing appears to have taken place where there was an available source of soft sediment to fill the open fractures. In characteristic fashion, parts of the mud matrix have crystallized to clear mosaic calcite. Coral remains are now mosaic calcite in which ghost skeletal structures are seen.

Coral-rich breccias are also placed in this facies. Thin sections of this rock show encrusting elements only as detritus. A few slides (sample Ts 16–1), however, show extensive encrustations of Foraminifera that resemble incrustate reef-wall limestone. Thus, the breccia is closely related to the reef-wall rock. The breccia is poorly sorted; it contains coral fragments as much as 1 inch across in association with fine-sand-size foraminiferal and algal debris, tests of *Rotalia* from 1 to 3 mm in diameter, and fragments of encrusting algae—including the nodular types—as much as one half inch long. These fossils are randomly packed in a fine-sand-silt matrix of triturated fossil debris containing local patches of mud. Primary porosity is low, but some pores were produced during a period of subaerial solution, which was followed by deposition of a thin layer of clear carbonate crystals on the void walls. The fine-grained parts of the matrix carry some finely disseminated reddish-brown clay contamination.

Limestones from the lagoon facies.—The three lithologic types included in this group occur in close association and are probably the result of local variations in conditions of deposition; they are described below.

Coral-molluscan coquinoid limestone makes up the main mass of the Alifan Limestone, as represented in the Alifan quarry. In thin section (pl. 14*C*) the characteristic poor sorting of this rock is obvious; pelecypod and gastropod shells and fragments of coral are loosely packed, in a finer grained matrix. There are three distinct size grades present: granule-size and larger fossil fragments, sand-size debris derived from shells, and carbonate mud. The relative proportions of these size grades vary from sample to sample. The degree of preservation of the fossils also varies from sample to sample, except for the coral remains that are present only as ghosts. Gastropod shells show up mainly as calcite mosaics. Pelecypod shells are represented by fragments that retain their original fibrous structure and by recrystallized mosaic calcite that grade outward into the fine-grained matrix.

Foraminiferal-algal microparacoquinites are limestones composed of foraminiferal and algal debris randomly oriented and packed in a partly recrystallized mud matrix that is cloudy in patches. Much of the fossil debris is between 0.1 and 0.5 mm in diameter. Scattered throughout this even-grained material are whole tests of *Rotalia* as much as 2 mm in diameter and occasional fragments of encrusting algae as much as 5 mm in diameter. The finer-grained fossil debris is a mixture of encrusting algae, articulate algae, encrusting Foraminifera, and mollusk shells. Also present are tests of small Foraminifera, among which are amphisteginids, miliolids, and uniserial, biserial, and coiled forms. Subaerial solution has produced a fine irregular secondary porosity. Primary pore space in the form of open cells of Foraminifera tests remains. Angular fragments of quartz, and rare euhedra (pl. 3*D*), are present in the Alifan Limestone (Gj 8–1) from the Fena basin. These fragments range from 0.1 to 0.5 mm. The quartz-calcite contacts are sharp, and there is no evidence of replacement of the quartz by calcite. Hathaway and Carroll (see p. 42) describe these euhedra as squat doubly terminated crystals similar to those described from a volcanic ash in Java.

Recrystallized mudstones in thin section reveal the intricate granoblastic texture formed during the recrystallization of what probably was an original lime-mud. In plain light (pl. 4*A*) the intergrown crystal boundaries are not readily apparent; however, under polarized light (pl. 4*B*) individual crystals are seen. No recognizable coarse fossil debris is present except a few fragments of pelecypod shells in one thin section. Fine, hairlike streaks of reddish-brown clay suggestive of bedding planes extend through parts of the matrix. Irregular patches of coarser grained crystals are separated from the finer grained matrix by sharp dividing lines. These coarser grained areas may represent filled burrowing tubes now distinct because of an original difference in grain size between the burrow filling and the original matrix. In one thin section an offset of one such relict tube along a warped surface suggests prelithification slumping of soft sediment. The type of recrystallization occurring in this rock is unique to the Alifan Limestone. The original mud seems to be in the process of being reorganized. Individual crystals are very intricately interlocked and intergrown, quite unlike the normal mosaic calcite in most of the Guam limestones. Each crystal retains numerous inclusions of original fine-grained material and the present size of the crystals appears to be dependent on the original grain size.

Limestones from the off-reef shallow-water facies.—The dominant fossil element in these microparacoquinites is *Rotalia*, tests of which make up from 35 to 60 percent of individual samples. The tests range from 1 to 2 mm in diameter; rare specimens are as much as 4 mm in diameter. Similar-size debris of encrusting algae and Foraminifera and articulate algae make up 5 to 10 percent of the limestone. The degree of sorting shown by the *Rotalia* tests may be biologic; however, the algal debris shows the same size characteristics; this similarity suggests some true hydraulic sorting of both the Foraminifera and the algae before deposition. These fossil elements are closely packed in a fine-sand and mud matrix. The fact that the Foraminifera tests and the algae show some minor interpenetration at some contact points suggests possible compaction. Perhaps the fossil elements were originally floating in the mud matrix. The matrix contains some fine-grained recognizable algal debris. In some samples (Ts 16–11) (pl. 14*B*), this matrix has undergone a partial recrystallization to clear calcite. The recrystallization begins from the surfaces of the fossil debris and proceeds into the mud-filled interstices, in the form of acicular crystals of clear calcite that grow perpendicular to the fossil walls. These peripheral growths gradually coalesce to form a clear interstitial cement. The lower, central part of plate 14*B* shows such a completely recrystallized area. Most of the thin section retains the original mud matrix. Because certain areas have been affected by solution, almost all the mud fill has been removed and the resultant void lined with clear calcite. Fossils surrounding such voids show three encrusting layers: (1) a coating of secondary calcite crystals, (2) a layer of residual dark mud, and (3) a clear primary deposit of calcite. In some thin sections all traces of the original mud has disappeared; the rock shows a grumose texture.

ENVIRONMENTAL RECONSTRUCTION

The Alifan Limestone accumulated under a variety of conditions. The deposits around Mount Santa Rosa include incrustate reef-wall rock and coral breccia that are argillaceous at the base. These relations suggest that during early Alifan time Mount Santa Rosa stood as an island around which grew a shallow-water reef complex. This island contributed clays to the reef and associated sediments. The transition upward to pure limestones in north and south Guam indicates a cessation of argillaceous contamination, probably due to a transgressive sea that covered Mount Santa Rosa and the south Guam volcanics and eliminated them as sources of sediments. In southern and central Guam no reef-wall limestones have been found; the bulk of the Alifan Limestone accumulated under lagoonal conditions. The articulated pelecypods and abundant long sticks of delicate branching coral indicate inplace accumulation. These deposits closely resemble modern deposits in Cocos Lagoon, where similar delicate branching corals contribute large amounts of similar sticks to a shallow sand bottom on which mollusks are common. Much of this unsorted coralliferous material is accumulating in protected lagoonal areas in water less than 5 feet deep. The local abundance of *Rotalia* in some rocks from the Alifan Limestone suggests time of adverse conditions for normal reef and lagoonal communities. According to Hedberg (1934, p. 475), *Rotalia beccarii* has a high tolerance for fresh water; where it occurs alone, brackish water is indicated. Thus the local accumulation of *Rotalia* tests may be the result of deposition under conditions of high fresh-water inflow very near shore, possibly just below the littoral zone.

BARRIGADA LIMESTONE

The Barrigada Limestone is well exposed on north Guam. It crops out in a large ring-shaped area 6 miles in diameter; the width of the outcrop averages approximately 1 mile. The formation, as exposed, is made up of massive gray to white indurated to friable dense to porous foraminiferal mudstones, microcoquinites, and microparacoquinites of the off-reef deep-water facies. The degree of induration varies; in zones of faulting the rock is a dense yellow, finely crystalline limestone that forms sharp, sheetlike ridges. On rolling or flat terrain the limestone is commonly friable, possibly owing to solution by percolating water.

ROCK DESCRIPTIONS

The Barrigada Limestone, unlike the limestones of Eocene (*b*) and Miocene (*e*) age previously described, does not display a complex suite of rock types. Rather, it is a monotonous expanse of foraminiferal limestone. Variations in fossil size, type of matrix, and porosity constitute the only lithologic differences over large areas.

The largest foraminiferal tests are associated with the finest matrix. Some rocks (sample Pv 10–2, pl. 15*A*) are foraminiferal mudstones containing abundant large tests in a fine-grained matrix, a strongly bimodal size distribution. Other rocks (sample St 8–1, pl. 15*C*), which are better sorted, are microparacoquinites containing small amphisteginid tests in a matrix that is not as fine grained as the mudstones. Still other rocks (sample Nr 1–7a, pl. 15*B*) are well sorted microcoquinites showing a texture close to that of a normal detrital sandstone.

All the tests show strong effects of abrasion and fragmentation; preferred orientation is lacking even among the flat tests. The high content of encrusting Foraminifera, all in fragments, suggests considerable reworking before deposition in the fine-grained matrix.

Samples Ov 7–1, 7–2, and 7–3, from depths of 94, 404, and 543 feet, respectively, in a well drilled for the transformer house at Naval Communications Station Finaguyen, show a considerable vertical variation in lithology. Sample Ov 7–1 is a foraminiferal microcoquinite similar to sample Nr 1–7a; porosity, mainly secondary, is low and in the form of fine irregular openings in the matrix. Sample Ov 7–2 is a porous breccia containing *Halimeda* segments, debris of coralline algae, and fragments of pelecypod shells; porosity is high, mainly secondary; voids take the shape of fossil fragments. Sample Ov 7–3 shows a fine-grained dark mud matrix in which are imbedded recrystallized *Halimeda* segments, coralline algae, and a few tests of large discoid Foraminifera; porosity is variable. One slide shows dissolution of numerous *Halimeda* segments and consequent high porosity. Another slide shows the matrix to be almost entirely fine grained and of low porosity. Under high magnification the rock shows a trace of red-brown detritus that closely resembles the fine-grained weathered volcanic detritus seen in more argillaceous rocks. In reflected light, patches of this coloration are seen. The material is very finely disseminated throughout the fine-grained dark matrix.

ENVIRONMENTAL RECONSTRUCTION

The fauna of the north plateau outcrops of the Barrigada Limestone are indicative, according to W. S. Cole (written communication, Mar. 26, 1953), of a bank (or forereef) deposit, undoubtedly on the outside of a reef, and a water depth of about 500 feet. The abundance of *Cycloclypeus* tests certainly precludes a reef or lagoonal origin for these sediments. The sporadic occurrence of coral and other shallow-water elements suggests that the limestones containing them were deposited on local highs on a generally deeper submarine bank. The worn and broken *Cycloclypeus* tests in a fine-grained matrix indicate transport of these tests before deposition in a quiet-water environment. The abundance of fragmented encrusting Foraminifera supports the idea of much predeposition transport. The general absence of reef contributions may be due to lack of reef-wall deposition during the late Miocene in the present north Guam area.

JANUM FORMATION

The Janum Formation crops out in seven places along the northeast coast of Guam between Lujuna Point and Anao Point. Sections exposed north and south of the type section at Catalina Point thin from a maximum of 70 feet; at Anao Point 6 feet is exposed, at Lujuna Point 4 feet. In outcrop the Janum Formation exposes compact to friable red-orange, pink, brown, yellow, and gray-white tuffaceous to relatively pure thin-bedded globigerinid-rich microparacoquinites. No scour and fill structures are seen, and beds a few inches thick can be traced across the outcrop. Rounded to subangular pebbles and cobbles of the Bonya Limestone are common, especially in the basal part of the Janum Formation. The scattered exposures may be due to lensing of the formation and pinching out between outcrops. At Lujuna Point a thin bed of the Janum pinches out between Bonya Limestone and Mariana Limestone in a well-exposed cliff.

ROCK DESCRIPTIONS

Three major sedimentation units are present in the Janum Formation at the type section. These units show variations in faunal content, volcanic contamination, and texture, all of which taken together indicate a shift upward in the section, from shallower water, relatively pure limestone to argillaceous, deeper water, basin sediments.

The uppermost 15 feet of the type section is made up of medium-grained argillaceous foraminiferal microparacoquinites (pl. 16*C*). The distinguishing characteristic of this unit is the high content of volcanic material, largely in the form of clay minerals weathered from single crystals and sand-size volcanic rock fragments. This clay content causes pink, brown, and orange-red coloration in reflected light and adds a dark-brown cast to the thin sections. The character of the volcanic fraction varies (see p. 37–48). In some samples (Ts 5–4 and Ts 4–4a), much sand-size material is present, but in a sample taken 15 feet lower in the section, volcanic contamination takes the form of evenly disseminated silt- to fine-sand-size, angular fresh magnetite. Tests of globigerinids and other smaller Foraminifera form as much as 50 percent of the rock; the remainder of the carbonate fraction is in the form of a mud matrix.

The middle sedimentation unit is made up of fine-grained, relatively pure limestone taken from 25 to 55 feet below the Janum-Mariana contact. This limestone (pl. 16*A*) is characterized by a high content (50 to 70 percent) of globigerinid and other smaller Foraminifera tests. These tests are as large as 0.25 mm in diameter, but average approximately 0.1 mm in section; the packing is unusually dense and many tests have apparently been crushed in place, not in subsequent transport. In one sample, many of the unbroken tests remain empty, but in another, similar tests are filled with fine mud. Volcanic contamination amounts to only a few percent, largely of clay minerals.

The lowermost sedimentation unit is a pure foraminiferal microparacoquinite (pl. 16*B*). Fossil remains (sample Ts 5–9) from this unit are of (1) globigerinids as much as 1 mm in diameter, biconvex, (2) discoidal amphisteginids of slightly larger diameter, and (3) a few fragments of *Cycloclypeus* tests. The amphisteginid tests show signs of wear and breakage. These fossils are all in a carbonate mud matrix that contains approximately 1 percent volcanic material, largely clay minerals. The total combined faunal content amounts to approximately 30 percent of the rock.

ENVIRONMENTAL RECONSTRUCTION

The three sedimentation units described from the Janum Formation are the products of three distinct depositional environments. The lowermost stratum at the type section contains a foraminiferal fauna suggestive of a forereef or bank environment. The abundant amphisteginid tests in both this stratum and the lowest sedimentation unit of the Janum Formation, which directly overlies it, indicate a depth of deposition probably between 40 and 100 fathoms (Ruth Todd, written communication, Aug. 22, 1952). The fauna shows the effects of vigorous transport. The basal part of the Janum at Catalina Point is a moderate-depth deposit unaffected either by volcanic activity or by the erosion of a volcanic terrane. The middle sedimentation unit, however, lacks all shallow-water faunal elements as well as significant volcanic contributions. In referring to samples from this middle unit, Ruth Todd (written communication, Oct. 30, 1952) states: "The benthonic population, represented by a good variety of species but few individuals, is indicative of depths between 100 and 1500 fathoms, more likely toward the shallow end of this range." The uppermost sedimentation unit reflects a decrease in the rate of sedimentation of globigerinid tests and an increase in the deposition of volcanic detritus. Higher in the section (samples Ts 5–4 and Ts 5–4a) the volcanic detritus is abundant and containing rock fragments as well as single crystals suggestive of subaerial erosion of volcanic terrane. The inclusion of Bonya Limestone pebbles indicates that erosion of the Boyna Limestone was in progress in north Guam during Janum time.

MARIANA LIMESTONE

The Mariana Limestone, which forms approximately 80 percent of the exposed limestone of Guam, is an emerged reef and was mapped in the field as five lithologic units (Tracey and others, 1963). The reef facies, largely made up of coral-algal incrustate limestone, forms a discontinuous peripheral belt at or near the present seaward-facing limestone cliffs and encloses the detrital facies and the molluscan facies, both of which are particulate limestone types of lagoonal origin. The forereef facies of the Mariana Limestone is a deposit of particulate limestone that is exposed only on the seaward slopes of the bounding limestone cliffs. The Agana Argillaceous Member is restricted to a fringe around the older volcanic rocks that were the source of the clay contamination in this member.

The areal distribution of mapped facies and members suggests that the surface of the north limestone plateau is a relatively undisturbed depositional surface, hence much can be inferred about the petrology of limestones of the Mariana from the field relations. The similarity of these limestones to present-day deposits in shallow-water environments around Guam also makes profitable a comparison of the facies relations deduced from field mapping with those deduced from the petrologic study.

The petrologic classification of limestone facies as used in this study—reef wall, lagoon, and forereef—may be recognized within the Mariana Limestone. Limestones of the reef-wall facies are represented within the mapped reef facies. Limestones of the lagoon facies occur within the mapped detrital facies and the mapped molluscan facies. Limestones of the forereef facies include the mapped forereef facies and a foraminiferal breccia of the mapped detrital facies. Rock types from all three limestone facies occur as lenses within the Agana Argillaceous Member of the Mariana Limestone.

The correlation of the limestone facies classification with the mapped facies of the Mariana Limestone follows.

Limestone-facies classification	*Mapped facies of the Mariana Limestone (Tracey and others, 1963, pl. 1)*	*Rock types*
Reef-wall facies	Reef facies	Incrustate: Coral-algal.
Lagoon facies	Detrital facies	Particulate:
		Coral-rich breccia.
		Halimeda-rich paracoquinite.
	Molluscan facies	Molluscan coquinoid.
Forereef facies	Forereef facies	Particulate:
		Foraminiferal microcoquinite.
		Foraminiferal-algal microcoquinite.
		Foraminiferal breccia.
	Detrital facies	Foraminiferal breccia.

ROCK DESCRIPTIONS

Incrustate limestones from the reef-wall facies.—In the field the rocks from the reef-wall facies occur within the mapped reef facies of the Mariana Limestone and are characterized by large numbers of coral heads in growth position. Most are of the massive reef-building types such as *Favia*, blunt stubby *Acropora* and *Pocillopora*, and meandrine or brain corals.

Algal growths cover many of the heads. These laminae were produced for the most part by algae of the genus *Porolithon*. Reef mollusks such as *Trochus*, *Turbo*, and elongate coral borers are abundant in places. The spaces between coral heads are filled with fine-grained white dense limestone containing lenses and pockets of *Halimeda* plates, algal detritus, gastropod shells and, rarely, pelecypod shells. Thin-section study shows that the corals are largely recrystallized and retain their coarse structure, but are composed of yellow-brown translucent, coarsely crystalline calcite. Many of the primary void spaces and some secondary solution voids are partially or wholly filled with yellow drusy calcite. The mass, or vuggy, porosity amounts to several percent, perhaps as much as 10 percent locally. The rock weathers to a gray, sharply pinnacled surface, upon which many relict coral structures are visible. In outcrops where a high percentage of algal material is present, the rock is extremely dense and appears dead-white. The weathered surface of algae-rich rock is smoother and lighter in color than the coraliferous variety. These rocks of the Mariana Limestone in thin section show typical characteristics such as mud-filled coral and a high content of in place encrusting algae (pl. 18*B*).

Amphistegina dominates the Foraminifera fossil group along with encrusting types such as *Carpenteria*. Pockets of sand-size, highly concentrated angular debris of articulate coralline algae occur in some samples but are subordinate to laminar algal growths. The effectiveness of the reef wall as a trap for fine sediment within a turbulent marine environment is shown by the high percentage of interstices filled with fine dark mud and fine-sand-size debris.

The areal distribution pattern, outcrop lithology, and characteristics in thin section of these rocks indicate that the mapped reef facies is the in place remnant of a shallow-water to surface-breaking, constructional reef front that rimmed the shoal-water detrital deposits of the Mariana Limestone.

Particulate limestones of the lagoon facies.—The detrital facies, as mapped in the field, is made up of two rock types of lagoonal origin: coral-rich breccias, which dominate volumetrically, and *Halimeda*-rich paracoquinites. These rocks, plus molluscan coquinoid limestones within the mapped molluscan facies, cover all the lagoonal deposits of the Mariana Limestone.

The breccias are dense to porous, indurated to friable, white, pink, and buff limestones that contain scattered remains of corals, gastropods, echinoid debris, and pelecypods. The degree of lithification is irregular. In some areas the rock is friable and white to pink, and contains few recognizable fossils. In other areas it is a dense recrystallized light-buff, slightly translucent rock in which an occasional echinoid spine is found.

Lenses containing approximately 10 percent coral are present. These are made up of white to light-brown, coarse-grained porous limestone and boulder-size coral remains in a poorly sorted matrix.

The *Halimeda* paracoquinites locally contain high concentrations of *Halimeda* segments (pl. 17*C*) within the larger mass of limestones just described. Staining of these limestones (samples Po 1–2 and Tw 8–1) by boiling in Meigen's solution revealed that most of the original carbonate produced in the algal segments was still present as aragonite. On a stained polished surface the original aragonite showed sharp boundaries against the enclosing calcite matrix. The internal tubes characteristic of *Halimeda* (segment sections on pl. 17*C*) were filled with calcite. Almost all the segments are entire and show some degree of local packing.

Three sets of carbonate deposits make up the matrix of the *Halimeda* paracoquinite (sample Po 1–2). Each segment is coated with a thin film of granular calcite. This coating appears as a bright band (pl. 17*C*), which is succeeded by a granular calcite layer. In other sections, however, the second layer is fibrous aragonite, as shown by the Meigen's solution test. Between this layer and a final fill of medium-grained clear anhedral calcite, lies a fine-grained dark mud fill. The fibrous aragonite shows as many as 5 distinct bands of dark lines which are probably a result of breaks in carbonate deposition.

The coquinoid limestones contain two rock types, a coraliferous-molluscan limestone and a pelecypod- and gastropod-bearing limestone that lacks corals. The first type is characterized by coraliferous and molluscan remains in a dense to porous, white to tan, fine-grained matrix. Casts, empty molds, and a few shell fragments are all that remain of the original shell material. The corals have been largely recrystallized into yellow translucent masses of calcite that show original structure. The rock weathers to light-brown to gray and has an irregular surface upon which corals and mollusk casts stand out in bold relief. The second type is a dense, fine-grained to sandy, light-tan rock in which randomly oriented casts and molds of large pelecypod valves locally occupy a large part of the rock. Gastropod-rich limestones are locally abundant.

The typical gastropod-bearing areas within the molluscan facies contain whole and fragmented small gastropod and pelecypod shells in a matrix of fine-sand- and silt-size calcite detritus (pl. 17*A*). A small percentage of this matrix is sand-size algal debris. The

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shells have recrystallized into mosaics of clear calcite that have both gradational and sharp boundaries with the matrix. Darker, finer grained streaks through the matrix are the only suggestion of bedding in thin section. The pelecypod-rich molluscan facies of the north plateau has not only the same kind of matrix as the detrital facies (sample Jj 6–1) from the Togcha River area but also traces of *Halimeda* segments and tests of miliolid Foraminifera. Many of the pelecypod valves have been dissolved, leaving disconnected pore spaces. However, original fibrous structure can still be seen in some shell fragments.

The relative abundance of gastropod and pelecypod remains and the traces of algae and tests of miliolids suggest a lagoonal fauna unaffected by large reef contributions. The fine-grained matrix indicates deposition in quiet water. The outcrop pattern of the molluscan facies, as mapped, supports the interpretation of these beds as lagoonal deposits, for they are localized within the rimming reef and detrital facies (Tracey and others, 1963, pl. 1).

Particulate limestones of the forereef facies.—The forereef facies type of limestone occurs within two mapped units of the Mariana Limestone, the forereef facies and the detrital facies. The forereef facies as mapped in the field forms apronlike wedges that dip away from and lie seaward of and topographically below the mapped reef facies. At Lafac Point the rock is a thin-bedded well-sorted friable porous foraminiferal microcoquinite (pl. 17*B*). A second area of exposure, flanking the mouth of the Togcha River, displays some breccia composed of pebbles and boulders of Bonya limestone in a matrix of weakly cemented foraminiferal tests. This matrix is like the foraminiferal limestone of the Lafac Point exposure. Some of the Togcha River exposures are well-sorted foraminiferal-algal microcoquinites.

The foraminiferal microcoquinite of the exposure at Lafac Point is characterized by an abundance of shallow-water and reef foraminiferal tests in unusual concentrations. *Calcarina* and *Amphistegina* predominate over lesser amounts of *Marginopora.* The normally spiny tests of *Calcarina* are smooth, probably owing to wear during transport from their usual reef habitat. Both the thick-walled *Calcarina* and the thinner *Amphistegina* tests show some breakage. These tests, and traces of echinoid spines, are loosely packed. The only matrix is a thin layer of fine-grained calcite that coats each piece of detritus evenly and serves as a weak cement. Hand specimens can be easily reduced to loose sand by finger pressure. The few echinoid spines have a thick growth of clear calcite in optical continuity with the typically monocrystalline spine. The porosity of this rock is high, approximately 30 percent, owing to the large intertest primary voids.

The physiographic and stratigraphic position of the mapped forereef facies, as well as the seaward dip and bedding at Lafac Point, demonstrate its forereef origin. The abundance of reef and shallow-water Foraminifera suggests the selective transportation, possibly as a distinct size grade, off the reef shallows to be deposited as forereef talus. The Togcha River exposures show, by virtue of the included Bonya Limestone detritus, active erosion of older limestones.

Parts of the mapped detrital facies within the Mariana Limestone are considered breccias of forereef origin because of included diagnostic Foraminifera. This rock shows the characteristic forereef Foraminifera, *Cycloclypeus*, in a poorly sorted matrix containing angular reef debris (pl. 17*D*). Almost all the large tests are partly fragmented. Some of the tests have worn and broken coatings of an encrusting Foraminifera; these tests must have come to rest once prior to their final incorporation in this breccia.

Agana Argillaceous Member.—This unit was differentiated in the field from the main mass of pure Mariana Limestone on the basis of its clay content. (See 37–45.) This clay is present in two forms: finely disseminated material in the limestone matrix where it amounts to several percent of the rock by weight; and slightly calcareous pockets and lenses, which in a few outcrops amount to as much as 50 percent of the rock by volume. Lenses of all these rock types occur in the Agana Argillaceous Member; faunally and texturally these lenses are correlative to rock types in the pure limestones.

Molluscan-rich coquinoid limestones of the Agana Argillaceous Member contain numerous casts and molds of the high-spired gastropod *Turritella filiola*, which are from 1/8 to 1/2 inch in length and randomly oriented in a dense to friable yellow fine-grained matrix. Thin sections show a matrix similar to that described for the pure molluscan facies. However, a strong yellow-orange stain seen in reflected light is due to the clay contamination, especially around the shells. Most of the shell material has recrystallized to medium-grained mosaic calcite. The clay contamination must have been brought into the Mariana Limestone by streams flowing off the southern volcanic rocks, as shown by the areal limitation of the argillaceous member.

ENVIRONMENTAL RECONSTRUCTION

The Mariana Limestone was deposited under a wide range of environmental conditions. Around the volcanic mass of central and south Guam, stream erosion contributed large quantities of volcanic clay to the near-shore limestone. Widespread shallow lagoons, bottomed with clay and fine argillaceous sand, were the habitat of a large population of mud-burrowing gastropods such as gave rise to the *Turritella filiola*-bearing coquinoid limestones. The present north plateau was the site of reef, lagoon, and forereef environments relatively uncontaminated by volcanic material. While the reef-wall limestone accumulated in place as a solid constructional reef front, *Cycloclypeus*-bearing breccias formed on the forereef slopes. Backreef lagoons accumulated reef and shallow-water detritus that resulted in coral breccia. Protected areas in the lagoon were collection sites for fine-grained sediments in which bivalves and gastropods flourished. Local concentrations of *Halimeda* were common. During the late stages of Mariana time, quantities of shallow-water Foraminifera tests were swept from their reef habitat and deposited as talus to form the mapped forereef facies.

SUMMARY AND CONCLUSIONS

The dominant rock-forming processes that built Guam were volcanism and reef growth accompanied by sedimentation in lagoon and forereef areas. The recurrence of field relations and of typical rock associations containing diagnostic fossils shows that the reef complexes tended to evolve along similar patterns through time. The older reef complexes are partially destroyed by volcanic explosions and erosions. The Mariana Limestone, on the other hand, postdates active volcanism and hence retains its original depositional pattern. The reefs of Eocene (*b*) age were largely destroyed, they now occur mainly as limestone fragments in volcanic breccia; other reef complexes of intermediate age are in various stages of preservation. Comparison of the limestones of Guam with material from reef complexes in Louisiana and Iraq shows that Tertiary reef complexes throughout the world are lithologically much alike.

Reef and associated limestones from the *Heterostegina* zone (late Oligocene or early Miocene in age) of southern Louisiana and from strata of Oligocene age in Iraq bear striking faunal and textural resemblances to the limestones of Eocene (*b*) and, particularly, Miocene (*e*) age described above (see pls. 19 and 20). A detailed comparison of limestones from these three areas was made by Forman and Schlanger (1957). The Louisiana reefs were of two types: scattered individual reefs that formed on topographic highs over submarine salt domes, and a single regional shelf reef. Conditions during *Heterostegina*-zone time are considered somewhat analogous to the present situation on the Gulf Coast continental shelf, where a number of small topographic prominences, having a relief of as much as 600 feet, reach to within 50 feet of sea level. Work by Stetson (1953) revealed living colonies of reef organisms on the crests and shoulders of these inferred domes. In Iraq, numerous reefs of various types contain a complete suite of reef-wall and associated limestones (Henson, 1950). The areal distribution and microfacies characteristics, such as faunal and floral content and texture, of limestones in all three areas enabled Forman and Schlanger (1957) to come to the following conclusions regarding reef growth during the early part of the Tertiary:

(1) Lower and middle Tertiary reef complexes, perhaps throughout the world, are characterized by basically the same faunal and floral assemblages; (2) these assemblages produced diagnostic limestone facies; (3) these limestone facies maintain predictable stratigraphic relations in the reef complex; (4) the nature of the substrata and the local geologic setting do not appear to be dominant factors in the formation of these reef complexes; (5) once favorable ecologic conditions are met, under widely differing circumstances, similar reef complexes will form.

Thus, partial preservation of a complex allows interpretation of the original position of the unpreserved parts. Reconstruction of depositional conditions for the Maemong Limestone Member is an example of such a reconstruction. The direction of dip of forereef deposits combined with the structural setting of south Guam indicates the existence of a former reef wall to the west. The application of thin-section studies to other ancient reef complexes, as first suggested by Henson (1950), will probably make possible more detailed interpretations of the geologic history of many limestone-volcanic islands in the open Pacific.

In all the reef complexes studied, the ratio of particulate limestone to incrustate reef-wall rock is large; in the Mariana, incrustate limestone amounts to perhaps 5 to 10 percent of the total volume of the formation. As Ladd (1950, p. 204) points out, the reef wall is "* * * like the walls and rim of a pail that holds water * * *". Yet this wall controls sedimentation around it by forming a barrier to oceanic circulation and maintaining shallow-water conditions, thereby producing a lagoonal environment that is in sharp contrast to the forereef environment. In the backreef areas sediments accumulate largely in place, and there is only local small-scale movement. The forereef deposits, on the other hand, show the effect of considerable transport and breakage. The sediments tend to decrease in grain size away from the reef wall, concomitantly with the decreasing ratio of debris transported from shallow water to indigenous Foraminifera, particularly planktonic. Submarine slumping from overloaded forereef slopes probably carries material into basins where the normal sedimentation is due to planktonic contributions. Limestones in the Maemong Limestone Member show streaks and lenses of foraminiferal-algal debris in thin fine-grained globegerinid beds. Beds of pure globigerinid mudstone a few inches thick alternate with beds of fine-grained foraminiferal-algal microbreccia to build up one section known to be at least 50 feet thick. These numerous alterations can hardly be ascribed to rapid changes in sea level or lateral shifting of the far away reef wall. The beds of algal-foraminiferal debris are probably composed of slumped material from upslope.

Comparisons of the various limestone units show that all the major fossil groups considered in the rock classification occur in both the oldest and the youngest limestones. Some organisms, such as coral and echinoids, contributed material in fairly steady amounts through time. Articulate coralline algae, however, appear to have been more abundant in the older limestones, but diminished as rock makers through time. Field observations indicate that this trend is real and study of limestones from other islands in the Pacific also tends to confirm this trend; limestones of Eocene (*b*) and Miocene (*e–f*) age carry large amounts of articulate coralline algae. Emery (1956, p. 1511) shows that coralline red algae reduced to sand size is the dominant constituent of modern submarine sediments in the surrounding shallows off Johnston Island. This high algal content is in contrast to the lower algal content of lagoon sediments from Bikini Atoll and Guam. The abundance of algae may be a function of the degree of enclosure of a lagoon by shoaling reef walls and islands. At both Bikini and Guam, lagoons are largely encircled by shoal reefs and islands, whereas at Johnston Island the surrounding shallows are largely open to the sea (Emery, 1956, pl. 1). Thus the possibility exists that the lower Tertiary reef complexes were more open to the sea and less bounded by reef walls and islands than the reefs of Mariana age, for example, that must have restricted circulation in the lagoon; the geologic map (Tracey and others, 1963, pl. 1) shows that the Mariana reef walls almost completely encircled the lagoon.

