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# MARINE LITHIFICATION OF REEF ROCK AND RHODOLITES AT A FORE-REEF SLOPE LOCALITY (-50m) OFF BERMUDA[1]

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## ABSTRACT

Focke, J. W. & C. D. Gebelein (1978). Marine lithification of reef rock and rhodolites at a fore-reef slope locality (-50 m) off Bermuda. *In:* H. J. Mac Gillavry & D. J. Beets (eds.): The 8th Caribbean Geological Conference (Willemstad, 1977). Geol. Mijnbouw, 57, p. 163-171.

At a depth of 50 meters the fore-reef slope at the northern margin of the Bermuda platform consists of solid reef rock interspersed with sand patches and channels. Coralline algae are the predominant framebuilders, the only common coral being *Montastrea cavernosa.* On the rippled sand abundant red algal nodules (rhodolites) occur with diameters up to 12 cm. Both reef and rhodolites show various stages of alteration and lithification by repetitive boring, secondary framebuilding, internal sedimentation and cementation. All processes are marine. Aragonite cement occurs only within the in situ deposited primary framework, and is probably a very early, *post mortem* precipitate. Magnesian calcite is the only common cement on all other substrates. Practically all porosity and permeability is destroyed within approximately 1500 years. Net accretion rates in the rhodolites are in the order of 0.05 mm/year. With local current patterns providing a suitable pumping mechanism, the very slow accretion rates are thought to be the main reason for the pervasive nature of diagenetic alteration on this fore-reef locality. Rhodolites of this type may be useful palaeo-environmental indicators for deep (more than 50 m) tropical waters.

## INTRODUCTION

The Bermuda platform is the shallowly submerged, carbonate-covered summit of a volcanic cone, with a surface area of some 650 km$^2$. In spite of its position well north of the reef belt, Bermuda sustains flourishing coral reefs as a result of the Gulf Stream. A series of islands consisting mostly of Pleistocene aeolianite is situated at the southeastern marging of the platform. At the northern and western margins barrier reefs enclose a wide lagoon with scattered patch reefs (Fig. 1). Two similar but smaller platforms, Challenger Bank and Argus Bank, are found to the south, but these platforms carry no islands. Most of the reefs on the Bermuda platform are built by hermatypic corals and associated organisms, and are comparable to Caribbean reefs (GINSBURG & STANLEY, 1970; GARRET ET AL., 1971), except that the important framebuilding reef-crest genus *Acropora* is missing, probably as a result of low minimum winter temperatures (BOSELLINI & GINSBURG, 1971). Along the exposed southern and northern margin reefs occur, built by coralline algae, *Millepora,* and vermetid gastropods (GINSBURG & SCHROEDER, 1973). In August 1974 we studied a location off North Rock (Fig. 1; 2) at a depth of 50 m;

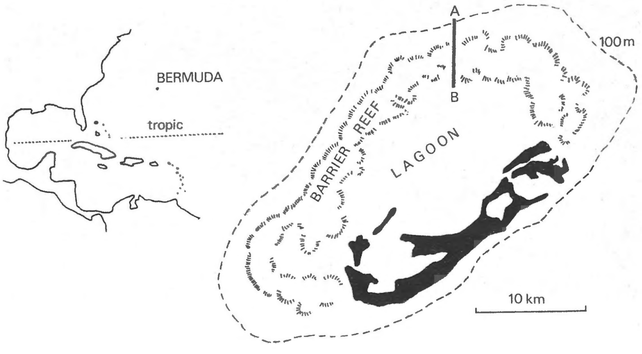

Fig. 1
Index map of the Bermuda platform.

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[4] Conrad died very unexpectedly on March 1 this year. A substantial part of his life has been devoted to the study of carbonate sediments, and his inspiring enthusiasm will be greatly missed. He was fully aware and in support of this paper in its present form.

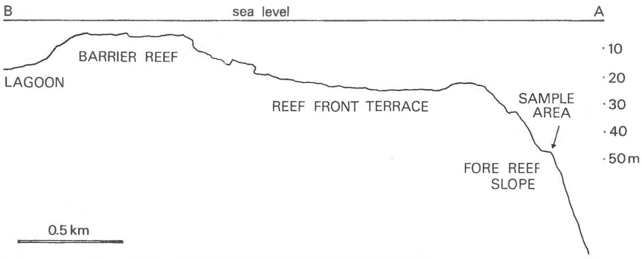

Fig. 2
Fathometer profile over the study location.

Fig. 3
Rocky reef surface at -50 m. Note sea whips in background, coralline algal surfaces (light coloured), brown algae (dark coloured) and the low relief.

