

Growth and submarine fossilization of algal cup reefs, Bermuda*

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ABSTRACT

Small charges of explosives were used to section cup-shaped reefs that occur on the margins of the Bermuda Platform. Study of these artificial outcrops, up to 10 m high, and the samples collected from them show how the reef-building community is rapidly converted to well-lithified reef rock in the marine development.

The reefs, known locally as boilers and breakers, occur along the wave-swept south shore of the Bermuda Islands and around the northeast and northwest margins of the Platform. They are cup-shaped, up to 30 m in long dimensions, and rise up to the sea surface as much as 12 m above the surrounding sea floor. The reefs are built by an intergrowth of encrusting organisms, principally crustose coralline algae, an encrusting hydrozoan, *Millepora* sp., and an attached gastropod, *Dendropoma irregulare*.

The growth framework of these algal cup reefs has extensive voids: large and intermediate-sized growth framework and shelter pores; borings of bivalves and sponges; and both intra- and inter-particle pores. A variety of vagile and sessile organisms (coelobites) inhabit these pores: an encrusting Foraminifera, *Homotrema rubrum*, is the most abundant attached coelobite; the tests of a variety of benthic Foraminifera and ostracods are common: branched coralline algae, barnacles, bivalves, ahermatypic corals, bryozoans, and burrowing crustaceans occur in varying abundance.

Beginning millimetres below the living surface, internal sediments accumulate in the extensive voids. Coarse-grained skeletal sand derived from the surface of the reefs is characteristic of the larger voids; lime mud with the tests of planktonic Foraminifera and planktonic algae occurs generally in the smaller voids. Most specimens from the interior of the reefs show multiple generations of internal sediment that vary in grain size, composition, and colour. The sand-sized sediments are pumped into the voids by the frequent and intense wave action; the lime mud settles out in the smaller, less agitated pores.

Cementation of internal sediments and surrounding growth frame begins centimetres below the living surface; it is so pervasive that marble-hard reef rock is developed within $\frac{1}{2}$ m or less. The cement is principally high-magnesium calcite

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of micrite size, and subordinately acicular aragonite, but there are locally wide variations in crystal size and morphology. The occurrence of the cement within the reefs well below sea level, the isotope ratios of the cement crystals, the mineralogy, and the age inferred from radiocarbon age determinations of the growth frame all indicate that the cement is submarine and deposited from water of oceanic composition.

The algal cup reefs of Bermuda demonstrate the reef-building ability of a community of encrusting organisms that form only crusts in the intertidal zone of the Mediterranean and Northern Brazil. The cup reefs of the northern margins of the Bermuda Platform are true reefs, not merely veneers covering eroded blocks of Pleistocene limestone. In their composition, location, and early diagenesis, the cup reefs closely resemble the algal or lithothamnion ridge of Pacific atolls. Syndimentary cementation of internal sediments and growth frame makes a major contribution to the rigidity of these ocean-facing reefs and atoll rims.

The assemblage of features that characterize the submarine fossilization of the cup reefs is widespread elsewhere in the modern seas: the floors of the Persian Gulf and parts of the Mediterranean; the margins of Pacific atolls; and the reefs off the north coast of Jamaica. This fossilization is characterized by reiterated generations of coelobites, internal sediments, and syndimentary cements that can in time replace a major part of the original growth framework. Major variations in the sequence of these generations from pore to pore is the signature of this kind of fossilization. The same features of fossilization are described from reefs in the Devonian, Permian, and Triassic.

INTRODUCTION

Much is known about the surface of modern reefs, their morphology, biota, and sediments. Much is known about ancient reefs, their stratigraphy, palaeontology, and petrography. Far too little is known about when, where, and how the living reef-building community and its associated sediments are transformed into reef limestone. This paper offers some new observations on fossilization in the marine environment; it reports the results of a study of the interior of one reef type on the Bermuda Platform. By comparing samples of living reef surfaces with those collected up to several metres below the surface it is possible to trace the changes from original growth framework to cemented reef rock.

The substantial post-World War II literature on the morphology of reefs, reef-building organisms, and sediments has been ably summarized by Ladd (1961, 1969) and by Stoddart (1969). The study of the several core borings from atoll reefs of the Pacific (Emery, Tracey & Ladd, 1954; Ladd & Schlanger, 1960; Ladd, Tracey & Gross, 1967) and from exposed Pleistocene reefs in Florida (Stanley, 1966; Matthews, 1968) have yielded valuable observations on the fossilization of reefs during subaerial exposure.

Two works report examples of submarine and/or intertidal fossilization of Holocene atoll reefs in the Pacific. Tracey (in Emery *et al.*, 1954) described two types of reef rock from a collection of surface samples across the reef flat and algal ridge. Ladd & Schlanger (1960) described well-lithified reef rock from a series of shallow borings that extend out about 200 m on the reef flat at Eniwetok. Most recently, Scoffin (1972) gave a preliminary report on the fossilization of patch reefs in the Bermuda Lagoon.

This paper is an extension of these earlier reports; it is focused on the growth and fossilization of reefs of the surf-swept margins of the Bermuda Platform. To study the

interior of these marginal reefs, we used small charges of explosives to make artificial outcrops, a technique pioneered by Shinn (1963) in Florida. Charges of explosives equivalent to a maximum of 12 lb of TNT were emplaced by divers in caverns at the bases of reefs. The explosives produced vertical sections up to 10 m high through the margins of the reefs. On these artificial outcrops we could compare the living surface of the reef with successively deeper and older specimens of the interior. Using SCUBA we could examine, sample, and photograph these artificial outcrops in much the same way outcrops on land are studied.

This paper first describes the reefs and reef-builders; next, the major features of fossilization are described and illustrated and interpretations suggested. The discussion considers the significance of the results for Bermuda and puts the new reef type in perspective; it treats the major topic of fossilization and compares the results from Bermuda with those reported from other areas. Finally, examples of what appears to be similar fossilization in ancient reefs are reviewed.

THE BERMUDA REEFS

Introduction

There are two major reef-building communities on the shallow part of the Bermuda Platform: (1) massive corals, algae, and associated invertebrates, and (2) an intergrowth of encrusting algae and invertebrates.

The reefs in which massive corals predominate are by far the most extensive, and are similar to the familiar lagoon reefs of Florida, the Bahamas, and the West Indies. They range from the semi-restricted Castle Harbour across the 10 miles wide North Lagoon to the edge of the platform, where they form the elevated rim of the Platform (see Fig. 1). Some of the principal coral elements of this assemblage extend to depths of at least 50 m (Land, Bricker & MacKenzie, personal communication, 1969). The gross morphology of these reefs and the biota were first described by Agassiz (1895) and Verrill (1907). More recently, Ginsburg & Stanley (1970), and Garrett *et al.* (1971) have described the organisms and sediments of specific reefs in the North Lagoon.

The other reef-building community on Bermuda, the subject of this paper, is an intergrowth of encrusting organisms that builds small cup-shaped reefs on the margins of the platform. These cup reefs rise up the intertidal zone from the coral-covered marginal rim of the platform, the 'ledge flats' of earlier authors (Fig. 1).

Earlier authors, Agassiz (1895) and Verrill (1907) used the terms 'boiler' or 'breaker' for these reefs, terms that come from their appearance on the sea surface, rather than their morphology or composition. In this literature, as well as in more recent works (Stanley & Swift, 1967), these structures are interpreted as eroded blocks of Pleistocene limestone veneered with reef-building organisms. However, examination of seven reefs using small charges of explosives has revealed that those on the northeast and northwest margins of the platform are indeed true reefs built by the same community of organisms now found on their surfaces (Ginsburg, Shinn & Schroeder, 1967; Ginsburg, Schroeder & Shinn, 1971b; Ginsburg, Marszalek & Schneidermann 1971a; and this paper).

To distinguish reefs built almost entirely by encrusting organisms from the more familiar coral reefs, Ginsburg, Shinn & Schroeder (1967) suggested the term 'algal cup reef'. Apparently similar algal reefs occur off Yucatan (Boyd, Kornicker & Rezak,

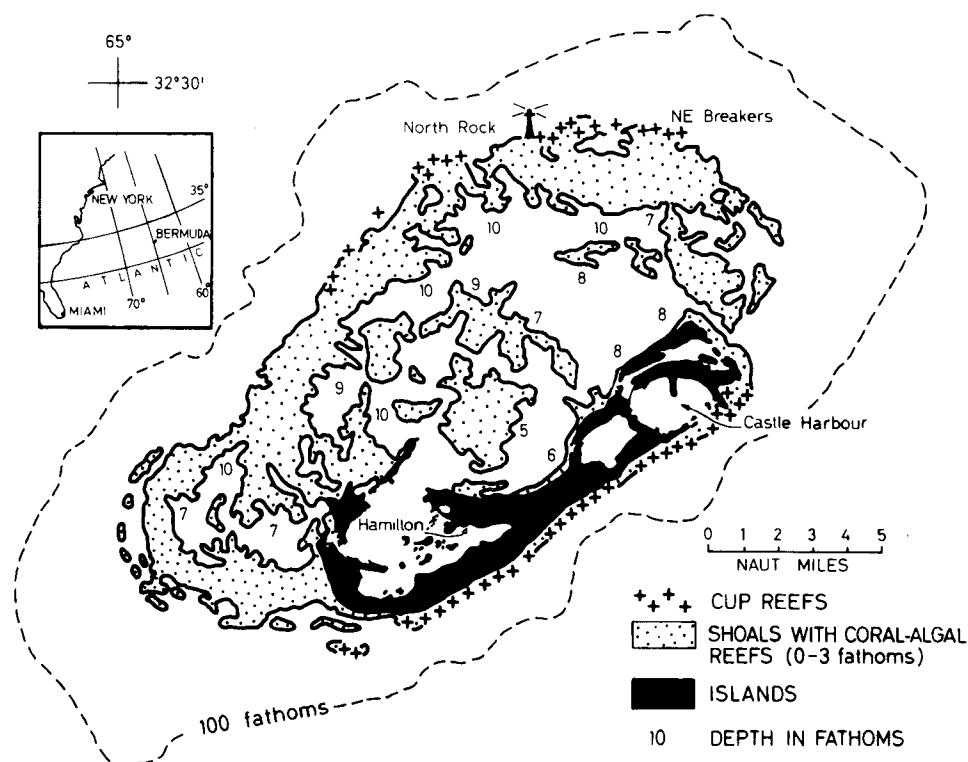


Fig. 1. The Bermuda Platform showing the generalized distribution of reefs.

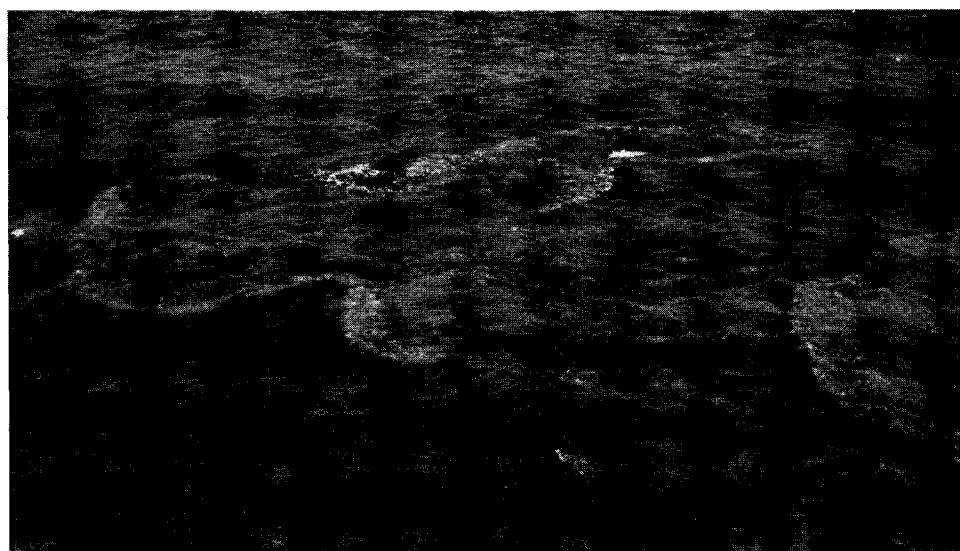


Fig. 2. Low altitude aerial oblique view of algal cup reefs of the Northeast Breakers group, see Fig. 1 for location. The left lobe of the lobate reef is about 15 m wide; the light coloured rims of the reefs which are awash at low tide are a few metres wide.

1963) off the coast of Brazil (Kempf & Laborel, 1968) and possibly in the eastern Bahamas (Storr, 1964).

Location of reefs examined and methods of study

The algal cup reefs are restricted to the margins of the platform; they are most abundant along the south shore, but there are two major clusters around the northern rim of the platform, one the Northeast Breakers, and the other unnamed, extending westward from North Rock (see Fig. 1). Our studies were concentrated on these two areas of the northern rim, but we have examined some of those along the south shore.

To study the interiors of these reefs we used small charges of explosives to section them, a technique pioneered by Shinn (1963). During four summers, 1966–69, we sectioned seven cup reefs on the northern margin and two on the south shore.

Small specimens were collected by divers and larger ones up to 1.5 m across were brought in with the winch on the *R/V Panulirus*. The samples were slabbed, and where necessary the cavities filled with resin so that the slabs could be polished. Large specimens, up to one-half metre across prepared in this way have proved particularly useful in studying the relationships between the organisms and internal sediments.

Algal cup reefs

Morphology and surface

In plan view cup reefs are circular, ellipsoidal, oblate or crescentic (Figs 2, 3). All the examples examined have an elevated rim that is awash at low tide and surrounds a

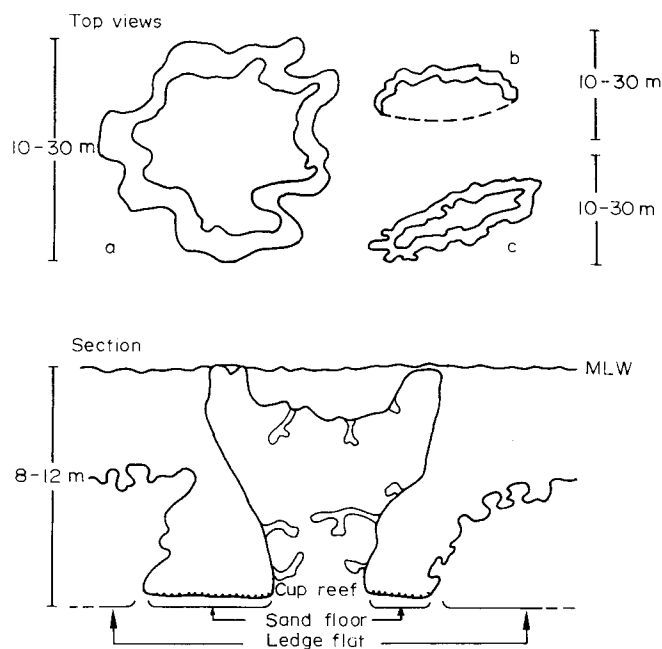


Fig. 3. Generalized plan views and a cross-section of cup reefs.

central depression, a micro-lagoon usually only a few metres deep but occasionally up to 5 m deep (Iams, 1970). In three dimensions the reefs are cup- or vase-shaped with

rough inward-sloping sides. Near the bases of many cup reefs there is a sand-floored, moat-like depression (Fig. 3) and there are numerous cavities a metre or more in diameter extending from the moat into the base of the reefs.