One of the most prevalent types of recrystallization is the conversion of original mud matrix to granular clear mosaic calcite. All gradations from relatively opaque mud to clear calcite have been noted. This point is important in interpretation of original textures inasmuch as a limestone that was deposited with a mud matrix might be mistaken for a coquinite that was later filled with precipitated calcite. The various fossil groups differ in their susceptibility to recrystallization. Coralline algae show a wide range of recrystallization; generally material from limestones of Eocene (*b*) and Miocene (*e*) age are better preserved than any other fossil group present. Yet in younger limestones, such as parts of the Alifan and Barrigada Limestones, algal fragments are bleached and dissolved while Foraminifera are well preserved. *Halimeda* segments show a change from microcrystalline aragonite to granular calcite; aragonitic *Halimeda* were found only in the Mariana Limestone. Because the persistence of aragonite in exposed limestones, as discussed above, may continue for long periods, the presence of aragonite is ruled out as unequivocable evidence of nonemergence. Corals are everywhere recrystallized; ghosts of original septal outlines are in mosaic calcite. These dust-line ghosts are tenacious and are present in the oldest limestones.

Recrystallization is accompanied by a reduction in the amount of strontium in the resulting limestone.

Dolomite is localized in the Alifan and Bonya(?) Limestones; even within these formations, its distribution is spotty. If dolomitization was a normal diagenetic effect, much more of the Guam limestone section should be dolomitic. The local occurrence of dolomite suggests that rather special conditions are necessary for its formation.

On Guam microstylolites occur only in the basal part of the Alifan Limestone. Except for minor interpenetration of foraminiferal tests in the Bonya Limestone, the microstylolites are the only features than can be ascribed to solution along preferred surfaces. The lack of microstylolites in samples from the deep cores taken below Eniwetok indicates that simple static loading is not the controlling factor in microstylolite formation.

Introduction of noncarbonate material into the pure limestone takes place in several ways, all traceable back to primary volcanic rocks as the original source. Silification of limestones owing to the eruption of immediately superjacent lava flows took place after deposition of limestones of both Eocene (*b*) and Miocene (*e*) age. The older limestones show both fissure fillings and metasomatic replacement by chalcedonic quartz. The globigerinid mudstones of the Maemong Limestone Member show numerous tests filled with beta-cristobalite. Lava flows directly overlie both of the silicified limestones and must have been the source of the silica. The mode of emplacement of the silica apparently depends on the condition of the limestone. The empty tests of planktonic Foraminifera provided convenient space for the siliceous solutions. In the limestones of Eocene (*b*) age, open fissures provided growth space. The absence of metasomatic replacement in the globigerinid mudstone from the Maemong Limestone Member is difficult to reconcile with such replacement in the limestones of Eocene (*b*) age.

The differentiation of the insoluble residues into two groups (see p. 43), one indicative of ash falls and pyroclastic contributions and the other characteristic of contamination by erosion of volcanic terrane, shows that volcanic activity in the immediate Guam area ceased after the deposition of the Bonya Limestone. The presence of primary volcanic material in the Mariana limestone indicates pyroclastic contributions. However, this contribution is light and is interpreted as airborne material from afar. Independent lines of evidence indicate that a period of intense surface weathering of volcanic rocks took place during the deposition of at least part of the Bonya Limestone and continued long enough to supply considerable clay to the basal part of the Alifan Limestone and most of the Janum Formation. Transport of manganese occurred during and perhaps shortly after the deposition of the Bonya Limestone. This transportation indicates the development of a drainage pattern and the resultant leaching of manganese on an island-wide scale. The presence of nordstrandite in the Alifan Limestone and the Janum Formation points to the movement of alumina either in solution or as detrital gibbsite or both; the occurrence of gibbsite itself indicates advanced weathering of volcanic terrane.

This paper may best serve as an introduction to study of reef and associated limestones from the western Pacific. Future work in this area should include comparison of rock associations both within island chains, such as the Marianas, and between widespread chains. Limestones such as these are sensitive indicators of uplift and emergence; studies of areal shifts from shallow to deep-water facies within correlated stratigraphic units can show whether tectonic activity was local or regional. In addition, study of insoluble residues may lead to an understanding of erosion cycles, through time, in the island arcs of the western Pacific.

PETROGRAPHY OF THE INSOLUBLE RESIDUES

By J. C. Hathaway and Dorothy Carroll

LABORATORY PROCEDURES

Laboratory procedures were designed to extract sand, silt, and clay grades of insoluble material from the limestones without altering individual minerals. For this reason, acetic acid (1:4) was used in place of the usual hydrochloric acid for removing calcium carbonate. Acetic acid has little effect on clay minerals.

SEPARATION

Thirty-one samples of limestone were crushed in a jaw crusher and rolls to pass a 60-mesh (0.25 mm) sieve. Approximately 100 grams of crushed limestone was dissolved in 1:4 acetic acid to remove the calcium carbonate from the sand, silt, and clay materials. Calcium carbonate was dissolved most rapidly when the acetic acid was kept dilute and the limestone-acid mixture was agitated with a magnetic stirrer. A temperature of about 50°C also increased the rapidity with which the calcium carbonate was dissolved. When the samples had dissolved to the point at which no reaction was obtained by treating a small portion of the sample with dilute hydrochloric acid (N/10), they were removed from the beakers and washed by centrifuging with distilled water. The washing was continued until the residue remained partly in suspension after 10 minutes at 2,000 rpm. The washed samples were dried and weighed as insoluble residue.

The insoluble residues were dispersed in distilled water to which a little sodium metaphosphate was added. The sand was removed by wet sieving with a 230-mesh sieve (62 microns). The material finer than 62 microns was further dispersed in water in 1,000-milliliter cylinders in an end-over-end shaker. These suspensions were fractionated by repeated centrifuging to separate the silt (2 to 62 microns) and clay (less than 2 microns) fractions. The excess water was removed from the resulting clay suspensions by filter candles under vacuum. The sand, silt, and clay fractions were dried and weighed and expressed as a percentage of the total insoluble residue.

MINERALOGICAL ANALYSIS

CLAY AND SILT MINERALS

The minerals in the clay and silt fractions were identified by X-ray diffraction using CuKα nickel filtered radiation. Various preparatory techniques requiring several X-ray diffraction patterns were used to identify the clay minerals. The minerals in the silt fractions were identified from X-ray diffractometer patterns of unoriented minerals. Powder photographs were made of samples that were too small to make satisfactory mounts on glass slides for diffractometer patterns.

MINERALS IN THE SAND GRADES

A weighed quantity of the sand from each sample was separated in bromoform (sp gr, 2.9) to obtain the light and heavy minerals for microscopic examination. In 14 samples the quantity of material of sand size was too small for bromoform separation. Magnetite was removed from all the samples with a small horseshoe magnet before the remaining heavy minerals were mounted on glass slides. If magnetite was present in appreciable quantities, it was weighed and expressed as a percent by weight of the sand fraction. The minerals were identified with a petrographic microscope.

PETROGRAPHY

QUANTITY OF INSOLUBLE RESIDUE

The quantity of insoluble residue in the limestones examined ranges from less than 1 percent to more than 42 percent (table 5). No systematic variation is apparent among the limestones, except that in the three samples of Bonya Limestone the quantity is small; it averaged 0.6 percent. In the Mariana Limestone the insoluble content ranges from 0.6 to 16.4 percent, in the Janum Formation from 0.8 to 18.1 percent; one sample of the Maemong Limestone Member of the Umatac Formation has 11.5 percent, but three others have less than one percent; two samples of the Maemong Limestone Member have 20.9 and 24.0 percent, but in these samples silica fillings of foraminiferal tests account for a large percentage of the insoluble residue.

TABLE 5.—*Weight percent of insoluble residues of Guam limestone*

[Analyst, Hildreth Schultz, U.S. Geological Survey]

Sample	Insoluble residue	
	Weight (grams)	Percent
Mariana Limestone:		
Sw 2-4	22.3	16.4
Pr 3-3	.8	.6
Ij 2-1	3.5	3.0
Alifan Limestone:		
Ru 8-3	9.9	8.5
Di 2-1	.5	.5
Di 2-2	9.8	7.8
Ts 9-1	2.0	1.3
Jl 3-2	.15	.1
Janum Formation:		
Ts 5-4	9.7	18.1
Ts 5-9	.9	.8
Rr 23-1	13.1	11.6
Rr 5-1	3.2	2.4
Bonya Limestone:		
Ut 6-1	.7	.5
Rr 13-1	.6	.5
Gi 2-1	.5	.4
Maemong Limestone Member of Umatac Formation:		
Gi 1-2a	11.1	11.5
Ef 1-1	.075	.1
Ed 1-1b	.9	.9
Ee 2-1	17.5	24.0
Df 9-1a	26.7	20.9
Il 5-2	.7	.8
Alutom Formation:		
Fk 4-11	1.8	1.3
Mahlac Member:		
Gj 11-1	36.6	42.1

The variation in insoluble-residue content must be explained by the variation in the amount of detrital material available in the area in which calcium carbonate was accumulating. Wentworth and Ladd (1931) and Bramlette (1926) have noted a similar variation in the rocks on Vitilevu and in the sediments being deposited in Pago Pago Harbor, Samoa.

The percent by weight of sand, silt, and clay grades in the insoluble residues of the limestones is given in table 6 and in figure 4. The mineral residues are concentrated in the silt (2 to 62 microns) and clay (less than 2 microns) grades; clay is more abundant than silt. Only a few samples contain much sand (greater than 62 microns).

TABLE 6.—*Sand, silt, and clay in insoluble residues of Guam limestone*

[Analyst, Hildreth Schultz, U.S. Geol. Survey. Results given in percent by weight; Tr., less than 0.01 gram]

Sample	Sand>62μ	Silt (2-62μ)	Clay (<2μ)
Mariana Limestone:			
Sw 2-4	2.1	50.0	48.0
Pr 3-3	Tr.	37.5	62.5
Ij 2-1	.3	12.0	87.7
Alifan Limestone:			
Ru 8-3	2.6	5.6	91.9
Di 2-1	8.0	26.0	66.0
Di 2-2	.2	7.6	92.1
Ts 9-1	.5	11.5	88.0
Jl 3-2	Tr.	26.7	73.3
Janum Formation:			
Ts 5-4	1.8	12.2	86.0
Ts 5-9	5.6	16.7	77.8
Rr 23-1	13.4	16.4	70.2
Rr 5-1	2.5	25.3	72.2
Bonya Limestone:			
Ut 6-1 [1]	10.0	35.5	54.5
Rr 13-1	1.7	5.0	93.3
Gi 2-1	Tr.	4.0	96.0
Maemong Limestone Member:			
Gi 1-2a	18.3	40.5	41.2
Ef 1-1	Tr.	Tr.	100
Ed 1-1b	2.2	21.1	76.7
Ee 2-1	3.8	55.1	41.1
Df 9-1a	14.9	67.4	17.7
Il 5-2	2.8	20.0	77.2
Alutom Formation:			
Fk 4-11	23.9	38.9	37.2
Mahlac Member:			
Gj 11-1	1.8	42.1	56.1

[1] Sand fraction of residue accidentally contaminated; percentages given for sample represent a careful estimate.

MINERALOGY

CLAY AND SILT GRADES

The minerals identified by X-ray examination are listed below; they are placed in two main groups: clay minerals and nonclay minerals. The clay minerals are montmorillonite, chlorite, mixed-layered montmorillonite-chlorite, mica, and minerals of the kaolinite group (kaolinite, fire clay, halloysite, and undifferentiated minerals). The nonclay minerals are divided into two groups, silicate minerals (quartz, cristobalite, plagioclase feldspar, and zeolites) and a nonsilicate group that contains gibbsite, nordstrandite, magnetite, hematite, goethite, lithiophorite (lithian manganese oxide) and pyrolusite, apatite, and a woodhouseite-like mineral (an alunite-type mineral in which calcium proxies for the potassium and phosphate proxies for some of the sulfate of alunite).

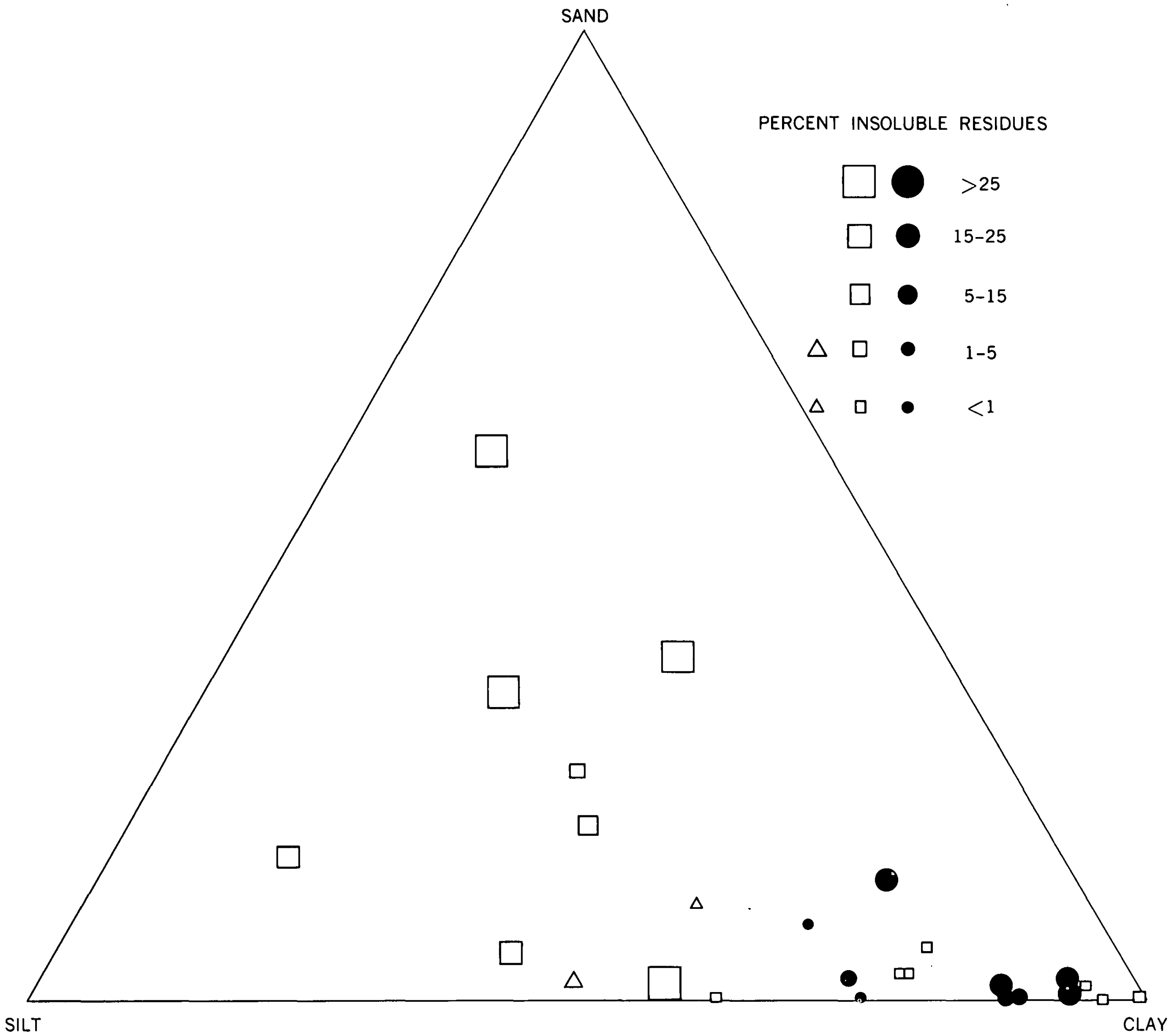

FIGURE 4.—Size distribution of the insoluble residues from selected limestones. The open squares represent samples containing a group 1, or fresh assemblage; the black circles represent samples containing a group 2, or weathered assemblage (table 10). The open triangles represent samples that fit neither category. The size of the symbol indicates the relative amount of insoluble residue according to the scale shown.

Estimates of the amounts of the various minerals in the samples are derived from the relative intensities of the diffracted lines. Inasmuch as many factors, such as variations in degree of preferred orientation, differences in degree of crystallinity, and variations in isomorphous substitution, in addition to quantity of a mineral, affect diffraction intensity, these estimates can give only a general indication of the relative amounts of the minerals present.

Of the minerals identified, two should receive special mention, nordstrandite and halloysite. Nordstrandite is a probable polymorph of gibbsite-bayerite. It has recently been reported from artificial preparations by Van Nordstrand, Hettinger, and Keith (1956), but had never been reported in a natural occurrence until 1962 (Hathaway and Schlanger, 1962, p. 265–266; Wall, and others, 1962, p. 264–265).

Identification of halloysite was based on the presence of broad, diffuse, and weak 001 reflections for a kaolinite-group mineral, and strong but broad hkl bands with no resolution of hkl reflections. A further criterion was the lack of distinct intensification of the 001 reflection in oriented aggregates of this mineral. Because electron micrographs were not made

Minerals identified in the different samples

Sample	*Fraction*	*Minerals identified*	*Parts in 10*
Mariana Limestone:			
Sw 2-4	Clay	Apatite	9
	Silt	do	10
Pr 3-3	Clay	do	8
		Montmorillonite	Tr.
		Quartz	Tr.
		Heulandite or clinoptilolite	Tr.
		Gibbsite	Tr.
	Silt	Apatite	8
		Heulandite or clinoptilolite	1
		Quartz	Tr.
		Feldspar	Tr.
Ij 2-1	Clay	Halloysite	6
		Goethite	3
	Silt	Goethite	5
		Halloysite	1
		Gibbsite	Tr.
Janum Formation:			
Ts 5-4	Clay	Montmorillonite	8
		Halloysite	Tr.
	Silt	Magnetite	6
		Nordstrandite	3
		Hematite	Tr.
Ts 5-9	Clay	Halloysite	9
		Montmorillonite	Tr.
	Silt	Magnetite	Tr.
		Hematite	Tr.
Rr 23-1	Clay	Halloysite	9
		Montmorillonite	Tr.
	Silt	Magnetite	8
		Halloysite	Tr.
Rr 5-1	Clay	Nordstrandite	4
		Goethite	2
		Woodhouseite-like mineral	3
	Silt	Nordstrandite	4
		Woodhouseite-like mineral	4
		Goethite	1
		Magnetite	Tr.
Alifan Limestone:			
Ru 8-3	Clay	Fireclay mineral	8
		Goethite	2
	Silt	Nordstrandite	4
		Goethite	4
Di 2-1	Clay	Montmorillonite	4
		Halloysite	4
		Nordstrandite	1
	Silt	Nordstrandite	8
		Goethite	2
Di 2-2	Clay	Montmorillonite	9
		Halloysite	Tr.
	Silt	Goethite	8
		Montmorillonite	1
Ts 9-1	Clay	Halloysite	5
		Montmorillonite-chlorite mixed-layer.	4
	Silt	Nordstrandite	4
		Woodhouseite-like mineral	3
		Goethite	1
		Quartz	Tr.
Jl 3-2	Clay	Halloysite	4
		Goethite	4
	Silt	Nordstrandite	Tr.
		Woodhouseite-like mineral	Tr.
Bonya Limestone:			
Ut 6-1	Clay	Lithiophorite	9
		Halloysite	Tr.
	Silt	Lithiophorite	Tr.
Rr 13-1	Clay	Montmorillonite	9
		Heulandite or clinoptilolite	Tr.
	Silt	Heulandite or clinoptilolite	5
		Quartz	Tr.
		Magnetite	Tr.
Gi 2-1	Clay	Montmorillonite	8
	Silt	Chabazite	7
		Quartz	1
		Feldspar	Tr.
Maemong Limestone Member:			
Gi 1-2a	Clay	Montmorillonite	9
		Halloysite	Tr.
	Silt	Montmorillonite	9
		Halloysite	Tr.
Ef 1-1	Clay	Mica	2
		Montmorillonite	1
		Kaolinite	Tr.
		Quartz	Tr.
		Feldspar	Tr.
Ed 1-1b	Clay	Montmorillonite	9
		Mica	Tr.
	Silt	Plagioclase	7
		Montmorillonite	1
		Kaolinite	Tr.
Ee 2-1	Clay	Montmorillonite	9
		Heulandite or clinoptilolite	Tr.
	Silt	Heulandite or clinoptilolite	9
		Montmorillonite	1
Df 9-1a	Clay	Beta cristobalite	8
		Montmorillonite	1
	Silt	Beta cristobalite	9
		Quartz	Tr.
		Feldspar	Tr.
Ii 5-2	Clay	Montmorillonite	Tr.
	Silt	Not determined.	

Minerals identified in the different samples—Continued

Sample	*Fraction*	*Minerals identified*	*Parts in 10*
Alutom Formation:			
Fk 4-11	Clay	Montmorillonite	8
		Analcime	1
	Silt	Analcime	9
		Feldspar	Tr.
Mahlac Member:			
Gj 11-1	Clay	Montmorillonite	9
	Silt	Heulandite or clinoptilolite	5
		Montmorillonite	4
		Quartz	Tr.

for these samples, there is no assurance that a tubular shape is present. However, inasmuch as the use of the terms kaolinite or fire clay would imply that a material of a higher degree of crystallinity was present, the term "halloysite" is preferred to describe this mineral.

SAND GRADES

The minerals identified in the total sand of the insoluble residues are given in tables 7 and 8. The quantities of heavy minerals in these residues vary; some contain very few heavy fractions, whereas others, notably limestones of the Maemong Member and the Janum Formation, have abundant heavy fractions; in some heavy fractions one mineral was present to the almost complete exclusion of others. The distribution of the various minerals is discussed at the end of this section.

The heavy minerals found are magnetite, ilmenite(?), augite, hypersthene, greenish-brown amphibole, basaltic hornblende, bluish-green amphibole, sphene, and zircon; sphene and zircon are very scarce. The minerals in the light fractions are plagioclase feldspar, quartz, clay aggregates, opaline silica (beta-cristobalite), zeolites, and apatite; apatite should, however, belong in the heavy fraction.

These minerals are common to the volcanic rocks of Guam as described by Stark (1963). The major well-crystallized constituents of these rocks are plagioclase feldspar and monoclinic pyroxene; the subordinate minerals are orthorhombic pyroxene, magnetite, occasional amphibole, and quartz. Zeolites are also present in some of the volcanics, but apatite and cristobalite have formed in the limestones. There are apparently only minor variations in the distribution of the volcanic minerals in the rocks and water-laid tuffs.

In addition to the small samples, the insoluble residues and minerals were examined in five large samples of limestone from the Janum Formation, Maemong Limestone Member, Alutom Formation, and Mahlac Member, respectively. These samples yielded more information about the amounts of detrital minerals in the limestones. Table 8 gives the quantities of limestone dissolved in acid to obtain the residues and size distribution of the residues.

TABLE 7.—*Minerals in the sand fractions (greater than 62 microns) of insoluble residues of Guam limestone*

[Tr., quantity too small to weigh; Tr.*, sand fraction too small for bromoform separation, but heavy minerals are present in the sand. Minerals are given in order of abundance]

Sample	Heavy residue (percent)	Heavy minerals >2.9 [sp gr]	Light minerals <2.9 [sp gr]
Mariana Limestone:			
Sw 2–4	Tr.	Magnetite, augite, hypersthene.	Clay mineral.
Pr 3–3	Tr.*	Magnetite, augite	Plagioclase feldspar, zeolite, quartz, apatite.
Agana Argillaceous Member:			
Ij 2–1	Tr.*	Magnetite	Apatite, plagioclase feldspar.
Janum Formation:			
Ts 5–4	44.1	Magnetite, augite	Altered grains, plagioclase feldspar.
Ts 5–9	Tr.*	Magnetite, apatite	Plagioclase feldspar.
Rr 23–1	94.3	Magnetite, augite, hypersthene.	Clay mineral, plagioclase feldspar, quartz (euhedra).
Rr 5–1	Tr.*	Magnetite, augite	Plagioclase feldspar, opaline silica, undetermined grains.
Ts 5–11	2.6	Amphibole, augite, magnetite.	Clay mineral, plagioclase feldspar.
Ts 5–12	6.7	Augite, amphibole, magnetite.	Plagioclase feldspar, altered grains, clay mineral.
Alifan Limestone:			
Ru 8–3	11.5	Magnetite	Altered grains[1] plagioclase feldspar.
Di 2–1	Tr.*	do	Apatite, quartz, plagioclase feldspar.
Di 2–2	Tr.*	Magnetite, zircon	Apatite, quartz, plagioclase feldspar.
Ts 9–1	Tr.*	Magnetite	Quartz, plagioclase feldspar, clay mineral.
Jl 3–2	Tr.*	do	Quartz, altered grains.
Bonya Limestone:			
Rr 13–1	Tr.*	Magnetite, augite	Opaline silica, quartz, plagioclase feldspar.
Gi 2–1	Tr.*	Magnetite	Opaline silica, quartz, zeolites, altered grains.
Maemong Limestone Member:			
Gl 1–2	3.9	Augite, magnetite	Clay mineral, opaline silica, plagioclase feldspar.
Ef 1–1	Tr.*	Magnetite	Opaline silica, quartz.
Ed 1–1b	Tr.*	Magnetite, augite	Plagioclase feldspar, opaline silica.
Eo 2–1	Tr.	do	Opaline silica.
Df 9–1a	Tr.	Augite, magnetite	Opaline silica.
Ed 7–2	24.4	Augite, hypersthene, amphibole, magnetite.	Altered grains, plagioclase feldspar, opaline silica, zeolites.
Ii 5–2	Tr.	Magnetite	------
Alutom Formation:			
Fk 4–1	Tr.	Magnetite, augite, hypersthene, sphene (?).	Opaline silica, clay mineral.
Ek 7	1.8	Amphibole, basaltic hornblende, magnetite sphene.	Plagioclase feldspar altered grains, opaline silica, quartz, zeolites.
Mahlac Member:			
Gj 11–1	4.4	Magnetite, hypersthene amphibole, zircon.	Plagioclase feldspar, opaline silica, clay mineral.
Gj 15–1	.2	Amphibole, augite magnetite.	Clay mineral, plagioclase feldspar, opaline silica.

[1] Altered feldspar plus clay minerals.

The +140 (0.25–0.105 mm) and the +270 (0.105–0.053 mm) grades of the insoluble residues were separated in bromoform to obtain the heavy minerals, the amounts of which are given in table 9. The minerals were identified by a petrographic microscope.

The heavy minerals identified in these residues are listed in order of abundance; all the samples contain an appreciable amount of magnetite.

Janum Formation (Ts 5–11).	Amphibole, brownish-green; augite.
Janum Formation (Ts 5–12).	Augite; amphibole, brownish-green.
Maemong Limestone Member (Ed 7–2).	Pyroxene; hypersthene; amphibole, brownish-green.
Mahlac Member (Gj 15–1).	Amphibole, brownish-green; basaltic hornblende; sphene.
Alutom Formation (Ek 7).	Amphibole, brownish-green; augite.

TABLE 8.—*Insoluble residues and size distribution in five large samples of Guam limestone*

Formation or member	Sample		Insoluble residue					
	No.	Weight (grams)	Weight		Grade size, in percent			
			Grams	Percent of sample	+60 mesh (0.25 mm)	+140 mesh (0.105 mm)	+270 mesh (0.053 mm)	−270 mesh
Janum Formation	Ts 5–11	801	31	3.9	2.9	25.9	16.3	54.8
Janum Formation	Ts 5–12	378	113	30.0	Tr.	18.0	25.4	56.6
Maemong Limestone Member.	Ed 7–2	257	27	10.5	1.1	34.5	25.3	37.5
Mahlac Member	Gj 15–1	626	131	21.0	2.1	11.2	16.4	70.1
Alutom Formation	Ek 7	464	36	7.7	.6	34.0	21.5	43.8

TABLE 9.—*Amount of heavy residue (sp gr greater than 2.9) in five large samples of Guam limestone*

Formation or member	Sample	Heavy residue			
		Weight (grams)		Percent of insoluble residue	Percent of whole sample
		+140	+270		
Janum Formation	Ts 5–11	0.56	0.25	2.60	0.10
Janum Formation	Ts 5–12	3.40	4.20	6.73	2.0
Maemong Limestone Member	Ed 7–2	5.76	2.80	24.40	2.55
Mahlac Member	Gj 15–1	.04	.21	.19	.04
Alutom Formation	Ek 7	.61	.15	1.84	.14

MINERALS PRESENT

Magnetite and pyroxene, present in varying amounts, are the most abundant minerals in the heavy fractions:

Magnetite.—Magnetite is quite abundant in most of the insoluble residues; it occurs in euhedral octahedra and in irregular grains, and there is no appreciable alteration to iron oxides. The sharpness of the small crystals is shown in plate 21*E*.

Ilmenite.—Black opaque grains not as strongly magnetic as magnetite are considered to be ilmenite. Ilmenite is not as abundant in these residues as magnetite.

Pyroxene.—Augite in stout prismatic grains is the principal pyroxene occurring in these heavy residues. Many grains are etched at the ends of the *c* crystallographic axis into low pyramidal forms. The grains are fresh and pale green to colorless, and exhibit the usual optical properties of augite, $Z \wedge c$ generally being 38° to 40°. Many grains contain small black inclusions that may be magnetite. Augite from the insoluble residue of the Janum Formation is shown on plate 21*A*. The small euhedral crystals in some residues occur and these may be zoned.

Hypersthene.—Hypersthene is a minor constituent in many of the residues. It is variable in appearance, from somewhat corroded grains having etching along the prismatic cleavage to massive fresh prismatic grains, some of which are individual crystals having well-developed pinacoid and prism faces. Inclusions are common. The hypersthene is strongly to weakly pleochroic in green and pink.

Amphibole.—Greenish-brown amphibole is abundant in the heavy residues of a number of the limestones, and is the principal mineral in the residue from the Mahlac Member of the Alutom Formation. This greenish-brown amphibole has the following optical properties: index of refraction γ=1.67–1.68; α and β just below 1.67, hence low birefringence. $Z \wedge c = 14°$. The pleochroism is Z=greenish-brown; X and Y= brownish-green. The grains are sharply angular cleavage fragments. Small inclusions of opaque grains (probably magnetite) and colorless grains, which may be sphene, are common. This amphibole is illustrated in plate 21*C*.

Dark-brown basaltic hornblende is associated with the greenish-brown amphibole in small quantities; it probably amounts to less than 5 percent of the total amphibole present. This hornblende has indices of refraction γ=just above 1.69, and α and β between 1.67 and 1.68. The extinction $Z \wedge c$ varies from 0° to a maximum of 9°. The pleochrism is strong with Z= deep brown; X and Y=yellow-brown. The birefringence is moderate.

A small quantity of a bluish-green amphibole having low birefringence also occurs in some of the residues. When fresh, it is strongly pleochroic with Z=greenish blue, X and Y=pale brown. The extinction, $Z \wedge c$ is 24°. Some of this amphibole is chloritized and it then has a very low birefringence. Many chloritized grains fail to extinguish completely.

Sphene.—Sphene is present in pale-brown slightly pleochroic angular grains having typical pleochroism.

Zircon.—A few grains of euhedral zircon occur in residues from the Mahlac Member, for example, Gj 11–1.

In the light fractions (sp gr $<$ 2.9), feldspar and clay aggregate grains are the principal minerals; quartz is present in some residues, as is opaline silica and zeolites:

Feldspar.—The feldspar is plagioclase in lathlike grains of small size. Twinning and zoning commonly occur, but many grains show neither, and they appear much like quartz except for their good cleavage and higher indices of refraction. The feldspar is about labradorite in composition. The zoned crystals were apparently phenocrysts in the lavas or unconsolidated tuffs. In general the feldspar is fresh and shows no alteration to sericite or to clay minerals, although some of the clay minerals have the appearance of altered feldspar.

Clay aggregates.—The clay grains are of indefinite aggregate appearance under the microscope; their birefringence is low, and most aggregates are isotropic. Associated with the clay are iron oxides, which produce a general light grayish brown color. Additional information about these minerals is given on p. 38.

Quartz.—Quartz grains occur in some of the residues as angular fragments showing no rounding by abrasion and as euhedral crystals. The latter are squat crystals made up of trigonal trapezohedrons or rhombohedrons without prism faces, generally described as double pyramids. A characteristic feature of these quartz grains is the presence of gaseous inclusions in the form of numerous bubbles. Quartz of similar type was described from volcanic ash in Java by Loos (1924, p. 92, pl. 9).

Opaline silica.—A small quantity of opaline silica was noted in a number of the residues, but it becomes an important constituent only in samples from the Maemong Limestone Member and from the Alutom Formation. In the limestone, this silica, which was identified in the silt and clay fractions as beta-cristobalite, forms internal casts of Foraminifera (pl. 21*E*). In some other samples, opaline silica is present as irregular fragments that have the appearance of having been part of the matrix of a rock or perhaps derived from volcanic glass.

Zeolites.—Several zeolites were identified in the clay and silt fractions, and larger grains occur in some of the sand fractions of these residues. Some grains are small cubes having penetration twins. The index of refraction is just above 1.48, and the crystals exhibit weak uniaxial interference figures. Such crystals were identified as chabazite. Other zeolites are isotropic. A radiating fibrous zeolite, whose index refraction is just below 1.53, is heulandite or clinoptilolite, but there was insufficient material for complete optical identification.

Apatite.—Brownish grains showing the structure of organic materials such as shell fragments, spicules, and Foraminifera occur in several of the residues.

These grains are isotropic or feebly birefringent and are similar in appearance to the apatite in some phosphate deposits.

GENERAL RELATIONSHIPS OF THE MINERALS

Montmorillonite is the most widespread of the clay minerals; it occurs in about 70 percent of the samples. Halloysite is the next most common mineral, occurring in 35 percent of the samples. Kaolinite, mixed-layered chlorite-montmorillonite, chlorite, and mica are the last abundant clay minerals.