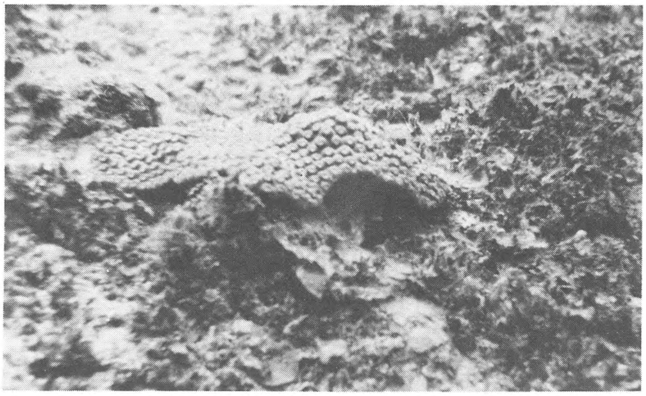

Fig. 4
Colony of *Montastrea cavernosa* surrounded by coralline algae and the brown alga *Padina*.

the results are presented in this paper to supplement an earlier report (FOCKE & GEBELEIN, 1977).

## METHODS

Samples for thin section study were impregnated under vacuum with epoxy resin containing a blue dye. Cement mineralogies were determined by staining one half of each thin section with Clayton yellow stain (WINLAND, 1971) which colours Mg in Mg-calcites, and by comparing the crystal habits seen in SEM with those of marine cements described by SCHROEDER (1972), ALEXANDERSSON (1972) and others (see comment by BADIOZAMANI ET AL., 1977). $^{14}$C-measurements, and carbon and oxygen stable-isotope analyses of rhodolite material were conducted by W. G. Mook, at Groningen.

## RESULTS

### *The study area*

The fathometer profile (Fig. 2), a run over the study locality perpendicular to the depth contours and the reef trend, shows part of the lagoon, the barrier reef (containing both coral and algal reefs), the reef-front terrace (with predominantly coral cover), and the fore-reef slope down to approximately 100 m. The study location is situated on a small break in the slope at ca. 50 m. It is not known if this break is a laterally consistent feature (i.e., a submarine terrace). The bottom at the locality is rocky (Fig. 3) with a few patches of sand. The rock surrounding the patches shows reef fabrics in the sense of SCHROEDER & ZANKL (1974), with coralline algae as dominant primary framebuilders. *Montastrea cavernosa* (Fig. 4) is the only common coral framebuilder, but its coverage is estimated to be no more than one colony per 100 m$^2$. Locally a few colonies of *Millepora* occur, and one single specimen of *Siderastrea ra-*