One's first impression of the underwater surfaces of the cup reefs is the sparseness of growth on them (Fig. 4). There are sheet-like growths of yellow-brown *Millepora* sp., often with protruding knobs a few centimetres in diameter; there are occasional small corals, *Diploria* sp. and *Porites astreoides*, and there are shrub-like growths of the brown alga *Stypopodium* sp. and *Sargassum*, but the prevailing impression is that

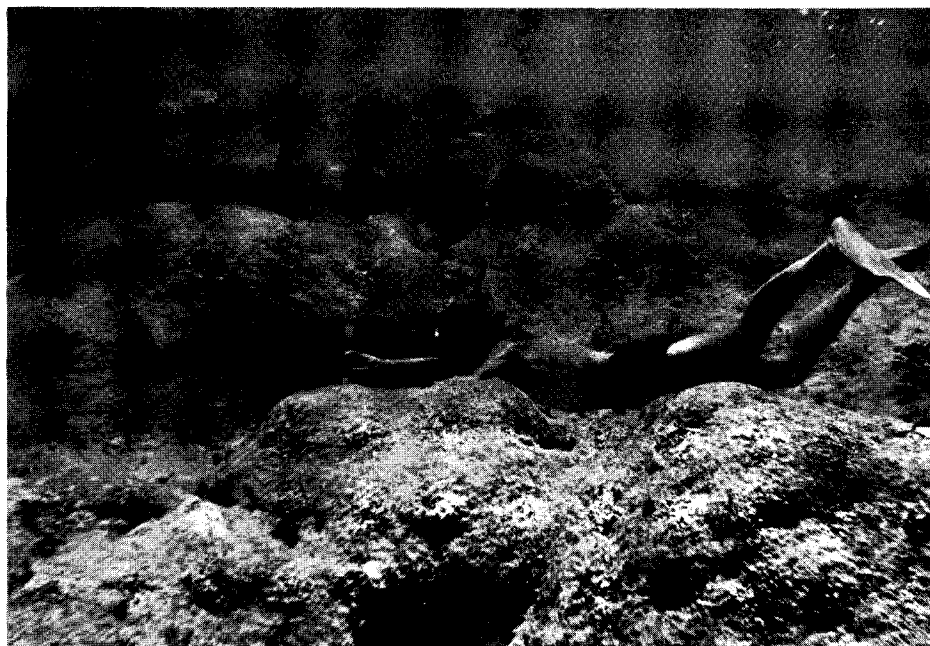


Fig. 4. Underwater view in the micro-lagoon of an algal cup reef southwest of North Rock (see Fig. 1). The depth in this lagoon is from 2 to 4 m; the elevated rim is visible in the background. The surface of the hummocky topography is an intergrowth of encrusting organisms; the small projections are uncalcified algae.

the reef is a mass of limestone with a sparse cover of organisms. However, closer inspection of the surface shows that it is an almost continuous living skin of crustose coralline algae and *Millepora* sp., in which numerous vermetid gastropods are embedded (Fig. 5). Examinations of numerous specimens from the surfaces of cup reefs around the northern platform margin as well as the descriptions of near-shore cup reefs on the south shore by Iams (1970) and Eggleston *et al.* (1971) show that the principal carbonate-secreting constituents are crustose coralline algae, *Millepora* sp. and attached vermetid gastropods (*Dendropoma irregulare*). There are large variations in the relative proportions of these encrusting organisms, even within individual large hand specimens, but lamellar growths of crustose algae and/or *Millepora* sp. with embedded gastropods generally form well over two-thirds of the surface.

Internal structure and compositions

The most striking feature of the interior of the cup reefs is the wide variation in

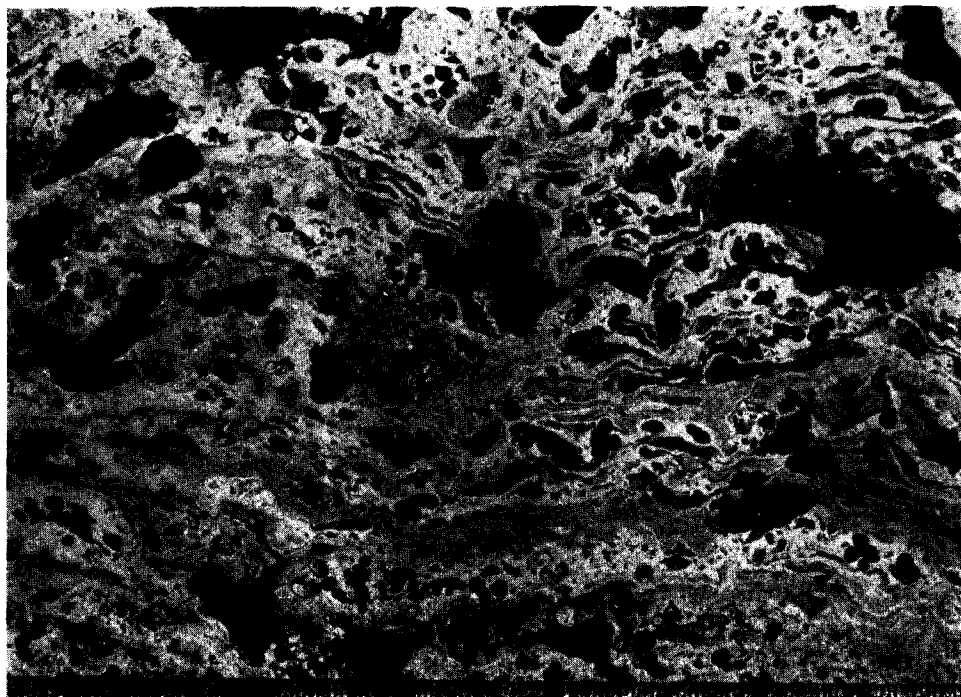


Fig. 5. Section of cup reef-rock from 10 cm below the surface of a reef in the Northeast Breakers group, scale in millimetres. The light-coloured layers are crustose coralline algae, the darker ones *Millepora* sp.; the small circles and clusters of circles are *Dendropoma irregulare*, some of which are filled with cemented lime mud.

structure, lithification and composition. In cross-section there are two major growth forms at the surfaces: (1) vuggy laminations with millimetre-scale crinkling, as planar sheets, low domes (Fig. 5) and in columns several centimetres in diameter and up to $\frac{1}{2}$ m high, and (2) unlaminated, irregularly-branched growths, (Figs 5, 7). A metre or so below the surface, the originally vuggy intergrowth of algae, *Millepora* sp. and gastropods is a thoroughly cemented limestone that rings under the hammer (Fig. 6); its numerous original voids are now lined with attached animal skeletons and filled with internal sediments. The description of growth and early diagenesis that follows is subdivided into frame builders, cavity dwelling forms, internal sediments, and cements.

Frame-building organisms

The distinction between the functions of the various elements of reef-building communities expressed by Lowenstam (1950) has been a valuable guide for the analysis of living and fossil reefs. Lowenstam (1950) recognized three functional groups; (1) frame-builders, (2) cemented or binding forms, and (3) sediment producing organisms. Ginsburg & Lowenstam (1958) used this approach to suggest that living coral algal reefs, like buildings, consist of a frame or walls of massive and branched corals (bricks), that is cemented by crustose coralline algae and other encrusting animals (mortar), and infilled with detrital sediment from algae, molluscs and Foraminifera (fill). In algal cup reefs the usually separate functions of frame-building and binding are combined in the lamellar encrusting forms.



Fig. 6. Underwater view of artificial section through a cup reef of the Northeast Breakers group (see Fig. 1 for location). The diver is about 4 m below the surface. The near vertical surfaces and angular fractures are typical of the well-cemented reef rock. The broken surface of one of the rare corals is visible in the block at right.

(1) *Lamellar crusts*. Crustose coralline algae and *Millepora* sp., an encrusting hydrozoan, are the most abundant organisms on the surfaces of the cup reef, and in specimens of the interiors. On the surface both grow scab-like, conforming to the substrate, and as projecting knobs. The knobs of coralline algae appear in section (upper part Fig. 7) as irregularly branched growths; those of *Millepora* sp. are conical up to 5 cm in diameter and 10 cm high (Fig. 7).

In a single large specimen, Walter Adey of the U.S. National Museum found that *Neogoniolithon* sp. was the most abundant crustose coralline alga, with subordinate amounts of *Mesophyllum syntrophicum* and *Peysonellia* sp.

In section, the alternation and intergrowth of crustose algae and *Millepora* sp. produces discontinuous laminations, with numerous convex upward undulations (Figs 5, 7). The laminations vary from less than a millimetre to several millimetres and they show crinkling and lateral discontinuities on the scale of several millimetres.

(2) *Vermetid gastropods*. Sessile vermetid gastropods are abundant on the surface of the cup reefs. They become covered with crustose algae or *Millepora* sp. so that only the small opercula is still exposed (Figs 5, 8). *Dendropoma irregulare* Orbigny is the only vermetid on the cup reefs of the northern rim of the platform; on the cup reefs of the south shore *Vermetus* sp. is also present. Estimates of abundance of *D. irregulare* by Iams (1970) and Eggleston *et al.* (1971) made on hand specimens from the surfaces of cup reefs on the south shore cluster between 10 and 20% by volume, but range up to 40%.

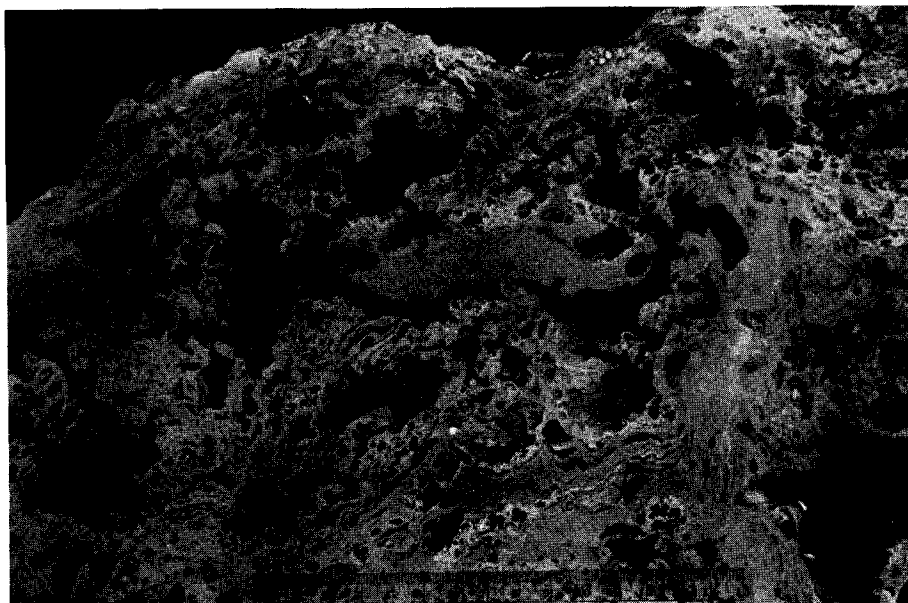


Fig. 7. Sawed section of the surface of a cup reef. Northeast Breakers Group. The crinkled laminations just above the scale consist of crustose coralline algae, light-coloured, and *Millepora* sp., dark. Above the 15 cm division the tapered projection is the section of a knob of *Millepora* sp. To the left of this projection the vuggy irregular growth is knobby crustose coralline algae with *Dendropoma irregulare*. A continuous rind of coralline algae roofs the vuggy growth and extension of the *Millepora* knob forming an interconnected network of irregular voids.

Vermetid gastropods are commonly restricted to the intertidal zone of rocky shores (Peres & Picard, 1952, 1957; Safriel, 1966; Shier, 1969) but on the surge-swept cup reefs of the northern platform margin they extend down the sloping sides of the cup reefs to 12 m.

(2) *Corals*. Isolated specimens of the common reef-building corals principally *Diploria* sp. and less commonly *Montastrea* sp. occur sporadically on the cup reefs. Low domal specimens up to about 30 cm grow on the sloping sides and in the micro-lagoon (Eggleston, 1972). These corals are never abundant, although specimens occur occasionally in the reef rock.

Pores

Pores or cavities in a wide range of sizes and shapes are an important element in the early diagenesis of the cup reefs. Because almost all the pores are initially open to some degree to the surface or to the larger caverns within the reefs (see Fig. 6) they provide a variety of protected niches for organisms, as well as traps for internal sediments. The total volume of these pore fillings, both organic and sedimentary, is a significant addition and modification of the growth framework.

Pore is used for all void spaces within the reefs regardless of size or origin following Choquette & Pray (1970).

(1) *Kinds of pores*. The pore type designations of Choquette & Pray (1970) are designated by brackets.

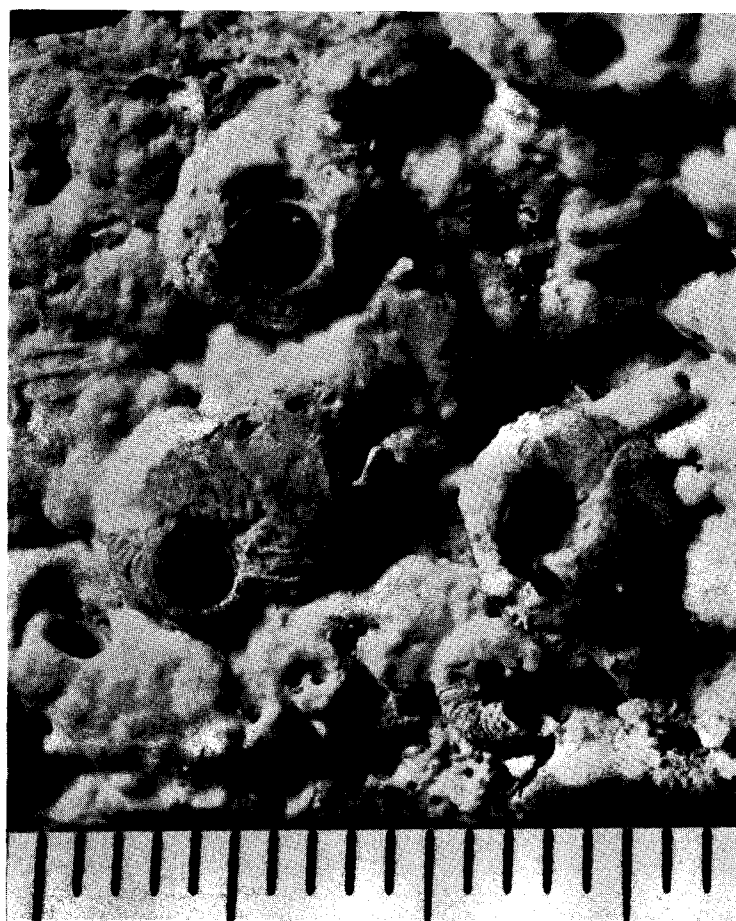


Fig. 8. *Dendropoma irregularis* attached to the cup reef surface of crustose coralline algae, Northeast Breakers Group. Metric scale. A juvenile specimen uncoated is shown in the lower right.