Of the nonclay minerals, no single group predominates. The zeolites, feldspars, goethite, and gibbsite-nordstrandite each occur in 30–35 percent of the samples. Quartz is extremely scarce, and in no sample does it occur as the predominant mineral. The greater part of the samples can be divided, however, on the basis of the major nonclay minerals into two categories that are, for the most part, mutually exclusive. These are: (1) the feldspar-zeolite group, and (2) the iron oxide-nordstrandite group. Nineteen of the 26 samples examined fall into one or the other of these groups. The remaining seven samples are either principally amorphous, or contain only clay minerals, or exhibit some unusual mineral composition. All nine samples in the feldspar-zeolite group contain montmorillonite as their major clay mineral constituent. Only one contains more than a trace of kaolinite group minerals. Of the ten samples in the iron oxide-norstrandite group, seven contain halloysite or other kaolinite-group minerals as their major clay mineral constituent. Of the remaining three samples in this group, one contains montmorillonite as its major clay mineral, the second contains mixed-layered montmorillonite-chlorite, and the third contains no clay minerals.

It seems justifiable, on the basis of the predominance of one type of clay or the other in these two groups, to expand their designations to include the most typical clay mineral. Group 1 would then be designated the feldspar-zeolite-montmorillonite group and group 2 the iron oxide-nordstrandite-halloysite group. As the nonclay assemblages have been shown most likely to be mutually exclusive, these are given precedence in placing a sample in given category. Where nonclay minerals are absent, the sample is classified on the basis of the predominant clay mineral.

If the samples are thus classified and compared with their stratigraphic position, it can be seen that most of samples from a stratigraphic unit fall into a common category. Such a comparison is shown in table 10.

TABLE 10.—*Comparison of the stratigraphic position and mineralogic classification of samples of Guam limestone*

[The following samples are omitted from this table because of unusual mineral composition as indicated: Sw 2-4, Mariana Limestone (apatite); Ut 6-1, Bonya Limestone (lithiophorite). X, present in sample]

Sample	Group 1 Feldspar-zeolite-montmorillonite	Group 2 Iron oxide-nordstandite-halloysite
Mariana Limestone:[1]		
Pr 3-3	X	
Agana Argillaceous Member:		
Ij 2-1		X
Janum Formation:		
Ts 5-4		X
Ts 5-9		X
Rr 23-1		X
Rr 5-1		X
Alifan Limestone:		
Ru 8-3		X
Di 2-1		X
Di 2-2		X
Ts 9-1		X
Jl 3-2		X
Bonya Limestone:		
Rr 13-1	X	
Gi 2-1	X	
Umatac Formation: Maemong Limestone Member:		
Gi 1-2a	X	
Ef 1-1	X?	
Ed 1-1b	X	
Ee 2-1	X	
Ef 9-1a	X	
Ii 5-2	X	
Alutom Formation:		
Fk 4-11	X	
Mahlac Member:		
Gj 11-1	X	

[1] Additional samples of Mariana Limestone were later examined and feldspar was identified.

Mineralogic examination of residual soils formed on the volcanic rocks of Guam was made as a separate study (Carroll and Hathaway, 1963). However, it should be mentioned that the data evolving from this study show a predominance of halloysite, gibbsite, and iron oxide, particularly goethite, in the weathered products of the volcanic materials. Hutton and Stephens (1956) have reported the occurrence of a similar clay-mineral assemblage in the soils of Norfolk Island that are formed on volcanic tuffs and basalts similar to those of Guam. The occurrence of this same type of assemblage, with the exception of gibbsite, in many of the insoluble residues of the limestones suggests that the noncarbonate fractions of the limestones shown in table 10 as containing a group 2 assemblage are derived from the erosion of soil formed by the subaerial weathering of the volcanic rocks. On the other hand, the relative instability of feldspars and zeolites to weathering and the occurrence of zeolites as alteration products of volcanic ash (Bradley, 1930; Ross, 1941; Coombs, 1952, 1954; Harris and Brindley, 1954) suggest that the noncarbonate fractions of the limestones containing a group 1 assemblage have their origin in ash falls accompanying volcanic activity. The occurrence of montmorillonite, a characteristic of the group 1 residues, supports a volcanic origin for this assemblage, as montmorillonite commonly occurs as the dominant mineral in bentonite, which are products of the devitrification of volcanic ash (Ross and Hendricks, 1945, p. 64–65; Grim, 1953, p. 361–364).

The distinction, then, between a limestone containing a feldspar-zeolite-montmorillonite assemblage and one containing an iron oxide-nordstrandite-halloysite assemblage may well serve to distinguish periods of volcanic activity from those of quiescence and subaerial weathering in the source area of the noncarbonate fraction.

Table 10 may be interpreted on the above-mentioned basis as indicating volcanic activity extending through deposition of the Bonya Limestone. After deposition of the Bonya Limestone, a period of subaerial weathering of the volcanic rocks is suggested by the occurrence of group 2 assemblages. A recurrence of volcanic activity, probably at some distance from Guam, during the time of deposition of the Mariana Limestone is suggested by the presence of group 1 assemblages.

ORIGIN OF NORDSTRANDITE AND WOODHOUSEITE-LIKE MINERAL

Nordstrandite was identified in five and possibly in six of the samples that contain group 2 mineral assemblages. Woodhouseite(?) was identified in two of the samples containing nordstrandite, and was tentatively identified also in the sample that contains nordstrandite(?).

These minerals occur in an assemblage that contains weathering products, such as halloysite and iron oxides, derived from the alteration of primary minerals. Nordstrandite has been found in soil in Borneo (Wall, *et al*, 1962, p. 264–265) but was not found in the soils on Guam. Woodhouseite(?) has not been identified in soils, but the related mineral alunite occurs in saline lake muds in Western Australia, where it has probably formed by oxidation of sulfides in the lake sediments (Simpson, 1948, p. 45). If woodhouseite(?), like alunite, is stable in an acid environment (pH about 4 or less), then it might be expected to survive weathering under acid conditions. It could, therefore, be deposited as a detrital mineral accompanying goethite and hematite. A woodhouseitelike mineral has been identified by the authors in a gray marine clay from a drill core in Bermuda. In that situation the mineral is probably authigenic.

Nordstrandite occurs as groups of radiating bladed crystals filling cavities in limestones. It is well shown in thin sections (pl. 4*C*, *D*; see also description of Alifan Limestone). The nordstrandite crystals formed authigenically in fractures in the limestone. Thin sections show that nordstrandite crystallized after lithification and fracturing of the limestone.

A possible origin for the development of nordstrandite in the limestones is as follows: Water draining from the volcanic rocks on Guam may pass through the limestones or along the interface of the volcanic rocks and limestones. While in the volcanic soil zone, this groundwater may have a pH as low as 4. The water can attack the calcium carbonate of the limestones and it can carry silica (SiO_2) in solution, but not alumina (Al_2O_3), which is insoluble between pH 4 and pH 9. Removal of SiO_2 from clay minerals occurs if they are leached in a limestone environment (Carroll and Starkey, 1959, p. 83–87), but Al_2O_3 remains. The pH of water within a limestone, however, rises to between 8 and 9, and alumina then becomes insoluble in it. Slight lowering of the pH would cause the alumina to become insoluble again, and it could crystallize as nordstrandite or gibbsite. It is probable that the detrital halloysite found in many of the limestones is the source of the alumina that recrystallized to nordstrandite.

Clay minerals in suspension in water moving through or over the volcanic rocks and deposited in the limestones may also be desilicated and contribute the alumina to the limestones. It is significant that two of the samples from Guam that contain appreciable quantities of nordstrandite (Di 2–1 and Ts 9–1) lie immediately superjacent to volcanic material.

The occurrence of nordstrandite in limestones that are appreciable distances stratigraphically or geographically from contacts with volcanic rocks suggests that gibbsite may recrystallize to nordstrandite. The association of nordstrandite with minerals of probable detrital origin and its absence in limestones containing a group 1 (volcanic) assemblage of minerals suggest that detrital gibbsite may be an important, if not the only, source of nordstrandite in these limestones.

MINERALOGICAL RELATIONSHIPS IN THE SAND GRADES

The distribution of the principal minerals of the sand grades listed in table 7 and table 9 are arranged in figure 5, which indicates variations found in the limestones at various stratigraphic positions. The variations in occurrence and in quantity suggest that detrital material became available at different geological times, but the picture is complicated by the fact that detritus has been available from two sources: directly as contributions from volcanic ash, and in-
by stream action from the island to the surrounding
directly as a weathering product that was transported

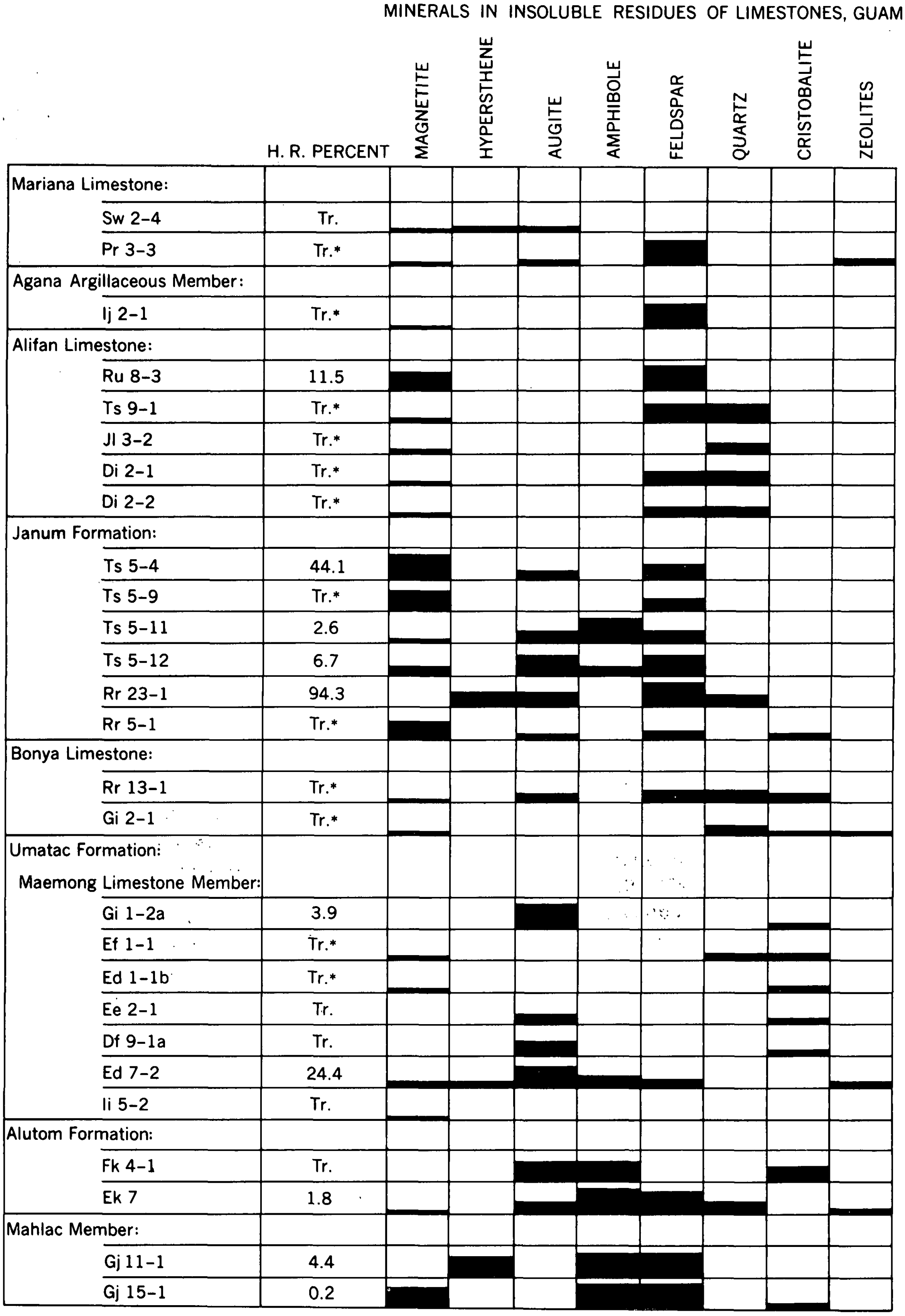

FIGURE 5.—Distribution of minerals in the sand-grade fraction (greater than 62 microns) in insoluble residues of selected limestones. Tr., a quantity too small to weigh; Tr.*, a sand fraction too small for bromoform separation, heavy minerals present in the sand; H.R. percent, weight percent of heavy minerals in insoluble residues. Quantitative estimates are from data given in table 8.

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marine environment in which carbonates were accumulating. This process was in part described by Wentworth and Ladd (1931, p. 35) as characteristic of Pacific Ocean islands that consisted of volcanic and nonvolcanic material.

The evidence from the silt- and clay-size minerals together with the character of the insoluble residue as shown in figure 4 can also be applied to the sand-grade minerals. Those samples that contain much sand-grain material are the result of the direct deposition of volcanic ash in the marine lime-depositing environment, whereas most of those containing much silt and clay result from the addition of weathered material removed from soil surfaces by erosion and transportation to bays and inlets by rivers. Examination of soil profiles on Guam (Carroll and Hathaway, 1963) has indicated that sand grades are scarce in soils, as are unweathered grains of minerals, with the exception of magnetite. Thus, those samples in which the heavy residue is very small (marked with as asterisk in fig. 5) are impoverished in ferromagnesian minerals that are directly derived from volcanic ash.

The quantities of heavy minerals present in the insoluble residues vary in the limestones examined. Those containing large quantities of heavy minerals are limestones of the Maemong Member and the Janum Formation (tables 7 and 9). The distribution of the individual heavy minerals is given in table 7 and below table 9. Augite and magnetite are commonly present in all the residues, but some residues consist almost exclusively of augite or of amphibole. Hypersthene is present in small quantities in a number of the residues. Amphiboles appear to be restricted in distribution and are absent from the samples of Mariana Limestone examined. Brownish-green amphibole is much more abundant than brown basaltic hornblende, which was found only in the residues of the Mahlac Member. It would seem that Eocene and Miocene limestones had a source of amphibole available to them, but that the Pliocene and Pleistocene limestones did not.

Greenish-brown amphibole accompanied by a little basaltic hornblende is the principal ferromagnesian mineral in volcanic ash of the Mahlac Member and the Alutom Formation, although some augite and hypersthene are also present. In the Maemong Limestone Member, amphibole is subordinate to augite and only a little hypersthene occurs. Sample Ed 7–2 contains a large heavy residue. One sample from the Maemong Member contains a concentrate of augite. The Bonya Limestone apparently received volcanic ash and limestones of the overlying Janum Formation may have had additions of ash for most of the samples contain augite and two contain amphibole, although these minerals may be detrital. No amphibole was found in beds younger than the Janum. Only one sample of the Janum contains hypersthene. The Alifan Limestone and the Agana Argillaceous Member of the Mariana Limestone contain practically no heavy minerals. Some limestones of the Mariana contain augite, and one sample, Ru 8–3 from the Alifan Limestone, has very abundant magnetite; both samples indicate a possible occurrence of volcanic ash additions, although both augite and magnetite persist as stable minerals in some of the soils and therefore could be detrital. The abundant hornblende and augite in samples of Eocene and Miocene age pose a problem in that these minerals are rare to lacking in the underlying volcanic rocks (Stark, 1963).

TABLE 11.—*Samples studied*

Sample	Slides studied	Location	Description
Alutom Formation			
Ii 8–1	1	One-half mi southwest of Talofofo Village.	Fragment from Bolanos Pyroclastic Member of Umatac Formation.
Fk 4–1	3	Naval Ammunition Depot; roadcut at main gate.	Fragments from limestone-bearing breccia of Alutom Formation.
2	3	do	Do.
3	2	do	Do.
4	1	do	Do.
5	2	do	Do.
6	2	do	Do.
7	2	do	Do.
8	1	do	Do.
9	3	do	Do.
10	2	do	Do.
11	3	do	Do.
Hj 1–1	3	Just south of Witek Road, northeast of Naval Ammunition Depot, Loop Road.	Fragments from limestone-bearing breccia of Alutom Formation.
2	1	do	Do.
3	3	do	Do.
4	1	do	Do.
5	1	do	Do.
6	1	do	Do.
7	4	do	Do.
8	2	do	Do.
9	3	do	Do.
10	1	do	Do.
11	1	do	Do.
Ek 7–1	3	100 yards east of bridge on north bank of Ayuga River, Santa Rita.	Bedded limestone of Alutom Formation.
2	2	do	Do.
3	2	do	Do.
4	2	do	Do.
Maemong Limestone Member of the Umatac Formation			
Fd 3–1	3	Geus River, 330 feet above sea level.	Gray-brown globigerinid mudstone.
Fd 4–1	1	Downstream 250 ft from Fd 3–1.	Foraminiferal-algal breccia.
Fd 5–1	3	Downstream 50 ft from Fd 4–1.	Gray-brown globigerinid mudstone.
Ed 6–1	2	Uppermost limestone bed at Geus Dam.	Coral breccia.
Ed 7–1	2	Upstream 200 ft from Geus Dam.	Limestone cobble from bed of coarse breccia.
2	2	Upstream 100 ft from Geus Dam.	Tuffaceous foraminiferal-algal microcoquinite.
Ed 5–1	2	Downstream 50 ft from Geus Dam.	Limestone from lapilli conglomerate.
Ed 4–1	4	Downstream 300 ft from Geus Dam.	Tuffaceous coral breccia.
Ed 3–1	2	Downstream 400 ft from Geus Dam.	Limestone from bed of pyroclastic conglomerate.
1t	1	do	Tuffaceous, foraminiferal-algal breccia.

TABLE 11.—*Samples studied*—Continued

Sample	Slides studied	Location	Description
Maemong Limestone Member of the Umatac Formation—Continued			
Df 9-1a	4	2,000 ft northeast of Umatac.	White globigerinid mudstone.
Ee 6-1	3	South fork Umatac River, 150 ft altitude.	Gray globigerinid mudstone.
Ee 7-1	2	South fork Umatac River, 200 ft altitude.	Foraminiferal-algal microcoquinite.
Ee 8-1	1	South fork Umatac River, 250 ft altitude.	Foraminiferal-algal coquinite.
Ef 2-1	1	North fork Umatac River, 350 ft altitude.	Foraminiferal-algal breccia.
2	2	do	Gray globigerinid mudstone.
Dh 11-1	1	10,000 ft east of Facpi Point, above Lamlam Road.	Banded globigerinid mudstone.
2	3	do	Foraminiferal microbreccia.
3	3	do	Do.
Erosional remnants of Maemong Limestone Member in the Fena basin area			
Hi 3-1	2	West side of large outlier north of Talofofo River, south of Witek Road.	White crystalline coral-algal incrustate limestone and *Halimeda* and foraminiferal-algal paracoquinites.
2	2	do	Do.
3	2	do	Do.
4	3	do	Do.
5	1	do	Do.
6	1	do	Do.
8	1	do	Do.
Hi 4-1	2	North side of large outlier north of Talofofo River, south of Witek Road.	White crystalline foraminiferal-algal paracoquinites.
2	1	do	Do.
3	1	do	Do.
4	1	do	Do.
5	1	do	Do.
Hi 5-1	3	Top of hill, 1.5 mi due east of Fena Dam, north of Maagas River.	Pink to white, dense, foraminiferal-algal paracoquinites.
2	2	do	Do.
3	1	do	Do.
5	3	do	Do.
Hi 7-1	3	Base of Maemong limestone, south side of Mahlac River.	White to red, globigerinid mudstone.
2	3	do	Do.
3	3	do	Do.
Boulders from the Bolanos Pyroclastic Member of the Umatac Formation			
Gi 1-1	1	Cut in bank opposite Fena Screen House.	White, foraminiferal paracoquinites and micro paracoquinites.
Ii 6-4	1	Talofofo Village Road near CAA transmitter.	Do.
18	1	do	Do.
32	1	do	Do.
Bonya Limestone			
Fi 5-1	1	Bunker 1-AT-13, Naval Ammunition Depot.	Buff-white bedded foraminiferal-algal coquinite.
2	1	do	Do.
Gi 2-1	1	Quarry, 600 ft north of Lost River Pumping Station.	Pink, tan, and white bedded flat-lying foraminiferal coquinite.
3	1	do	Do.
Gi 4-1	2	From Gi 2 locality, 50-60 ft above Bolanos Pyroclastic Member.	Foraminiferal coquinite carrying cobbles and boulders of Maemong Limestone Member.
2	2	do	Do.
3	1	do	Do.
Gj 1-1	1	Bottom of stream bed east of Bunker 2-AT, Naval Ammunition Depot.	Buff foraminiferal coquinite.
2	1	do	Do.
Gj 6-1	1	Basal part of Bonya Limestone at Bunker 2-AT, Naval Ammunition Depot.	Gray-white dense breccia carrying mollusks, algae, and coral.
2	1	do	Do.
3	1	do	Do.

TABLE 11.—*Samples studied*—Continued

Sample	Slides studied	Location	Description
Bonya Limestone—Continued			
Ih 5-1	1	South bank of Talofofo River, .1 mi above its confluence with Ugum River.	White, buff, brown, and black manganiferous coquinite and breccia.
3	1	do	Do.
5	1	do	Do.
8	1	do	Do.
Ih 10-1	3	North bank of Talofofo River, across valley from Ih 5 locality.	Buff bedded foraminiferal microcoquinite, dipping 15° E.
2	3	do	Do.
Ih 14-1	2	North bank of Talofofo River, one-fourth mi northwest of Ih 10 locality.	Foraminiferal-algal coquinite.
Jj 1-1	1	One mi west of mouth of Togcha River, in channel.	Foraminiferal-algal microparacoquinite.
Jj 5-2	1	60 ft above river channel. 1.2 mi west of mouth of Togcha River.	Gray to buff argillaceous foraminiferal paracoquinite.
Jj 5-3	1	do	Do.
Jj 9-1	2	Mouth of Togcha River gorge, one-half mi north of Talofofo Village.	Thick-bedded argillaceous foraminiferal microparacoquinite.
2	1	do	Do.
Rr 13-1	2	In small coastal reentrant 2,200 ft southwest of farmhouse at Lujuna Point.	Dense white bedded foraminiferal mudstone.
Ts 2-1	2	Sink hole on terrace, 600 ft north of beach at Jaum Point.	Do.
Ut 6-1	2	Cobble (xenoclast) in Janum Formation, 2,500 ft southwest of Anao Point.	Black manganiferous foraminiferal limestone.
Rr 19-1	2	Lujuna Point, 50 ft above sea level.	Dense white foraminiferal mudstone.
Rr 20-1	2	Lujuna Point, 110 ft above sea level.	Dense white bedded foraminiferal mudstone.
Alifan Limestone			
Eh 3-1	1	Base of Mount Almagosa, 1,000 ft northeast of road fork leading to Chepeck and Dobo Springs.	Dense red detrital fossiliferous mudstone.
2	1	do	Do.
3	2	do	Do.
4	1	do	Do.
5	3	do	Do.
6	2	do	Do.
7	2	do	Do.
8	2	do	Do.
Di 2-1	2	Base of limestone, 6,000 ft south of Mount Alifan.	Pink slabby fossiliferous coquinoid limestone.
2	2	do	Do.
Ej 3-1	4	Low on west slope of Mount Alifan between its peak and village of Agat.	Dense red coral-molluscan coquinoid limestone.
2	3	do	Do.
3	2	do	Do.
4	3	do	Do.
Ej 4-1	2	Basal bed in the Naval Ammunition Depot quarry.	Dense red mudstone.
Dh 12-1	2	Highest point on Mount Lamlam.	Dense red-mottled fossiliferous coquinoid limestone.
Dh 13-1	2	do	Do.
Gj 8-1	2	Bunker 2-AT, Naval Ammunition Depot.	Buff-white argillaceous microparacoquinite.
Jl 2-2	6	1.5 mi west of Yona	White foraminiferal microparacoquinite.
Jl 3-2	2	One mi west of Yona at limestone-volcanic contact.	Do.
Ts 16-1	5	2,500 ft east southeast of Mount Santa Rosa.	Pink, white, and buff, miniferal microparacoquinites and breccias.
2	2	do	Do.
3	1	do	Do.
4	2	do	Do.
5	2	do	Do.
6	2	do	Do.
7	2	do	Do.
8	5	do	Do.
9	3	do	Do.
10	1	do	Do.
11	2	do	Do.
12	3	do	Do.
13	3	do	Do.

TABLE 11.—*Samples studied*—Continued

Sample	Slides studied	Location	Description
Alifan Limestone—Continued			
Tt 7-1	1	2,500 ft northeast of Mount Santa Rosa.	Pink-orange argillaceous limestone, incrustate in part, dolomitic in part (7-4).
2	1	do	Do.
3	2	do	Do.
4	3	do	Do.
Ru 8-3	3	4,200 ft west of Salisbury Junction.	Pale orange-pink argillaceous mudstone.
Ts 9-1	1	2,450 ft east southeast of Mount Santa Rosa.	Massive dense pink-yellow-orange foraminiferal microparacoquinite.
Barrigada Limestone			
Nr 1-7a	1	Deepest level, Harmon Quarry.	Foraminiferal microcoquinite.
Ov 7-1	2	NCS Finaguyen Transformer well, 94 ft.	Do.
2	3	NCS Finaguyen Transformer well, 404 ft.	Coral breccia.
3	4	NCS Finaguyen Transformer well, 543 ft.	Algal mudstone.
Ov 4-1	2	1,000 ft northeast of NCS Finaguyen.	White soft to hard foraminiferal mudstone.
Ov 5-1	2	1,000 ft north of NCS Finaguyen Gate.	White dense foraminiferal mudstone.
Pv 9-1	1	2,750 ft southwest of Potts Junction.	Massive cream-colored foraminiferal mudstone.
Pv 10-2	2	1,870 ft southeast of Potts Junction.	Do.
St 8-1	1	Foot of north slope of Mount Santa Rosa.	White foraminiferal microparacoquinite.
Sv 5-1	1	3,000 ft northeast of entrance to Andersen Air Force Base.	White foraminiferal mudstone.
Janum Formation			
Rr 2-1	2	400 ft north of house at Lujuna Point.	Friable yellow-gray foraminiferal microparacoquinite.
Rr 3-1	3	do	Do.
Rr 5-1	2	100 ft northeast of house at Lujuna Point.	Indurated orange-pink tuffaceous microparacoquinite.
Rr 8-1	3	On trail to Lujuna Point, 150 ft altitude.	Do.
Rr 9-1	3	On trail to Lujuna Point, 200 ft altitude.	Do.
Rr 23-1	1	On trail to Lujuna Point, 175 ft altitude.	Do.
Rr 14-1	2	2,200 ft southwest of Lujuna Point.	Friable light-pink foraminiferal microparacoquinite.
Ts 5-4	2	Uppermost bed at type section, Catalina Point.	Friable brown tuffaceous microparacoquinite.
4a	2	10 ft below Ts 5-4	Brown tuffaceous microparacoquinite.
6	1	30 ft below Ts 5-4	Friable white foraminiferal microparacoquinite.
7	3	50 ft below Ts 5-4	Do.
9	3	70 ft below Ts 5-4	Dense white foraminiferal microparacoquinite.
Uu 1-3	3	Anao Point	Friable orange-pink tuffaceous microparacoquinite.
Mariana Limestone			
Po 1-1	1	On cliff rim, Tarague Beach.	Massive incrustate limestone.
Rx 18-1	1	do	Coraliferous incrustate limestone.
Rx 19-1	1	do	Do.
Rx 20-1	1	do	Algal incrustate limestone.
Rx 21-1	1	do	Coral-algal incrustate limestone.
Sx 1-1	1	Tarague Beach, mean tide level.	Do.
Sx 2-1	2	Tarague embayment	Do.
Tw 7-1	1	Tarague cliff rim	Do.
Kr 2-1	2	Ypao Point, core-depth 15-20 ft.	Coral breccia.
2	4	Ypao Point, core-depth 30-35 ft.	Do.
3	2	Ypao Point, core-depth 45-50 ft.	Do.
Kr 3-1	1	Ypao Point, core-depth 35 ft.	Do.

TABLE 11.—*Samples studied*—Continued

Sample	Slides studied	Location	Description
Mariana Limestone—Continued			
Po 1-2	1	Cliff rim at Taguan Point.	Buff *Halimeda* paracoquinite.
Rx 7-1	1	500 ft south of Tarague cliff rim.	Buff *Halimeda* and molluscan paracoquinite.
Tw 8-1	1	Foot of Tarague cliff	Do.
Jj 6-1	1	6,000 ft north of Talofofo village.	Molluscan microcoquinoid limestone.
Pr 3-3	1	Foot of Barrigada Hill, north side.	White *Turitella*-bearing coquinoid limestone.
Ij 2-1	1	West side of Camp Witek	Do.
Qu 4-1	1	4,600 ft north of Mataguac hill.	Orange detrital coquinoid limestone.
2	1	do	Buff pelecypod-bearing coquinoid limestone.
Jh 1-1	2	1,500 ft east of Talofofo village.	White coral-foraminiferal breccia.
2	2	do	Do.
Uu 3-1	3	Base of type section, Lafac Point.	White friable foraminiferal microcoquinite.
Rr 16-1	2	Lujuna Point	White foraminiferal breccia.
Rx 17-1	1	Tarague embayment	Do.
Sw 2-4	3	2,600 ft east-southeast of Tarague well No. 4.	Phosphatic limestone.

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[Major headings are in italic]

PLATES 1–21

PLATE 1

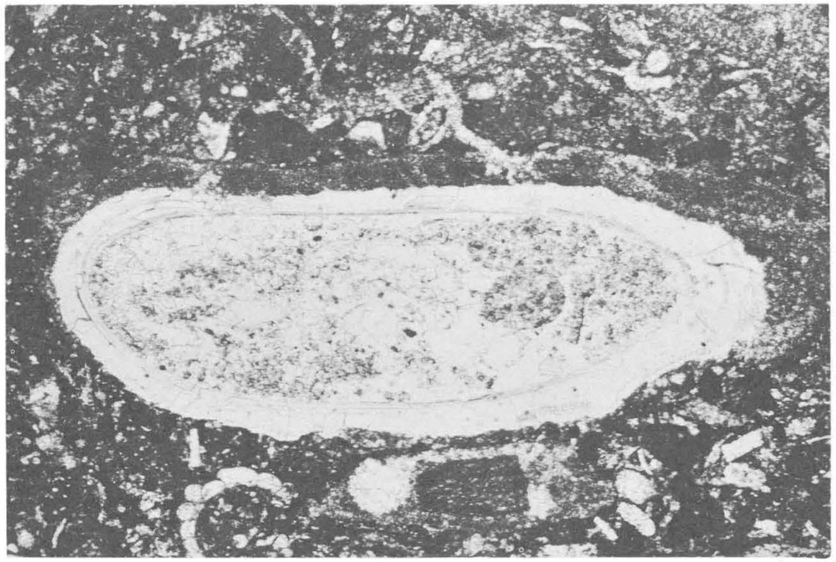
A, *B*. Section through a mollusk shell, sample Fk 4–5, × 20.

A. Plane-polarized light. The shell section is filled with a coarsely crystalline mosaic of clear calcite that still shows strong traces of an original detritus-fine-grained matrix relationship much like the matrix now surrounding the shell. This crystalline fill is in sharp contact with the inner edge of the shell wall. The shell wall is cut by fine cracks, generally radial or zigzag with respect to the wall surface. It retains a light-yellow color and, according to the color pattern, apparently part of its original shell structure, a laminar inner layer and a prismatic outer layer.

B. Crossed nicols. The present crystalline structure overides the color pattern and apparent traces of original structure described above. The radial and zigzag fractures seen in plain light are the borders of optically discontinuous calcite crystals in the shell mosaic. Although the outer shell wall is finely pitted, recrystallization has not proceeded outwards into the matrix.

C. Sample Hj 1–1, × 8. A two-stage sequence of void filling. The branching vein ends in small fractures along which minor movement has taken place. In completely particulate rock this type of vein suggests postlithification solution along fracture lines. Following the widening of the fractures, a deposit of finely fibrous calcite partially filled the openings. After this chemical deposition, the remainder of the cavities were filled with carbonate mud detritus. The detrital fill is vaguely banded. In some veins the mud fill has begun to recrystallize into clear calcite. Completion of this recrystallization would make the rock appear to have been subject to two periods of chemical deposition rather than to one chemical and one detrital period.

D. Sample Hj 1–5, × 25. Limestone in which a fracture system is well developed. These fine fractures are completely sealed by crystalline calcite. The cracks swell and pinch out but maintain their angular relationships. Minor offsetting of a fraction of a millimeter is common. These fractures are restricted on Guam to limestones of Eocene (b) age.