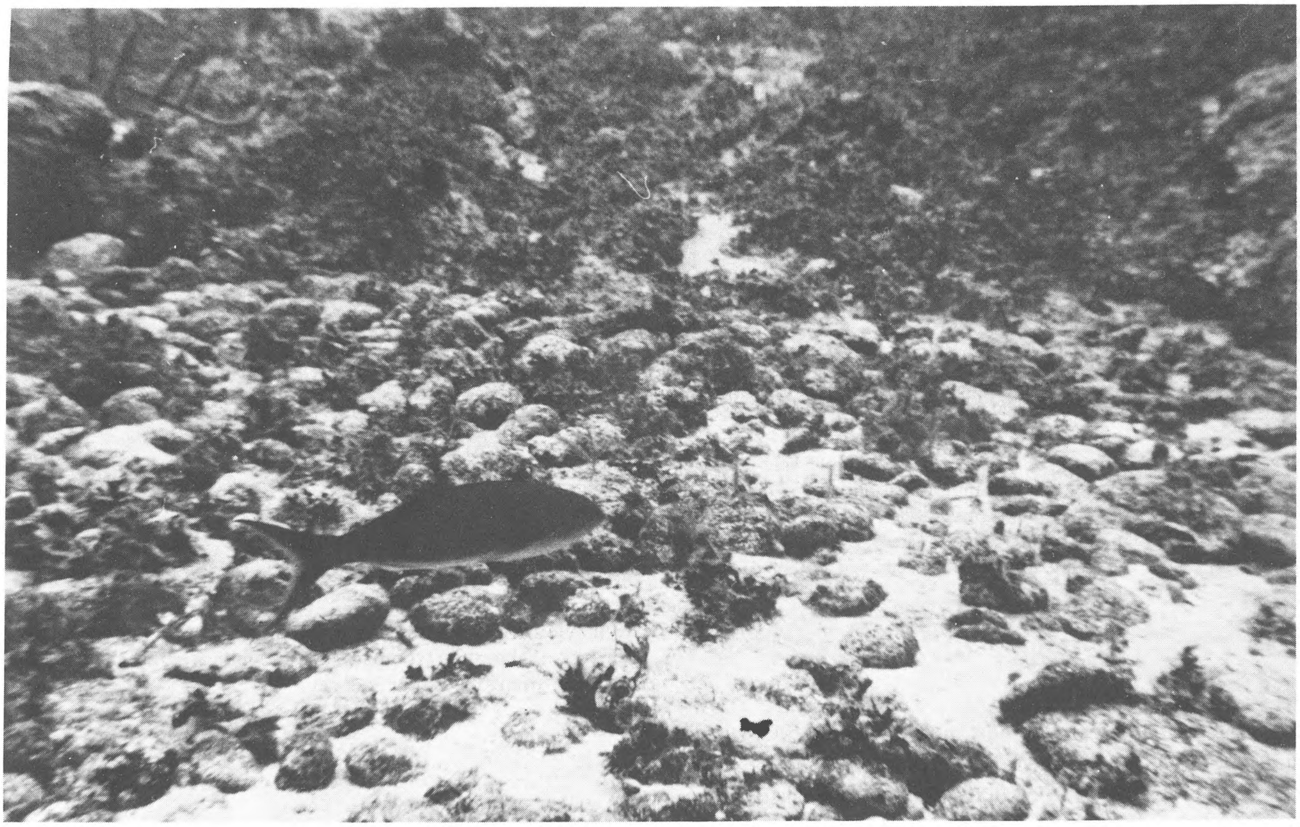

Fig. 5
Sand patch with rhodolites and, in the background, reef rock covered with brown algae.

*dians* was found. Attached to the rocky surface, sea whips and the brown alga *Padina* are very abundant. Except for the few coral colonies, there is very little relief (Fig. 3). The sand on the patches is rippled on a decimeter scale; on this sand red algal nodules (rhodolites) were found in large numbers (Fig. 5). Diameters vary from 3 to 12 cm, colours from pink and brown to deep purple; some rhodolites are flattened. Surfaces are smooth or slightly globose.

### *Internal structure*

The internal structure of reef rock and rhodolites varies greatly between samples. At least two species of coralline algae predominate as primary framebuilders (Fig. 6); in some samples *Montastrea cavernosa* dominates over a few square centimeters (Fig. 7). On a millimeter scale foraminifera (mostly *Homotrema rubrum*), cheilostome bryozoans, small encrusting bivalves, serpulid worms and vermetid gastropods may be important as primary or secondary framebuilders. In one sample of the rhodolites a siliceous sponge was found to be a major framework element. The framebuilders produce a variety of pores such as described by GINSBURG & SCHROEDER (1973, figures 9 and 10). The algal framework is generally dense, the other organisms produce a more open structure. On the average, about 50% of the solid reef material consists of preserved primary framework.

Sediment occurs in all pore types (Fig. 8), but even in a single sample or thin section its amount and composition varies greatly. Most of the sediment consists of angular, silt-sized skeletal fragments (Fig. 10A), usually larger than 100 microns. The angularity implies a lack of abrasion and is also seen in the surrounding loose sediment. Most abundant constituents are fragments of molluscs, free-living foraminifera, coralline algae, corals and echinoids. The surrounding sediment may consist of up to 30% foraminifera, mostly *Amphistegina.* The particles have concave outer margins and a scalloped nature, characteristic of fragments produced by boring (clionid) sponges (JAMES ET AL., 1976, Fig. 12C; MOORE ET AL., 1976, Fig. 16). Distinct generations of internal sediment can be distinguised; younger generations are usually less micritized, less cemented, finer, and better sorted than older generations, reflecting a decreasing permeability with age as more and more pores are destroyed by sedimentation and cementation. Grain size within a void largely depends on the size of the aperture; sealed pores such as often found in the framework are often exclusively filled with cement (Fig. 9A).

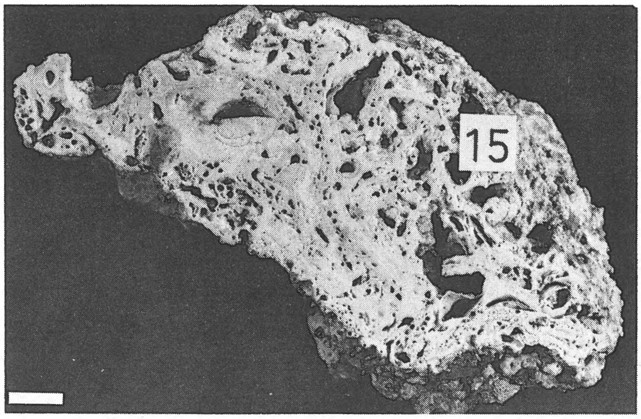

Fig. 6
Section reef rock; the upper surface of the sample was the living surface of the reef. Note the predominant coralline algal framework, bivalve (large holes) and sponge (small holes) borings. Internal sediment, for example in one of the bivalve borings, has been lithified less than 2 cm below the living surface. Scale bar = 1 cm.