(a) Intra-particle pores range in size from 20 μm in the coralline algae and some Foraminifera through 5 mm in the chambers of gastropods and worm tubes to a centimetre or more in the chambers of bivalves and barnacles (Fig. 9) [mc or MS-WP, or mg GF].

(b) Growth framework and shelter pores that range in size from a millimetre to 5 cm result either from the open growth form of one organism or through the roofing-over of irregular growth surfaces by 'tents' of the lamellar encrusting forms (Figs 7, 10, 11) [mg GF; mg SH].

(c) Bio-erosional pores made by boring animals include tubes of boring bivalves, cellular pore networks, and the ragged border of vugs made by boring sponges (Figs 12, 13a, b) [mg CH; mg Vug].

(d) Interparticle pores within internal sediments range from the micron scale in mud-sized material to as much as a few millimetres in the local occurrences of granule and pebble-sized sediments [mc-mg BP].

The most abundant boring mollusc is *Lithophaga nigra*, the black date mussel (Fig. 13a). *Lithophaga bisulcata* and *Gastrochaena hians* are common but less abundant than

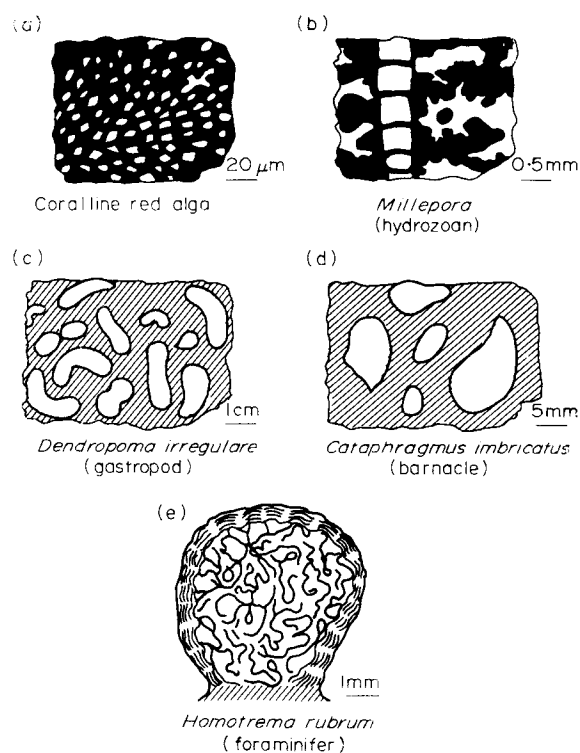


Fig. 9. Schematic drawings of intraparticle pores in reef-building organisms.

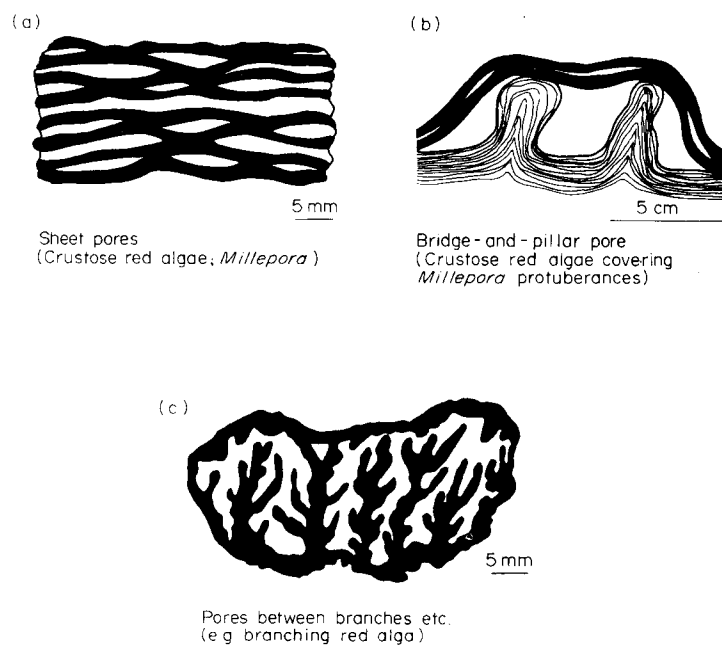


Fig. 10. Schematic drawings of growth-frame and shelter pores produced by the principal reef-builders.

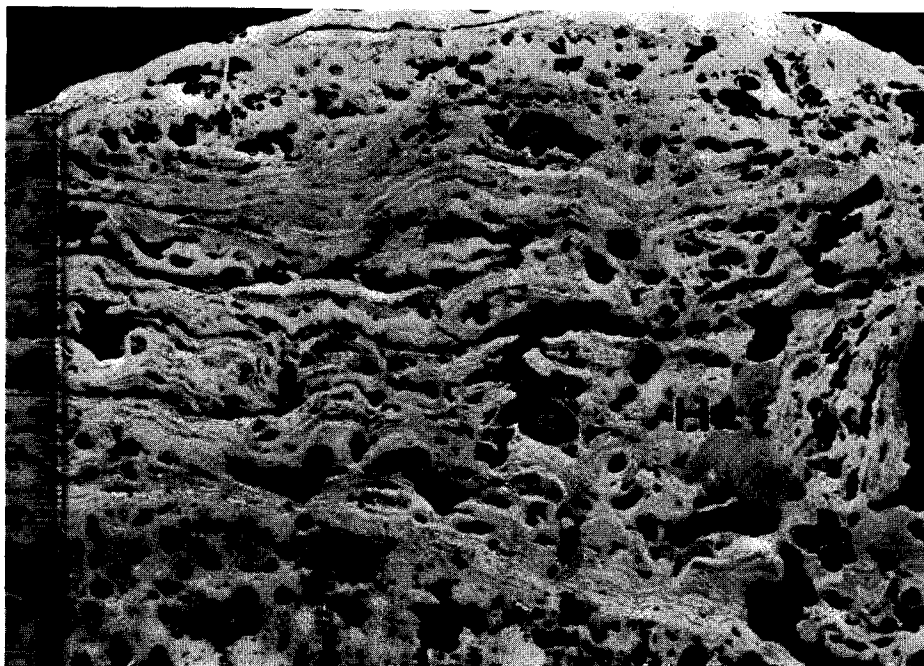


Fig. 11. Sawed section of reef rock, Northeast Breakers Group. The original voids, sheet pores, were filled with coloured resin and here appear black. The light coloured laminations are coralline algae, the darker ones, *Millepora* sp. Sections of the coelobite *Homotrema rubrum* are designated H. The top of a plate of a coral is visible at the bottom.

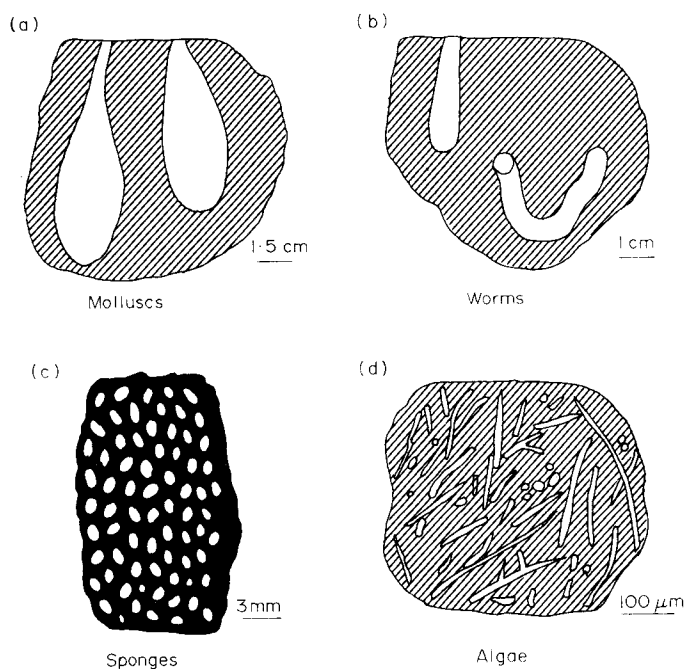


Fig. 12. Schematic drawings, sectional views of pores made by boring organisms.



Fig. 13. (a) A sawed section of cup reef surface from a reef near North Rock (Fig. 1) showing filled and open bivalve borings. At the left centre a sediment-filled bivalve boring is cut by a second sediment-filled boring which in turn is cut by an empty boring. Sponge borings occur at the surface, far right. (b) View of sawed edge of cup reef surface North Rock area. The sawed surface above the scale shows the vesicular network of sponge borings, *Cliona lampra*. The top of the specimen shows wrinkled crusts of coralline algae of the growing surface.

L. nigra. Occasional specimens of four other species were found: *Spengelaria rostrata*, *Gregariella coralliphaga*, *Petricola lapidida*, and *Botula fusca*.

The boring sponge, *Cliona lampa*, produces the familiar cellular pattern on exposed surfaces (Fig. 13b). Another boring sponge, *Siphonodictyon* sp., enlarges smooth bivalve borings to produce rough, irregularly shaped vugs (James, 1970).



Fig. 14. Vuggy pore network, subsurface reef rock from Wreck Reef west of North Rock (Fig. 1). Below the scale the rough surface of a specimen from the blasted face of a cup reef; the surfaces of the projections and irregular pore networks are blackened.

Above the scale a sawed section of this pore type shows well cemented remnants of the growth frame and first generation internal sediment (1) with irregular black lines marking the outlines of vuggy pores. A second generation of internal sediment—friable lime mud (2), occurs in some of the earlier vugs and is cut by a second generation of vuggy pores, seen clearly at left of (2).

Another type of pore network occurs sporadically in the cup reefs; it is a highly irregularly interconnected system of anastomosing channels and vugs that has a spongy appearance in three dimensions, and is dendritic in section (Fig. 14). The surfaces of this pore network are characteristically blackened. This pore network clearly cuts cemented frame and cemented internal sediment, indicating formation below the growth surface by solution of unknown origin.

*Coelobites** (organisms that live in pores or caverns)

A variety of organisms live in the open pores and caverns of the cup reefs; some are vagile, others are firmly attached to the walls, and some are so weakly attached, or have such fragile skeletons that they disintegrate post mortem into fragments.

Encrusting forms

Homotrema rubrum (Lamarck). This bright pink sessile Foraminifera is by far the most abundant coelobite, locally it is abundant as a frame-builder (Fig. 15). *H. rubrum* grows in protected but well-flushed habitats ranging from the interior of branched and sheety growths of crustose algae (Fig. 11) to cavities well within the interior of the reef. It occurs in almost every cavity and in many forms a semi-continuous lining on the walls. Rooney (1970) estimated the abundance of *H. rubrum* as two individuals/cm² on a specimen from a cup reef of the South Shore, and he found it equally abundant within the coral reefs of the North Lagoon and margin.

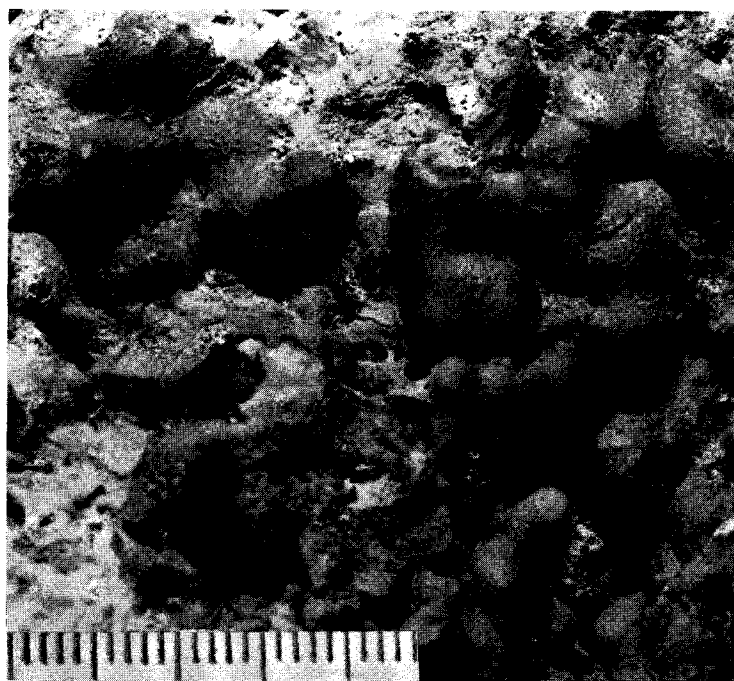


Fig. 15. Near surface cavity in reef rock lined with *Homotrema rubrum*. For sectional views of *H. rubrum* see Fig. 11.

Emiliani (1951) recognized five morphologic types of *H. rubrum*, and both he and Lowenstam (1968) suggested that the variations in growth form were related to variations in microenvironment. Rooney (1970) was unable to confirm a convincing

*Coelobites (coelum—*Gk.* hollow; biote—*Gk.* life). This term, suggested by Cesare Emiliani, is used here to include all organisms living in voids or pores within the reef. The term includes the 'cryptic habitat' of Jackson, Goreau & Hartmann (1971) and sciaphile (shade-loving) of Laborel (1960) and other French authors.

relationship between test form and micro-environment from his study of eighteen specimens from reefs that cover the major range of environments across the North Lagoon. Rooney (1970) found the globose form to be the most abundant form on coral reefs and cup reefs: only 15% branched forms occur on the two cup reefs he examined.

Barnacles. Individuals or small groups of barnacles occur in several of the cup reefs; in one reef, successive generations produce a solid mass of barnacle rock a few decimetres in size. Generally, barnacles are far less abundant than *H. rubrum* or *Dendropoma irregulare*. The most common species is *Cataphragmus imbricatus*, identified by V. A. Zullo (Fig. 16a). *Tetracita stalactifera* is also present. Barnacles occur almost exclusively in the pores and caverns below the surface. In section, barnacles appear as subcircular or polygonal rings, often partly filled with internal sediment (Fig. 16b).

Ahermatypic corals. Isolated corallites and phaceloid aggregates of corallites occur in many of the larger cavities within the reef. *Astrangia solitaria* Lesueur is the most common; *Guynia annulata* Duncan is also present. Two new species, *Coenogyathus goreau* Wells and *Rhisopsamnia bermudensis* Wells were discovered in our collections (Wells, 1972).

Other encrusting forms. The pelecypod, *Spondylus*, occurs sporadically in cavities within the cup reefs; its lower valve, attached to the wall, is incorporated into the frame.

Encrusting and branched bryozoans occur in the cup reefs, but only the encrusting forms are considered here. They are volumetrically insignificant under protected overhangs as well as on the walls of cavities well beneath the surface (Cuffey, 1972). Sheet-like growth of *Cribillaria radiata* (identified by Roger Cuffey), see Fig. 25, are common as are isolated, disc-shaped cavities of lichenoporoid cyclostomes in the larger cavities below the surface (*ibid*).

Serpulid worm tubes varying in diameter from 0.1 to 1 cm occur sparsely in the cavities of the cup reefs, but only locally do they make a volumetrically significant contribution to the reef rock.

Vagile forms

The most common vagile form is the echinoid *Diadema antillarum* that lives in near-surface depressions and cavities that it excavates. A variety of Foraminifera and crustaceans, ostracods and crabs are numerically quite abundant, judging from the abundance of their tests in the internal sediments (see below and Table 1). A few crustacean burrows, see Fig. 24, that resemble those made by *Callianassa* occur in the internal sediments of large pores.