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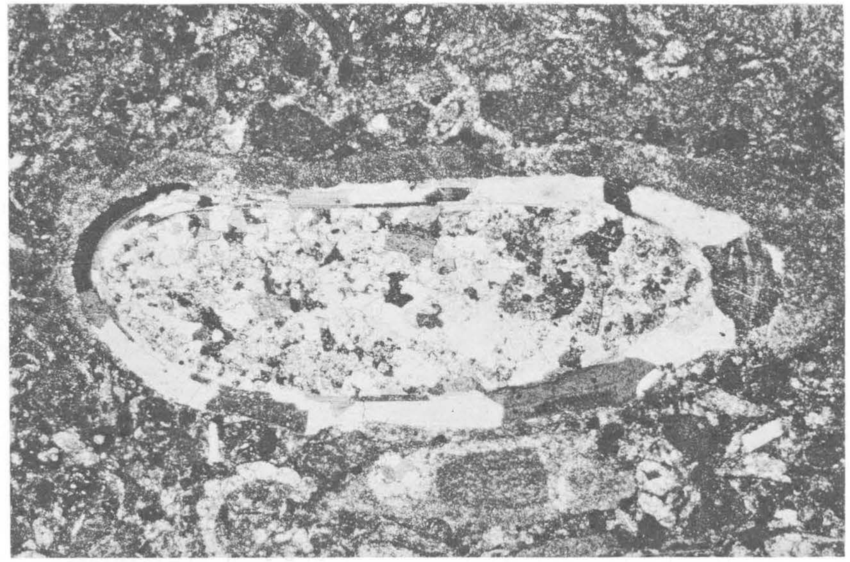

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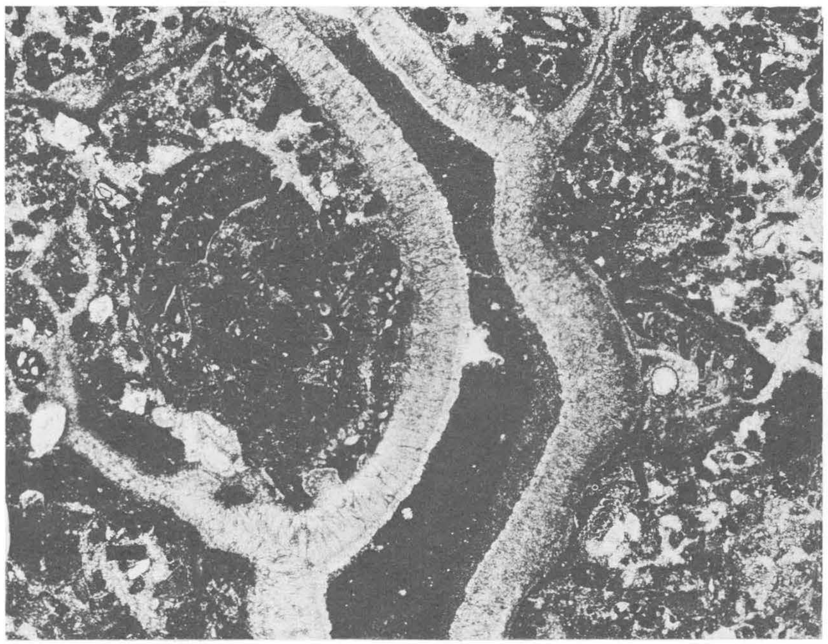

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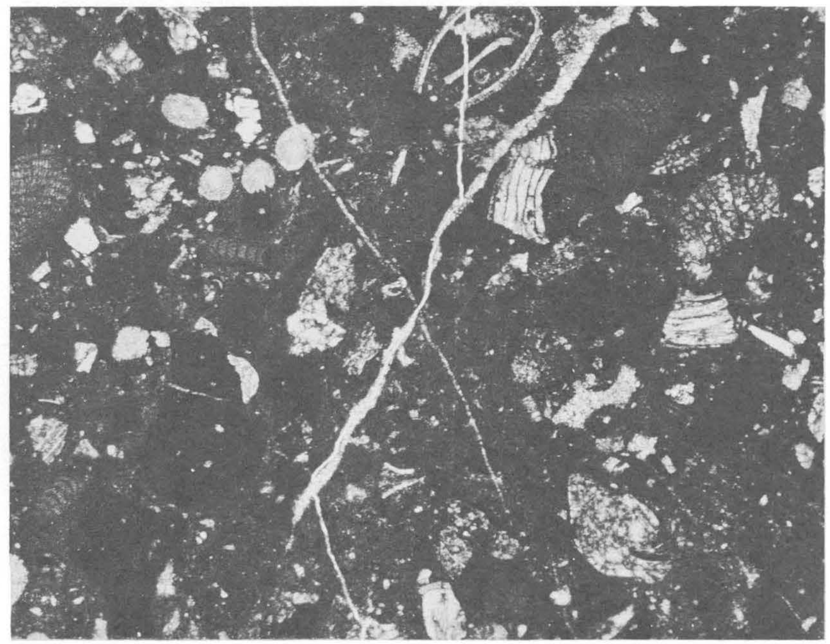


D

SECONDARY FEATURES IN LIMESTONE FROM THE ALUTOM FORMATION

PLATE 2

A, B. Silica-filled cavity in sample Ek 7–4, × 25.

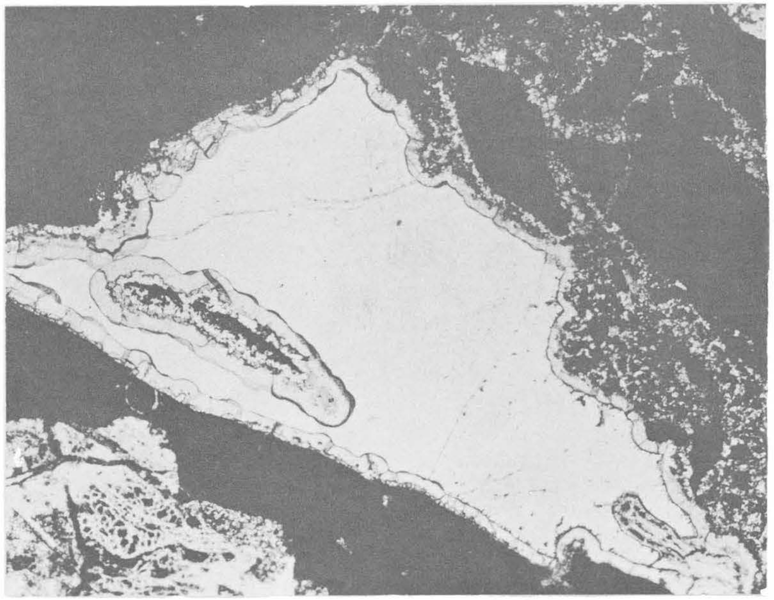
A. Plane-polarized light. The roughly triangular white area might be taken for a void except for the fine fractures that cross it. The clear calcite lining of the former opening stands out in high relief above the silica filling. Not shown in the photomicrograph are fractures that lead into the cavity from the lower and upper right hand corners of the triangle.

B. Crossed nicols. The silica filling and the calcite lining show contrasting crystal forms. The silica has taken the form of fibrous sheaves that show undulatory extinction. These extend inward from the calcite lining, perpendicular to the walls of the original cavity. In places the silica is in the form of a fine-grained mosaic of anhedral crystals. The clear calcite lining shows up as a uniformly thick rim of optically discontinuous crystals.

C, D. Metasomatic replacement by silica in sample Ek 7–4, × 25.

C. Plane-polarized light. The white areas show the silicified parts of the rock. The dark surrounding area is unaffected limestone; the gray indistinct areas within the clear silica are occupied by incompletely altered limestone. The contact between the unaltered limestone and that completely replaced by silica is sharp and definite. The texture of the limestone has been subdued but not effaced by the silica replacement. Where the contact between replaced limestone and the original rock passes through an easily recognized fossil, organic structures can be definitely followed across the contact. This feature is shown in the upper left corner of the photomicrograph. The curving row of evenly spaced dark ellipses are sporangia in a fragment of *Archaeolithithamnium*, which straddles the silica-limestone contact. This line of sporangia can be followed from unaltered algae into fibrous silica.

D. Crossed nicols. The habit of the silica in the replaced part of the rock is roughly the same as that in the void filling described above. In this type of silicification, fossil fragments are more clearly replaced than is the matrix material, particularly the fine-grained mud.



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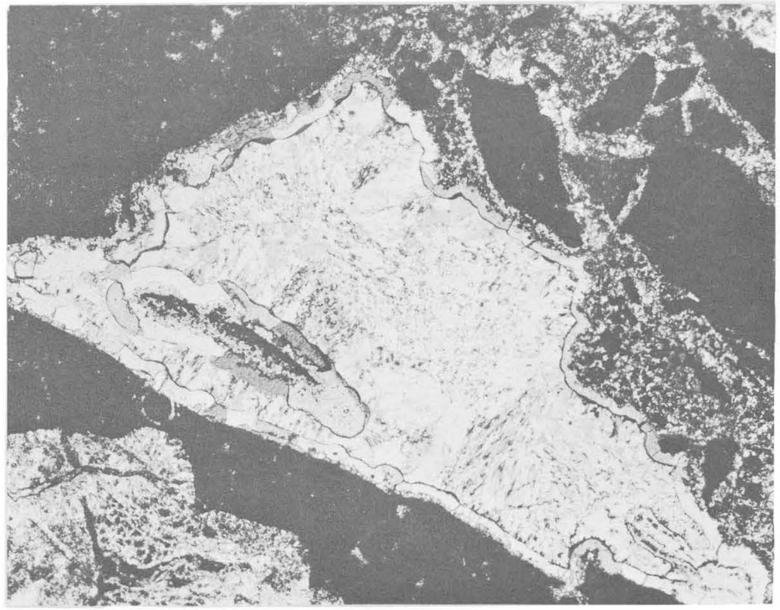
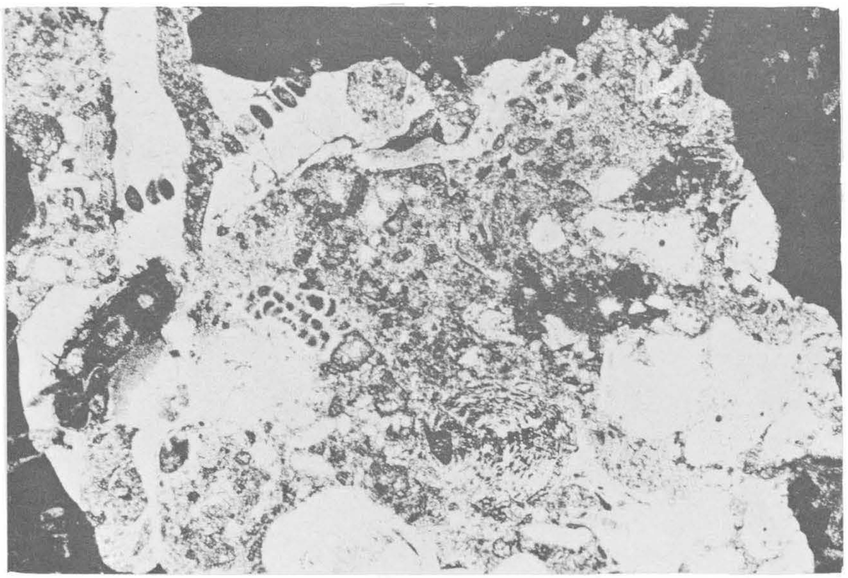


B



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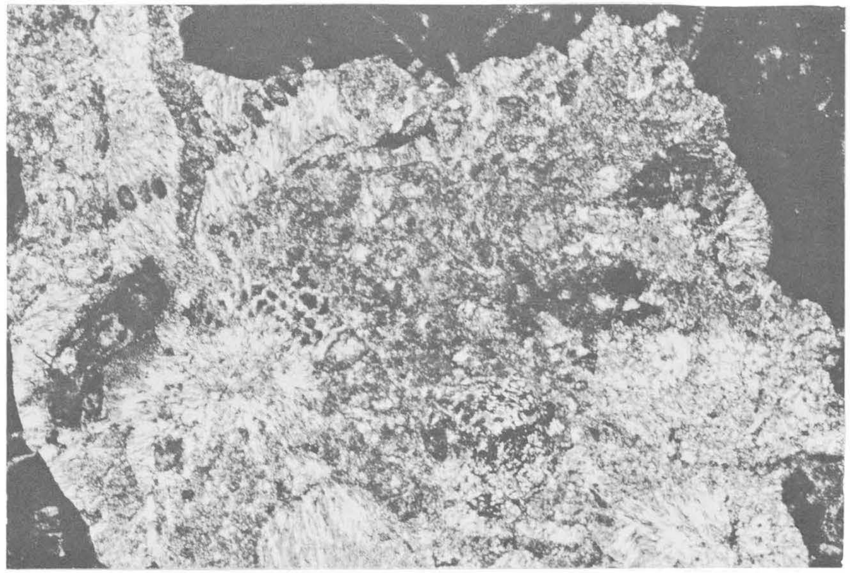


D

SILICIFIED LIMESTONE FROM THE ALUTOM FORMATION

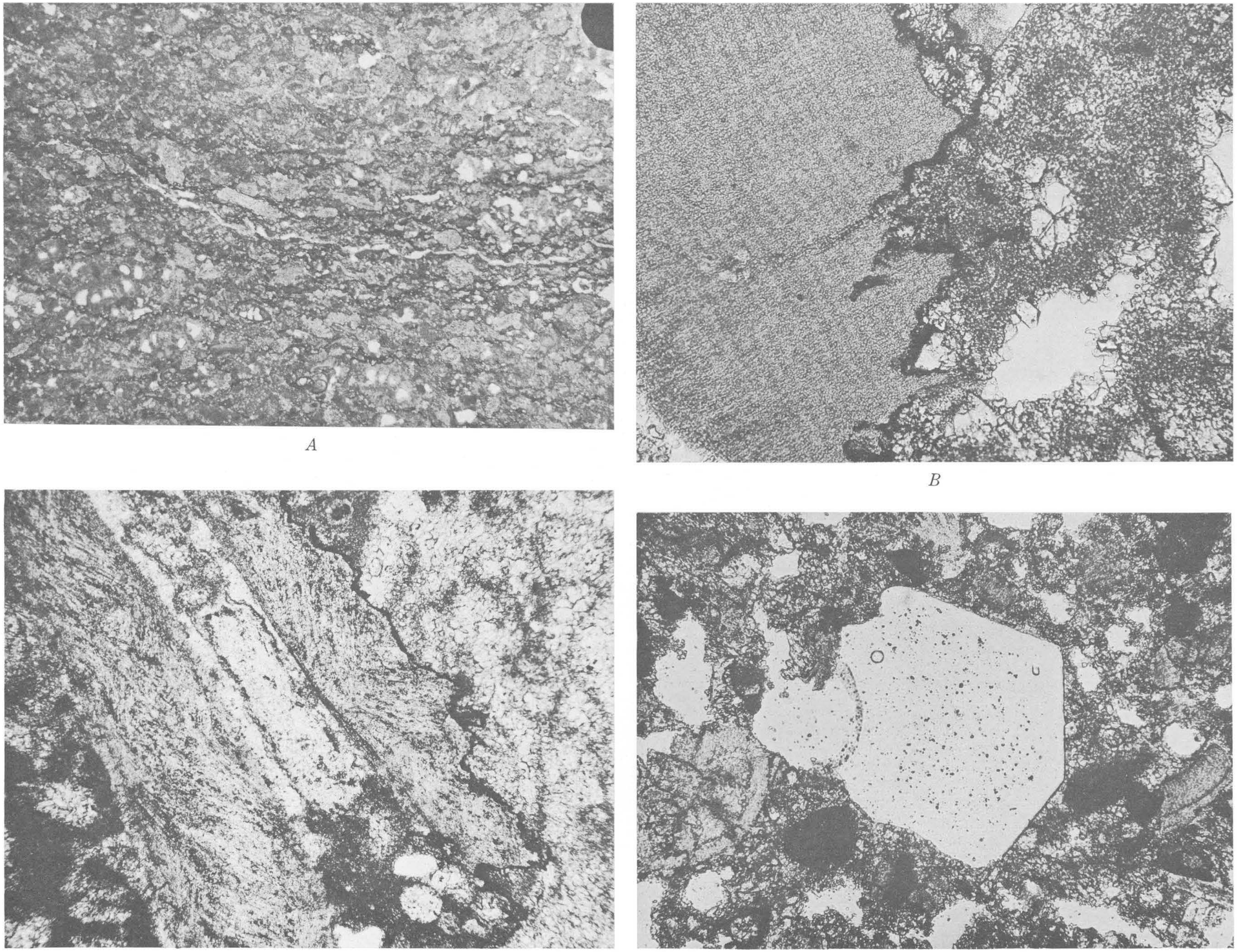
PLATE 3

A. Sample Eh 3–5, × 15. A band of bifurcating and intersecting microstylolite seams cross the thin section from left to right. These seams have amplitudes of from 0.1 to 0.25 mm. The microstylolites are closely spaced; in one section, 14 seams were counted in a distance of 10 mm. Each seam is rendered distinct by an included film of reddish-brown clay. Interpenetration of fossils is common along each seam. The lithology of this specimen is identical to that of sample Eh 3–2 (pl. 14*D*).

B. Sample Di 2–1, × 160. Detail view of a mollusk shell-matrix contact along a microstylolite seam. The clay concentration shows up well as the dark band between the solid shell on the left and the porous recrystallized fine-grained matrix on the right.

C. Sample Di 2–1, × 90. Detail view of a mollusk shell having a microstylolite contact on the right and a normal contact on the left.

D. Sample Gj 8–1, × 100. A euhedral crystal of quartz typical of the Alifan Limestone in central Guam.



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MICROSTYLOLITES AND QUARTZ IN THE ALIFAN LIMESTONE

PLATE 4

A, B. Sample Ej 4–1, × 90. Recrystallized carbonate mud.

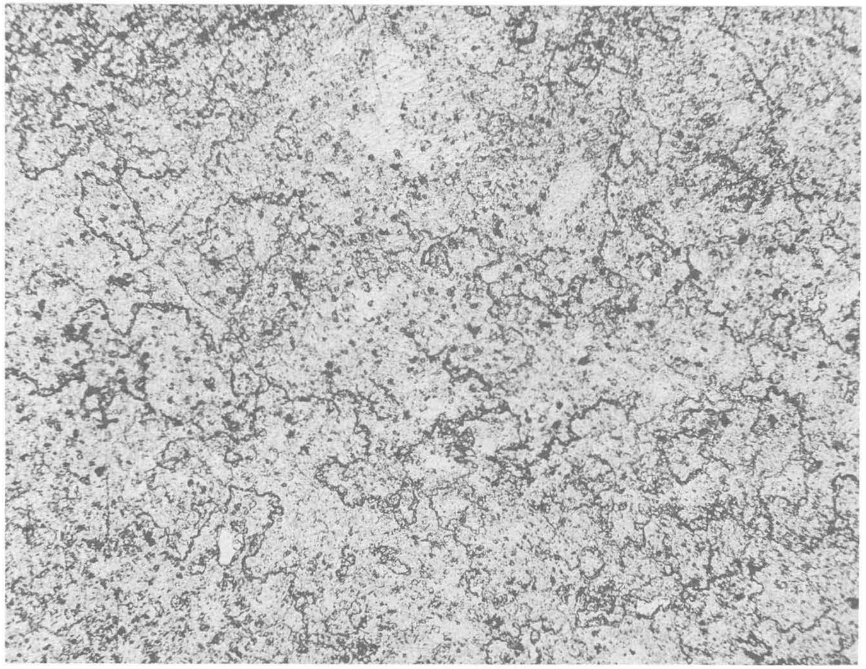
A. Plane-polarized light. The otherwise featureless microcrystalline matrix is cut by a system of fine dark serpentine boundary lines that separate areas of differing relief.

B. Crossed nicols. The rock is revealed to be made up of an intricate intergrowth of calcite in the form of a mosaic of single crystals. This type of recrystallization has only been seen in the lagoonal mudstone of the Alifan Limestone.

C, D. Sample Dh 12–1, × 50. Nordstrandite cavity filling.

C. Plane-polarized light. Nordstrandite occupies light area in the center of the photomicrograph. This area was evidently a solution cavity within which was deposited a thin layer of calcite. Fractures, now calcite-healed for the most part, lead away from the former cavity.

D. Crossed nicols. Nordstrandite shows up as bladed crystals radiating from a point in the original cavity. Some nordstrandite has been deposited within incompletely filled fractures. The nordstrandite is evidently a late deposit that followed postdepositional lithification, fracturing, subaerial solution, and calcite deposition.



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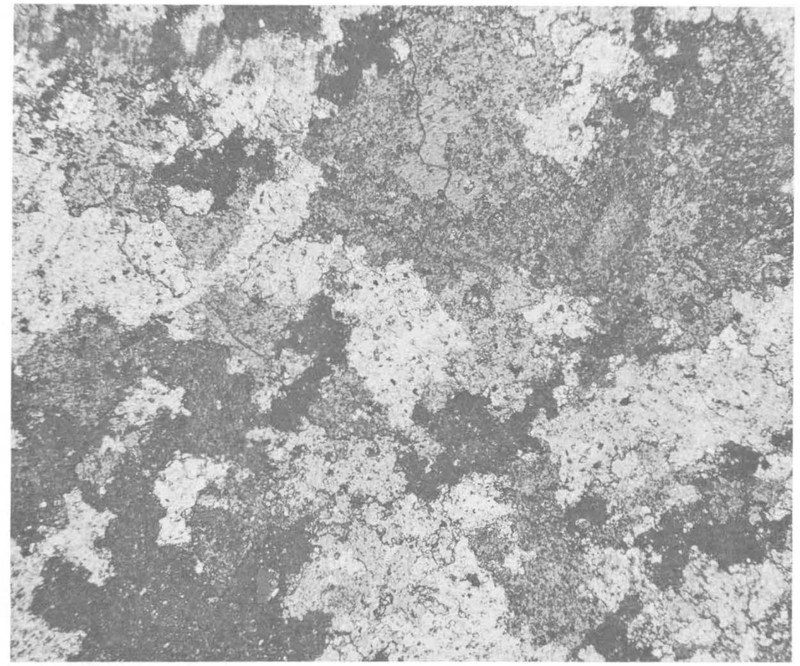

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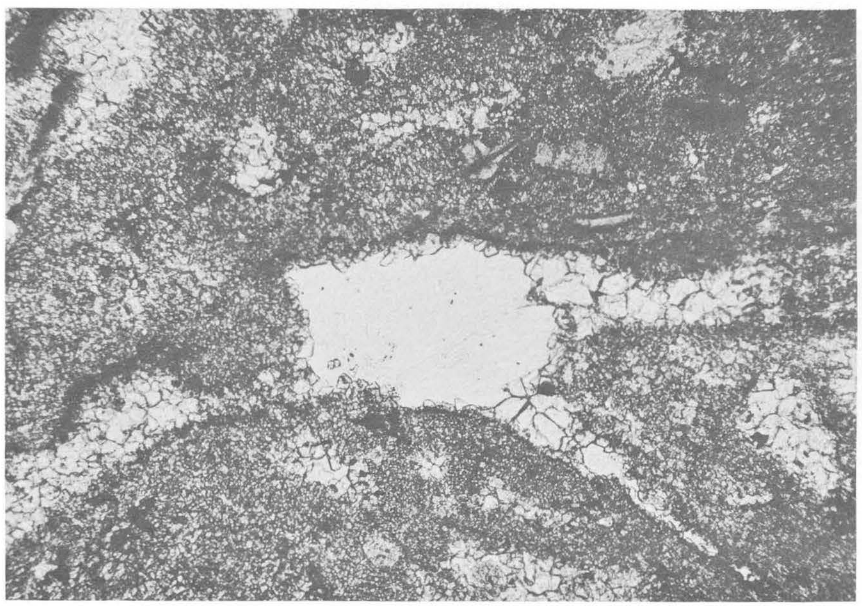

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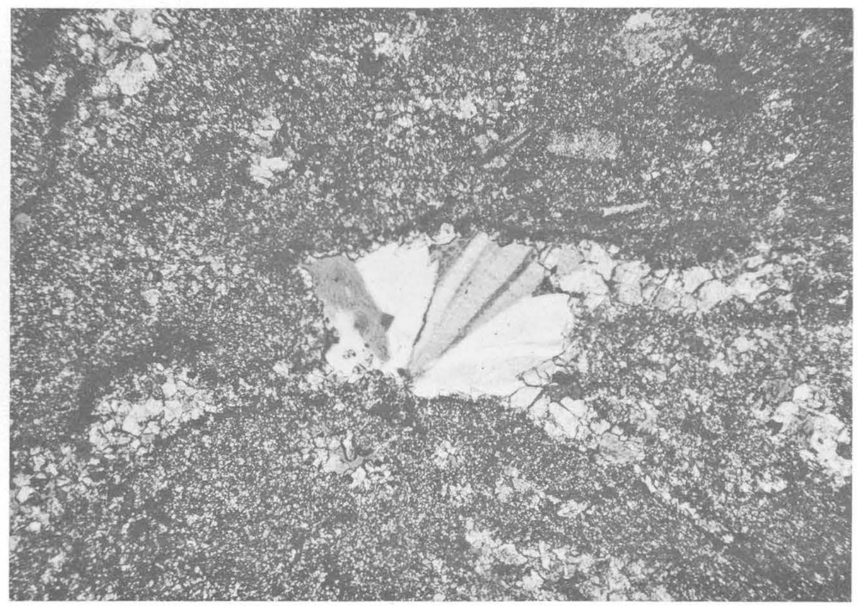

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RECRYSTALLIZED MUD AND NORDSTRANDITE IN THE ALIFAN LIMESTONE

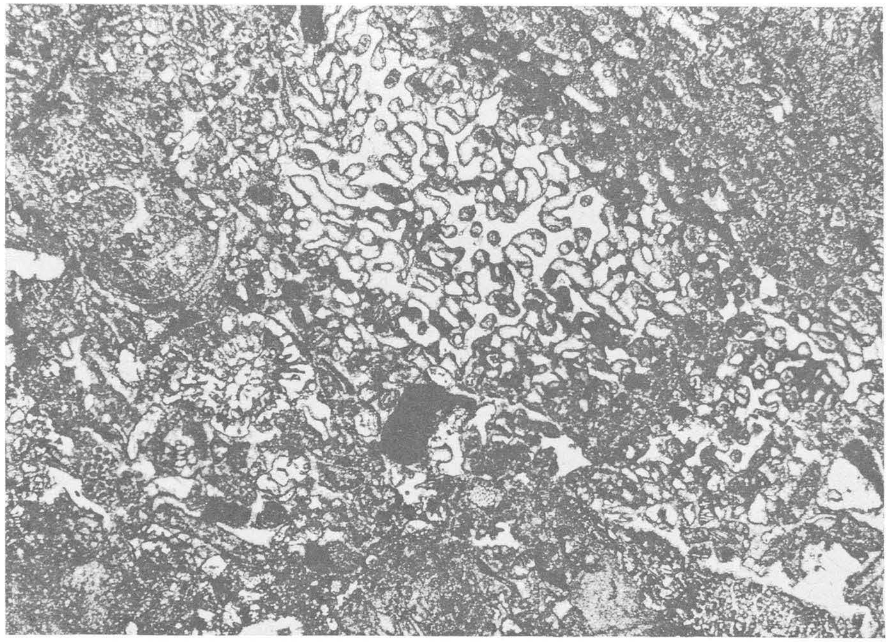
PLATE 5

A. Sample Ts 16–8, × 20. The original structure of a coral fragment is preserved only as fine dust lines that define a ghost. The original interseptal openings are now lined with small euhedral crystals of dolomite. Both the coral ghost and the dolomite linings are invested in a clear calcite mosaic, individual crystals of which fill in several interseptal openings. The Foraminifera test to the lower left is enclosed within a single water-clear calcite crystal.

B, *C*. Sample Ts 16–8, × 140. Detail view of the dolomite crystals lining interseptal openings. Many of the rhombs show irregular centers within an euhedral shell. The clear structureless areas are late-stage calcite fillings.

D. Sample Tt 7–4, × 170. Detail view of dolomite crystals and unaltered areas. These dark patches are rimmed with dolomite but contain none.

E. Sample Tt 7–4, × 80. Dolomite crystals within a fine-grained calcite matrix. Some textural control over the distribution of the dolomite is shown by the relatively unaltered dark patches.



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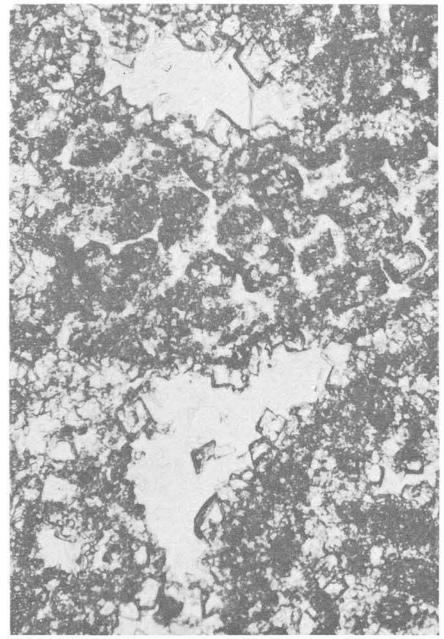

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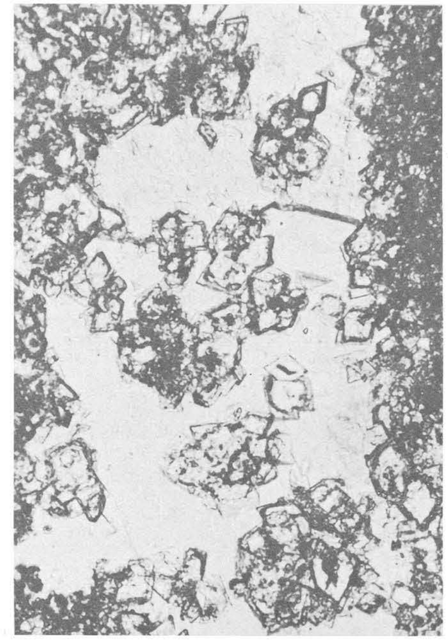

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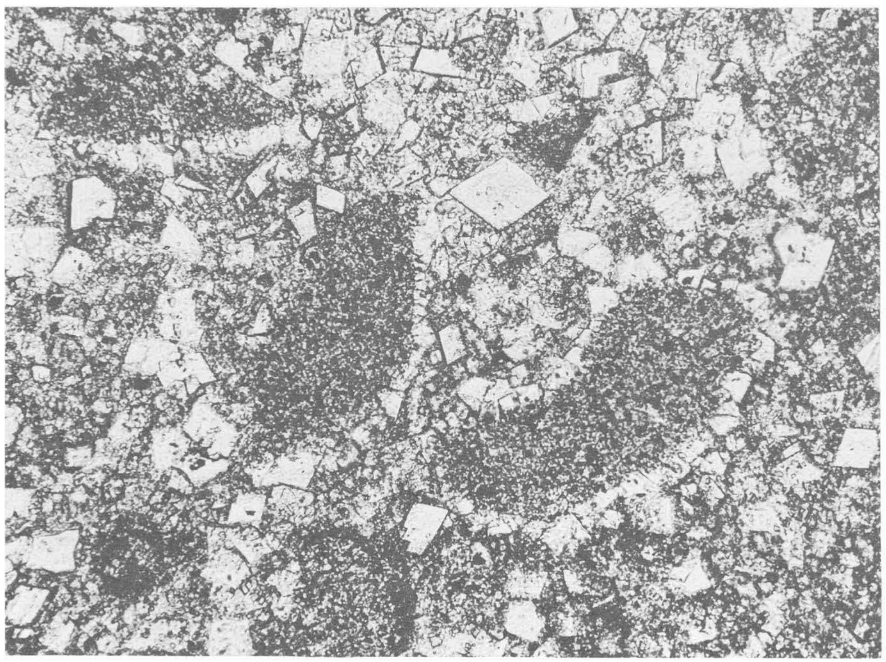

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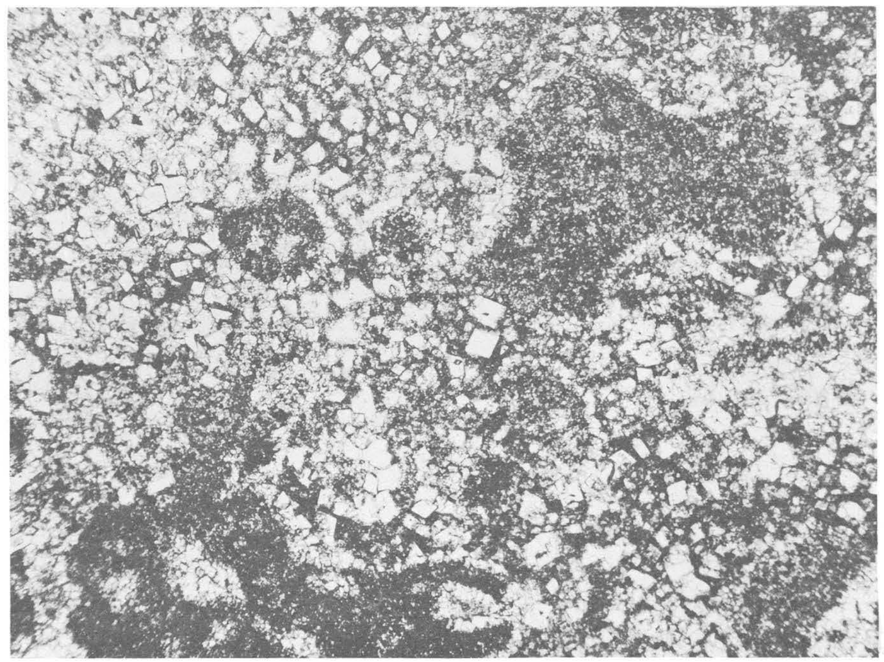


E

DOLOMITE IN THE ALIFAN LIMESTONE

PLATE 6

A, B. Sample Sw 2–4, Guam, × 20.