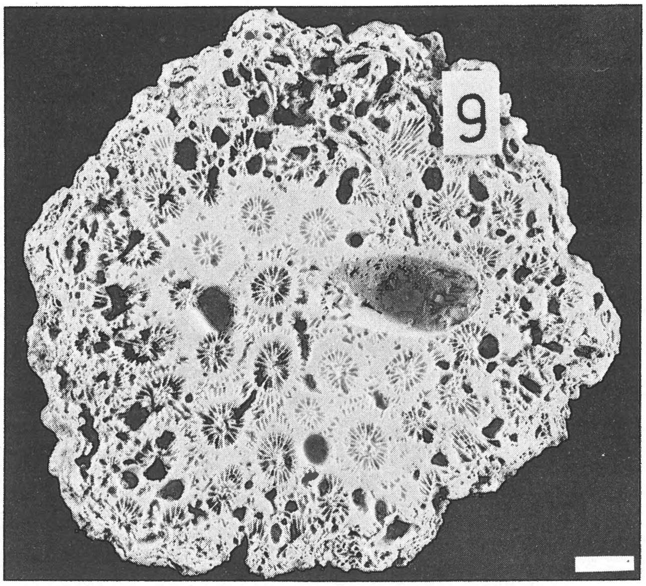

Fig. 7
Sectioned rhodolite with a coral core and thin coralline algal crust. The lack of alteration (compare figure 8) indicates that the nodule is relatively young. Scale bar = 1 cm.

Boreholes usually form the best interconnected pore system, and generally these are the first sites of internal sedimentation and cementation (Fig. 6). Micritic sediment is distinguished from micrite cement by its brown colour in thin sections, the cement being more clear and transparent (Fig. 10). Geopetal fills are common (Fig. 6); although they all have the same orientation in the reef rock, they occur at many different angles in the rhodolites.

Four main types of boring have been distinguished; (1) bivalve borings, several millimeters to more than a centimeter in diameter and up to several centimeters long (Fig. 7, 8 and 9B); (2) sponge borings, round or irregular, one to two millimeters in diameter; (3) fungal channels, highly curved and often branched up to 10 microns wide; and (4) algal (possibly in part also fungal) borings, 1 to 5 microns wide, more or less straight and only rarely branched. Because the boreholes are often interconnected and occur at many different scales, they greatly increase the permeability of the rock, thus playing an important enhancing role in the diagenetic alteration of the rock.

Lithification is pervasive throughout reef rock and rhodolites; its presence can be detected within a few millimeters below the living surface (Fig. 6). Sparry magnesian calcite rhombs constitute by far the most common cement. The crystals are clear and transparent (Fig. 10B) and have well defined crystal faces (Fig. 9D), with dimensions of 1 to 6 microns. Subordinate amounts of cements are made up by aragonite needles up to 100 microns long (Fig. 10C), and by elongate magnesian calcite prisms, up to 40 microns long (Fig. 9C). Magnesian calcite cement occurs both on calcitic and aragonitic substrates; aragonite cement, however, occurs only on aragonitic substrates and only within the primary framework.

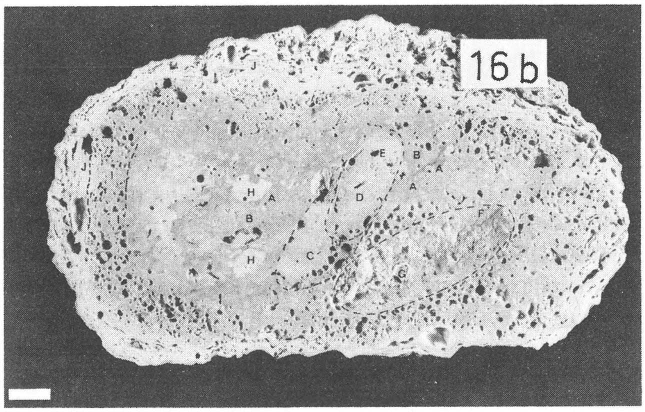

Fig. 8
Polished section of rhodolite the core of which has been altered by multiple generations of boring, internal sedimentation and cementation. A: coral skeleton, with a few scattered pieces of coralline algae probably the last remnants of the primary framework; B: oldest recognized phase of lithified internal sediment, in itself made up of several generations; C: bivalve boring, truncating phase B, filled with sediment and lithified prior to phase D; D: bivalve boring, truncating phase C, filled with sediment and lithified prior to phase E; E: sponge boring, possibly equivalent to phase F; F: bivalve boring, younger than phase D; G: secondary framebuilders, younger than phase F; H: friably cemented internal sediment, probably one of the youngest generations; I: zone of intense sponge borings, showing the discontinuous nature of the processes; J: outer coralline algal rim with visible growth generated void space. Scale bar = 1 cm.