The forms that are poorly attached to the reef or so weakly calcified that they disintegrate easily post mortem are red and green algae, sponges, and alcyonarians. Of these only certain branching red algae and some of the sponges occur in cavities; the green algae, alcyonarians, and some sponges live on the exposed reef surface.

*Internal sediments**

Sediment of sand, silt, and clay-sized occurs in the pores and caverns of the cup reefs. The amount of this internal sediment, its grain size and composition, and its distribution vary enormously, even in a single large hand specimen.

*This descriptive term seems preferable to 'secondary deposits' used by Newell (1955) for similar material.

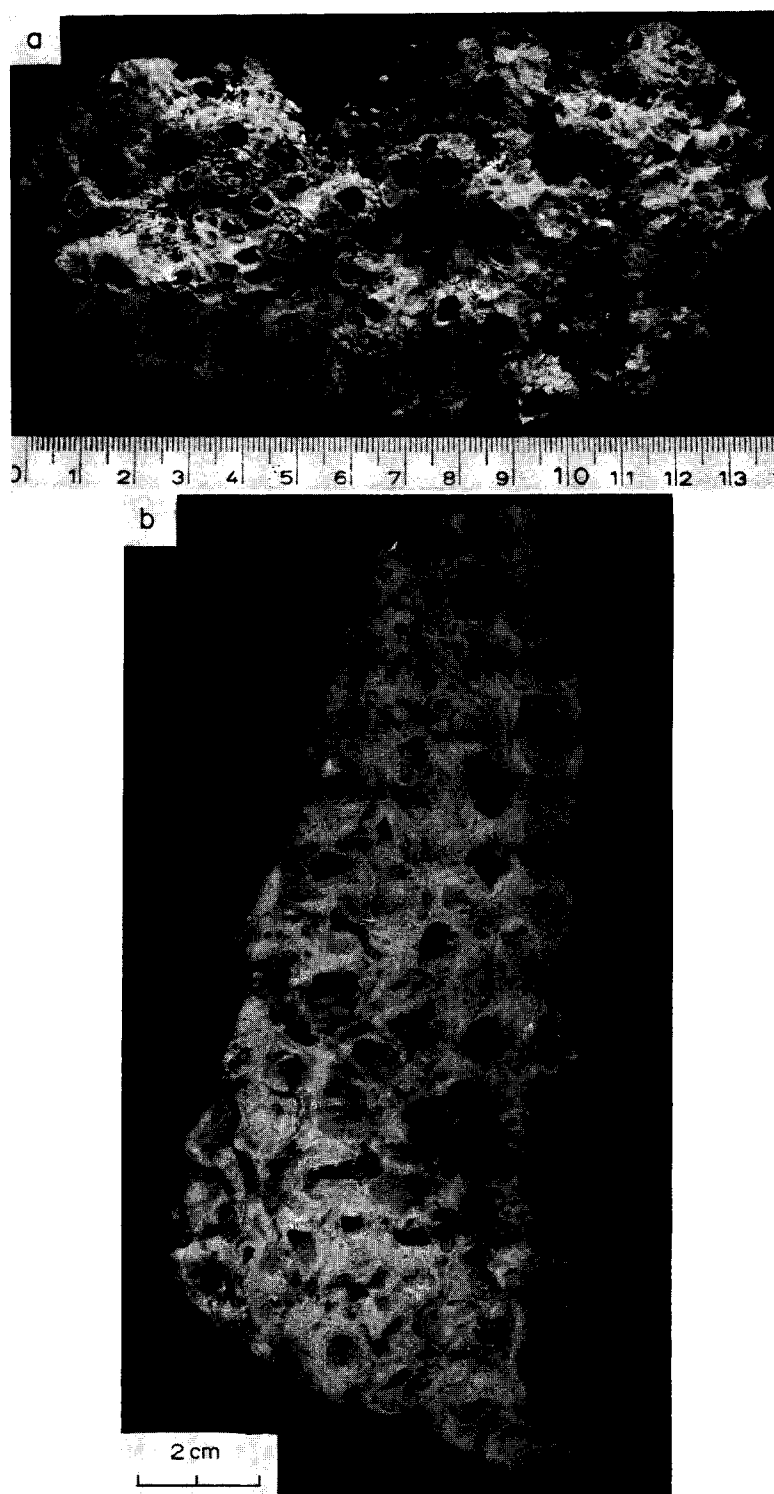


Fig. 16. (a) Cluster of barnacles, *Cataphargmus imbricatus* from a large subsurface void in a cup reef of North Rock; the small bulbous growths are *Homotrema rubrum*. (b) Sawed surface of barnacle rock from the same reef as (a). The barnacle tests are white and have geopetal fills and complete fillings of well-cemented skeletal sand or lime mud.

Table 1. Constituent composition of a sample of unconsolidated internal sediment from an algal cup reef of the Northeast Breakers group*

Phylum, class, or order	Family genus, or species	Particles	Relative Abundance
Foraminifera	(See below†)	Whole tests	Abundant
Porifera	_____	Small spheres; monaxons, tetraxons, and triradiate spicules	Common
Alcyonaria	<i>Pseudopterogorgia</i> sp.	Sclerites	Common
Bryozoa	Crisiidae	Fragments of branched colonies	Abundant
		Fragments of encrusting colonies	Rare
Gastropoda	Caecidae (8 species)	Juveniles	Common
Pelecypoda	Arcidae	Juveniles and Prodissoconchs	Common
Annelida	Serpulidae	Fragments of tubes	Common
Ostracoda	_____	Mostly single smooth valves‡, often larval stages	Abundant
Cirripeda	_____	Plates	Common
		Whole tests	Rare
Decapoda	_____	Fragments	Rare
Echinoidea	Cidaridae;	Spines	Common
	Spatangidae (?)		
Ophiuriidea		Whorls, plates, spines	Rare

* Identified by W. Resch, Innsbruck.

† Among the Foraminifera identified are: *Rhizammina*, *Dendronina*, *Hemispherammininae*, *Cyclogyrinae*, *Wiesnerella auriculata*, *Nodobacularella*, *Nubeculina*, *Quinqueloculina*, *Pyrgo*, *Triloculina*, *Miliolinella*, *Biloculinella*, *Parrina*, *Peneroplis*, *Glandulina*, *Compressigerina*, *Discorbis*, *Neonorbina*, *Siphonina*, *Cibicides*, *Globocassidulina*, *Heterolepa*, several species of *Rotalina*, *Homotrema rubrum*, *Globorotalia ex. gr. menardi*.

‡ In thin-sections of other samples of internal sediments, numerous specimens of ostracods with both valves still joined have been observed.

(1) *Distribution and stratification.* Internal sediments occur in all types and sizes of caverns and pores. Medium to coarse sand and granule-sized skeletal debris is the most common sediment in caverns and larger pores that are interconnected; some of these fillings are geopetal (Figs 16b, 17) but in the larger voids and open networks they are complete. Lime mud is the usual internal sediment in smaller pores like the chambers of *D. irregulare* (Fig. 5).

The amount of internal sediment varies from a trace in the well laminated compact structure (Figs 5, 7) to more than 50% in the irregularly branched growth form (Fig. 18). Multiple generations are common, and most specimens show at least two that differ in grain size and colour (Figs 17–19).

Stratification is usually restricted to fine sand and mud-sized sediment; lamination is planar (Fig. 19), inclined (Fig. 20) or occasionally undulating or rippled. Some laminae are graded, and finer sediment capping earlier coarser-grained geopetal fill gives the appearance of grading (Fig. 19).

(2) *Texture and fabric.* The grain size of the internal sediments ranges from clay to coarse sand and granule sizes. The variations are so large between sediments in adjacent pores, or even within a single pore, that a summary can at best give the range of variations.

Twenty-four samples of internal sediment were examined in thin section, the proportions of mud and sand-sized grains estimated, and thirty sand-sized grains in each

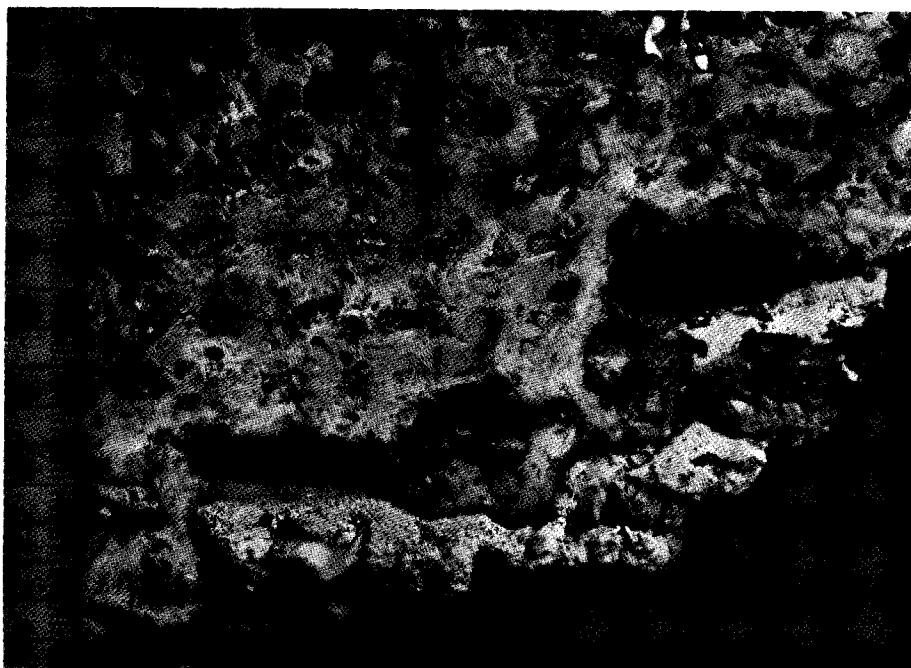


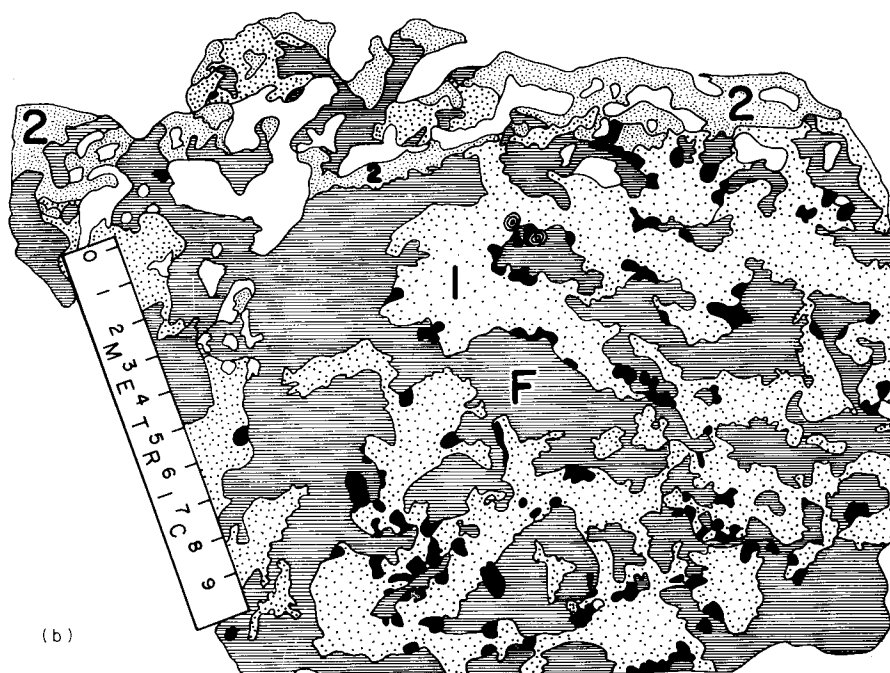
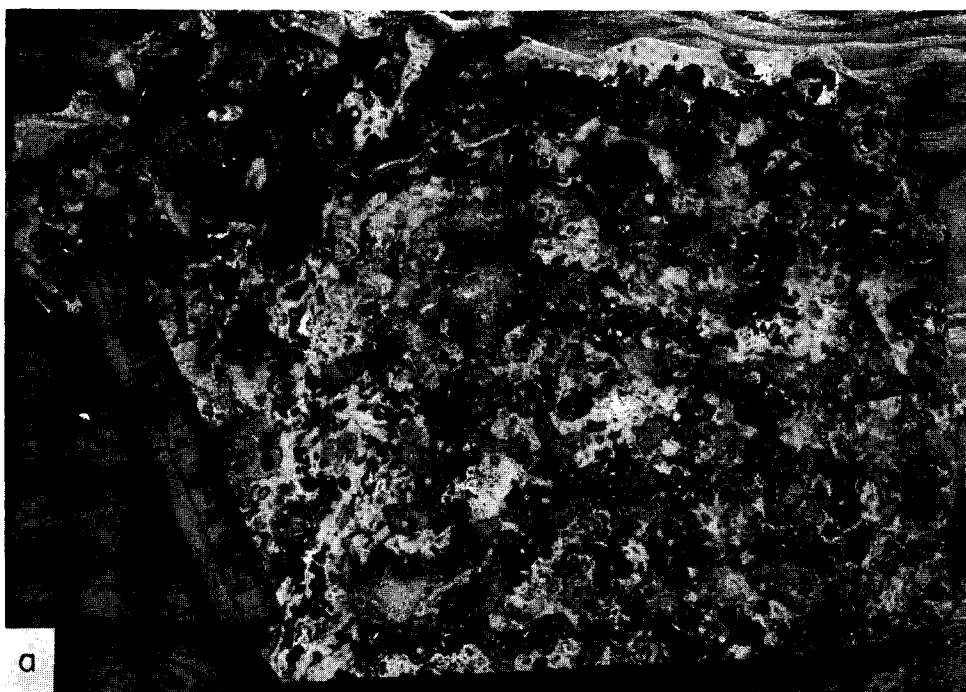
Fig. 17. Sawed slab of reef rock from the subsurface of a reef of the Northeast Breakers group (see Fig. 1 for location). The well cemented rock is an intergrowth of crustose coralline algae, *D. irregulare* with *Homotrema rubrum* and fine-grained internal sediment filling former voids.

The two voids in the lower half of the specimen have geopetals of coarse skeletal sand, a new generation of internal sediment; a large shell fragment is visible in the one at left. The coarse skeletal sand is sufficiently cemented to be sawed but less compact than the earlier internal sediments in the reef rock above. These flat-floored geopetal fills and the irregular tops of the remaining voids above them are characteristic of stromatactis, a common structure in ancient reef limestones.

sample were measured and, where possible, identified. From these estimates, three intergrading textural types can be described: (1) medium to coarse grainstones and a few packstones and wackestones; the sorting of the framework fraction varies from well-sorted to poorly-sorted; the skewness is usually positive: (2) fine sand-sized grainstones with large variations in sorting, but with generally negative skewness: (3) very fine sand and coarse silt-sized wackestones with variable sorting and skewness.