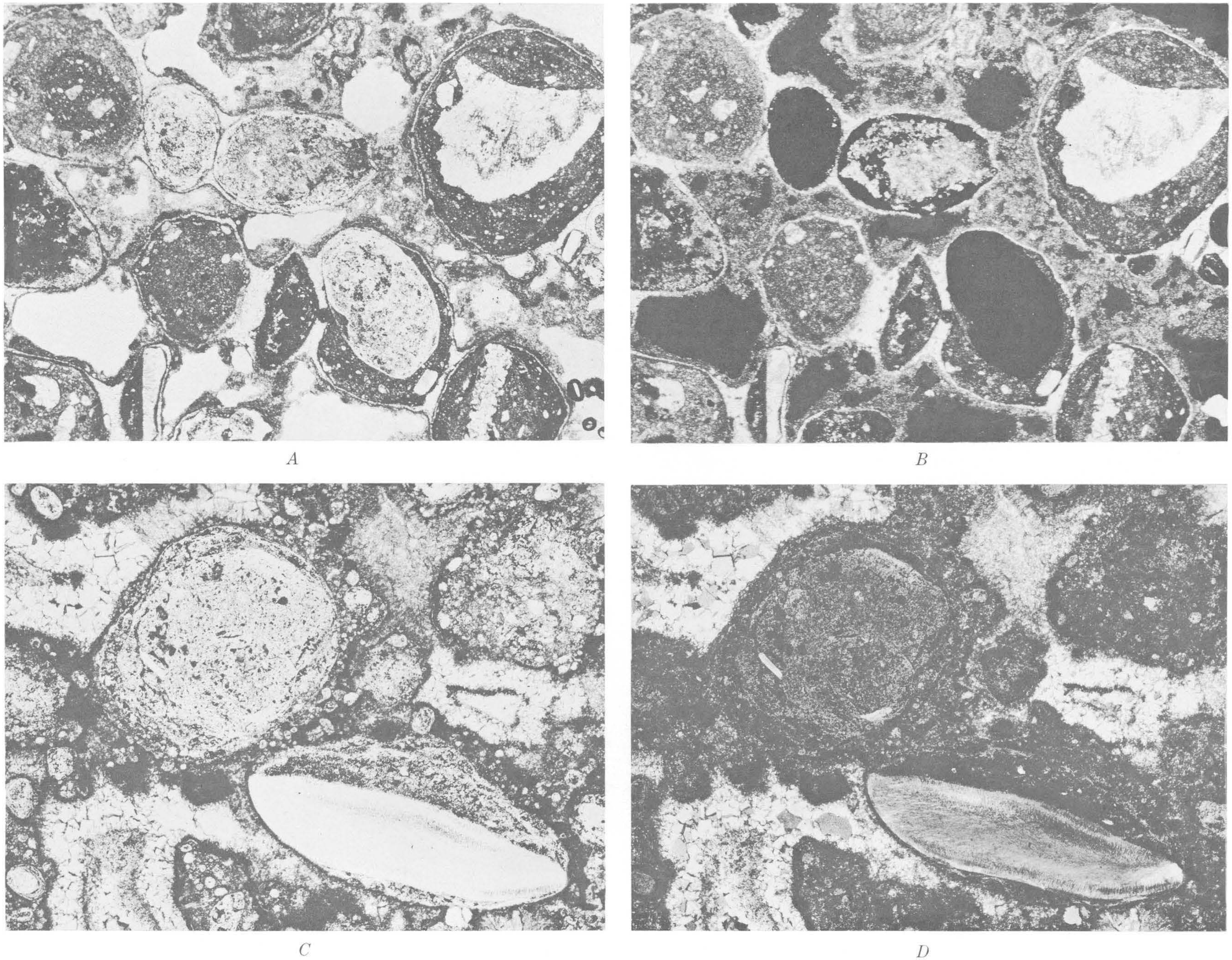
A. Plane-polarized light. Well-rounded phosphatic pellets of two kinds, microcrystalline and amorphous. The internal structure of the first type is shown by the pellet in the upper left corner. The darker central part is the result of one period of deposition, the lighter peripheral part the result of a later period. The light-colored tabular shell fragments lie roughly parallel to the circumference. The pellet in the lower right corner shows a light interior and a darker exterior. Roughly concentric banding in several shades of brown can be seen around the large shell fragments in the pellet to the upper right. Some of these shell fragments are original aragonite.

B. Crossed nicols. The three ellipsoidal pellets in the center are amorphous. The lowermost of these has a center of amorphous phosphate upon which has accumulated a later layer of particulate phosphate and shell debris. The center pellet shows incomplete alteration. Relict structures of shell fragments can be seen in the amorphous pellets. The initial calcite cement shows up as a light band between pellets and the later interstitial phosphate deposits.

C, D. Sample from Anguar, × 20.

C. Plane-polarized light. Two large pellets, one built around a fragment of mollusk shell, are in a calcite matrix. These pellets have altered to amorphous phosphate, but the internal structures can still be seen. The spherical pellet shows concentric banding and relict structures of tabular shell fragments. Clustered about the large pellets are smaller spherical bodies of phosphate.

D. Crossed nicols. The large shell fragment in the ellipsoidal pellet is replaced by amorphous phosphate. The finely recrystallized lime mud matrix shows up as gray patches against the bright crystalline interstitial fillings of clear calcite.



PHOSPHATIC LIMESTONE FROM GUAM AND FROM ANGUAR, PALAU ISLANDS

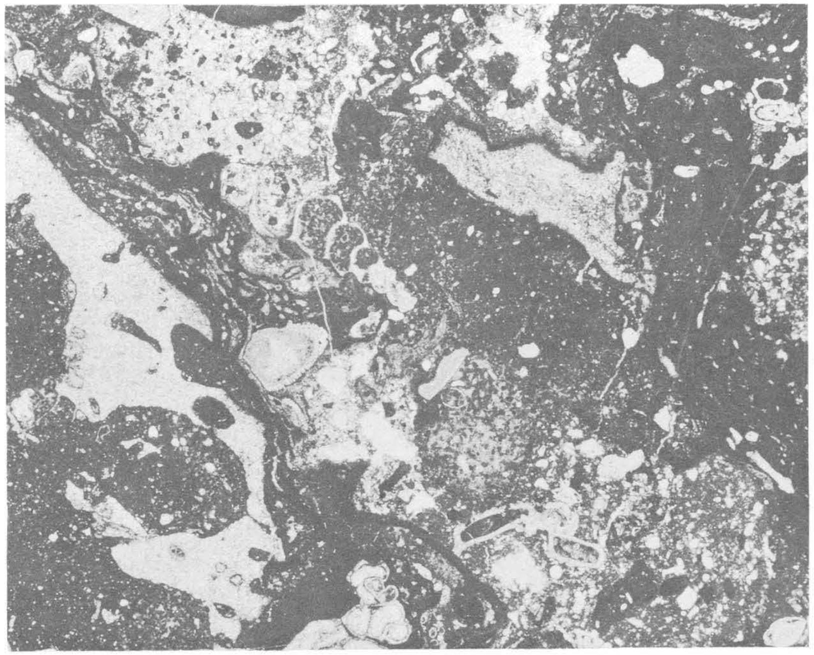
PLATE 7

A. Sample Fk 4–2, × 8. Algal incrustate limestone from the reef-wall facies. Long sinuous dark bands of encrusting algae coat and bind organic debris. These bands also extend, unbroken, through the fine-grained particulate matrix. Much of this matrix has recrystallized into mosaic calcite. The calcareous algae and the encrusting Foraminifera retain their original structures, whereas the coral, *Halimeda*, and molluscan remains are all highly recrystallized. Alternations of the algal bands and layers of detritus indicate that, within the photic zone, periods of detrital deposition alternated with nondepositional periods that allowed algal growth to proceed. Pockets of volcanic material, such as the area to the upper left of the gastropod section, indicate subaerial erosion of volcanic terrain or volcanic activity. (See pl. 10*A* for a Maemong Limestone Member equivalent and pl. 19*A* for an equivalent limestone from the *Heterostegina* zone of southern Louisiana.)

B. Sample Fk 4–5, × 8. Molluscan-algal paracoquinite from the lagoon facies. Disarticulated valves and fragments of mollusk shells are conspicuous in this limestone. All the shell material has recrystallized into coarse mosaic calcite that is not obvious in plain light but that shows up well between crossed nicols (pl. 1*A*, *B*). The shells retain strong traces of their original fibrous structure, in the form of yellow streaks and bands that cross the crystal boundaries, despite the fact that these crystals are not in optical continuity. These shells also maintain, in many places, sharp boundaries against the matrix.

C. Sample Fk 4–9, × 8. Foraminiferal-algal microparacoquinite from the lagoon facies. The limestone contains numerous well-preserved tests of miliolid, uniserial, biserial, and coiled small Foraminifera in addition to algal rods. These are all imbedded in fine-grained anhedral mosaic calcite. Traces of the original mud matrix have been largely effaced by postdepositional alteration. The interior spaces in the Foraminifera tests are filled with calcite texturally identical to that in the surrounding matrix. The calcite suggests an original mud fill for the tests, probably the result of infiltration. The abundance of miliolids and other small benthonic forms is indicative of a backreef shoal-water environment. (See pl. 10*D* for a Maemong Limestone Member equivalent and pl. 20*B* for an equivalent limestone of Oligocene age from Iraq.)

D. Sample Fk 4–1, × 8. Foraminiferal-algal paracoquinite from the shallow-water off-reef facies. Tests of *Fabiana* are common in foraminiferal-algal debris. This material is imbedded in a fine-grained dark mud matrix, some of which has recrystallized into patches of clear calcite. These patches are limited, in some places, by bounding algae that have resisted alteration. The rock is completely particulate and much of the fossil material is in fragmental condition. The abundance of disjointed rods of articulate coralline algae indicates a fairly shallow source area for much of the detritus. Numerous large fossil fragments floating in the mud matrix are suggestive of rapid transport and deposition of coarse detritus into a quiet water environment.



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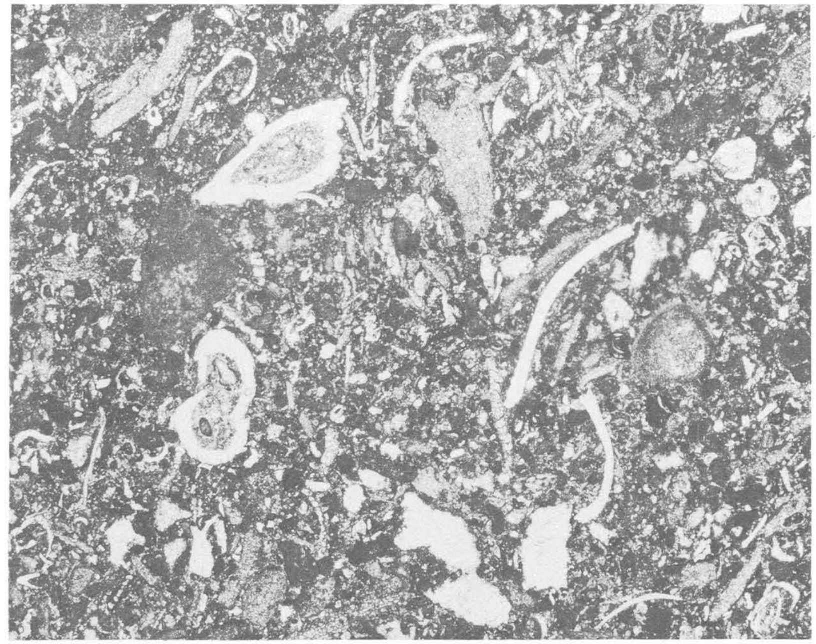

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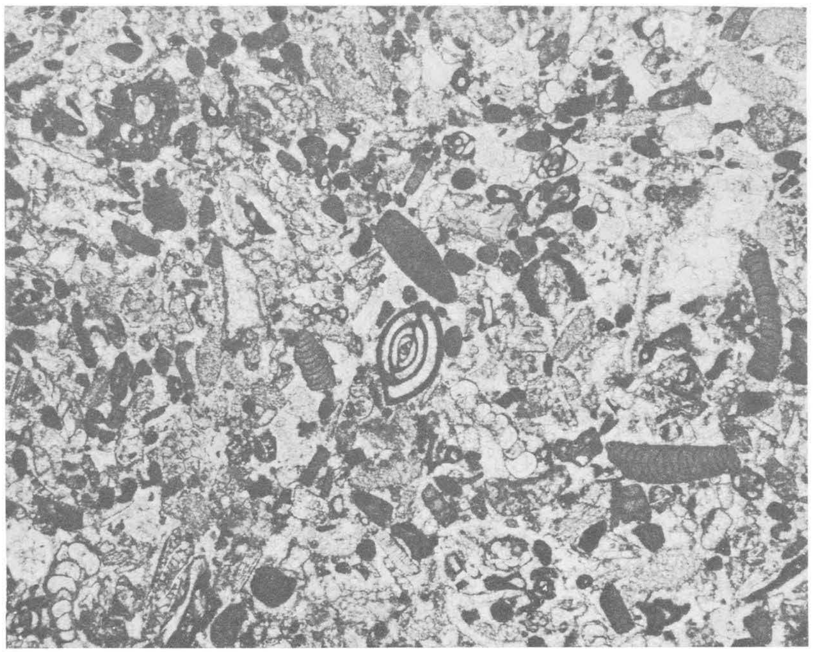

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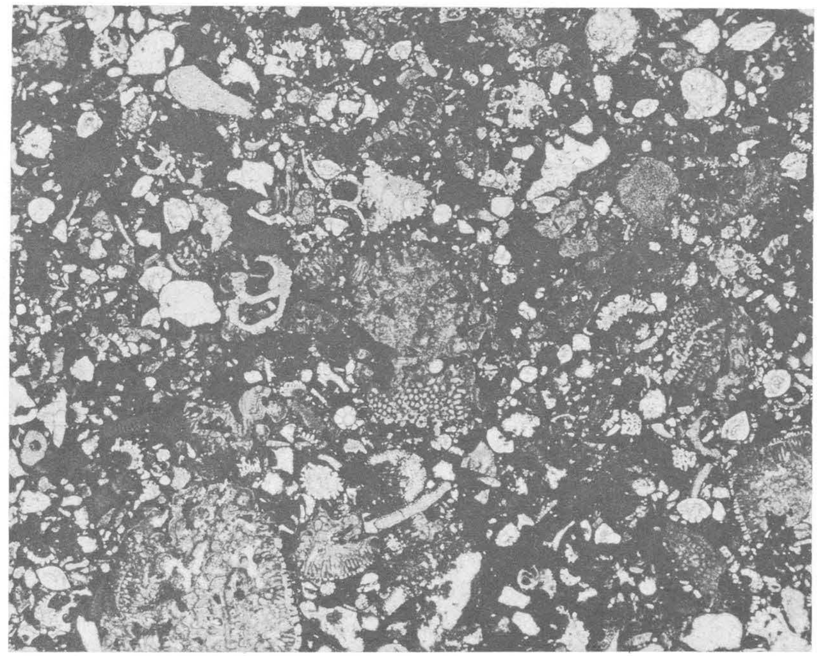


D

LIMESTONE FROM THE ALUTOM FORMATION

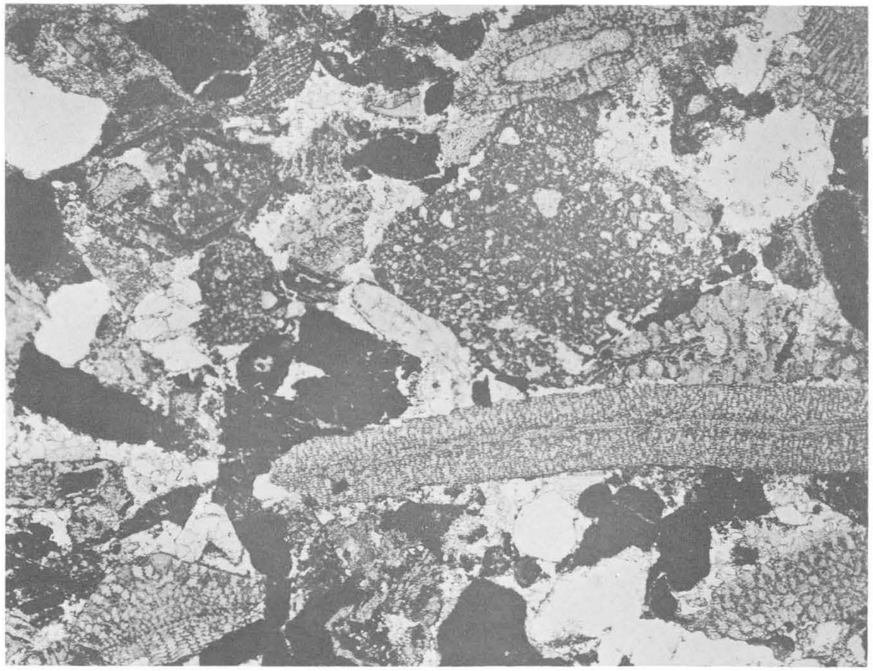
PLATE 8

A. Sample Ek 7–2, × 16. Foraminiferal-algal, volcanically contaminated coquinite from the forereef facies. Broken tests of large Foraminifera and debris of calcareous algae dominate. Both articulate and encrusting algae are common, but the encrusting type is all fragmental and serves no binding function. The intact framework is cemented by coarse-grained clear calcite, now porous as the result of subaerial solution. The large Foraminifera show a tendency towards preferred orientation parallel to the bedding. The texture of the rock and the abundance of large Foraminifera suggests deposition on a forereef slope. (See pl. 11*B*, *C* for a Maemong Limestone Member equivalent and pls. 19 and 20 for similar limestone from southern Louisiana and Iraq.)

B. Sample Ek 7–3, × 20. Foraminiferal-algal microcoquinite from the forereef facies. This sample was taken a few feet, stratigraphically, from sample Ek 7–2. Its fossil composition is almost identical to the coarser grained Ek 7–2, except for a trace of well-preserved globigerinid Foraminifera indicative of deeper water deposition. The elongate particles show a preferred orientation parallel to the bedding, and the texture indicates considerable sorting and transport of material before final deposition.

C. Sample Ek 7–1, × 25. Foraminiferal mudstone from the basin facies containing well-preserved tests of globigerinid Foraminifera. A trace of coiled tests of small Foraminifera is also present. These fossils are imbedded in a chalky matrix that appears dark brown in transmitted light and brilliant white under reflected light. Volcanic material includes angular fragments of magnetite, plagioclase, and some green and brown ferromagnesian minerals, probably pyroxene and amphibole. This sample was collected in the same sequence of beds as were Ek 7–2 and Ek 7–3. (See pl. 11*E* for the Maemong Limestone Member equivalent and pls. 19 and 20 for similar limestones from southern Louisiana and Iraq.)

D. Sample Ii 8–1, × 8. Foraminiferal paracoquinite, composed largely of tests of *Biplanispira*, from the forereef facies. Much of the remainder of the rock is made up of well-rounded pebbles of limestone (lower right corner of the photomicrograph). These particles are in a clear calcite matrix that shows exceptionally sharp contact with the enclosed detritus. This mosaic textures is secondary after an original mud matrix. Traces of the original matrix can be seen as dark patches. The recrystallization proceeds from the detrital grain outward into the mud. In the initial stages, each detrital grain shows a halo of clear calcite. (See pl. 10*C* for this type of recrystallization in the Maemong Limestone Member.)



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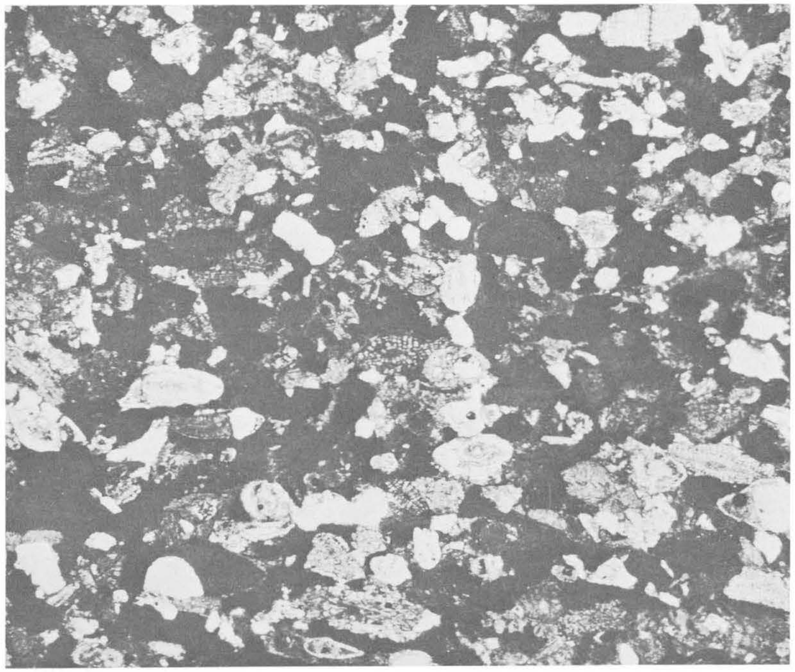

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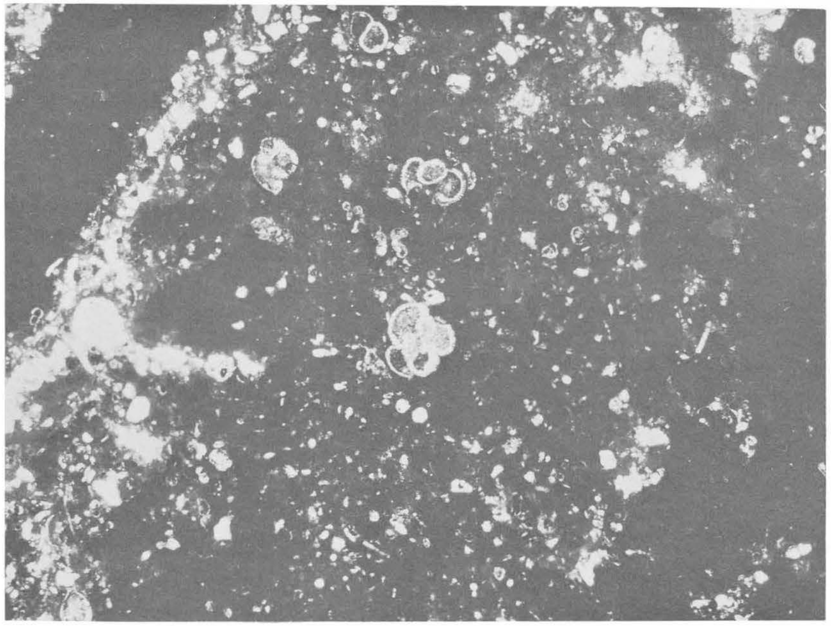

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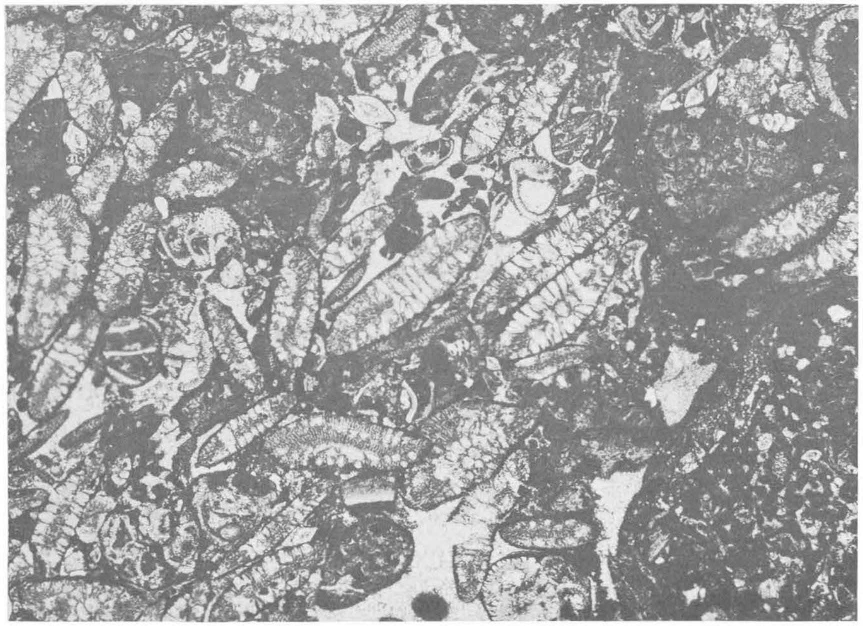


D

LIMESTONE FROM THE ALUTOM FORMATION

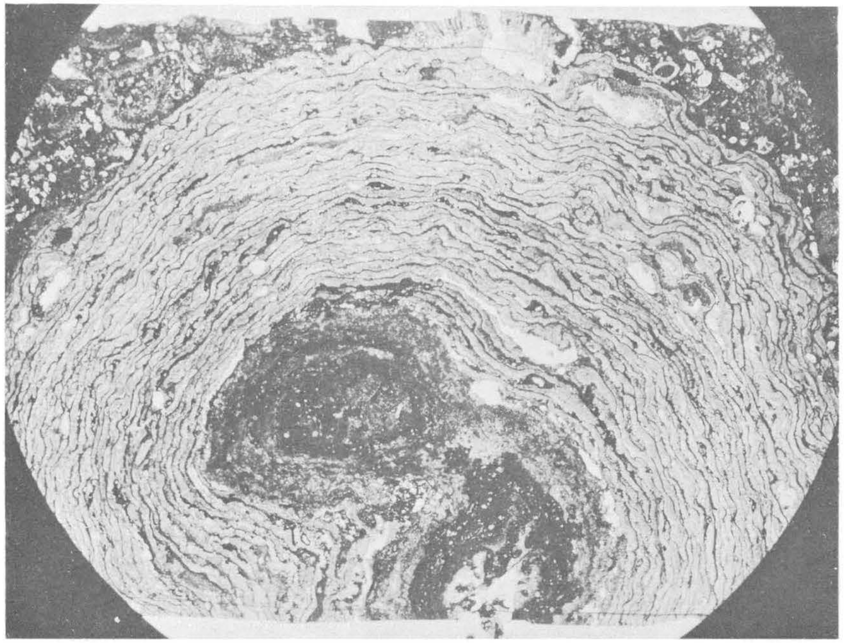
PLATE 9

A. Sample Fk 4–7, × 3. A roughly spherical growth of encrusting algae. Approximately 35 to 40 layers are present although no one layer completely covers the entire mass. The growth appears to have begun on the dumbbell-shaped mass of encrusting algae and detritus in the foreground of the photomicrograph. Between many layers of the algae are lesser amounts of a thin-walled encrusting Foraminifera. The entire nodule is enclosed in a paracoquinite matrix similar to sample Fk 4–1 (pl. 7*D*).

B. Sample Fk 4–7, × 25. Detail view of the algal nodule described above.

C. Sample Hj 1–4, × 46. Thin-walled encrusting Foraminifera that serves to bind organic particles together. This form resembles twisted skeins of netting that wind through the rock. Under low magnification this organic deposit can be easily overlooked and mistaken for a fine-grained particulate matrix.

D. Sample Fk 4–6, × 170. Detritus-filled interseptal spaces in recrystallized coral. The dark areas running vertically in the photomicrograph are masses of fine-grained detritus that have filled the original openings in the corallum. The aragonite skeleton of the original coral has been replaced by fine-grained anhedral mosaic calcite. This mosaic does not extend into the interseptal spaces; within these the matrix is microcrystalline. Part of the wall area of the interseptal voids is coated with dark tubular wormlike structures that appear to be an organic encrustation. Within these detrital fills, some of the dark flecks resemble algal particles.



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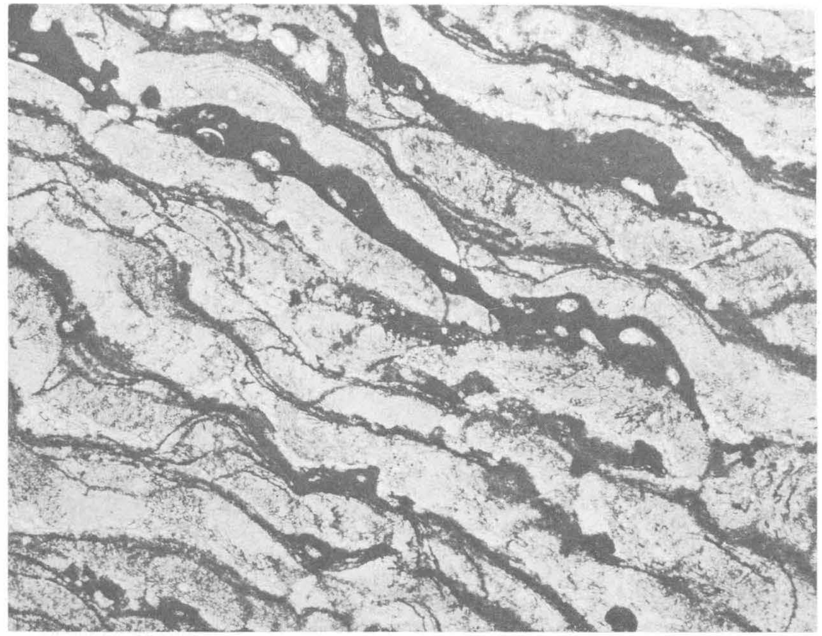

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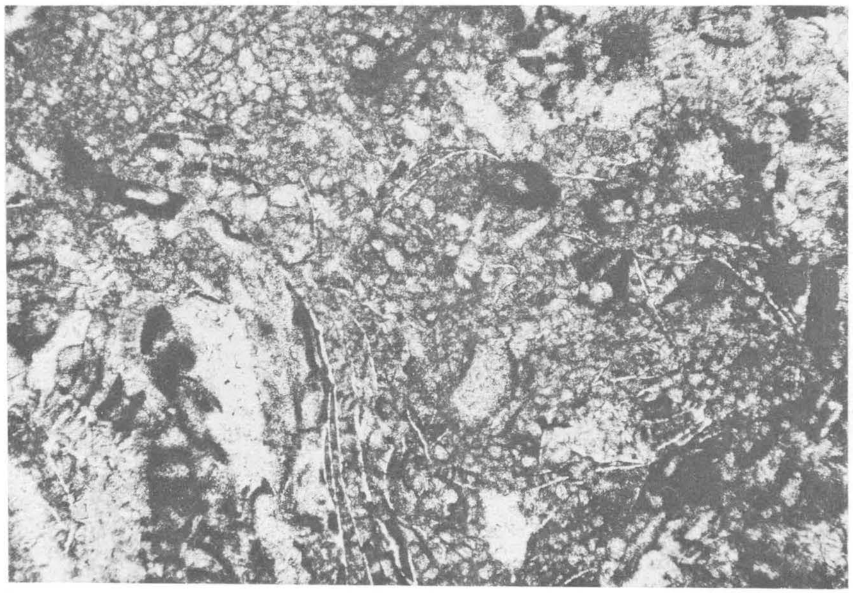

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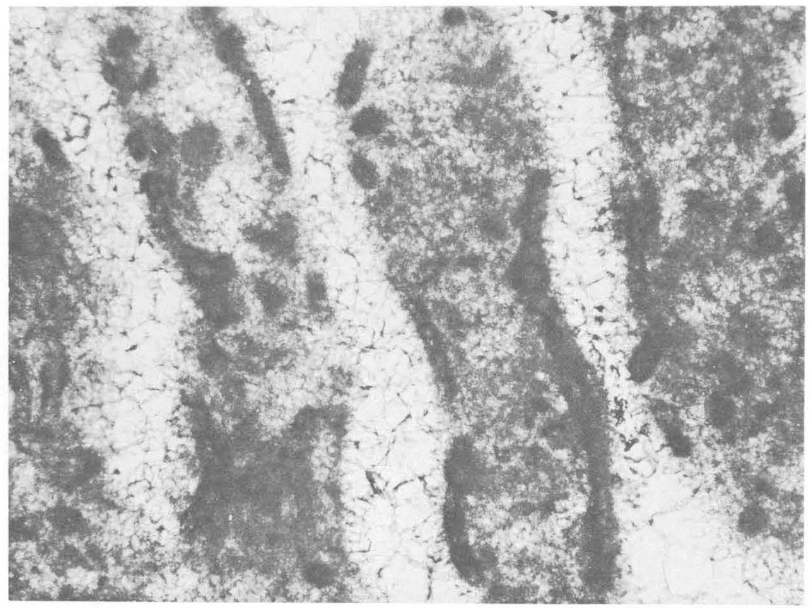


D

ENCRUSTING ALGAE, ENCRUSTING FORAMINIFERA, AND RECRYSTALLIZED CORAL FROM THE ALUTOM FORMATION

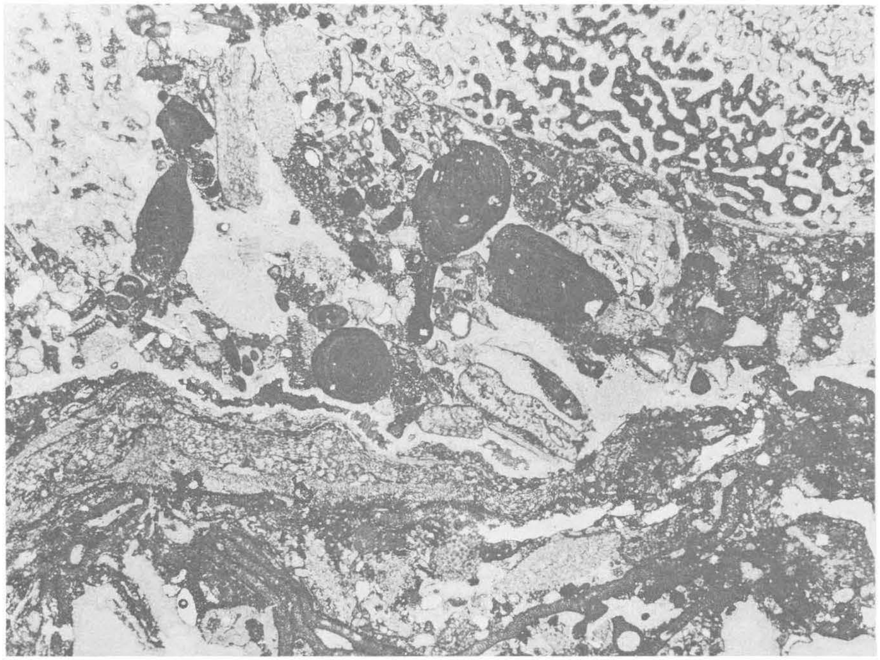
PLATE 10

A. Sample Hi 3–4, × 8. Coral-algal incrustate limestone from the reef-wall facies. Laminae of encrusting algae and Foraminifera are characteristic. Fragments of nodular encrusting algae (dark circular pieces) and *Halimeda* are present. The recrystallized coral shows dark mud-filled interseptal spaces that produce a jigsaw puzzle effect. These larger fossil elements are in a particulate matrix of fine-grained organic debris and mud. Much of this mud matrix has recrystallized into fine-grained calcite. (See pls. 7*A*, 14*A*, 18*B*, and 19*A* for equivalent facies from the Alutom Formation, the Alifan Limestone, the Mariana Limestone, and southern Louisiana.)