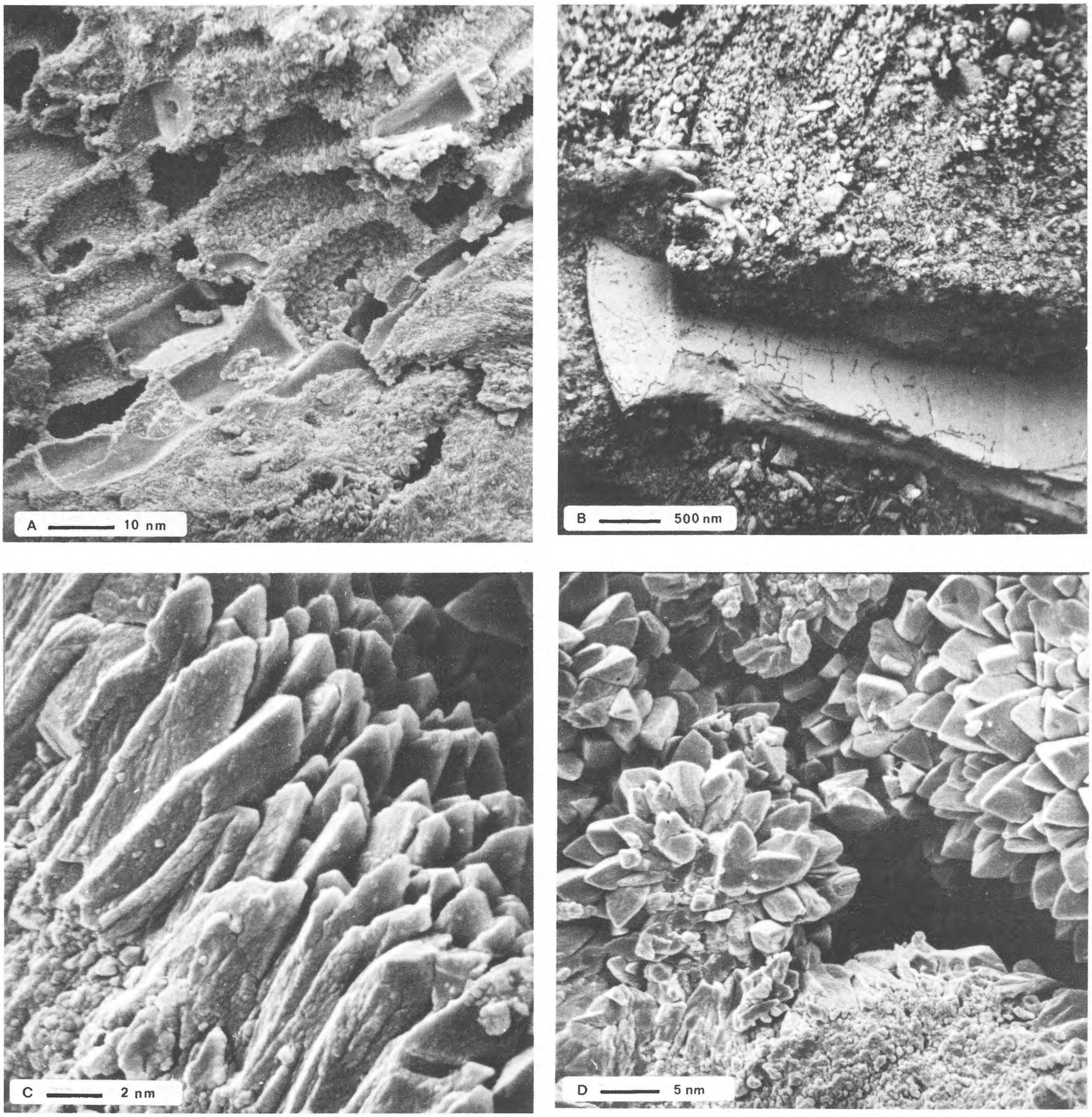

Fig. 9
A: algal cells, partially covered with magnesian calcite cement;
B: bivalve borer and lithified internal sediment;
C: elongate form of magnesian calcite cement;
D: magnesian calcite rim cement; micritized grain in lower half of photo.

The prismatic magnesian calcite occurs mostly as an isopachous syntaxial overgrowth inside foraminiferal tests (Fig. 10D). Uniform staining by the Clayton yellow stain indicates that there is no significant variation in the magnesian content of the cement. Deposition of sediment, especially fine-grained, may retard the formation of cement linings in pores; interior chambers of corals, algae etc., where no sediment accumulates, are the preferential locations for thick isopachous linings. Increased permeability on the other hand greatly enhances cementation, and probably for this reason internal sediment deposited in interconnected, well flushed bivalve and sponge bore holes is generally the first site for lithification (Fig. 6). This relatively rapid lithification of borehole sediment fills doubtlessly allows the preservation of geopetal structures at different angles within a single rhodolite.