(3) *Constituent composition.* The constituent composition of internal sediments shows the same large variations as their grain size. The most abundant constituents of sand-sized sediments identified in thin sections from nine samples are fragments of branched and crustose coralline algae, *H. rubrum* and molluscs. Subordinate constituents include Foraminifera, *Halimeda*, echinoid debris, serpulids, and ostracods. In the mud-sized internal sediment, two species of coccoliths were identified in electron micrographs: *Coccolithus huxleyi* is the most common, *Syracosphaera* sp. is rare. A planktonic diatom, *Coscinodiscus* sp. was identified by J. Gerloff.

The most common internal sediment is sand-sized and derived largely from the reef frame and from coelobites attached to the frame as indicated above. The composition of fine-grained internal sediment is however quite different. Table 1 is an inventory made by W. Resch of Innsbruck of the constituents in one small sample washed



- | | | | |
|--|--|--|--------------------------------------|
| | Growth framework of coralline algae, <i>Millepora</i> sp. and <i>D. irregulare</i> | | Coelobites - <i>Homotrema rubrum</i> |
| | First generation internal sediment, here coarse skeletal sand | | Voids |
| | Second generation internal sediment, here lime mud | | |

Fig. 18. (a) Sawed surface of a specimen of cup reef rock from 3.5 m below the surface of a reef in the Northeast Breakers Group. The 0 mark on the scale is up. (b) Tracing of the sawed surface shown in (a). Following cementation of the first generation internal sediment the resulting reef rock was locally cut by vuggy pores, see also Fig. 14; irregular black lines, visible in the upper left mark these surfaces. The second generation of internal sediment lies on these blackened surfaces over both growth frame and first generation internal sediment. The radiocarbon age of the growth framework of this specimen is 3190 ± 210 years B.P.; the age of a bulk sample is 2980 ± 160 years B.P.

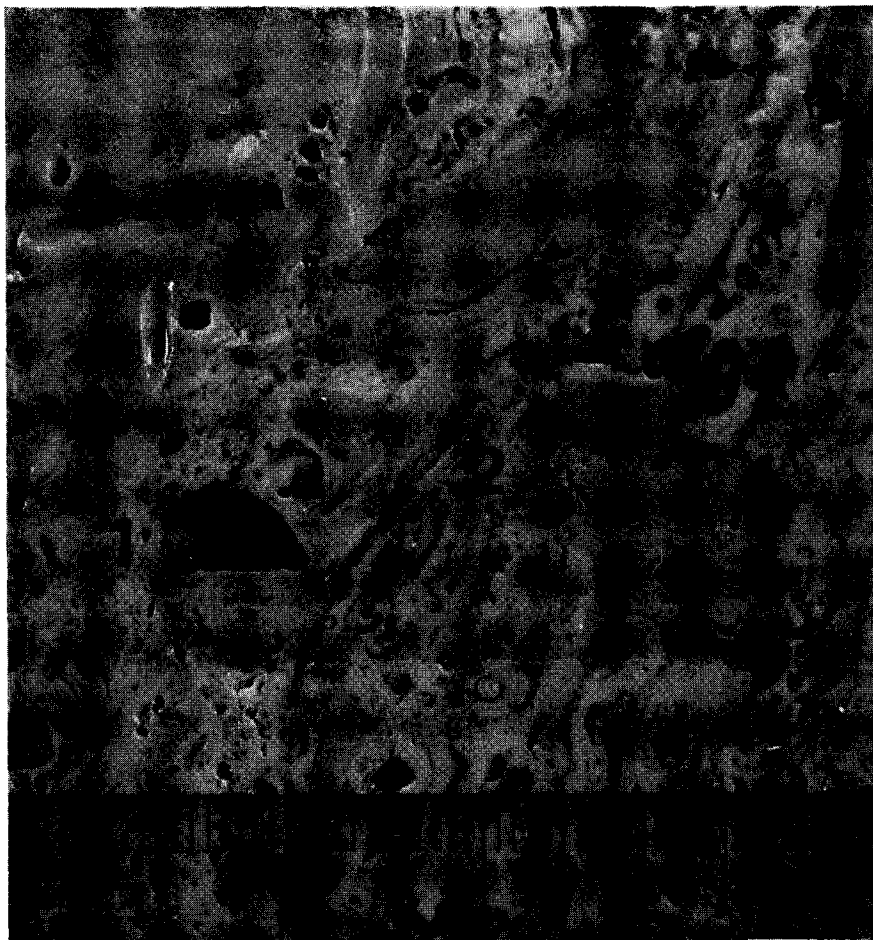


Fig. 19. Sawed surface of cup reef rock from below the surface of a reef of the Northeast Breakers Group showing geopetals and filled voids. This specimen came from the side of a cup reef and therefore the growth laminations of crustose coralline algae with *D. irregulare*, small circles and ovals, are nearly vertical. 1, A bivalve boring half-filled with fine lime sand that shows a vague lamination; 2, an irregular void, probably a sponge boring, shows two generations of internal sediment—the basal three-quarters skeletal sand, the upper quarter laminated lime mud.

free of lime mud. Table 1 shows that none of the constituent particles in this sample come from the reef framework itself. Instead, the grains are either from vagile and attached coelobites, from animals that live on the surface of the reef, or from the plankton. Pteropods and a single planktonic Foraminifera were found in this particular sample, but in other samples planktonic elements, coccoliths, and diatoms are present.

Several pores have geopetals that consist almost exclusively of fine-sand-sized peloids. The peloids are oval and ellipsoidal in section, consist of micrite-size crystals, and lack internal structure. Bulk X-ray analysis of these peloids indicates they consist of high-magnesium calcite. Some are probably faecal pellets of invertebrates, possibly from animals that rasp off the coralline algal crusts; others are probably fragments of the calcified algal filaments described by Schroeder (1972a).

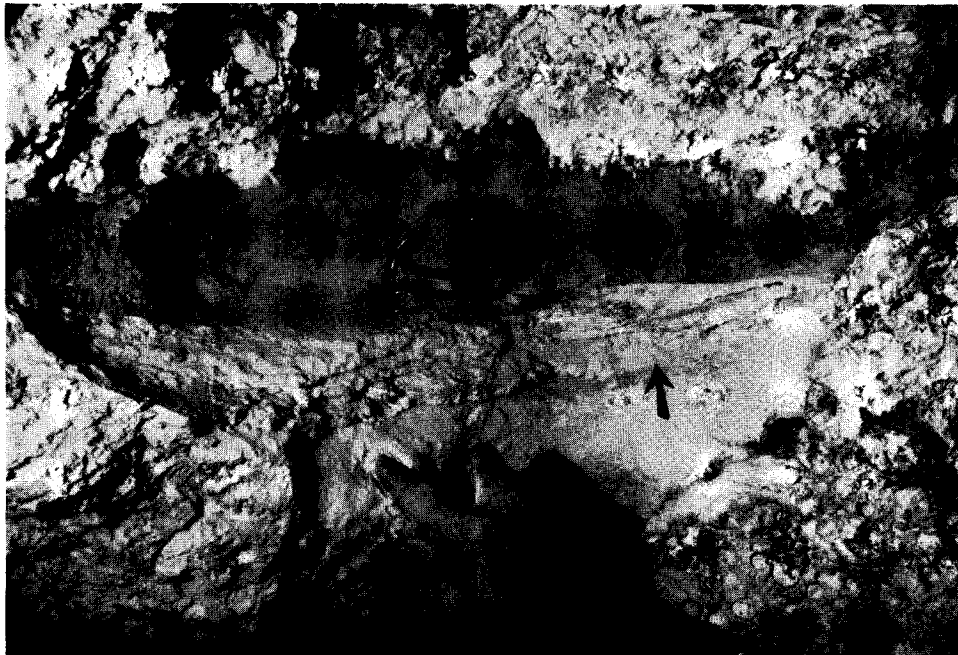


Fig. 20. Underwater view of a geopetal in a cavern exposed in the blasted surface of a reef of the Northeast Breakers Group. Figure 5 from Shinn (1971) with permission of the author and the Gulf Coast Association of Geological Societies. The upper part of geopetal fill between the arrows is cemented and shows low-angle laminations that have slightly varying dip directions; to the left of the light meter there are clasts of the overlying roof rock cemented into the upper layer. Below the cemented layer the internal sediment is soft lime mud; Shinn (1971) reports seventeen genera of ostracods from this mud.

(4) *Mineralogy.* We have not investigated the mineralogy of bulk samples of the sand-sized internal sediments because the variations in constituent composition described above indicate that it can be expected to vary considerably depending on the relative proportions of various constituents. The mineralogy of three samples of the mud-sized sediment was estimated by X-ray spectrometry using Lowenstam's curve (Lowenstam, 1954) for the relationship between peak height and percentage. The percentage of aragonite in these samples was 45, 55, and $65 \pm 10\%$. The calcite in all three samples is high-magnesium with 16–17 mol % Mg CO_3 estimated from the shift of the major calcite peak (211) on the X-ray diffractogram.

Deposition of internal sediments

Sand-sized internal sediment is derived from organisms living on or within the cup reefs. The constituents of one finer-grained sample (Table 1) are largely vagile forms, but in most others there are substantial proportions of grains derived from encrusting coelobites and from the reef framework. The sand-sized fraction is probably moved into the pore systems by the combination of wave surge and gravity. The cup reefs face the open Atlantic and are exposed to almost continuous wave surge. As a result, there is no particulate sediment on the exposed surfaces of the reefs. This wave surge deposits sediment within the pore system and fills the smaller pores with a single opening: gastropods and barnacle chambers (Figs 5, 16b, 19).

The same sources that provide the sand-sized internal sediment, coelobites and framework, probably also contribute significantly to the silt-sized fraction and perhaps to the clay-sizes as well. The intensive bio-erosion of the framework by sponges, echinoderms, and animals that rasp off the surface is probably a major source of mud-sized internal sediment. In addition, the presence of planktonic elements, pteropods, Foraminifera, coccoliths, and diatoms in the internal sediments strongly suggests that sediment derived from elsewhere on the platform accumulates in the pores. When turbid water moves into the quiet-water pore system, suspended particles from various sources must settle out.

The multiple generations of internal sediment with large variations in grain size and the attendant stratification are considered to be the result either of changes in the openings of individual voids, changes in the connections of the system, or changes in supply of sediment. The progressive filling of voids near the surface can reduce the wave surge effect within underlying cavities and produce the observed sequence of sand to mud. Seasonal variations in wave surge, from the frequent winter gales to the calmer summer winds, could also produce the sequence of grain size and the stratification (Figs 19, 20). This same seasonal variation in wave action and temperature may also effect changes in the quantity and composition of attached organisms, that would in turn affect the amount and composition of sediment for cavity filling.

Cement

The cup reefs that were dissected with explosives fractured like well-lithified limestones. The reefs are so thoroughly cemented that the small charges of explosives invariably produced angular blocks and vertical faces (Fig. 6). In one cup reef, a small charge on one side of the reef fractured a block a few metres long off the overhanging lip of the other side of the reef some 10 m from the charge.

In hand specimen, the reef rock is so thoroughly cemented that it can be slabbed and polished like a limestone (Figs 16b, 18). Measurements supplied by Philip Choquette of Marathon Oil Research Center show that cementation has locally reduced the porosity of composite samples of internal sediment and growth frame to less than a few percent.

The cements of the cup reefs have been described in several publications (Ginsburg *et al.*, 1967; Ginsburg *et al.*, 1971a, b; Schroeder, 1972a, b; Shinn, 1971); only a general resume will be given here. The most common type of cement is a magnesium calcite micrite containing 15–17 mol % MgCO_3 . It occurs in pores of internal sediment and in intra-skeletal pores (Fig. 21a). Less common is the aragonite needle cement which frequently lines the chambers of *Dendropoma irregulare* (Fig. 21b). Various cements may occur sequentially in the same cavity (Ginsburg *et al.*, 1971b; Schroeder, 1972b). Table 2 summarizes the mineralogy, morphology, and abundance of the various types of cement.

A variety of evidence indicates that the cement crystallized from seawater within the reefs.

(1) Mineralogy—high magnesium calcite cement is not known to occur outside the marine environment.

(2) Isotope ratios—the carbon and oxygen isotope ratio determinations provided by Choquette (Ginsburg *et al.*, 1971b) fall within the ranges for skeletons of marine organisms from Bermuda.

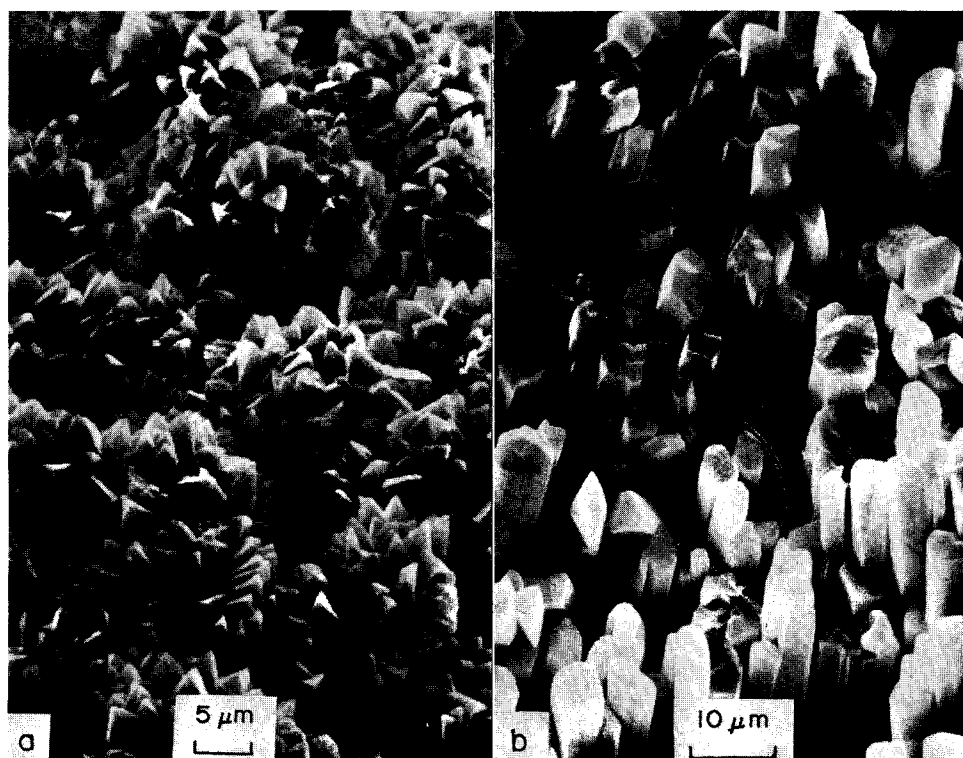


Fig. 21. (a) SEM micrograph of magnesium calcite micrite cement from a specimen of reef rock, see also Ginsburg *et al.* (1971b) and Schroeder (1972b) for further details. (b) SEM micrograph of aragonite needle cement in cup reef rock, see Schroeder (1972b).