B. Sample Hi 3–2, × 8. *Halimeda* paracoquinite from the lagoon facies. This sample was taken from within a few feet of the reef-wall limestone described above. It probably represents a local accumulation of *Halimeda* segments near the reef wall. *Halimeda* and subrounded fragments of encrusting algae dominate in a finely crystalline matrix of gray dusty calcite. The *Halimeda* segments have been completely recrystallized to calcite; only dust-line ghosts of segments remain.

C. Sample Hi 4–5, × 12. Foraminiferal-algal paracoquinite showing recrystallization of an original carbonate mud matrix. The four irregular areas in the center of the figure are unrecrystallized remnants of an original matrix. The two patches in the lower left corner are separated by a large Foraminifera test around which have grown scalenohedrons of dusty calcite. These crystals are arrayed perpendicular to the outer surface of the test and are encroaching on the mud. The patch in right center is surrounded by a dark line that is the base of growth of the crystals now encroaching on the remaining mud. Evidently the original carbonate mud has been largely destroyed by recrystallization that proceeded outward from the fossil debris. The bright pore spaces are, in part, the results of the solution of rods of algae. The large void in the upper left corner appears to be the result of removal of the residual mud matrix.

D. Sample Gi 1–1, × 16. Miliolid- and peneroplid-rich microparacoquinite from the lagoon facies. Abundant tests of delicate benthonic Foraminifera are in a calcite matrix. This matrix appears to have recrystallized from an original mud. Rounded fragments of encrusting Foraminifera and segments of algae represent elements that may have undergone transport.



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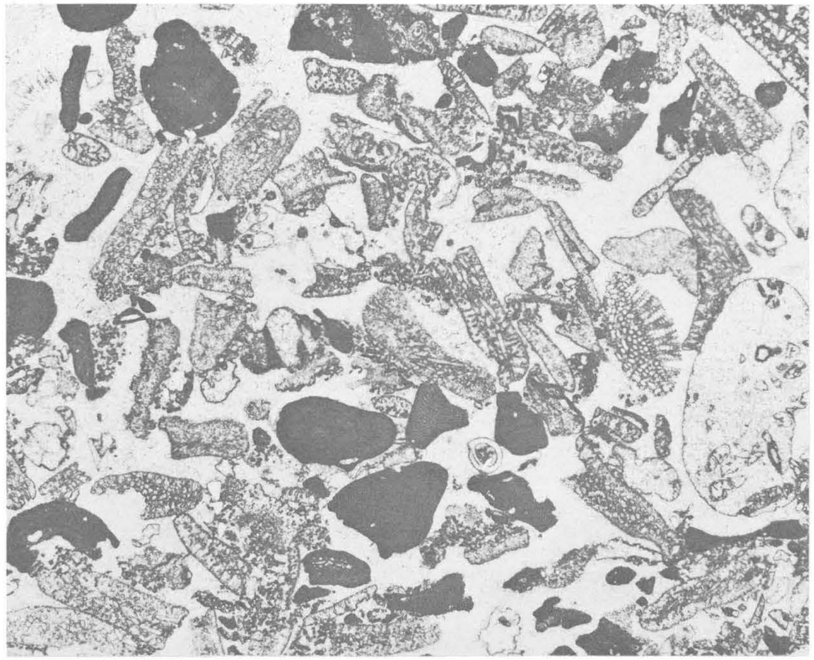

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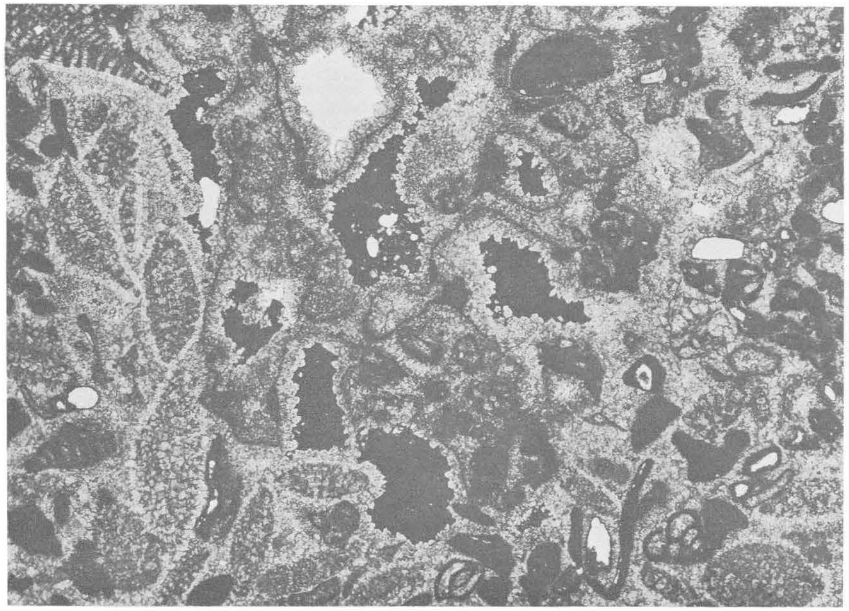

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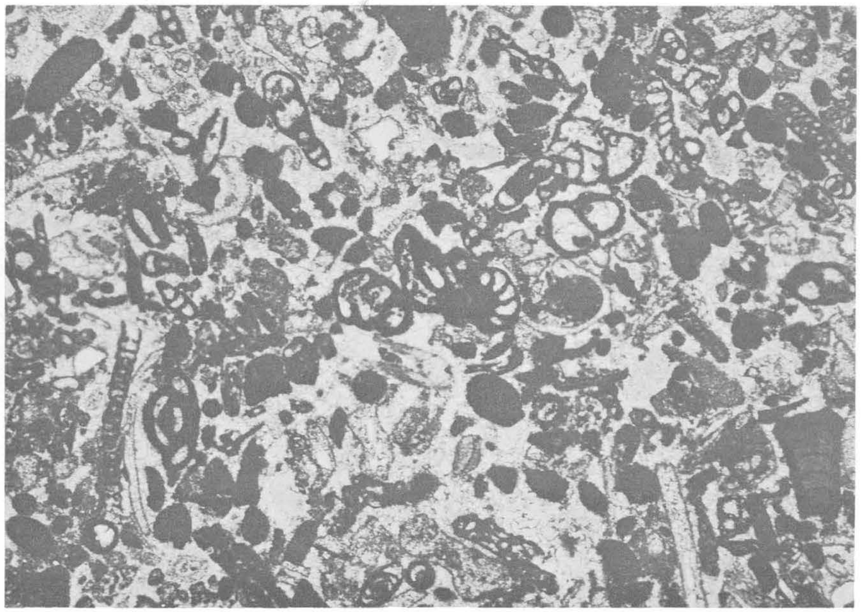


D

SAMPLES FROM THE REEF-WALL AND LAGOON FACIES OF THE MAEMONG LIMESTONE MEMBER OF THE UMATAC FORMATION

PLATE 11

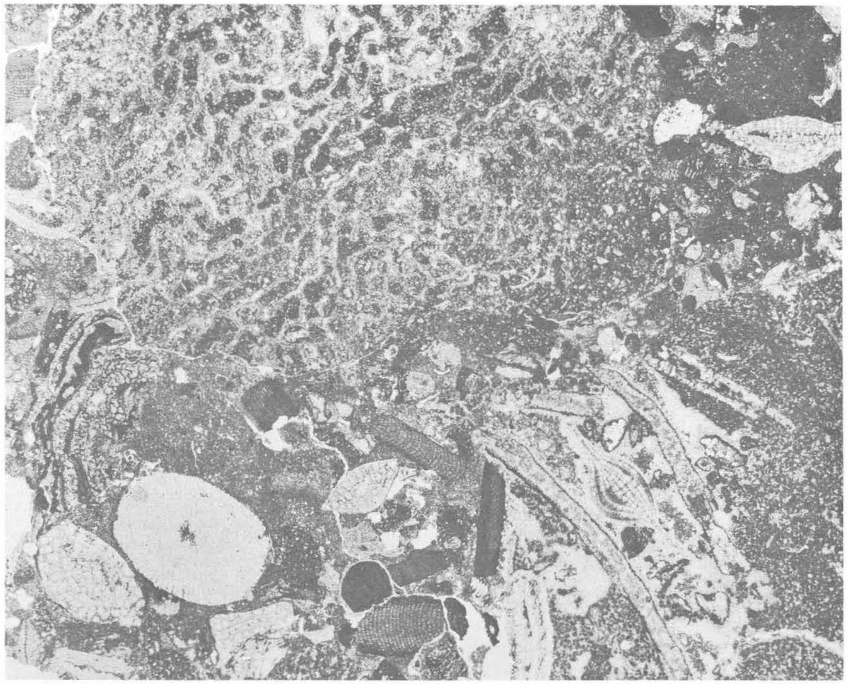
A. Sample Ed 6–1, × 8. Poorly sorted coral breccia in which coral fragments, pieces of foraminiferal-algal encrustations from pre-extant limestones, discoidal Foraminifera tests, *Halimeda,* and other algal debris are abundant. The encrusting algae and Foraminifera perform no binding function; these are present only as particulate elements. This unsorted debris is in a fine-grained matrix.

B. Sample Ef 2–1, × 6. Foraminiferal-algal breccia from the forereef facies. Worn and broken tests of very large discoidal Foraminifera dominate this poorly sorted limestone; fragments of coralline algae are subordinate. The discoidal tests show a preferred orientation parallel to the largest test in the photomicrograph. The fragmentation of such large tests suggests vigorous transport.

C. Sample Ee 7–1, × 12. Algal-foraminiferal microcoquinite of the forereef facies. This limestone shows definite effects of mechanical sorting. In addition to clastic detritus, such as the abundant coralline algae derived from relatively shallow water sources, the rock carries some planktonic tests of globigerinid Foraminifera.

D. Sample Dh 11–3, × 8. Foraminiferal microbreccia from the forereef transition facies. Lenses and strings of benthonic detritus are scattered through a fine-grained mud matrix in which float numerous well-preserved tests of globigerinid and globorotalid Foraminifera.

E. Sample Df 9–1a, × 20. Globigerinid-globorotalid mudstone from the basinal facies. Abundant tests of plantonic Foraminifera float in a relatively pure mud matrix; a small percentage of fine-grained volcanic material is present. No trace of reef-derived debris is seen in these well-bedded limestones.



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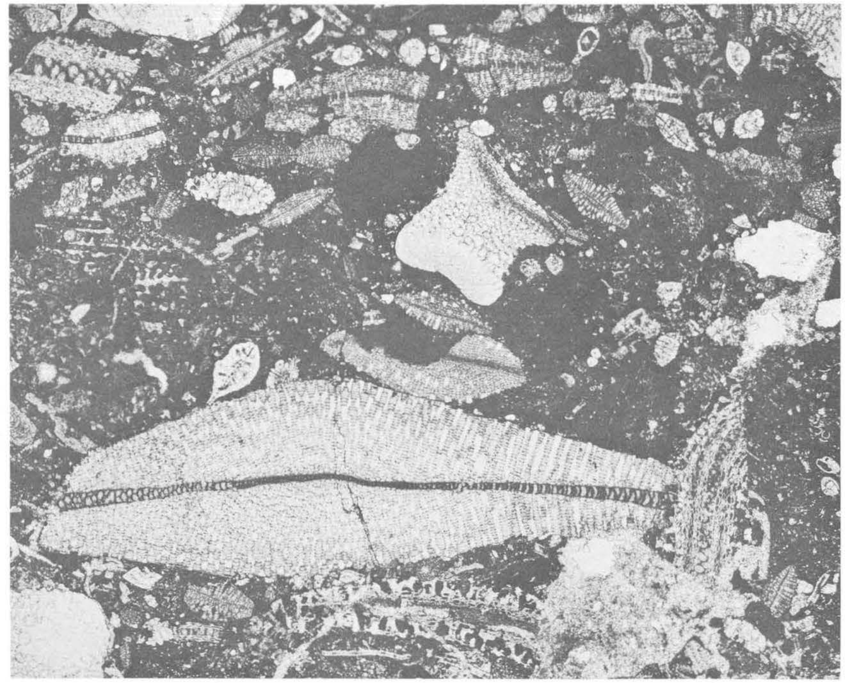

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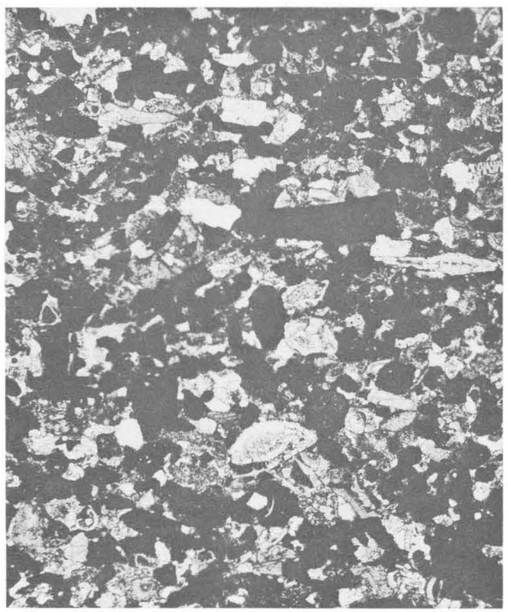

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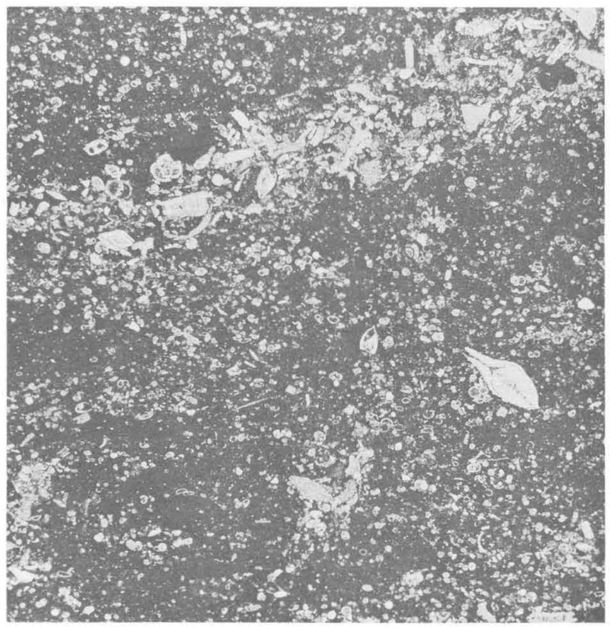

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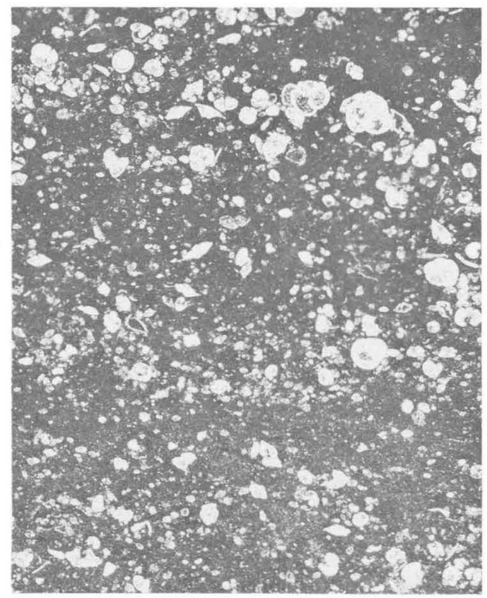


E

SAMPLES FROM THE FOREREEF AND BASIN FACIES OF THE MAEMONG LIMESTONE MEMBER OF THE UMATAC FORMATION

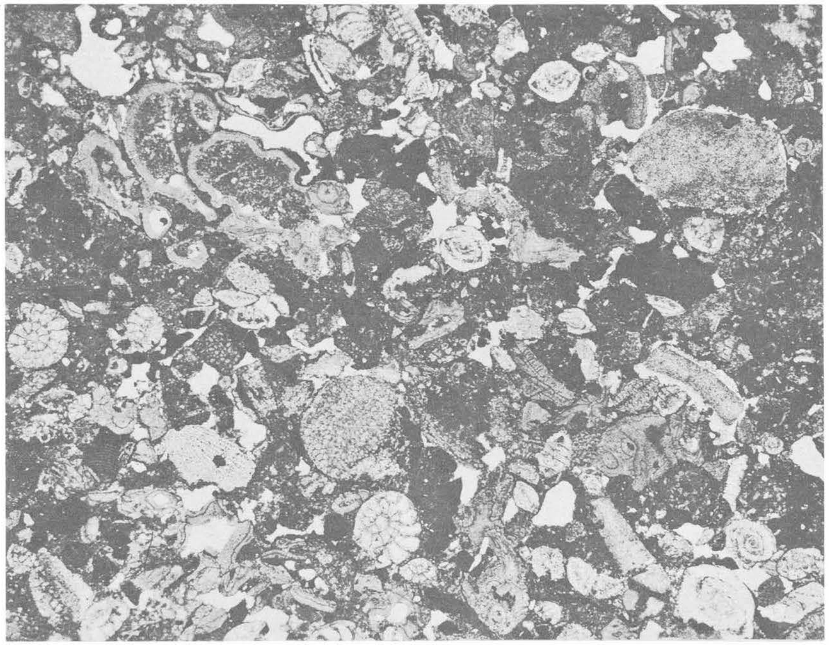
PLATE 12

A. Sample Fi 5–1, × 8. Foraminiferal-algal coquinite from the forereef facies. Worn and broken tests of small and large thick-walled Foraminifera, mainly amphisteginids and subordinate amounts of *Lepidocyclina* and operculinids are characteristic, together with fragments of incrusting and articulate types. Echinoidal debris is common. These fossil elements are closely packed in a matrix of fine-grained fossil debris and a little dark mud. Primary porosity in the form of open cells in Foraminifera tests is largely preserved; solution of the matrix has produced some secondary porosity.

B. Sample Ih 10–1, × 8. Foraminiferal-algal micrococquinite from the forereef facies. Small thick-walled tests of amphisteginids and algal debris dominate. The fossil elements show the effect of wear and breakage. Rounded, completely weathered grains of fine-grained volcanic rocks are present; these are in the same size grades as the fossil material and probably underwent transport along with the fossils. (See pls. 8*B* and 11*C* for similar limestones from the Alutom Formation and the Maemong Limestone Member.)

C. Sample Jj 9–1, × 14. Foraminiferal-algal microparacoquinite from the forereef transition facies. In this facies, tests of globigerinid Foraminifera are common in contrast to the forereef facies in which these planktonic tests are lacking. These tests and sorted algal and foraminiferal debris are in a mud matrix. In this limestone, the matrix is dominant over the fossil material in contract to the coarser grained limestones described above, in which the fossil elements form an intact framework.

D. Sample Jj 9–2, × 14. Foraminiferal paracoquinite of the off-reef deep-water facies. Benthonic Foraminifera of great diameter relative to thier thickness are common. These fossils locally show a high degree of alinement in preferred orientation. These tests and finer debris of Foraminifera and algae are in a porous matrix of partly recrystallized mud.



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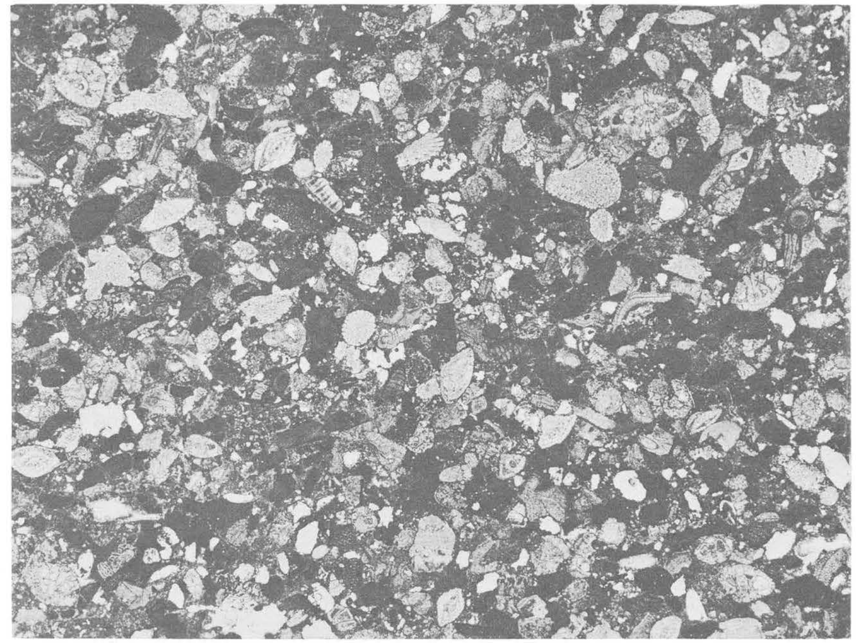

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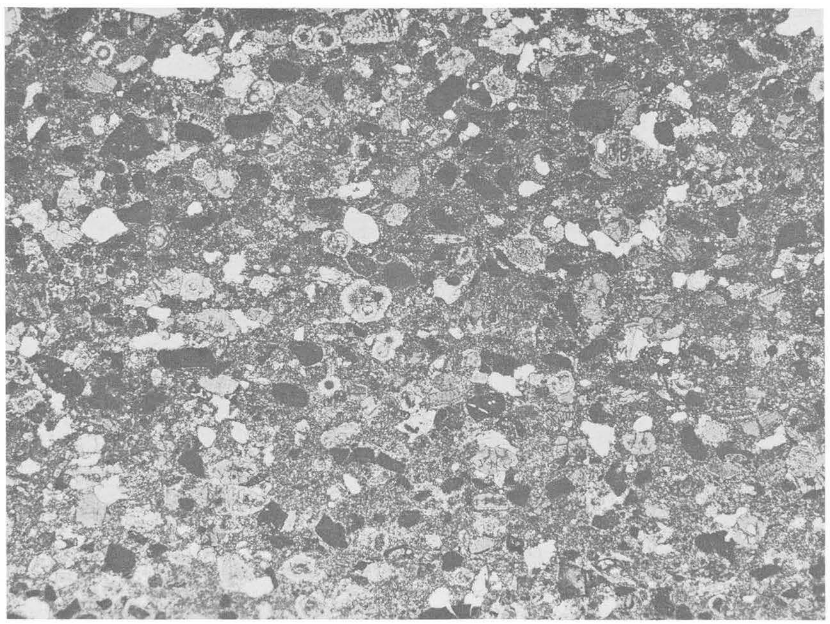

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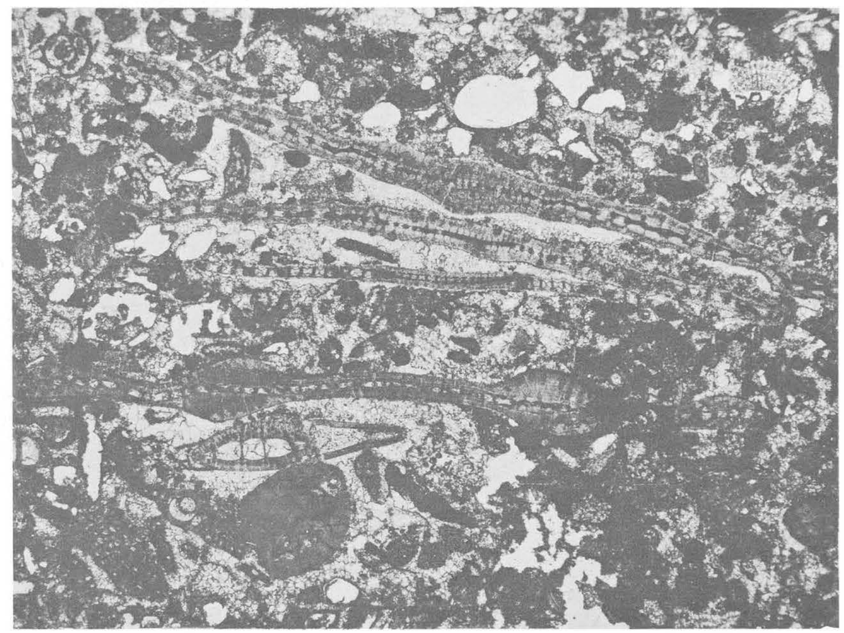

D

SAMPLES OF THE BONYA LIMESTONE

PLATE 13

A. Sample Rr 13–1, × 8. Foraminiferal mudstone of the off-reef deep-water facies. Broken tests of *Cycloclypeus*, whole tests of amphisteginids, and rare *Lepidocyclina* are loosely packed and float in a mud matrix. Rare fragments of pelecypod shells are present. Common, but not shown in the photomicrograph, are nodular masses of encrusting Foraminifera, probably *Gypsina*. The position of many broken fragments of *Cycloclypeus* tests indicates that these thin fossils broke after burial. Throughout the thin section these tests show a tendency towards parallel alinement. The lack of reef detritus suggests the absence of a nearby upslope reef wall. This limestone is interpreted as having accumulated on a submarine bank too deep for reef growth and too shallow for deposition of planktonic Foraminifera in any abundance.

B. Sample Gi 4–2, × 8. Rounded pebble of the Maemong Limestone Member (dark area to the right) in a matrix of Bonya Limestone. These included pebbles are a common feature of the Bonya Limestone. They are probably derived from the Bolanos Pyroclastic Member as fragments, rather than directly from outcrops of the Maemong Limestone Member.

C. Sample Ih 5–3, × 25. Manganese oxides in the Bonya Limestone. Black and brown manganese oxides have partly replaced the fine-grained matrix of this limestone. Thin films of these oxides have also been deposited along cell walls and in perforations of Foraminifera tests.

D. Sample Ih 5–3, × 25. Advanced stage of replacement by manganese oxides. The echinoid-spine has been infiltered by black metallic oxides. The black area below and to the right of the spine has been massively replaced. This deposit cuts across grain boundaries. The ragged edge shown by the Foraminifera tests below the echinoid spine is the result of replacement.

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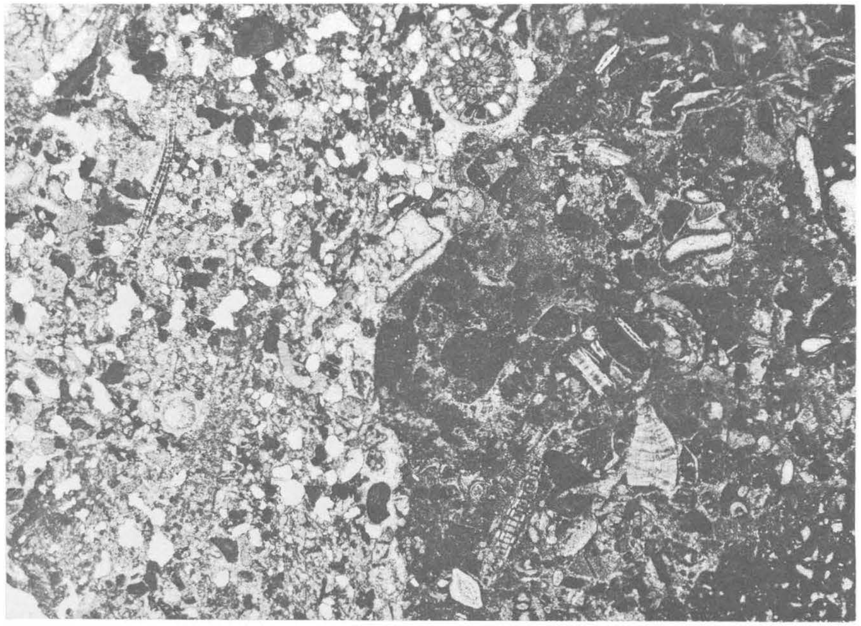

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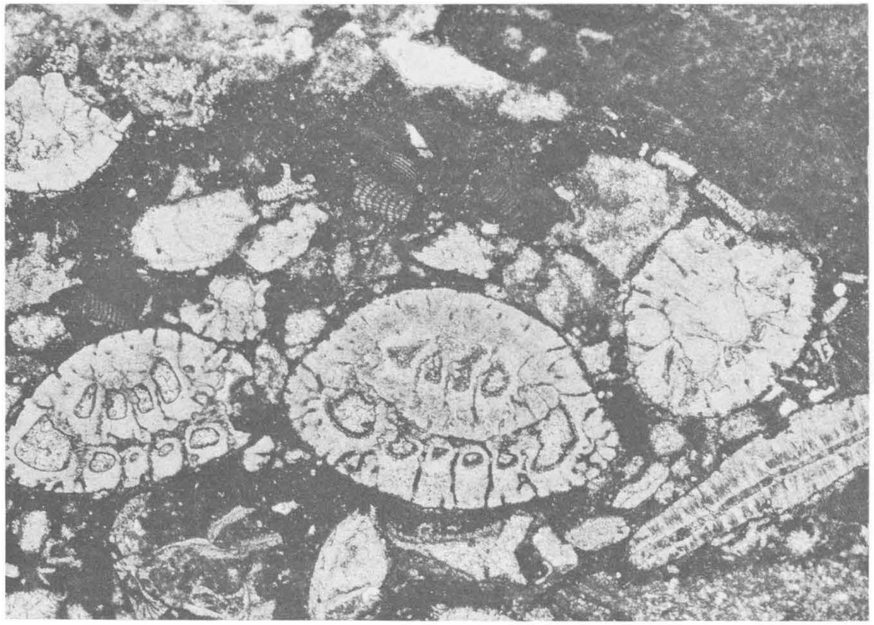

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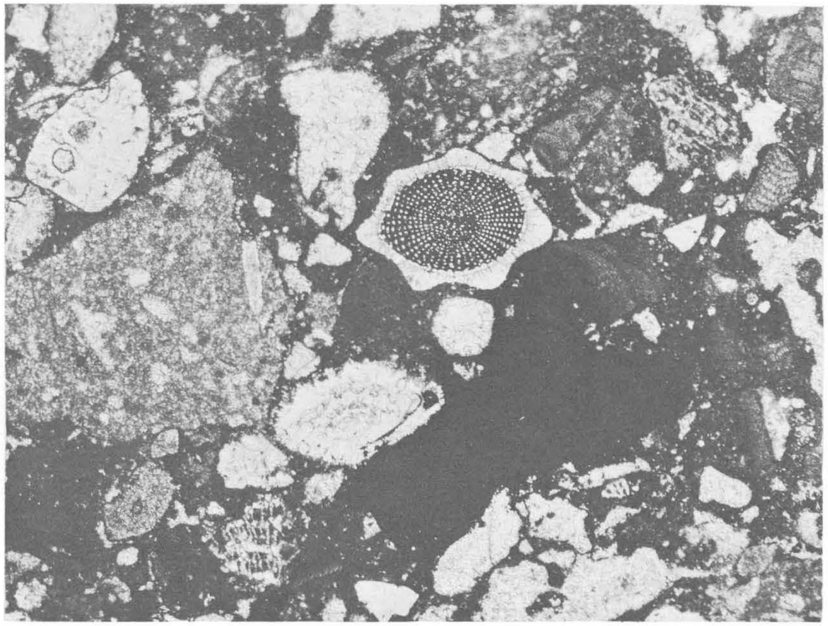

D

SAMPLES OF THE BONYA LIMESTONE

PLATE 14

A. Sample Tt 7–3, × 6. Algal incrustate limestone from the reef-wall facies. Thick interlaminations of encrusting algae and encrusting Foraminifera are cut by fractures along which separation of the rock framework has taken place. The texture of this limestone is directly comparable to incrustate rocks from the Alutom Formation (pl. 7*A*); the Maemong Limestone Member (pl. 10*A*); the Mariana Limestone (pl. 18*B*). Alterations of algae and Foraminifera bind detritus. Some of the fractures show lateral separations, in the plane of the thin section, as much as several millimeters in width. The separated laminae show sharp edges that can be matched across the fractures. These fractures are filled by sand-size foraminiferal debris. Where the fracture filling is mud, some recrystallization has converted the fine-grained clastic material into clear anhedral mosaic calcite.

B. Sample Ts 16–11, × 12. Foraminiferal microparacoquinite from the off-reef shallow-water facies dominated by tests of *Rotalia*. These tests and a few rounded fragments of encrusting algae and encrusting Foraminifera are packed in a matrix of fine sand and dark mud that has undergone recrystallization. The white area in the upper part of the photomicrograph had its matrix entirely recrystallized. (See pl. 10*C* for an example of this in the Maemong Limestone Member.)