Micritization of framework and sediment is pervasive. It is most evident in sediment of silt and sand size, where the progressive, time-dependent, destruction of the grain texture can be clearly seen (see above). The generated texture is darker and finer grained than the surrounding micrite cement (Fig. 9D, 10B). Both primary micrite sediments and micritized grains can be seen to recrystallize into larger crystals of magnesian calcite. Recrystallization also occurs in coral skeletons. The fan-like arrangements of sclerodermites is obliterated without aragonite needle cement, the side boundaries and terminations of the needles can be clearly distinguished, but the boundary between the cement and the skeletal crystals is completely obliterated.

### *Geochemical analyses*

Stable carbon and oxygen isotopic analyses from the core of a rhodolite gave the following values:
$^{13}C_{PDB} = +2.13 \times 10^{-3}$
$^{18}O_{PDB} = -3.88 \times 10^{-3}$
The core material consisted of a heterogeneous mixture of coralline algal framework, internal sediment and cement. $^{14}C$-measurements were made on two samples from a single rhodolite, one measurement on material near the central core and one on material near the periphery. Ages obtained are:
1520 ± 50 years BP for the core
645 ± 45 years BP for the periphery
Again, the material in each sample was a heterogeneous mixture of framework, sediment and cement.

## DISCUSSION

### *Fore-reef studies*

Fore-reef studies on Jamaica (GOREAU & LAND, 1974) and other caribbean areas have revealed that scleractinian framework may be present as deep as 75 m below sealevel. Studies still in progress in Bermuda indicate that scleractinians are a dominant framework component on the reef-front terrace to depths of at least 30 m (Kemerer, in prep., Univ. West Virginia). Our data, however, indicate that scleractinians are nearly absent from the Bermuda fore-reef at 50 m, coralline algae constituting the bulk of the primary framework at this depth. While we do not have enough data for sweeping generalizations, we suggest that this depth zonation of framework builders on Bermuda is related to changes in light intensity and wavelength with depth, and should occur in other areas. In clear tropical waters, the depth at which this transition occurs is probably related to minimum annual temperatures in the water column.

### *Lithification*

The cements which have been found in reef rock and rhodolites are of marine origin as shown by their mineralogies, fabrics and cystal habit, the frequent alternation of cementation with marine processes such as boring and internal sedimentation, and geochemical analyses (see above). The presence of early submarine cements in living and fossil reefs has recently been well documented (e.g.: LADD & SCHLANGER, 1960; ZANKL & SCHROEDER, 1972; SCOFFIN, 1972; GARRET ET AL., 1971; JAMES ET AL., 1976; MACINTYRE, 1977; GINSBURG & SCHROEDER, 1973; NEWELL, 1955; KREBS, 1972; ZANKL, 1971; SCHROEDER, 1974). Two models have been forwarded to explain the precipitation of carbonate minerals in the marine environment (ALEXANDERSSON, 1974): (1) a physicochemical model, in which supersaturation of seawater with respect to calcium carbonate is sufficient to cause precipitation; and (2) a biochemical model, which claims biological control to be of crucial importance to the precipitation process.

LAND & GOREAU (1970) considered cementation on the Jamaican reef as a biologically induced process, based on carbon and oxygen isotope enrichment in the cements. FRIEDMAN ET AL. (1974) related reef cementation to photosynthesis. ALEXANDERSSON (1974), describing cementation in North Sea rhodolites, reported a correlation of these cements with metabolic activity of the framebuilding alga. As the seawater was undersaturated with respect to calcium carbonate, he was able to rule out a physico-chemical origin of the cements.

It seems likely that organisms may have a similar influence on cementation in environments of supersaturation. Indeed cements associated with still living organisms are common, for example aragonite rims just below the living tissue in coral skeletons (HUBBARD, 1975; MACINTYRE, 1977). These cements, however, are always formed prior to the bulk of the reef cement. Where more than one generation of cement occurs, the aragonite is always overlain by magnesian calcite, never the other way around. The aragonite cement occurs only in the skeletons of the framework; the internal sediment, obviously postdating the primary framework, never shows aragonite rims, even on aragonitic grains within this sediment. This last observation clearly indicates that the distribution of the aragonite cement is not a matter of host control, and that aragonite cement results from a precipitation process which is dif-