Table 2. Mineralogy, morphology and abundance of cements

Types	Composition	Fabrics	Maximum long dimension (μm)	Relative abundance
1	Aragonite	Needle	400	Abundant
2	Aragonite	Spherulitic	400	Common
3	Aragonite	Lath	20	Rare, locally abundant
4	Mg-calcite 15–17 mol % MgCO_3	Micrite	8	Very abundant
5	Mg-calcite 15–17 mol % MgCO_3	Scale	20	Rare, locally abundant
6	Mg-calcite 15–17 mol % MgCO_3	Palisade	80	Common
7	Mg-calcite 15–17 mol % MgCO_3	Algal palisade	200	Abundant
8	Mg-Calcite 15–17 mol % MgCO_3	Blocky	60	Rare

(3) Occurrence—(a) Cemented internal sediment occurs within less than a centimetre of the living surfaces of the reefs whose depths extend to 8 m below present sea level. (b) The cement alternates with marine internal sediment. (c) The cement coats the filaments of endolithic algae in pores (Schroeder, 1972a). (d) Cemented sediment occurs in the coral covered sea floor from which the cup reefs rise.

(4) Age—It is impossible to obtain a sample of cement large enough for radiocarbon age determination. However, age determinations cited below of skeletons in well-cemented specimens of reef rock down to 3.5 m below the surface are all Holocene.

The occurrence of cemented internal sediment less than a centimetre below the living surface, and the multiple generations of cement crystals (Ginsburg *et al.*, 1971a; Schroeder, 1972a) all indicate that the crystallization of cement begins centimetres below the living surface, and that it continues within the reef mass. The occurrence of cement so near the living surface, the position of the cup reefs on the open ocean margin of the platform, and the almost continual wave surge to which they are subject, are all indications that the cement is deposited from water of oceanic composition. It seems most unlikely that the water from which the cement is deposited has undergone any significant changes in ion concentration or temperature.

Sequential growth

Most large specimens of cup reef-rock show multiple generations of pores, coelobites, internal sediments, and cements. These multiple generations are most evident on the macroscopic scale, but they may also occur in some of the smallest pores as well.

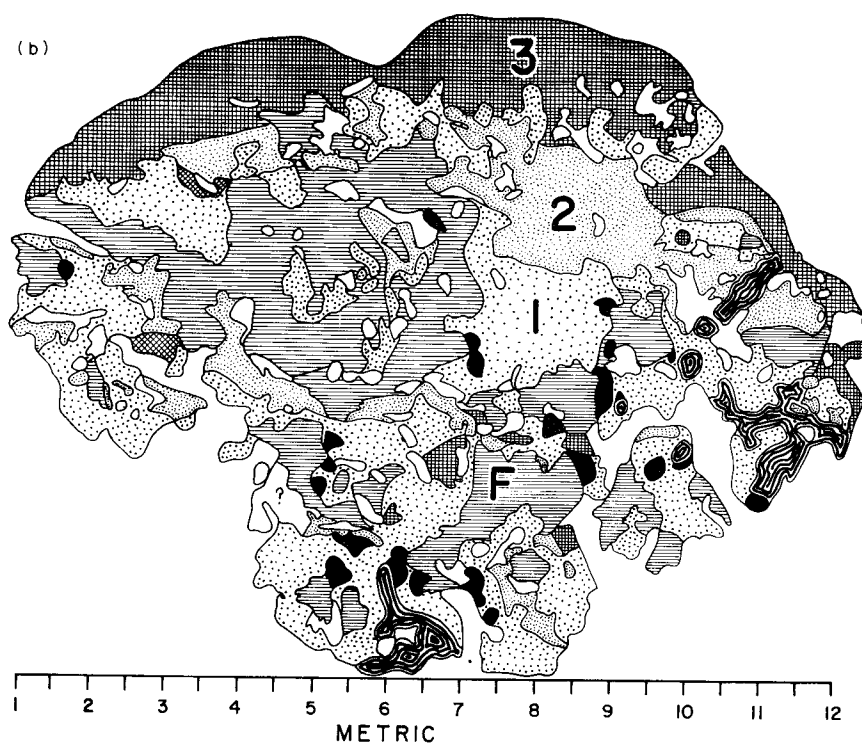
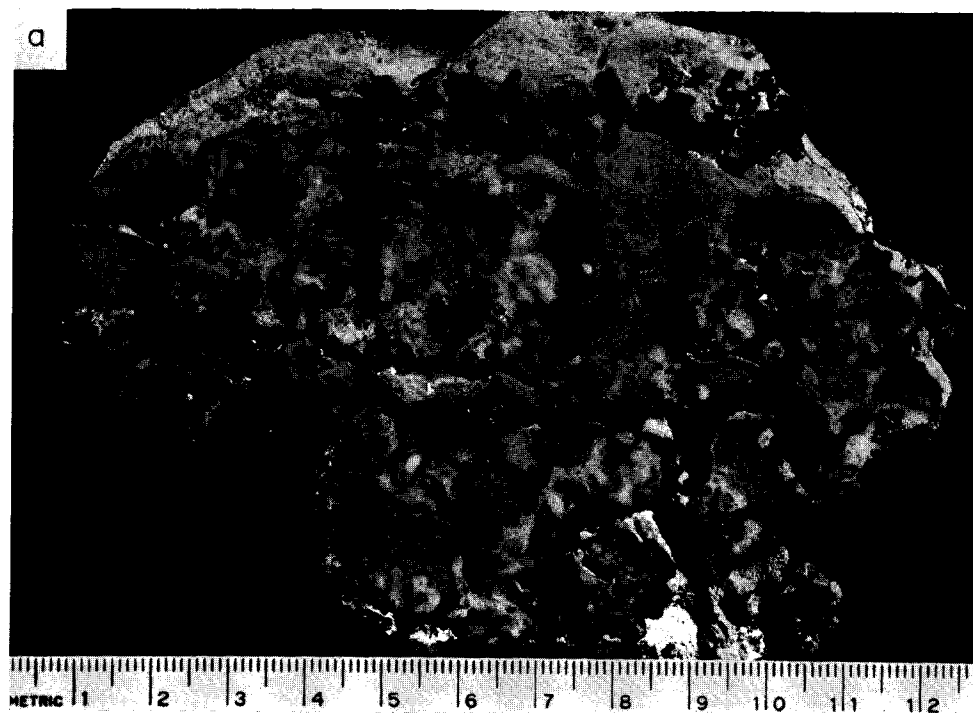
Figure 13a shows three generations of bivalve borings, of which the first two are filled with internal sediment. In Fig. 19 a sponge boring has a two-generation fill of sediment. A complex sequence of internal sediments in a crustacean burrow is illustrated in Fig. 24.

Multiple generations of growth and early diagenesis are particularly evident in the fillings of larger voids. In Figs 14 and 17 there are two generations of vuggy pores and two generations of internal sediment; Fig. 18 shows how a second generation of internal sediment caps the first and the frame; Fig. 22 illustrates a three-generation sample.

In some larger voids, frame-builders and/or coelobites may punctuate the successive stages of sedimentation and cementation. In Fig. 23, frame-builders cover open sponge borings and partly filled bivalve borings. In Fig. 25 coelobitic bryozoans grew on palisade cement that caps internal sediment. In Fig. 26 coccoliths occur in the detritus on the second generation of aragonite needle cement that in turn grew on algal filaments calcified by high-magnesium calcite.

Radiocarbon ages

Several specimens were dated from two reefs in the Northeast Breakers Group near Latitude 32°28'42" North; Longitude 64°41'15" West. A sample of the surface crusts of coralline algae from the reef we named Haversack East is contemporary <160 years B.P. A sample of reef rock 50 cm below the surface taken from the same large slab as the surface specimen has an age of 700 ± 170 years B.P. A sample taken 30 cm below the surface of a second reef named Haversack East, has an age of 1170 ± 180 years B.P. A second sample from this reef taken 3 m below the top but within approximately $\frac{1}{2}$ m of the side of the reef has an age of 1250 ± 180 years B.P. A third sample from Haversack East reef taken 3.5 m from the top, 1 m from one side of the reef and 2 m from the other has an age of 3190 ± 210 years B.P. for the growth



frame of coralline algae and 2980 ± 160 years B.P. for the whole rock of which approximately half is well-cemented internal sediment.

These dates indicate rapid but variable rates of growth ranging from 1 cm/8.5 years for the sample at 3.5 m from Haversack East to 1 cm/39 years from 30 cm below the surface of the same reef. For comparison the rate of eustatic rise during this period is about 1 cm/16 years. The relatively large difference between the two dates from Haversack East, 3 m— 1250 ± 180 years and 3.5 m— 3190 ± 210 years suggests there is lateral as well as vertical growth because the first sample was taken nearer the side of the reef than the second. Lateral growth was evident in the blasted sections where growth laminations paralleled the near vertical reef surfaces.

DISCUSSION

Significance of results for Bermuda

The origin of the structures here termed algal cup reefs has been the subject of considerable discussion by several previous authors. All these studies were limited to the examples along Bermuda's south shore; our research concentrated largely on examples on the northern rim of the platforms (Fig. 1). All previous authors agree that the structures on the south shore are not organic reefs but eroded remnants of Pleistocene eolian limestone, thinly encrusted by organic growths (Nelson, 1837; Agassiz, 1895; Verrill, 1907; Prat, 1935; Stanley & Swift, 1967). Only one of these works (Stanley & Swift, 1967) provides direct observations of the 'reefs' from below sea level; it reports exposed eolianite on and within some reefs.

Our studies of cup reefs (breakers) on the northern margins of the Bermuda Platform that are superficially indistinguishable from those on the south shore, give quite a different result. In none of the seven examples did we find an eolianite core. In three of the reefs examined, our artificial sections penetrated to depths of several metres; 8 m in reefs of the Northeast Breakers group, and 6 m in a reef west of North Rock. It is evident that the community or organisms now on the surface has produced the several metres of observed relief and that these structures must be regarded as organic reefs, *sensu strictu*.

During our study, we dissected one of a discontinuous line of reefs in front of Castle Harbour on the South Shore, see Fig. 1. Here we found only a thin veneer of

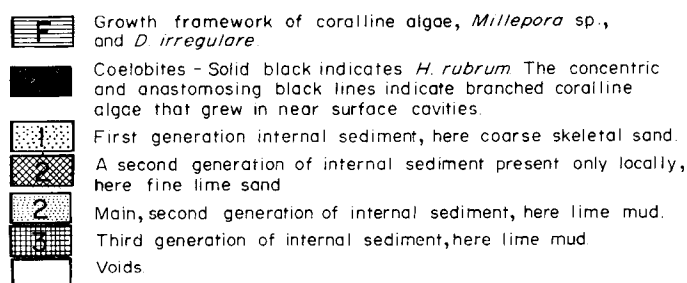


Fig. 22. (a) Sawed surface of a specimen of reef rock from a cup reef of the Northeast Breakers Group. (b) Tracing of the surface shown in Fig. 22a. The vuggy pores that separate the three generations of internal sediment were probably similar to those shown in Fig. 14. At several places, above scale dimension 7 cm and 9 cm, the third generation sediment lies directly on the first generation.

encrusting organisms, overlying stratified calcareous sand. The sand and its inclined laminations closely resembles the Pleistocene eolianites of Bermuda. This finding offers support for the interpretation of the 'reefs' of the south shore proposed by earlier authors. However, in a section through a boiler 'reef' at Hungry Bay on the south shore, one of us (J.S.) found 4–5 m of organic frame.

From all the available evidence we conclude that the structures termed boilers and breakers by earlier authors are of two kinds: some are eroded remnants of Pleistocene eolianite with a rind of Holocene encrusting organisms; others are true reefs built by the same community of organisms.

Comparison with other occurrences

The algal cup reefs described here demonstrate the reef-building ability of a community of encrusting organisms that was previously known only as crust-forming growth in the intertidal zone of the Mediterranean and the northern coast of Brazil. In the Western Mediterranean, Peres & Picard (1952), Molinier (1955), Peres & Picard (1957) have described narrow platforms (*trottoirs*) and visor-like projections, *corniches* of encrusting organisms on rocky shores. In the Eastern Mediterranean, Safriel (1966) described similar rims on intertidal platforms of the Israeli coast. Vermetid gastropods, *Vermetus* and *Dendropoma* and crustose coralline algae are the principal contributors to these growths.

All authors who have described or studied these crusts emphasize their thorough cementation. Blanc & Molinier (1955) report that the main cement in examples from the Western Mediterranean is cryptocrystalline, 0.01–10 μm , and they infer that it is magnesium calcite from X-ray analyses of bulk samples. Safriel (1966) describes the platform margins along the Israeli coast as 'cemented organic encrustations' in which even the *Dendropoma* shells are filled with 'cement'.

Crusts of vermetid gastropods and crustose coralline algae similar to those in the Mediterranean have been described from the northern coast of Brazil by Kempf & Laborel (1968). Here the intergrowth forms borders or fringes along the rocky shores and rims the seaward sides of coral reefs. The authors call attention to similarities with the intergrowths in the Mediterranean and Bermuda, and they also suggest that the vermetid-coralline algae association in the Atlantic may be analogous to the algal ridge (*Lithothamnion* ridge) of Indo-Pacific atolls.

Shier (1969) described reefs of vermetids, *Vermetus (thylaeodus) nigricans* from the southwest coast of Florida. These reefs, up to 1½ m thick, occur on the low-energy Gulf shoreline at the seaward margin of a labyrinthine network of mangrove islands, oyster bars, and shallow bays known as the Ten Thousand Islands. Coralline algae are absent on these reefs and there are no indications of cementation.

Micro-atolls whose surfaces consist of crustose coralline algae have been described by Boyd *et al.* (1963) off Cozumel Island on the east coast of the Yucatan Peninsula. The micro-atolls are cylindrical structures 12–25 ft in diameter with an elevated rim surrounding a central lagoon; six species of coralline algae are reported from the few samples examined, but there is no mention of other organisms or cementation in this preliminary note.