C. Sample Dh 13–1, × 8. Molluscan coquinoid limestone from the lagoon facies. Completely recrystallized shells of gastropods and pelecypods, *Halimeda* segments, and coral fragments are in a sand and mud matrix. Also present are well-preserved tests of miliolid Foraminifera. The shell-matrix contacts are vague and transitional; the entire thin section appears faded and washed-out owing to intense recrystallization. The original constituents have not been subjected to winnowing action by currents; the rock is poorly sorted.

D. Sample Eh 3–2, × 10. Foraminiferal microcoquinite. Sand-size fragments of articulate and encrusting algae, encrusting Foraminifera, and shell debris are in a matrix of clear microcrystalline calcite. Also present are well-preserved tests of large *Rotalia* and small miliolid tests.

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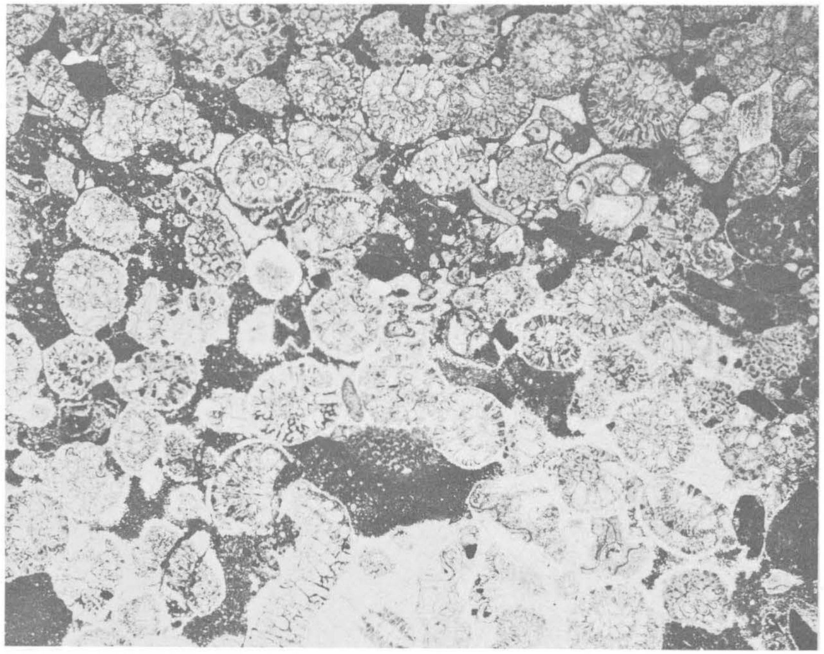

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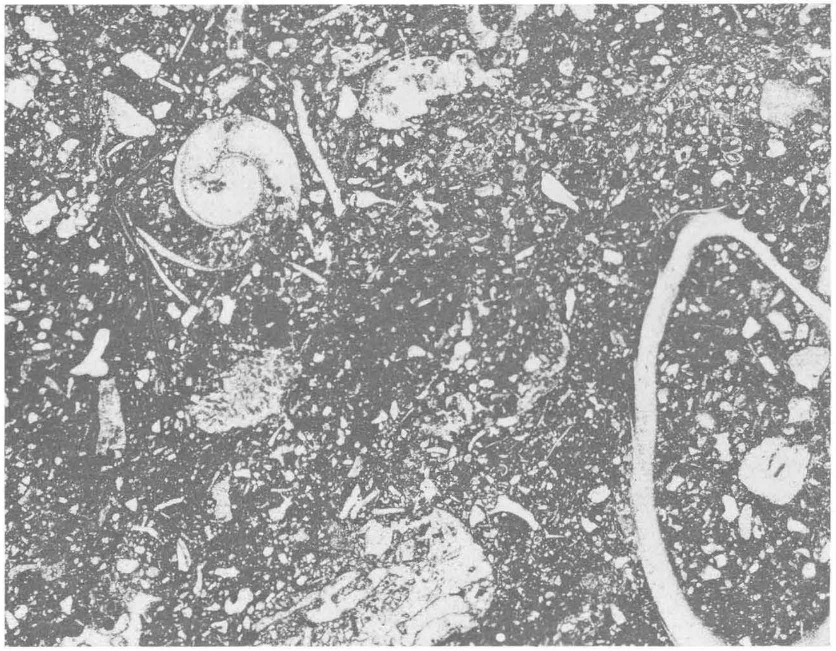

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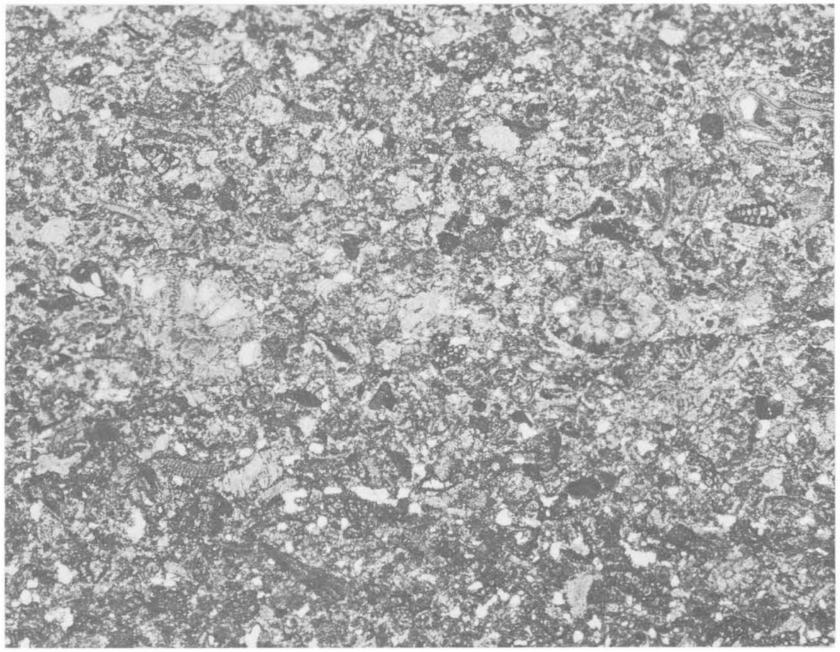


D

SAMPLES OF THE ALIFAN LIMESTONE

PLATE 14

A. Sample Tt 7–3, × 6. Algal incrustate limestone from the reef-wall facies. Thick interlaminations of encrusting algae and encrusting Foraminifera are cut by fractures along which separation of the rock framework has taken place. The texture of this limestone is directly comparable to incrustate rocks from the Alutom Formation (pl. 7*A*); the Maemong Limestone Member (pl. 10*A*); the Mariana Limestone (pl. 18*B*). Alterations of algae and Foraminifera bind detritus. Some of the fractures show lateral separations, in the plane of the thin section, as much as several millimeters in width. The separated laminae show sharp edges that can be matched across the fractures. These fractures are filled by sand-size foraminiferal debris. Where the fracture filling is mud, some recrystallization has converted the fine-grained clastic material into clear anhedral mosaic calcite.

B. Sample Ts 16–11, × 12. Foraminiferal microparacoquinite from the off-reef shallow-water facies dominated by tests of *Rotalia*. These tests and a few rounded fragments of encrusting algae and encrusting Foraminifera are packed in a matrix of fine sand and dark mud that has undergone recrystallization. The white area in the upper part of the photomicrograph had its matrix entirely recrystallized. (See pl. 10*C* for an example of this in the Maemong Limestone Member.)

C. Sample Dh 13–1, × 8. Molluscan coquinoid limestone from the lagoon facies. Completely recrystallized shells of gastropods and pelecypods, *Halimeda* segments, and coral fragments are in a sand and mud matrix. Also present are well-preserved tests of miliolid Foraminifera. The shell-matrix contacts are vague and transitional; the entire thin section appears faded and washed-out owing to intense recrystallization. The original constituents have not been subjected to winnowing action by currents; the rock is poorly sorted.

D. Sample Eh 3–2, × 10. Foraminiferal microcoquinite. Sand-size fragments of articulate and encrusting algae, encrusting Foraminifera, and shell debris are in a matrix of clear microcrystalline calcite. Also present are well-preserved tests of large *Rotalia* and small miliolid tests.

PLATE 15

A. Samples Pv 10–2, × 8. Foraminiferal mudstone of the off-reef deep-water facies containing tests of *Cycloclypeus*, *Amphistegina*, and *Operculinoides*. Almost all these large tests show considerable wear and breakage; an encrusting type, *Gypsina*, is present only in fragments and does not bind detritus. These tests are in a recrystallized mud matrix. A trace of well-preserved to worn tests of miliolids and globigerinid Foraminifera is present. The porosity is low and is largely secondary owing to subaerial solution of the original mud matrix. The globigerinid tests are little altered and show pseudo-uniaxial crosses in polarized light. The abundance of *Cycloclypeus* coupled with the lack of reef detritus precludes a reef or forereef origin. The limestone was probably deposited on a submarine bank in water several hundreds of feet deep.

B. Sample Nr 1–7a, × 25. Friable micrococquinite. Most of the specimen is an aggregate of subangular to rounded grains of unidentifiable debris, probably of organic origin. The detritus shows a high degree of sorting that cannot be ascribed to inherent size of the material. The particles are loosely cemented in a matrix of fine-grained clear anhedral calcite.

C. Sample St 8–1, × 12. Porous foraminiferal microparacoquinite. Debris of amphisteginids, operculinids, and encrusting *Gypsina* and *Carpenteria* is in a matrix similar to (but somewhat porous due to solution) that of sample Pv 10–2 (pl. 15*A*). Whole *Cycloclypeus* tests are lacking; fragments are rare.

PLATE 16

A. Sample Ts 5–7, × 20. Microparacoquinite from the basin facies, composed mainly of tightly packed whole and fragmental tests of globigerinid Foraminifera. Test fragments show a preferred orientation parallel to fine laminae, several millimeters thick, produced by streaks and lenses of fine-grained debris. The tests, and a small percentage of volcanic material, are in a mud matrix. Many cells in the large unbroken tests are empty, but the majority are filled with matrixlike material. Volcanic material is present as clay and a few single crystals of magnetite, feldspar, and ferromagnesian minerals. The high content of broken tests appears to be due to crushing and flattening. The faunal assemblage indicates a depth of deposition of 100 to 1,500 fathoms, probably towards the shallow end of this range.

B. Sample Ts 5–9, × 8. Foraminiferal microparacoquinite from the basin facies. Tests of amphisteginid and globigerinid Foraminifera and a trace of *Cycloclypeus* test fragments are loosely packed in a mud matrix. The amphisteginid tests show preferred orientation parallel to the bedding. The worn amphisteginid and broken *Cycloclypeus* tests indicate some transport of material. The high content of amphisteginids in this sample indicates a depth of deposition possibly as shallow as 40 to 100 fathoms; the abundant globigerinids suggest the lack of any barrier to the circulation of oceanic currents.

C. Sample Ts 5–12, × 27. Argillaceous foraminiferal microparacoquinite from the basin facies. Abundant well-preserved tests of globigerinids float in a mud matrix that also encloses abundant volcanic material in the form of deeply weathered single crystals and sand-size fragments of fine-grained crystalline rocks.

D. Sample Rr 9–1, × 8. Pebbles of the Bonya Limestone in the Janum Formation. The pebbles are white pure limestone whereas the enclosing Janum Formation sediments are pink to red and contain disseminated volcanic clay.

PLATE 17

A. Sample Jj 6–1, × 20. Molluscan micrococquinoid limestone from the lagoon facies. Completely recrystallized small gastropod shells and disarticulated valves of pelecypods float in a fine-grained detrital matrix containing algal and foraminiferal debris. A trace of well-preserved miliolids and coiled Foraminifera tests, possibly a life assemblage, is present. Recrystallization has reduced the shells to anhedral mosaic calcite. The primary porosity of the rock was undoubtedly low, but solution of shell fragments and patches of the matrix has resulted in secondary porosity.

B. Sample Uu 3–1, × 25. Foraminiferal micrococquinite from the forereef facies. This porous friable limestone is made up almost entirely of worn tests of *Calcarina*, *Amphistegina*, and *Marginopora*, that are loosely packed with a trace of echinoid spines. Each test is coated with a thin layer of clear granular calcite that serves as a weak cement; tests can be easily rubbed from the rock. The rock shows a high degree of biologic sorting owing to the inherent size of the tests.

C. Sample Po 1–2, × 17. *Halimeda* paracoquinite from the lagoon facies. Disjointed segments of the green alga, *Halimeda*, ranging in width from 2 to 8 mm, make up much of the rock. Traces of articulate and encrusting algae, tests of shallow-water Foraminifera, and fragments of molluscan remains constitute the remainder of the fossils. The state of preservation of the *Halimeda* and their relationship to the matrix varies within a single thin section. The area covered by the photomicrograph shows *Halimeda* segments, originally aragonite, that are now fine-grained mosaic calcite within which the original organic structures are well preserved as darker gray areas. These segments, and the other fossil elements, are in a crystalline calcite matrix, the result of the recrystallization of an original mud matrix. In other parts of the thin section, calcite-coated segments are in a matrix of banded fibrous aragonite and late-stage granular calcite, which is the result of carbonate deposition within what must have been an open-work gravel of *Halimeda*. Some segments retain a light brown color and are still composed of cryptocrystalline aragonite; many have been completely removed by solution and leave *Halimeda*-shaped voids in the matrix.

D. Sample Rr 16–1, × 17. Foraminiferal breccia from the forereef facies containing worn and broken tests of *Cycloclypeus*. These large tests and lesser amounts of all the fossil groups considered are randomly oriented in a sand-size matrix that contains angular debris of the same fossil types. The rock shows high porosity, mainly secondary, due to solution. The fossil content and texture of this limestone resemble that of material dredged from the outer slopes of Bikini Atoll at depths ranging from 580 to 800 feet.

PLATE 18

A. Sample Rx 19–1, × 20. Recrystallized corallum. The originally aragonitic corallum, and an interseptal carbonate filling, have recrystallized into medium-grained anhedral mosaic calcite. The outline of the original skeletal material is preserved in a jigsaw-shaped pattern visible as cloudy darker calcite against the clear lighter calcite of the interseptal filling. There is some tendency for the calcite within the cloudy areas to remain as a distinct crystal, optically discontinuous, separated from the crystals in the filling. However, most of the crystal boundaries cross the corallum-interseptal filling boundaries. Between crossed nicols the corallum-interseptal filling boundaries are partially obscured by the large continuous crystals. The limestone has virtually no porosity at present, in contrast to what originally was an extremely porous coral structure.

B. Sample Tw 7–1, × 3. Coral-algal incrustate limestone from the reef-wall facies. Thick laminar masses of encrusting algae coat and bind recrystallized mud-filled coral. Caught within the algal laminae are tests of *Marginopora*, *Halimeda* segments, and other reef debris. A few lighter colored laminae of encrusting Foraminifera contribute to the cementing mass. *Halimeda* segments are abundant in the detritus surrounding the coral-algal mass. Anhedral, clear, mosaic calcite fills much of the original void space. Some of these void spaces were partially filled by fine detritus; the upper surfaces of these deposits are parallel throughout the slide as well as parallel to the upper surface of the algal colony. This parallism is indicative of mud filling of the reef limestone during reef growth.

C. Sample Kr 2–3, × 3. Coral breccia from the lagoon facies. Poorly sorted large fragments of algal- and foraminiferal-encrusted coral, echinoid spines and plates, *Halimeda* segments, pelecypod shells, and tests of smaller discoidal Foraminifera are in a porous medium-grained matrix.

PLATE 19

A. Coral-algal incrustate limestone from reef-wall facies, × 8. This sample is identical to Hi 3–4 from the Maemong Limestone Member (pl. 10*A*). Fossil elements include mud-filled algal-encrusted coral, disjointed *Halimeda*, alga detritus, and tests of Foraminifera. Much of the detritus between the coral is in a fine-grained mud matrix. Cores from this facies show coral heads in growth position (Forman and Schlanger, 1957).

B. Coral breccia from the forereef facies, × 8. This limestone has an equivalent in sample Ed 6–1 from the Maemong Limestone Member (pl. 11*A*). Many of the fossil elements in this material are also common to rocks from the reef-wall facies. However, all the components are detrital in the forereef facies. Cores from this facies show characteristic bedding.

C. Foraminiferal-algal microparacoquinite from the off-reef facies, × 8. Tests of large *Heterostegina* and some miogypsinids dominate; fragments of coralline algae are also present. This limestone is equivalent to that represented by sample Hi 4–5 from the Maemong Limestone Member (pl. 10*C*).

D. Foraminiferal mudstone from the forereef transition facies, × 8, containing tests of large benthonic lepidocyclinids and small planktonic globigerinids that float in a matrix of fine-grained detritus and mud. The discoidal tests of the large Foraminifera show a high degree of parallelism. This material is comparable to rock from the bedded forereef transition facies of the Maemong Limestone Member (pl. 11*D*).

PLATE 20

The limestones of Oligocene age from the forereef facies at Kirkuk, Iraq, are comparable to (1) samples Ek 7–2 (pl. 8*A*) and Ek 7–3 (pl. 8*B*) from bedded limestones of Eocene (*b*) age in the Alutom Formation, (2) samples Ef 2–1 and Ee 7–1 from bedded sections of the Maemong Limestone Member (pl. 11*B*, *C*), and (3) bedded sections of the Bonya Limestone (pl. 12*B*).

A. Limestone from the reef-wall facies, × 8. This limestone is considered equivalent to rock from southern Louisiana (pl. 19*A*), the Maemong Limestone Member (pl. 10*A*), and limestone from the Alutom Formation (pl. 7*A*).

B. Foraminiferal microparacoquinite from the lagoon facies, × 20. This fine-grained miliolid-rich rock is directly comparable to material from the Maemong Limestone Member (pl. 10*D*) and limestone from the Alutom Formation (pl. 7*C*).

C. Foraminiferal microbreccia from the forereef facies, × 8.

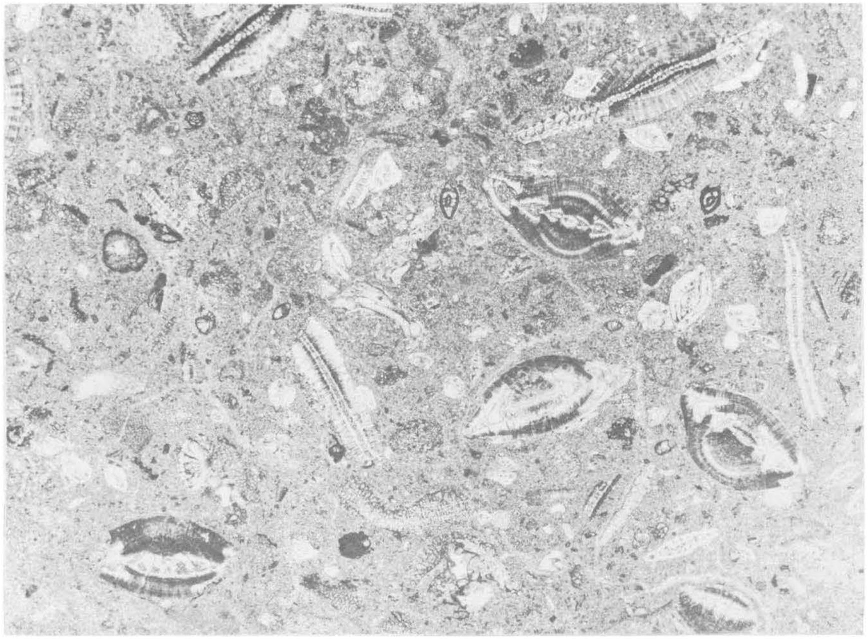
D. Foraminiferal microbreccia from the forereef facies, × 8.

PLATE 15

A. Samples Pv 10–2, × 8. Foraminiferal mudstone of the off-reef deep-water facies containing tests of *Cycloclypeus*, *Amphistegina*, and *Operculinoides*. Almost all these large tests show considerable wear and breakage; an encrusting type, *Gypsina*, is present only in fragments and does not bind detritus. These tests are in a recrystallized mud matrix. A trace of well-preserved to worn tests of miliolids and globigerinid Foraminifera is present. The porosity is low and is largely secondary owing to subaerial solution of the original mud matrix. The globigerinid tests are little altered and show pseudo-uniaxial crosses in polarized light. The abundance of *Cycloclypeus* coupled with the lack of reef detritus precludes a reef or forereef origin. The limestone was probably deposited on a submarine bank in water several hundreds of feet deep.

B. Sample Nr 1–7a, × 25. Friable micrococquinite. Most of the specimen is an aggregate of subangular to rounded grains of unidentifiable debris, probably of organic origin. The detritus shows a high degree of sorting that cannot be ascribed to inherent size of the material. The particles are loosely cemented in a matrix of fine-grained clear anhedral calcite.

C. Sample St 8–1, × 12. Porous foraminiferal microparacoquinite. Debris of amphisteginids, operculinids, and encrusting *Gypsina* and *Carpenteria* is in a matrix similar to (but somewhat porous due to solution) that of sample Pv 10–2 (pl. 15*A*). Whole *Cycloclypeus* tests are lacking; fragments are rare.



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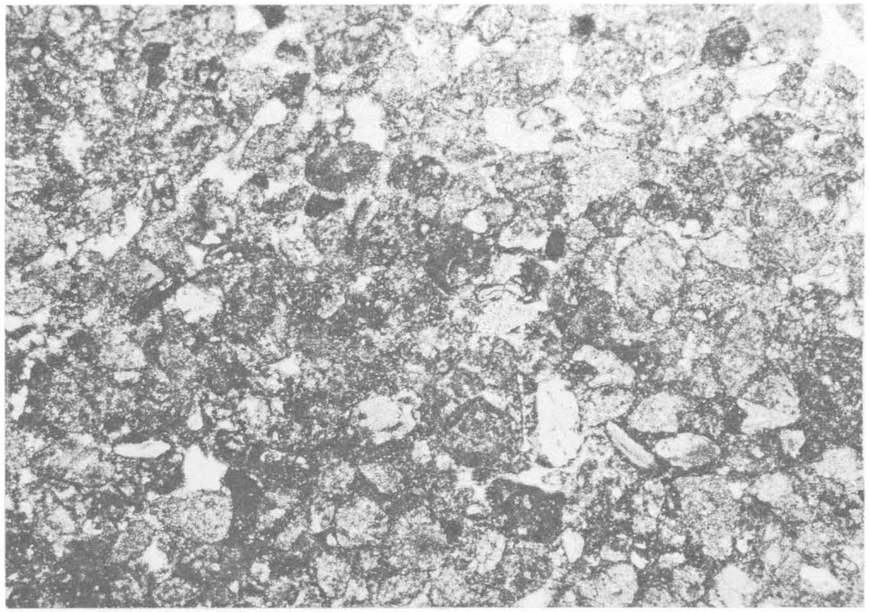

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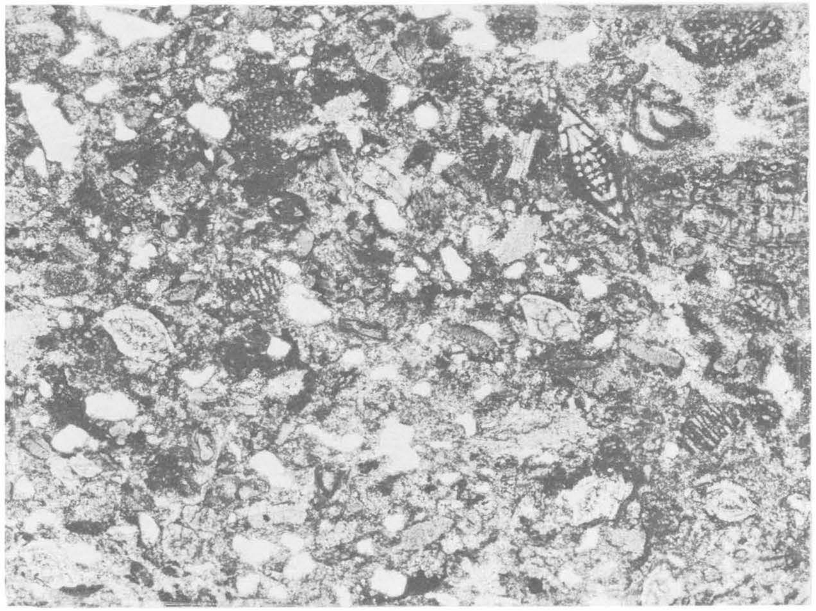


C

SAMPLES OF THE BARRIGADA LIMESTONE

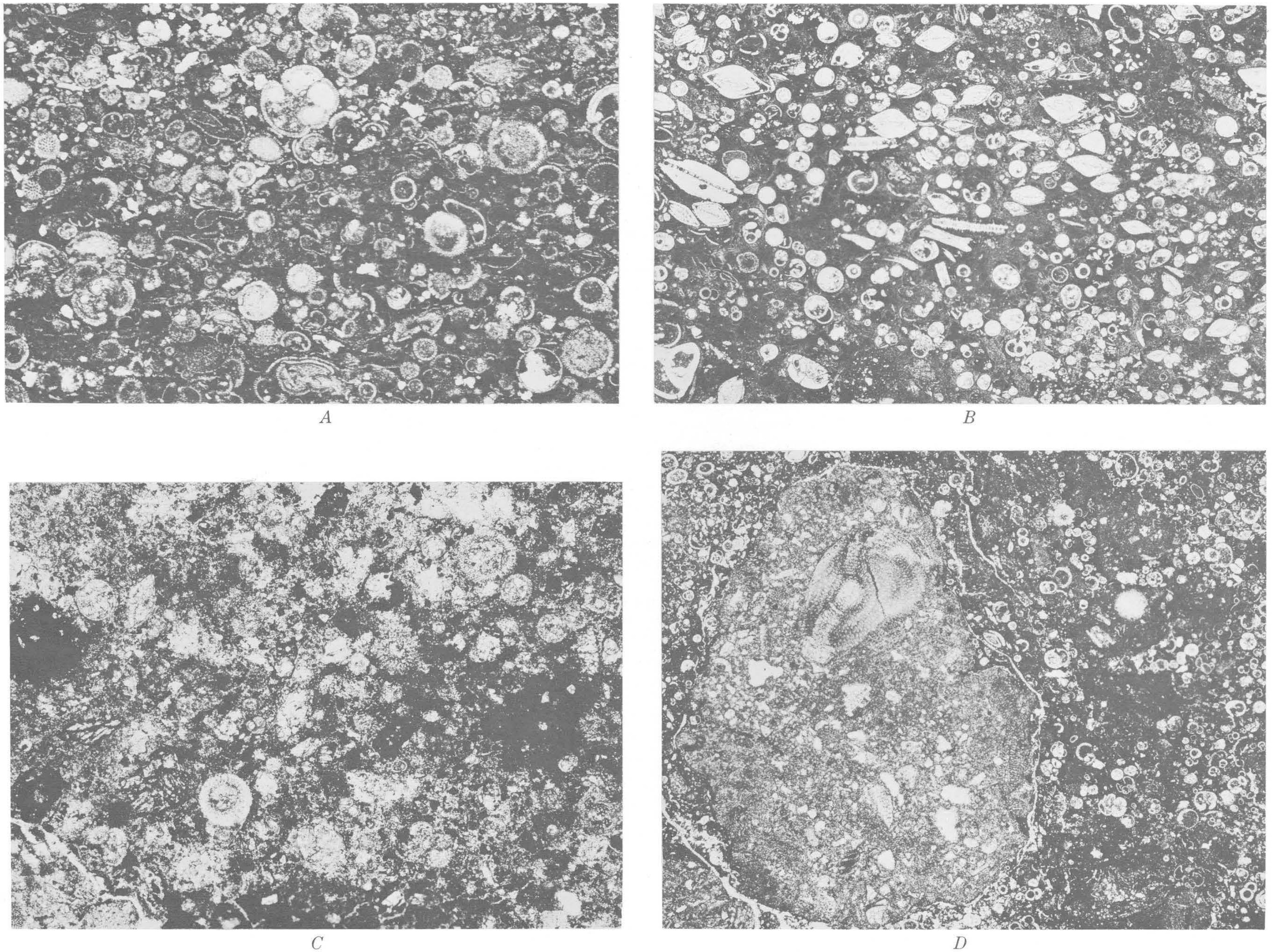
PLATE 16

A. Sample Ts 5–7, × 20. Microparacoquinite from the basin facies, composed mainly of tightly packed whole and fragmental tests of globigerinid Foraminifera. Test fragments show a preferred orientation parallel to fine laminae, several millimeters thick, produced by streaks and lenses of fine-grained debris. The tests, and a small percentage of volcanic material, are in a mud matrix. Many cells in the large unbroken tests are empty, but the majority are filled with matrixlike material. Volcanic material is present as clay and a few single crystals of magnetite, feldspar, and ferromagnesian minerals. The high content of broken tests appears to be due to crushing and flattening. The faunal assemblage indicates a depth of deposition of 100 to 1,500 fathoms, probably towards the shallow end of this range.

B. Sample Ts 5–9, × 8. Foraminiferal microparacoquinite from the basin facies. Tests of amphisteginid and globigerinid Foraminifera and a trace of *Cycloclypeus* test fragments are loosely packed in a mud matrix. The amphisteginid tests show preferred orientation parallel to the bedding. The worn amphisteginid and broken *Cycloclypeus* tests indicate some transport of material. The high content of amphisteginids in this sample indicates a depth of deposition possibly as shallow as 40 to 100 fathoms; the abundant globigerinids suggest the lack of any barrier to the circulation of oceanic currents.

C. Sample Ts 5–12, × 27. Argillaceous foraminiferal microparacoquinite from the basin facies. Abundant well-preserved tests of globigerinids float in a mud matrix that also encloses abundant volcanic material in the form of deeply weathered single crystals and sand-size fragments of fine-grained crystalline rocks.

D. Sample Rr 9–1, × 8. Pebbles of the Bonya Limestone in the Janum Formation. The pebbles are white pure limestone whereas the enclosing Janum Formation sediments are pink to red and contain disseminated volcanic clay.



A B C D

SAMPLES OF THE JANUM FORMATION

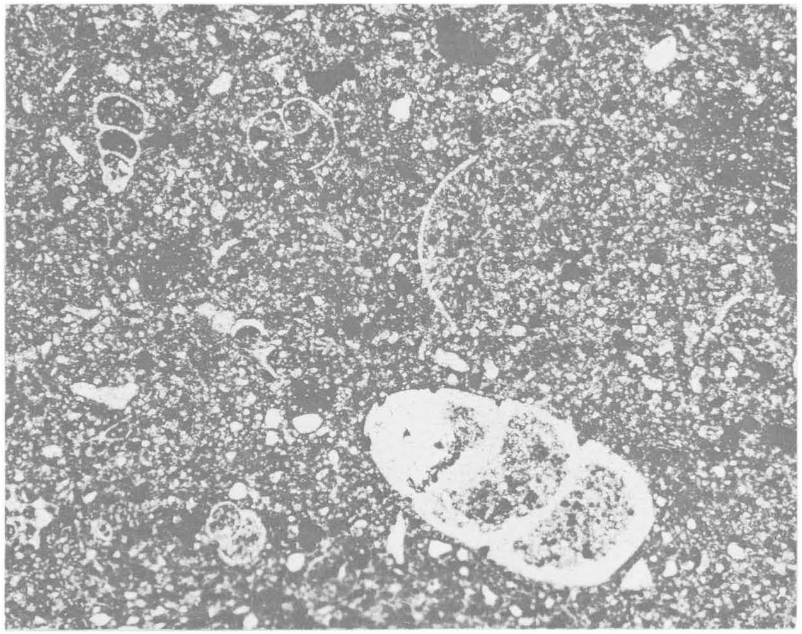
PLATE 17

A. Sample Jj 6–1, × 20. Molluscan microcoquinoid limestone from the lagoon facies. Completely recrystallized small gastropod shells and disarticulated valves of pelecypods float in a fine-grained detrital matrix containing algal and foraminiferal debris. A trace of well-preserved miliolids and coiled Foraminifera tests, possibly a life assemblage, is present. Recrystallization has reduced the shells to anhedral mosaic calcite. The primary porosity of the rock was undoubtedly low, but solution of shell fragments and patches of the matrix has resulted in secondary porosity.

B. Sample Uu 3–1, × 25. Foraminiferal microcoquinite from the forereef facies. This porous friable limestone is made up almost entirely of worn tests of *Calcarina*, *Amphistegina*, and *Marginopora*, that are loosely packed with a trace of echinoid spines. Each test is coated with a thin layer of clear granular calcite that serves as a weak cement; tests can be easily rubbed from the rock. The rock shows a high degree of biologic sorting owing to the inherent size of the tests.

C. Sample Po 1–2, × 17. *Halimeda* paracoquinite from the lagoon facies. Disjointed segments of the green alga, *Halimeda*, ranging in width from 2 to 8 mm, make up much of the rock. Traces of articulate and encrusting algae, tests of shallow-water Foraminifera, and fragments of molluscan remains constitute the remainder of the fossils. The state of preservation of the *Halimeda* and their relationship to the matrix varies within a single thin section. The area covered by the photomicrograph shows *Halimeda* segments, originally aragonite, that are now fine-grained mosaic calcite within which the original organic structures are well preserved as darker gray areas. These segments, and the other fossil elements, are in a crystalline calcite matrix, the result of the recrystallization of an original mud matrix. In other parts of the thin section, calcite-coated segments are in a matrix of banded fibrous aragonite and late-stage granular calcite, which is the result of carbonate deposition within what must have been an open-work gravel of *Halimeda*. Some segments retain a light brown color and are still composed of cryptocrystalline aragonite; many have been completely removed by solution and leave *Halimeda*-shaped voids in the matrix.