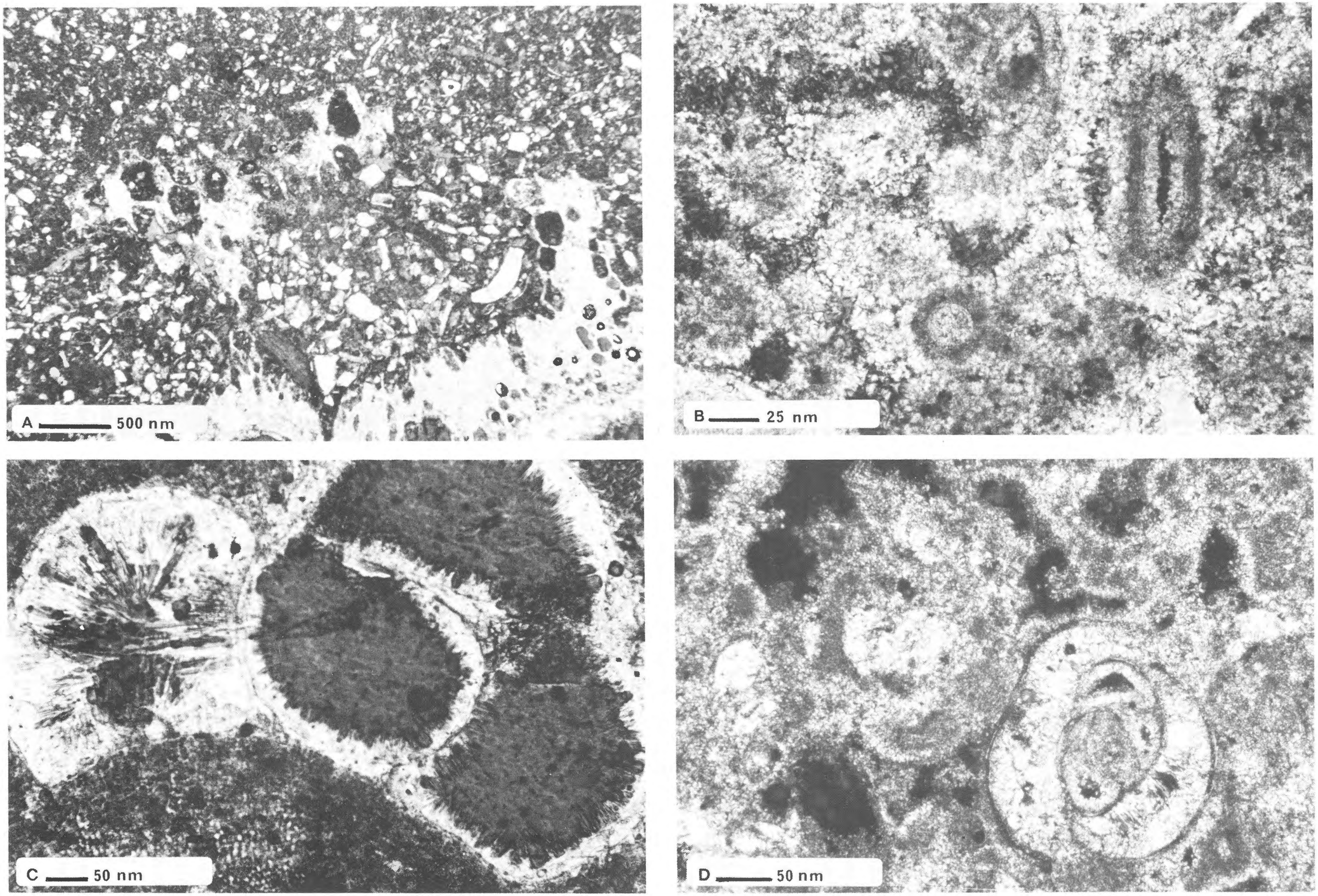

Fig. 10
A: angular internal sediment; B: well cemented micritized ‘peloidal’ internal sediment;
C: acicular aragonite cement within vermetid gastropod shell;
D: prismatic magnesian calcite cement filling interior of foraminiferal test.

ferent from those forming the bulk of the reef cement and which is separated from those processes in time.

Stable isotope analyses by FAIRBANKS & MATTHEWS (in prep.) indicate an early *post mortem* aragonite addition to the coral skeleton of 6%. Although there is thus little doubt that organic processes are in several ways involved with the cementation process, there is no evidence to support a crucial role of biological processes in production of the bulk of the cement. Where *post mortem* processes in areas of undersaturation are essentially destructional (ALEXANDERSSON, 1974), they are mostly constructional on Bermuda. After the death of the framebuilders, lithification continues until practically all pore space is destroyed. The North Sea rhodolites contain 3-5% cement when alive, and this cement is removed again after the death of the organisms.