The remarkable growth of the encrusting community on Bermuda is strikingly similar to that of the crustose coralline algae on the seaward margins of Indo-Pacific atolls. The algal or *Lithothamnion* ridge and the Bermuda cup reefs share the following characteristics: (1) they occur in intertidal surf-swept positions; (2) they are built of

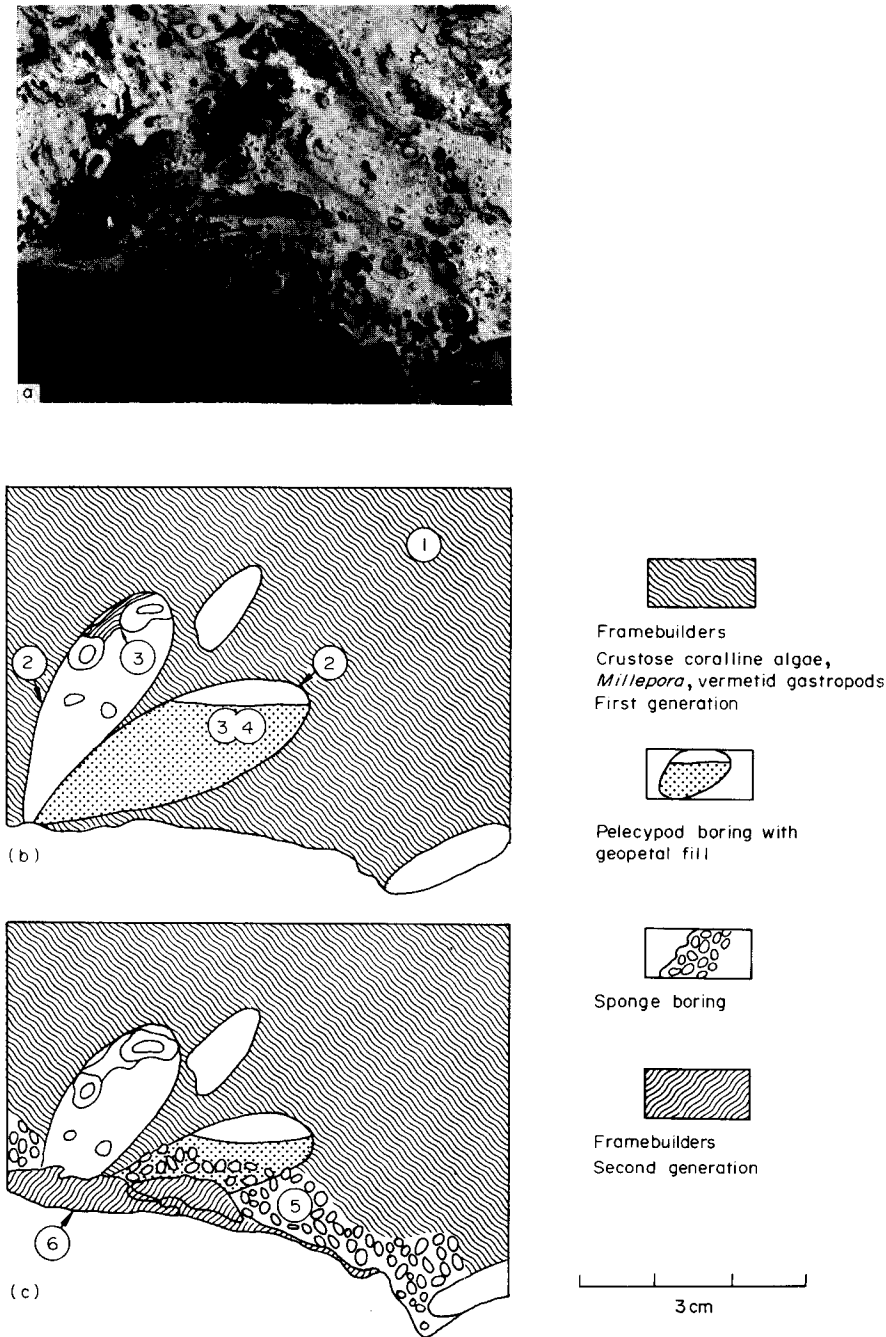


Fig. 23. Sequential growth of reef rock: (1) growth frame formed at the surface; (2) bivalve borings; (3) internal sediment and/or coelobites partly fill borings; (4) cementation; (5) boring sponges riddle surface and cemented internal sediment in bivalve borings; (6) a second generation of frame-builders covers the bored surface.

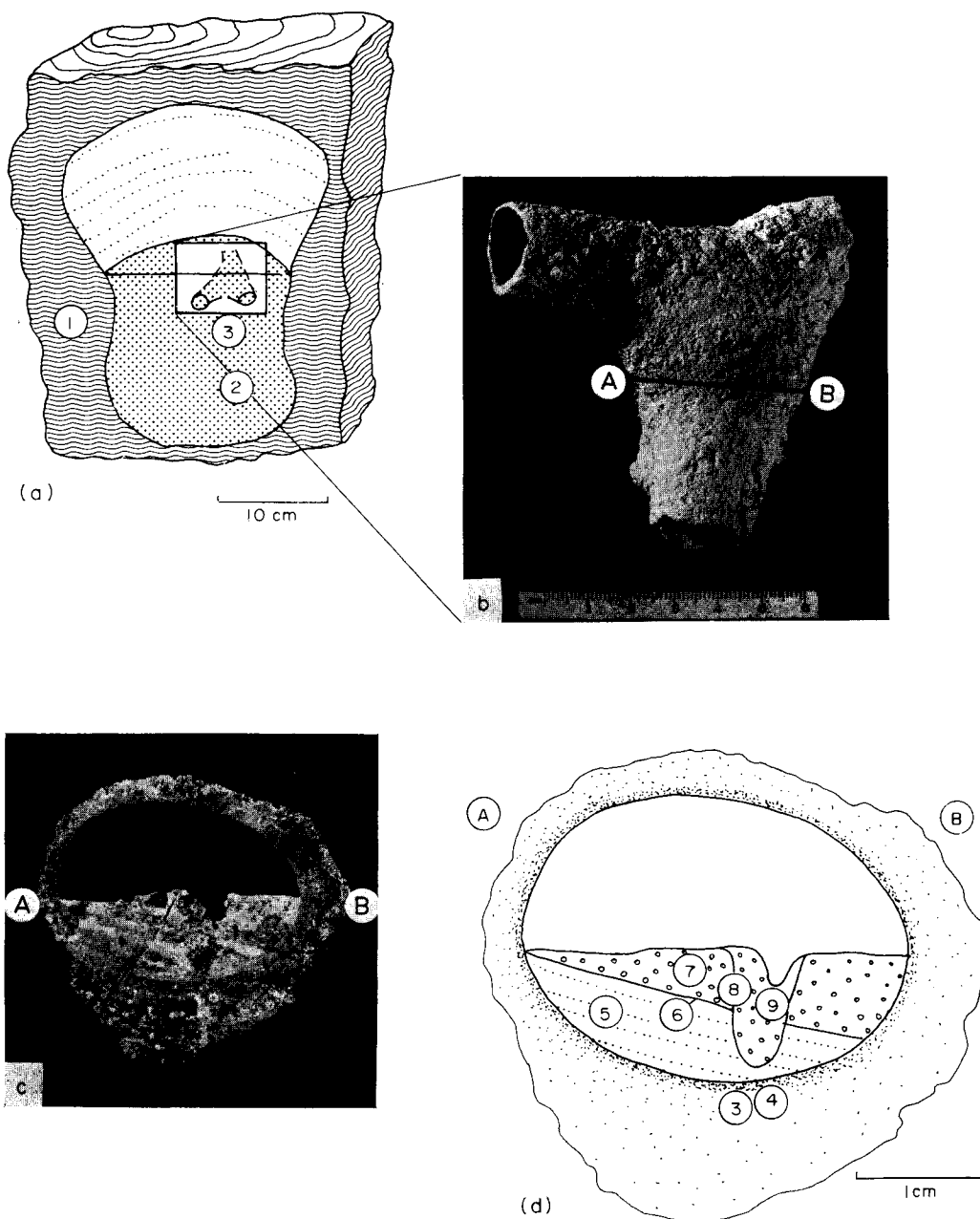


Fig. 24. Sequence within a large void in reef rock, Northeast Breakers Group. (a) Diagram of large void in reef rock: (1) growth frame; (2) geopetal fill of internal sediment; (3) crustacean burrow within internal sediment. (b) Cemented crustacean burrow. (c) Section A-B of crustacean burrow. (d) Diagram showing sequence in (c); (4) cementation of crustacean burrow; (5) deposition of laminated internal sediment in burrow; (6) burrow tilted or direction of sediment supply changed; (7) deposition of coarse-grained internal sediment; (8) animal burrow penetrates coarse internal sediment; (9) deposition of internal sediment in burrow.

encrusting organisms, principally crustose coralline algae; (3) they have appreciable internal sediment; and (4) they are thoroughly cemented.

The location and morphology of the algal ridge has been described from several Pacific atolls (Gardiner, 1898; Finckh, 1904; Tracey, Ladd & Hoffmeister, 1948; Emery *et al.*, 1954). We have been unable to find extensive descriptions or analyses of the internal structure and composition of the algal ridge, but published illustration in the works cited above, as well as descriptions summarized by Howe (1912) suggest that crustose corallines are the major contributor to the rock beneath the living algal pavement. The occurrence of cemented internal sediment in the algal ridge and nearby reef flat was first noticed by Darwin (1842) and Dana (1872). In their report on core borings from the reef flat of Eniwetok, Ladd & Schlanger (1960) describe numerous examples of well-cemented internal sediment. We examined these cores and found that much of the rock is indistinguishable from that in the cup reefs.

Functional aspects of reefs

The separation of reef-building organisms into functional categories: frame-building, frame-binding, and sediment-producing and trapping was recognized by Walther (1888), if not before. The importance of destruction by organisms was appreciated by Finckh (1904). Lowenstam (1950) suggested the first three functions as ecological categories; Kornicker & Boyd (1962) added the categories of frame destruction, inhibition of reef growth, and sediment moving. Our study of the algal cup reefs calls attention to the multiple roles and functions of several organisms. Crustose coralline algae and *Millepora* sp. are impressive examples of organisms that have multiple functions; they are principal frame builders as well as frame binders. In addition, they produce a variety of voids (Figs 7, 10, 11) that form habitats for coelobites and traps for internal sediment. *Homotrema rubrum*, the encrusting Foraminifera, is a frame-binder where it forms crusts in voids as well as a major contributor to the internal sediments.

The importance of void size and shape in determining the kind of coelobites in reefs was emphasized by Jackson *et al.* (1971) from studies of Jamaican coral reefs. A similar relationship occurs in the cup reefs; in addition the sizes and throats of voids determine the texture and amount of internal sediment that fills them. It may be appropriate to consider void formation as a function of reef building organisms along with those described above.

The functional approach to reef development is traditionally limited to organisms, but the algal cup reefs and their counterparts in Pacific atolls (see especially Newell, 1955) emphasize the critical contribution of internal sedimentation and cementation for growth and stability. Because these largely inorganic processes can make such a significant contribution to the reef rock they deserve as much attention as the purely biological aspects of reef growth.

Early diagenesis

The study of the interiors of the cup reefs demonstrates that major additions to and modifications of the growth framework occur below the living surface. The repetition of pore formation, growth of coelobites, deposition of internal sediments, and cementation make a major, often predominant contribution to the ultimate reef rock. The filling of pores with encrusting coelobites and internal sediment that is rapidly cemented produces a pervasive mortar that solidifies and strengthens the growth framework.

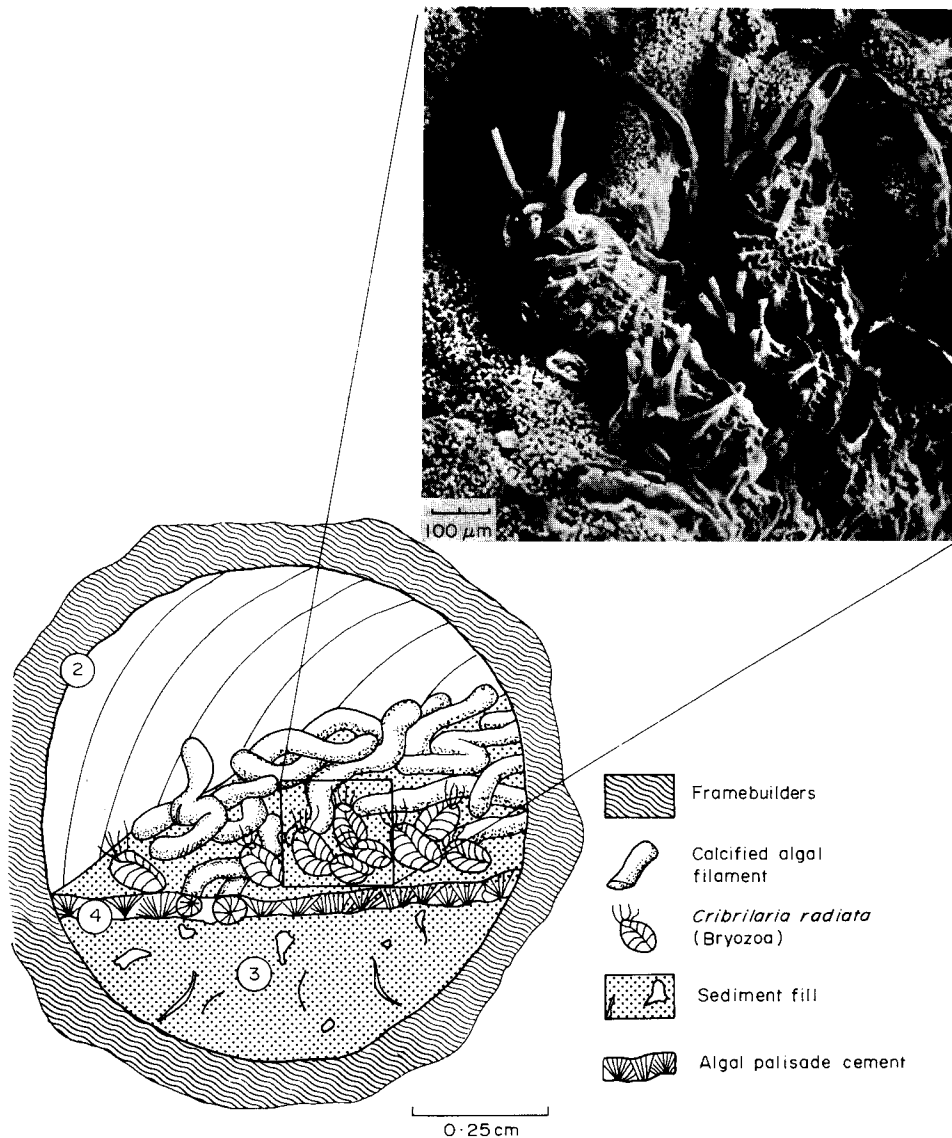


Fig. 25. Sequence in bivalve boring: growth frame—wavy lines; (2) bivalve boring; (3) geopetal of internal sediment; (4) palisade algal cement and calcified algal filaments (see Schroeder, 1972a for details); (5) coelobitic bryozoans grow on cement.

Boring bivalves and sponges penetrate the growth frame as well as the cemented sediment filling the pores. These borings are in turn filled with sediment and cemented; the frequent repetition of boring and infilling can in time replace a significant volume of the growth framework. In the cup reefs, all stages of this replacement can be seen; Fig. 22 shows an advanced stage of the replacement in which more than half of the reef rock is now well cemented internal sediment.