D. Sample Rr 16–1, × 17. Foraminiferal breccia from the forereef facies containing worn and broken tests of *Cycloclypeus*. These large tests and lesser amounts of all the fossil groups considered are randomly oriented in a sand-size matrix that contains angular debris of the same fossil types. The rock shows high porosity, mainly secondary, due to solution. The fossil content and texture of this limestone resemble that of material dredged from the outer slopes of Bikini Atoll at depths ranging from 580 to 800 feet.



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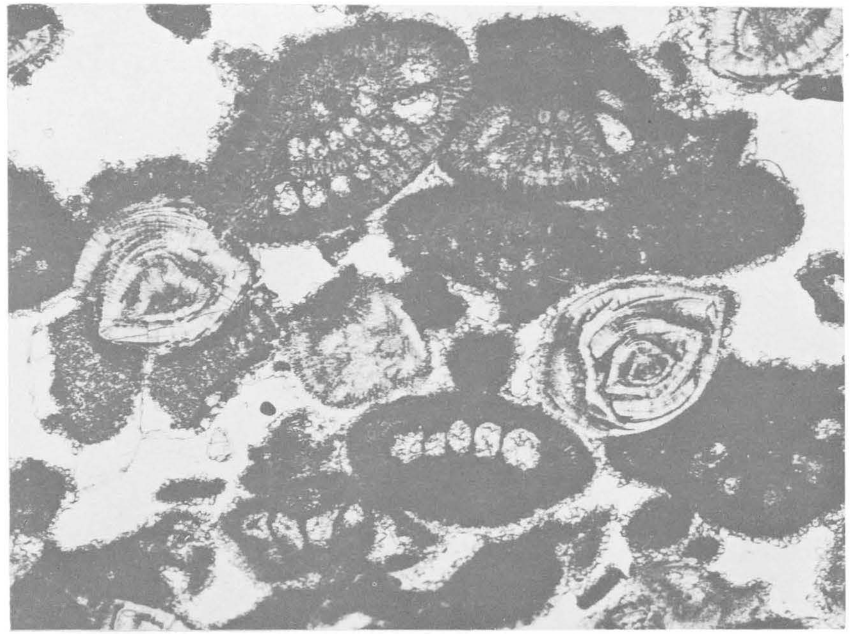

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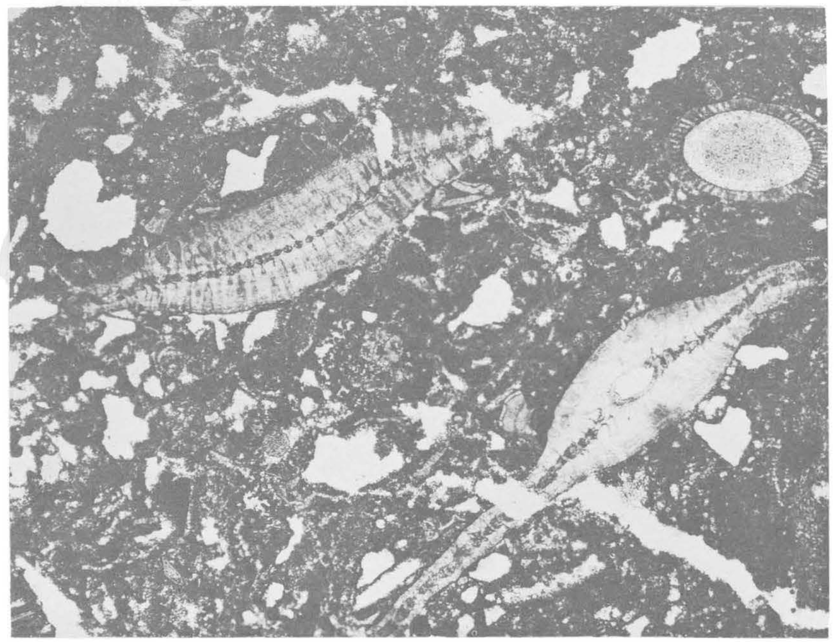


D

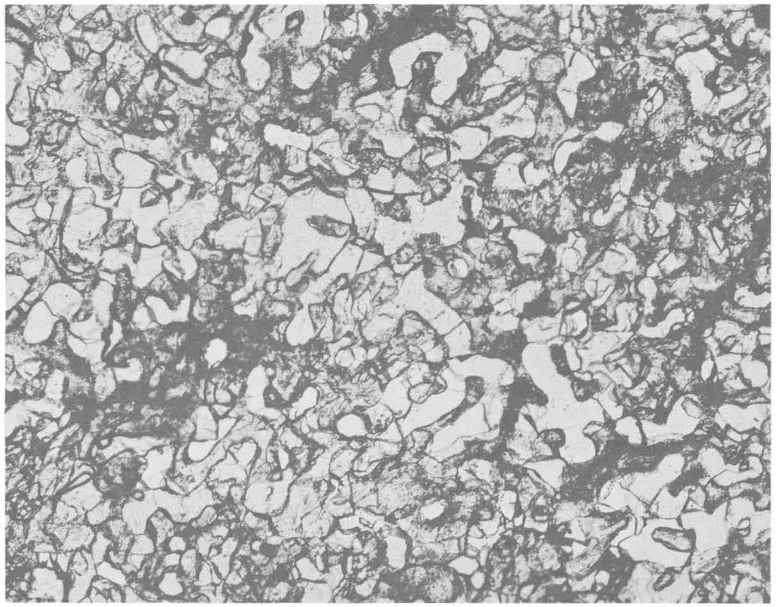
SAMPLES OF THE MARIANA LIMESTONE

PLATE 18

A. Sample Rx 19–1, × 20. Recrystallized corallum. The originally aragonitic corallum, and an interseptal carbonate filling, have recrystallized into medium-grained anhedral mosaic calcite. The outline of the original skeletal material is preserved in a jigsaw-shaped pattern visible as cloudy darker calcite against the clear lighter calcite of the interseptal filling. There is some tendency for the calcite within the cloudy areas to remain as a distinct crystal, optically discontinuous, separated from the crystals in the filling. However, most of the crystal boundaries cross the corallum-interseptal filling boundaries. Between crossed nicols the corallum-interseptal filling boundaries are partially obscured by the large continuous crystals. The limestone has virtually no porosity at present, in contrast to what originally was an extremely porous coral structure.

B. Sample Tw 7–1, × 3. Coral-algal incrustate limestone from the reef-wall facies. Thick laminar masses of encrusting algae coat and bind recrystallized mud-filled coral. Caught within the algal laminae are tests of *Marginopora*, *Halimeda* segments, and other reef debris. A few lighter colored laminae of encrusting Foraminifera contribute to the cementing mass. *Halimeda* segments are abundant in the detritus surrounding the coral-algal mass. Anhedral, clear, mosaic calcite fills much of the original void space. Some of these void spaces were partially filled by fine detritus; the upper surfaces of these deposits are parallel throughout the slide as well as parallel to the upper surface of the algal colony. This parallism is indicative of mud filling of the reef limestone during reef growth.

C. Sample Kr 2–3, × 3. Coral breccia from the lagoon facies. Poorly sorted large fragments of algal- and foraminiferal-encrusted coral, echinoid spines and plates, *Halimeda* segments, pelecypod shells, and tests of smaller discoidal Foraminifera are in a porous medium-grained matrix.



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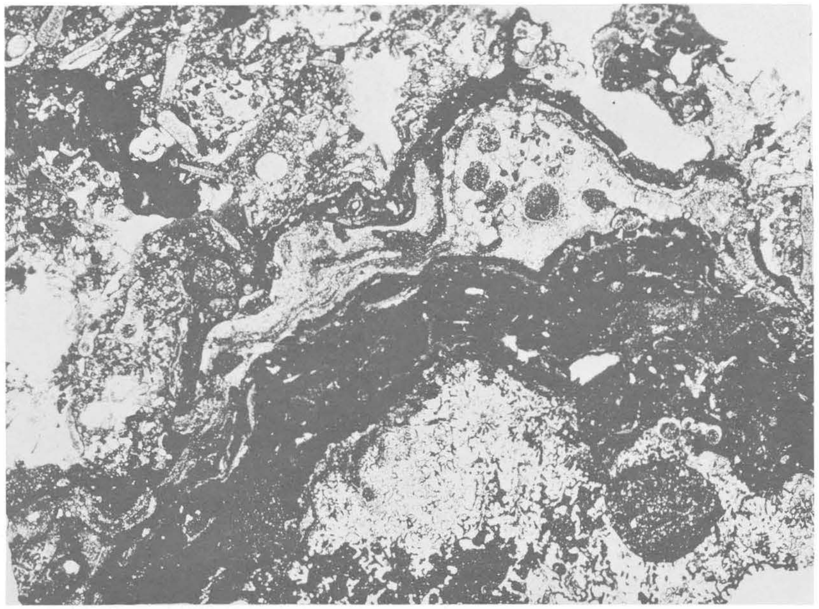

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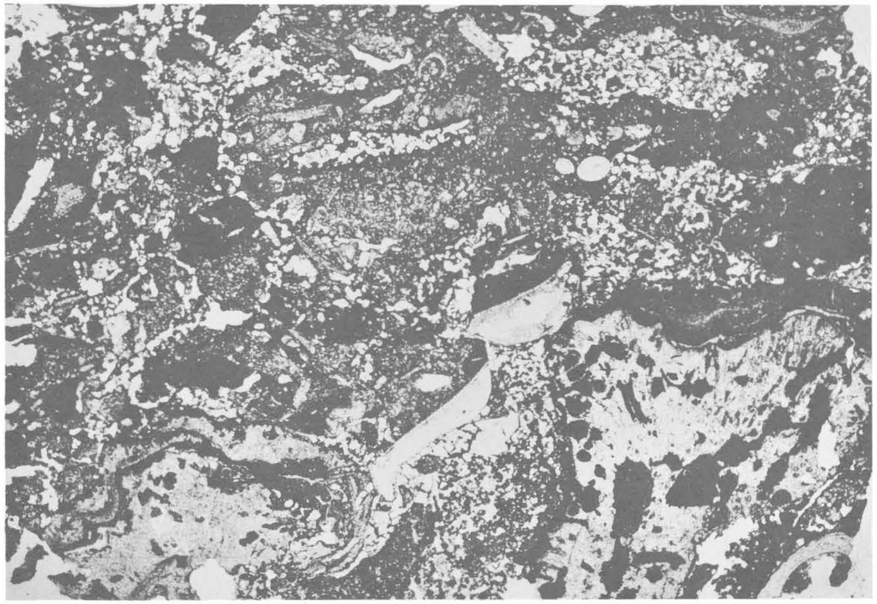


C

SAMPLES OF THE MARIANA LIMESTONE

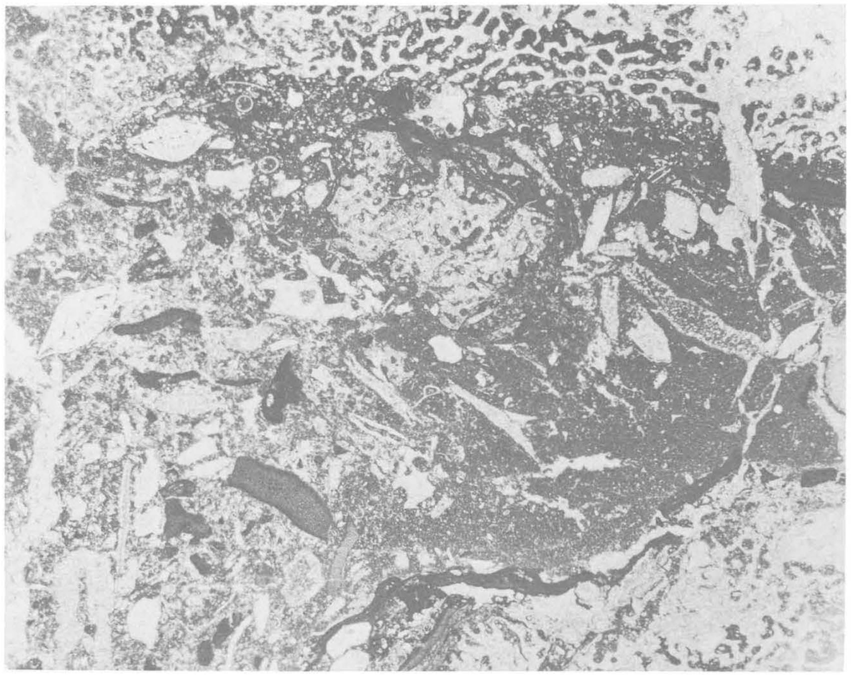
PLATE 19

A. Coral-algal incrustate limestone from reef-wall facies, × 8. This sample is identical to Hi 3–4 from the Maemong Limestone Member (pl. 10*A*). Fossil elements include mud-filled algal-encrusted coral, disjointed *Halimeda*, alga detritus, and tests of Foraminifera. Much of the detritus between the coral is in a fine-grained mud matrix. Cores from this facies show coral heads in growth position (Forman and Schlanger, 1957).

B. Coral breccia from the forereef facies, × 8. This limestone has an equivalent in sample Ed 6–1 from the Maemong Limestone Member (pl. 11*A*). Many of the fossil elements in this material are also common to rocks from the reef-wall facies. However, all the components are detrital in the forereef facies. Cores from this facies show characteristic bedding.

C. Foraminiferal-algal microparacoquinite from the off-reef facies, × 8. Tests of large *Heterostegina* and some miogypsinids dominate; fragments of coralline algae are also present. This limestone is equivalent to that represented by sample Hi 4–5 from the Maemong Limestone Member (pl. 10*C*).

D. Foraminiferal mudstone from the forereef transition facies, × 8, containing tests of large benthonic lepidocyclinids and small planktonic globigerinids that float in a matrix of fine-grained detritus and mud. The discoidal tests of the large Foraminifera show a high degree of parallelism. This material is comparable to rock from the bedded forereef transition facies of the Maemong Limestone Member (pl. 11*D*).



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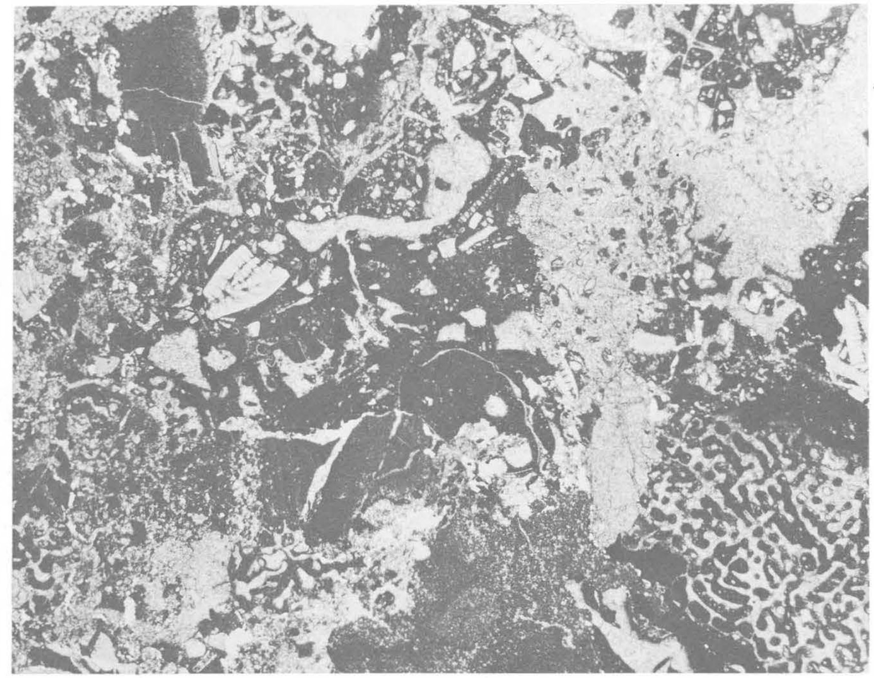

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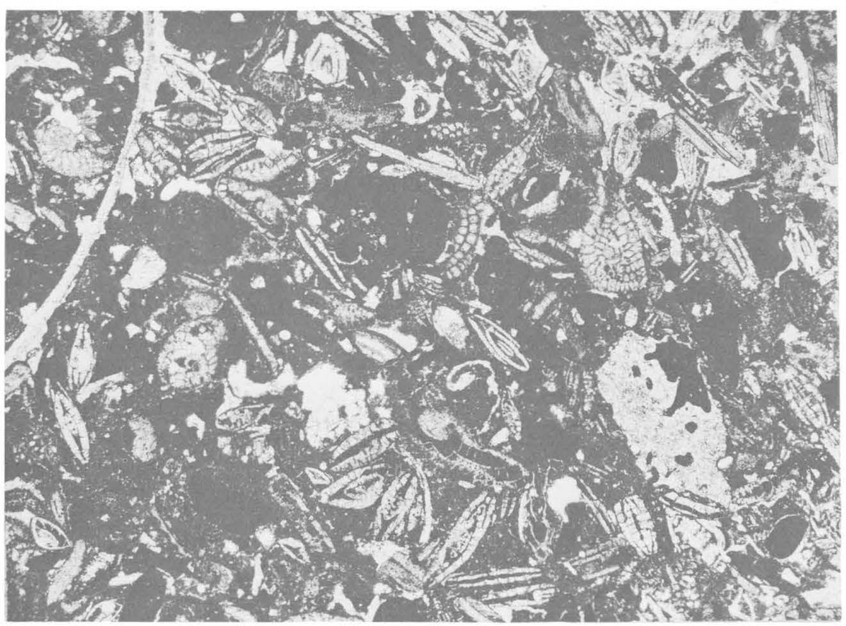

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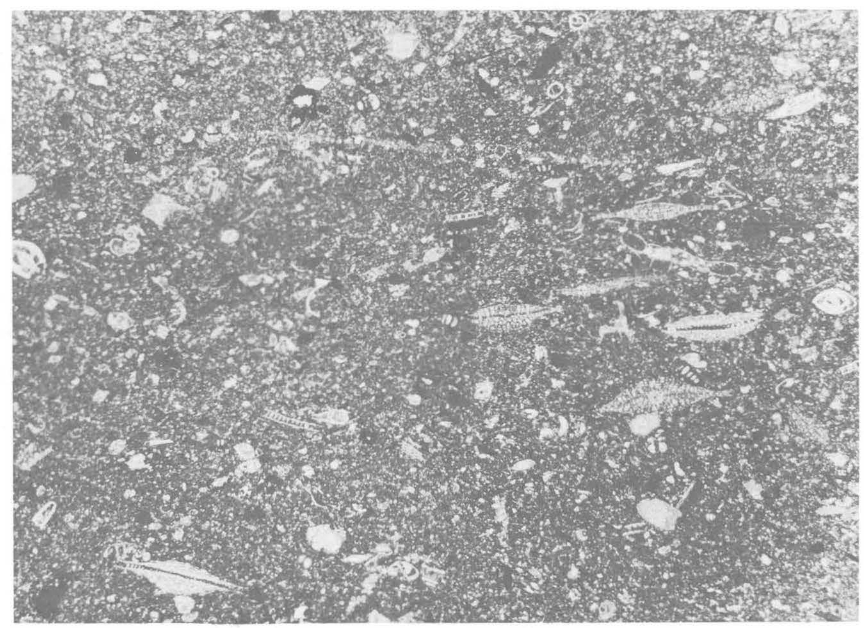


D

LIMESTONE FROM SOUTHERN LOUISIANA

PLATE 20

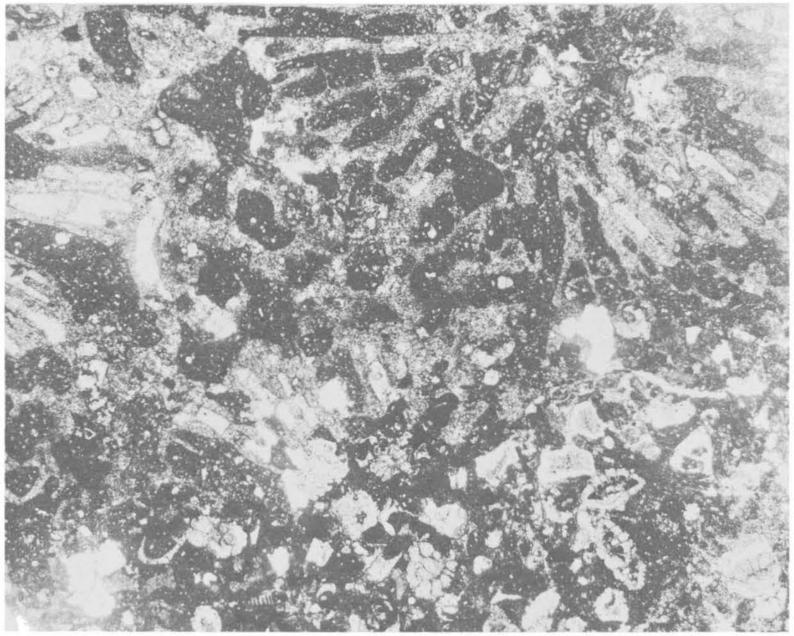
The limestones of Oligocene age from the forereef facies at Kirkuk, Iraq, are comparable to (1) samples Ek 7–2 (pl. 8*A*) and Ek 7–3 (pl. 8*B*) from bedded limestones of Eocene (*b*) age in the Alutom Formation, (2) samples Ef 2–1 and Ee 7–1 from bedded sections of the Maemong Limestone Member (pl. 11*B*, *C*), and (3) bedded sections of the Bonya Limestone (pl. 12*B*).

A. Limestone from the reef-wall facies, × 8. This limestone is considered equivalent to rock from southern Louisiana (pl. 19*A*), the Maemong Limestone Member (pl. 10*A*), and limestone from the Alutom Formation (pl. 7*A*).

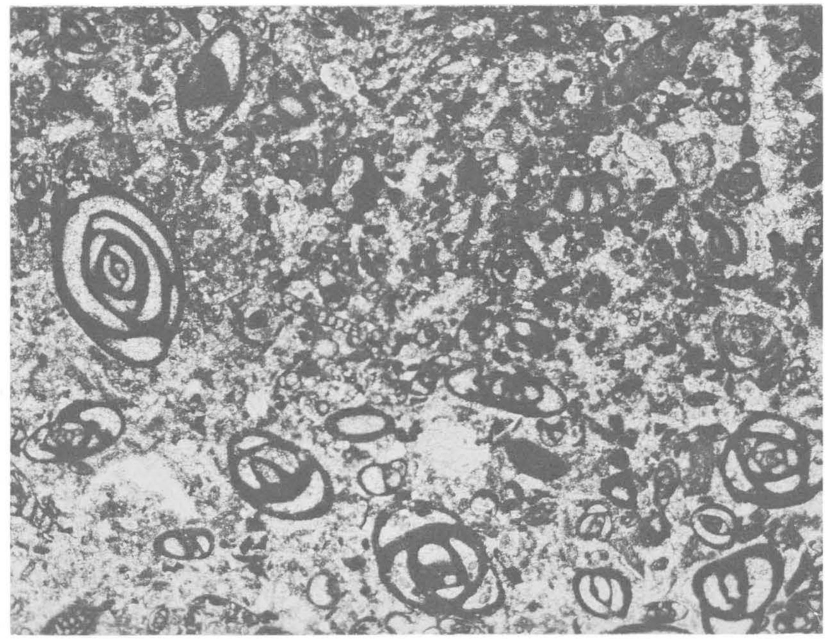
B. Foraminiferal microparacoquinite from the lagoon facies, × 20. This fine-grained miliolid-rich rock is directly comparable to material from the Maemong Limestone Member (pl. 10*D*) and limestone from the Alutom Formation (pl. 7*C*).

C. Foraminiferal microbreccia from the forereef facies, × 8.

D. Foraminiferal microbreccia from the forereef facies, × 8.



A



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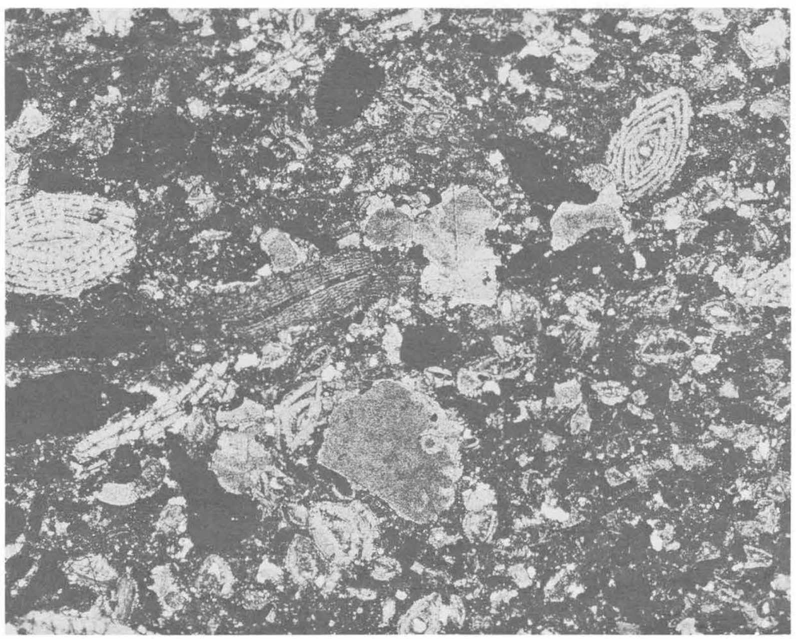


C

D

LIMESTONE OF OLIGOCENE AGE FROM KIRKUK, IRAQ

PLATE 21

A. Heavy minerals, in the 0.25- to 0.10- mm-size grade, of the Janum Formation from sample Ts 5–4, × 33. Augite and amphibole (table 9).

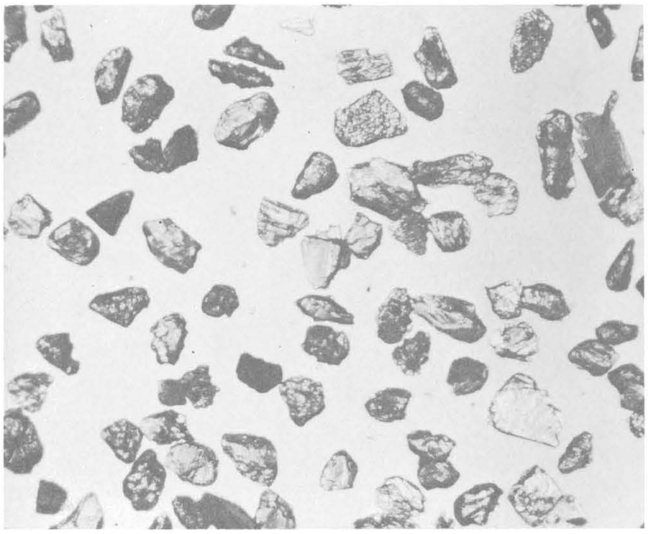
B. Heavy minerals, in the 0.25- to 0.10- mm-size grade, of the Maemong Limestone Member from sample Ed 7–2 × 32. Augite, hypersthene, and amphibole (table 9).

C. Heavy minerals, in the 0.25- to 0.10- mm-size grade, of the Mahlac Member from sample Gj 11–1, × 33. Brown-green amphibole, basaltic hornblende (table 9).

D. Heavy minerals in the 0.25- to 0.10- mm-size grade, of the limestones in the Alutom Formation from sample Ek 7, × 34. Brown-green amphibole, augite (table 9).

E. Magnetite octahedra in the Janum Formation from sample Rr 23–1, × 32.

F. Foraminifera test fillings of opaline silica (beta-cristobalite) in the Maemong Limestone Member, × 32.



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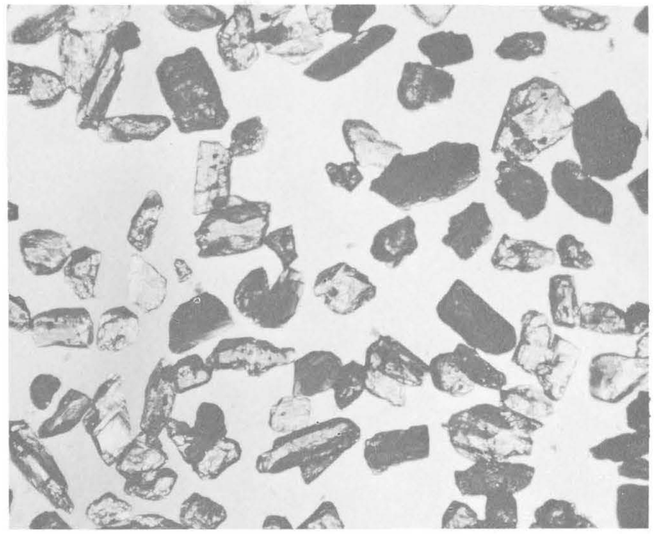

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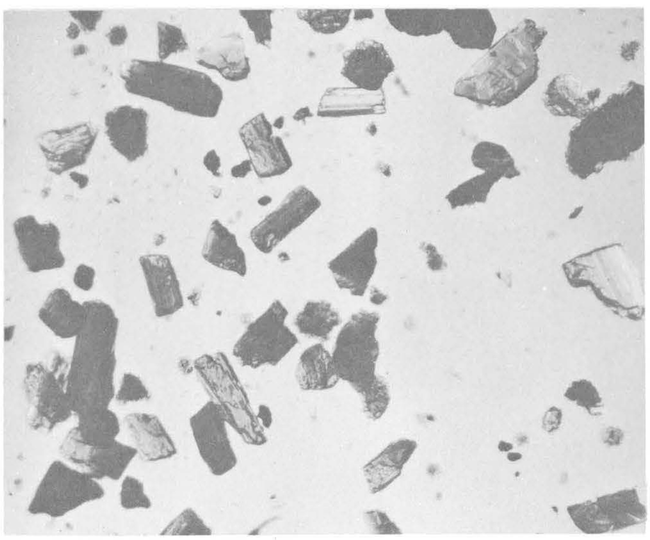

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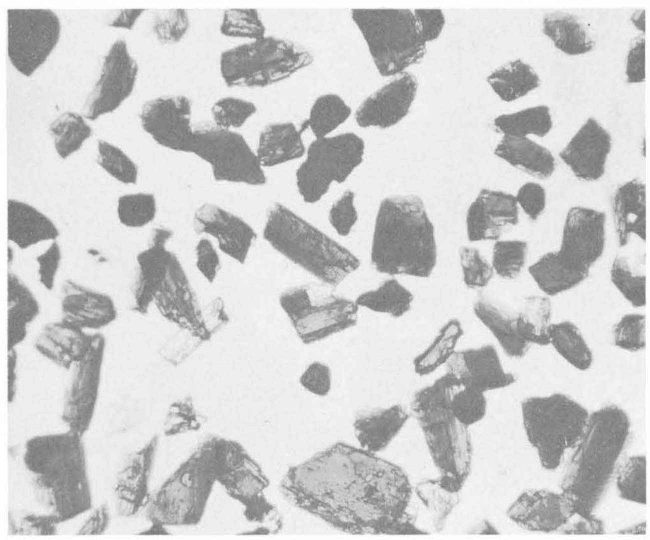

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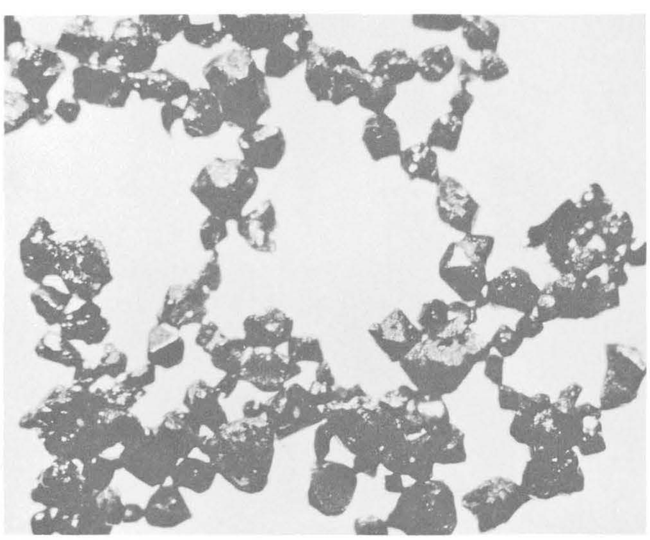

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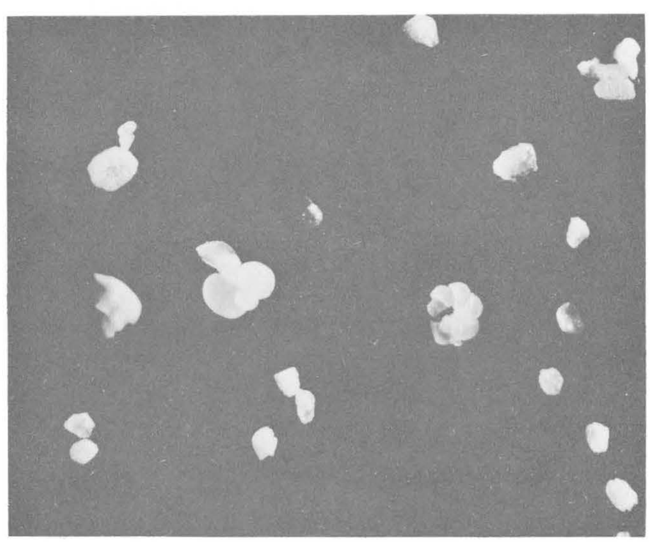

F

INSOLUBLE RESIDUES FROM SELECTED GUAM LIMESTONE

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