The Bermuda rhodolites contain up to 30% cement in their core, which is mainly formed and preserved after the death of the organisms. These comparisons leave little doubt that physico-chemical supersaturation is at least one of the main factors controlling marine lithification. To fill a cavity with precipitated carbonate, enormous quantities of water must flow through the pore system and an efficient pumping mechanism is therefore needed to make widespread cementation possible. Surf-beaten reef crests (GINSBURG & SCHROEDER, 1973; ADEY & BURKE, 1976; JAMES ET AL., 1976), littoral algal/vermetid benches (BLANC & MOLINIER, 1955; FOCKE, 1977) and beachrocks (GINSBURG, 1953; TAYLOR & ILLING, 1969) are therefore preferential cementation sites. Although the rounded ripples on the Bermuda fore-reef indicate sporadic surf activity (probably related to overturning of the rhodolites and the presence of distinct internal sediment generations), the main pumping mechanism is probably provided by oceanic current patterns. Both in the winter and in the summer season, warm surface water flows down over the fore-reef (UPCHURCH, 1970; BODEN & KAMPA, 1953).

Because of the need for an external pumping mechanism, marine lithification is a near-surface process. Low net accumulation rates will expose the reef rock to circulating water for a long time, thus enhancing pervasive lithification and other alteration processes. Areas of very slow accretion rates are therefore other preferential lithification sites. The more than 700 m deep 'lithoherms' from the Florida Straits (NEUMANN ET AL., 1977) are probably a remarkable example of this control; some hardgrounds may be another example (SHINN, 1969). Radiocarbon dates obtained from a rhodolite suggest a net accretion rate in the order of 0.05 mm/year. This is two orders of magnitude lower compared to accretion rates of shallow water coral reefs which may be as high as 15 mm/year (ADEY & BURKE, 1976), and still one order of magnitude lower than accretion rates obtained in other fore-reefs (cf. GINSBURG & JAMES, 1973). The importance of accretion rate has been documented by MACINTYRE (1977) for Panamanian reefs. Fore-reef areas with low net accretion rates are highly cemented, while rapidly accumulating portions of the shoal *Acropora palmata* zone are poorly cemented despite having much more efficient water pumping.

In summary, without ignoring the possible influence of biological processes, it seems that the pervasive presence of marine diagenetic features, including lithification, on the Bermuda fore-reef is controlled mainly by the supersaturation of seawater, the presence of a reasonably efficient pumping mechanism in the form of oceanic currents, and the very low net accumulation rates of this reef.

### *The rhodolites*

Algal nodules have been reported from numerous fossil and modern environments (BOSELLINI & GINSBURG, 1971), marine as well as terrestrial. Bluegreen algal nodules should be referred to as oncolites, red algal nodules as rhodolites (BOSELLINI & GINSBURG, 1971) or rhodoliths (BINDA, 1973). Rhodolites have been reported from very shallow to very deep, and from tropical to boreal marine environments (ADEY & MACINTYRE, 1973). It has been pointed out by them (p. 900) that there is not yet a straightforward way to relate rhodolite characteristics to environmental conditions. Massive concentric rhodolites are often associated with deep tropical water, but they also occur in some very shallow back-reef environments, and it is not clear to what extent relations of rhodolite morphology and environmental conditions such as have been described by BOSELLINI & GINSBURG (1971) may be generalized for palaeo-environmental interpretations. In shallow tropical environments, however, fast growth of red algae and frequent overturning produce nodules without much diagenetic alteration, while in deeper tropical water very slow growth rates, coupled with sporadic overturning, produce the typical well lithified nodules described in this paper. Slow growing in tropical water is mainly related to decreased light conditions and therefore to depth. Slow growing is also common in temperate and arctic waters (ADEY, 1970) but as we have seen (ALEXANDERSSON, 1974) these undersaturated waters inhibit the evolution and preservation of these diagenetic features. For these reasons rhodolites of the type described in this paper might be useful palaeo-environmental indicators of relatively deep (more than 50 m), supersaturated (tropical) water.

## CONCLUSIONS

At the studied locality, the Bermuda fore-reef slope at a depth of 50 m consists of *in situ* accumulated reef rock, interspersed with sand patches which are covered by large numbers of algal nodules. In the reef-rock as well as in the nodules, coralline algae are dominant as framebuilding organisms. Only rare coral framebuilders remain. Reef-rock and nodules show pervasive marine diagenesis, including repeated sequences of framebuilding, boring, internal sedimentation and precipitation of cement. Of the factors controlling the distribution and the impact of these diagenetic processes, three are considered to be of main importance: supersaturation of sea water, a pumping mechanism, and a slow accretion rate. Although all three factors are favourable for diagenesis, it is the relatively great length of time, available as a result of very slow accretion rates (in the order of 0.05 mm per year), which is the main reason for the pervasiveness of the marine diagenesis on this location.

## ACKNOWLEDGEMENTS

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