One of the most diagnostic aspects of the early diagenesis of cup reefs is its extreme diversity. All of the major elements, pores, coelobites, internal sediments, and cement

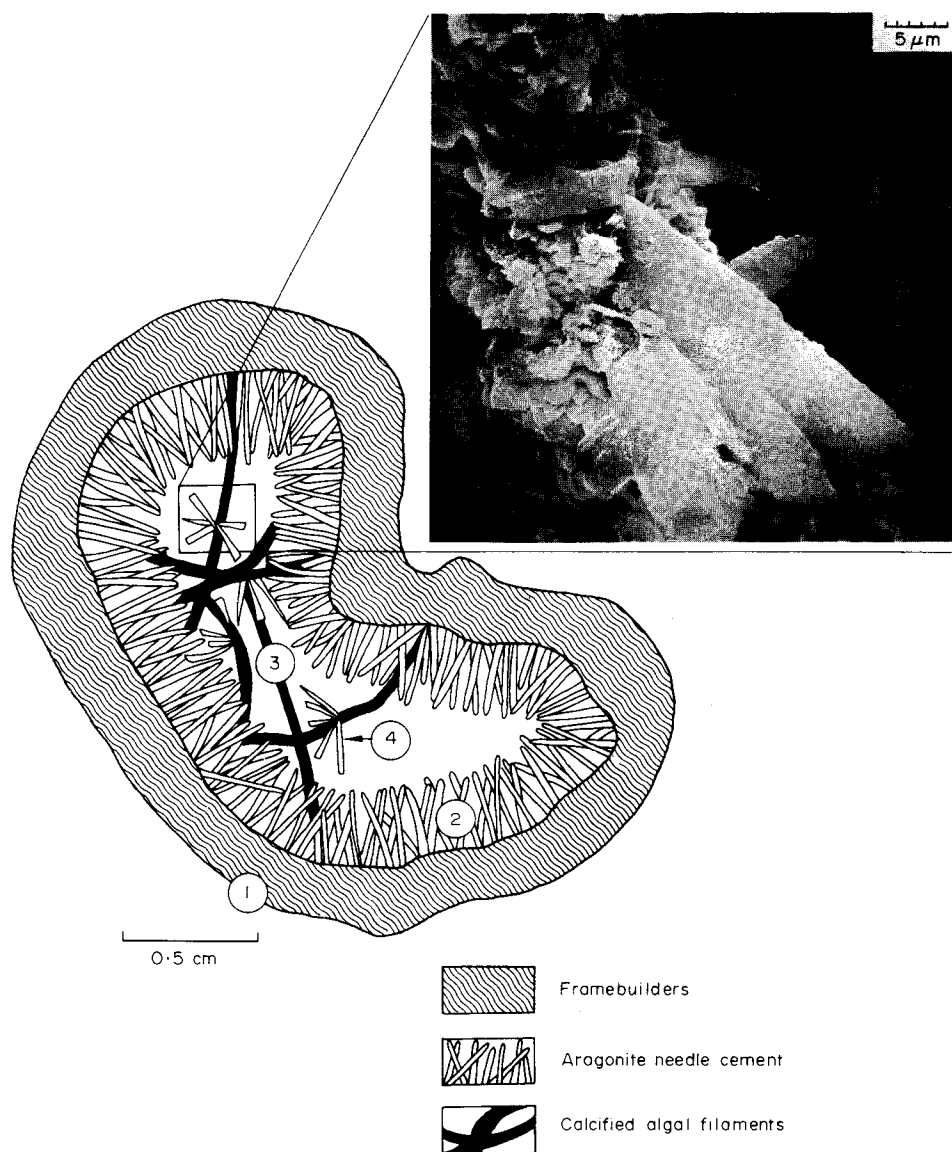


Fig. 26. Sequence of cements in an intraskeletal pore: (1) chamber of gastropod shell, *D. irregularis* (see Fig. 5 for macro-view of these shells); (2) lining of aragonite needle cement; (3) algal filaments coated by magnesium calcite (see Schroeder, 1972a); (4) clusters of aragonite needles on calcified algal filaments; (5) deposition of coccoliths (pelagic algae) on aragonite needles.

vary widely in time and space within individual hand specimens and even within individual pores. Most hand specimens show at least three types of pores: inter- and intra-, particle, and borings, growth framework and shelter pores are less common. The size and connections of these pores strongly influence the occurrence of coelobites and the grain size of internal sediments. Moreover, because the sizes and continuities of the pores change as they are lined or partially filled with sediment, the nature of the

fillings also changes. These sequential changes may be surprisingly large (Figs 17, 22) and they extend down to the scale of individual pores (Figs 19a, 23–26).

The wide variations in the sequences of coelobites, internal sediments, and cements that fills pores indicates that each pore has its own diagenetic history and that the process domains of this early diagenesis can be as small as an individual pore. Moreover, the repetition of pore formation by borers and subsequent filling produces a complex rock in which it is difficult to correlate the relative ages of pore fillings beyond a few decimetres.

Comparison with other Holocene examples

How unique is the early diagenesis of the Bermuda cup reefs? The same features that are so prominent in Bermuda have been described from Pacific atolls, from the floor of the Persian Gulf, from the intertidal and subtidal zones of the Mediterranean. Preliminary reports suggest that they also occur in the reefs off the North Coast of Jamaica, in the Red Sea, the Bahamas, and in British Honduras.

In the upper 70 ft of the Funafuti boring, where there was reasonably good core recovery, Hinde's descriptions (1904, pp. 195–199) mention repeatedly the presence of coelobites and cemented internal sediments.

At 65 ft, Hinde reports (1904, p. 198) that the sample contained fragments of coral broken by the drill mixed with an extremely wide variety of fresh-looking tests and spicules: fifteen species of Foraminifera, abundant alcyonarian spicules, crustacean claws, ascidian spicules, small specimens of seven species of gastropods, ovoid pellets, fragments of *Halimeda* and branched coralline algae. The occurrence and the variety of remains suggests that the sample, like that described in Table 1 is from an unconsolidated internal sediment in a pore within or between corals.

On the microscopic scale, the upper part of the Funafuti boring also shows the same sort of diagenetic features as were found in the Bermuda cup reefs. Cullis (1904) described both calcite and aragonite cements from the upper 100 ft that . . . 'furnish a crystalline cementing material by which the original organisms and organic fragments of the rock are bound together, and the cavities, within and between them, more or less completely filled up' (Cullis, 1904, p. 396). The coincidence of high magnesium with zones where the cement is most abundant leaves little doubt that the calcite cements in the Funafuti boring, like those in the Bermuda cup reefs are high magnesium calcites.

Emery *et al.* (1954) describe two types of reef rock from Bikini atoll: (1) Algal limestone ' . . . composed principally of *Lithothamnion* in position of growth. Cavities in the *Lithothamnion*, and spaces between branches or knobs, are filled or partly filled by fine granular detritus consisting in part of tests of foraminifers. Open cavities are in places coated with encrusting forms such as *Miniacina* or *Homotrema*' (Emery *et al.*, 1954, p. 30); and (2) detrital limestone forming the reef flat that consists of rounded and angular fragments of reef-building organisms and up to 30% benthic Foraminifera in a pastey matrix (Emery *et al.*, 1954, pp. 30–31). Ladd & Schlanger (1960) summarize their observations on shallow borings on Eniwetok Atoll as follows. 'The seaward margin of the existing reef, where corals and other skeletal materials are closely bound together by encrusting algae and Foraminifera, appears to be one of the most resistant parts of the reef but the shallow holes put down on the reef flat of Eniwetok indicates that a plate of solid rock may exist beneath the reef flat . . . much of the hard rock beneath the flat has been cemented by intergranular films of drusy

calcite, possibly at intertidal levels, but the process is not clearly understood' (Ladd & Schlanger, 1960, p. 900). Elsewhere (p. 901) they call special attention to the increasing percentage of well lithified rock found in holes drilled closest to the seaward rim of the atoll.

The initial reports of the extensive subsea cementation in the Bermuda cup reefs (Ginsburg *et al.*, 1967) were soon followed by reports of similar cementation in Jamaica (Land & Goreau, 1970) and in the Red Sea (Friedman, Amiel & Schneiderman, 1970). Both these descriptions are limited to the cements, but there is every reason to expect that the more complete reports will indicate the presence of coelobites and internal sediments. Zankl & Schroeder (1972) describe an example of the major replacement of growth framework by repeated boring, internal sedimentation, and cementation in coal reefs off North Eleuthera, Bahamas.

In his descriptions of the extensive cemented crust on the floor of the Persian Gulf, Shinn (1969) clearly showed that these crusts are the product of multiple cycles of sedimentation, lithification-animal boring-sedimentation, etc. (Shinn, 1969, p. 123).

The subtidal algal crust described by Alexandersson (1969) from the Mediterranean consists of a thin 'algal covering' of crustose algae and other encrusting organisms overlying a '... mosaic of dense and hard fine-grained limestone in varying shades of white, yellow and brown ...'. Within this mosaic, Alexandersson finds remnants of organic framework of the 'algal covering', and he interprets the limestone as the result of reiterated boring, internal sedimentation, and cementation.

Studies of the early diagenesis of coral reefs are in the exploratory phase, but features similar to those in cup reefs have been reported. Garrett *et al.* (1971) and Scoffin (1972) have described coelobites from coral reefs in Bermuda; Ginsburg & James (1973) illustrate internal sediment and cement from the fore-reef of British Honduras.

Environment of early diagenesis

There are no existing measurements of the conditions within the cavities of cup reefs or, for that matter, any reefs. However, from their position at or near the platform margins and from the organic and physical features of the pore fillings, one can make some judgments of the conditions within the cavities.

The algal cup reefs are termed boilers or breakers in Bermuda because most of the time oceanic swell and sea breaks or boils around them. This frequent and intense wave action sweeps surface sediment into the caverns and pores below.

The direct force of breaking waves moves water through the surficial void system of the cup reefs. However, the occurrence of coelobites and coarse sand-sized internal sediment in voids well below the surface demonstrates that within the reefs there are currents strong enough to bring sand to the cavity openings. Flushing and deposition could also occur through the Venturi effect: The 'wakes' of waves that break over the cup reefs 'pull' water out of the voids so quickly that the equally high velocity turbulent inflow could transport coarse sand sizes. As the passageways that interconnect pores and lead to the surface are constricted by progressive infill or growth on the surface, the velocity and frequency of flushing should decrease. This progressive decrease in flushing may explain the upward decrease in grain size of certain pore fillings (Fig. 19a). The lamination in these finer grained sediments might record periodic fluctuations in wave agitation and/or sediment supply that are climatic (winter storms?).

Because the crystallization of cement within internal sediments and frame precedes, accompanies, and follows deposition of internal sediments and growth of coelobites, it must also take place when the cavities are frequently flushed. Whether it is this frequent and rapid (?) flushing that triggers the crystallization through purely physical effects, or whether this same flushing removes or adds organic films or stimulates some other unspecified organic activity is unknown.

At this stage in our understanding of the environments of early diagenesis, we can best describe the conditions within the cup reefs and seaward margins of atolls as frequently flushed with 'normal' or oceanic sea water. The most diagnostic criteria for recognizing this frequently flushed phase of diagenesis will be the alternation and variation in time and space of coelobites, internal sediments, and cements.

Early diagenesis of fossil reefs

In his extensive work on the Devonian reef complex of the Rhenish Schiefergebirge, Krebs (1966, 1969, 1971) described features comparable to those of the cup reefs. The reef facies itself is characterized by the following features. '(a) The appearance of massive to tabular, mostly convex upward warped stromatoporoids, tabulate corals (Alveolites, Favosites, Heliolites) and rugose corals (Hexagonaria, Phillipsastrea) in growth position. (b) Overgrowth and encrustation by stromatoporoids, corals, and calcareous algae. (c) Deposition of reef detritus and skeletal components in niches, lenses, and layers between the autochthonous reef dwellers. (d) Early cementation of interskeletal voids with crusts of fibrous or bladed calcite' (Krebs, 1971, pp. 47-48). The cavities within the rubble accumulated on the fore-reef slope exhibit complex diagenetic sequences in which Krebs (1971) interprets the cementation as submarine.

In the Alpine Triassic reefs at the German/Austrian border near Salzburg (Zankl, 1969, 1971a,b) the original frame-builders, corals and calcisponges, may be succeeded by as many as four generations of coelobites, encrusting foraminifers, calcisponges, blue-green algae, two generations of sediments, and two generations of cement. Zankl considers all except the final drusy or blocky calcite cement to be submarine.

The Permian Reef Limestone of New Mexico and Texas show features of early diagenesis believed to be submarine (Newell, 1955). In these reefs, the frame-builders include calcareous sponges, a hydrocoralline, lamellar algal crusts, massive and pinnate bryozoans. Secondary frame-builders include bryozoans, brachiopods, and pelecypods. The voids formed or left by these organisms are coated with a clear fibrous calcite cement, which Newell suggests was precipitated from solution from relatively clear turbulent water 'presumably at a level a few inches below the surface of the growing reef' (Newell, 1955, p. 308). Subsequently, detritus was deposited in these cavities; this detritus (internal sediment) comprises 'as much as one-half of the substance of the Capitan Reef in West Texas' (Newell, 1955, p. 306).

Geological significance

The preceding review and comparison of examples of early diagenesis in Holocene reefs and ancient reefs indicates that the features found within the algal cup reefs of Bermuda are widespread in time and space. This kind of early diagenesis has several implications for our interpretations of both Holocene and older reefs.

(1) The alternation of boring, infilling of pores and cementation continually produces additional substrate surface for the attachment of organisms in much the same

way as the growth of reef-building corals. The organisms that inhabit this immense void system may play a significant role in the food and nutrient cycle of the entire reef.

(2) In reefs of this type there is as much or more growth below the surface in the void system as from frame builders on the surface. Coelobites and internal sediments develop in environments vastly different from those on the surface, yet they are intimately intermixed in the ultimate reef rock. The works of Krebs & Zankl (see above) demonstrate how essential the recognition of this compound aspect of reef growth is to the interpretation of ancient reefs.

As suggested above, by Alexandersson (1969) and Zankl & Schroeder (1972), continued boring, infilling, and cementation can all but obliterate the original growth framework and produce a complex rock that is largely pore filling.

(3) The solidifying and strengthening effects of this kind of early diagenesis appear most pronounced on the exposed seaward margins of modern reefs, reef flats, and probably the algal or *Lithothamnion* ridge of Pacific Atolls and the cup reefs of Bermuda. This geologically rapid lithification may play a vital role in the existence of the wave-resistant marginal zone.

If further research confirms the restriction of this kind of early diagenesis in reefs to wave-swept environments, its recognition in fossil reefs may add precision to the reconstruction of their environment and position.

(4) The early diagenetic additions to and modifications of the growth framework can significantly reduce porosity and permeability and reorient the pore fabric as well (Ginsburg & Schroeder, 1972). This reduction and restructuring, as well as the unstable nature of the high-magnesium calcite cement, will certainly influence, if not control, subsequent diagenesis. Land (1971) has suggested that the magnesium calcite cement could provide a significant reservoir of magnesium for subsequent dolomitization.

CONCLUSIONS

(1) A community of encrusting organisms, coralline algae, hydrozoans, and attached gastropods is capable of building reefs on the wave-swept margin of the Bermuda Platform. This community is both frame-building and cementing.

(2) There is major addition to and modification of the growth framework of algal cup reefs in the void system below the surface. The repeated alternation of animal boring, coelobites, deposition of internal sediment, and cementation adds to and/or replaces up to half of the growth framework and locally reduces porosity to a few percent or less.

(3) Submarine cementation of the growth framework and internal sediments begins less than a centimetre below the surface and within less than $\frac{1}{2}$ m the reef rock is a well-lithified limestone. The cement, most commonly micrite-size high-magnesium calcite crystallizes in the pore system that is frequently flushed by water of oceanic composition.

(4) The subsurface addition to the growth framework strengthens and solidifies the growth framework, enhancing its wave resistance and providing additional hard substrate for attached organisms.

(5) Features of subsurface addition and early diagenesis like those found in the Bermuda reefs are reported from the marginal zone of Pacific Atolls and from reefs in the Devonian and Triassic of Germany and Permian of west Texas. Criteria for its

recognition include (a) wide variations in composition, texture, and fabric; (b) alteration of cement and internal marine sediment and (c) evidence of syndimentary lithification.

(6) The early diagenesis found in the Bermuda cup reefs may significantly reduce the porosity and permeability of growth framework and strongly influence the nature and pattern of later diagenesis.

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