JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 49, NO. 2, P. 0379–0386
FIGS. 1–4, JUNE, 1979

0022-4472/79/0049-0379/$03.00

EARLY CEMENTATION AND LITHIFICATION IN INTERTIDAL CRYPTALGAL STRUCTURES, BOCA JEWFISH, BONAIRE, NETHERLANDS ANTILLES[1]

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ABSTRACT: On the shore of the Boca Jewfish area of the Lac, Bonaire, N.A., blue-green algae perform a sediment-stabilizing and binding function resulting in a wide variety of cryptalgal structures. The morphology and zonation of these structures is related to variation in desiccation, sediment influx, water agitation and algal "species." The zonation of intertidal structures consists of stromatolites and oncolites, lithified nodules, smooth mat and tufted mat. A cryptalgal crust pavement is found in protected supratidal areas. In the middle intertidal zone, cryptalgal nodules are lithified during intertidal exposure by pervasive pore-reducing, micritic, high-Mg calcite cement, which is pendent in its distribution around sediment grains. Calcium carbonate cement also occurs as rinds on algal filaments. Precipitated calcium carbonate is found in minor amounts on filaments and mucus within tufted and smooth mats. The preservation potential of the nodules is enhanced by rapid and early cementation. The other structures, not lithified by significant amounts of early cement, have lower preservation potentials. The normal marine salinity of the Lac indicates that growth of cryptalgal structures in fresh, brackish, or hypersaline waters is not essential for their early cementation and lithification.

INTRODUCTION

Cryptalgal structures (algal laminites, oncolites, stromatolites, and thrombolites; Aitken, 1967) are common and important environmental clues in many modern and ancient carbonate environments. To facilitate interpretation of ancient shallow-water carbonate and evaporite sequences, a major focus of study has been on modern cryptalgal structures from tropical settings such as the Persian Gulf, the Bahamas, Florida, Bermuda, and Shark Bay, Western Australia (see Walter, 1976). Comparison between modern and ancient occurrences needs evaluation of the preservation potential of modern cryptalgal structures and the diagenetic processes prior to final fossilization, as emphasized by Park (1977). This paper documents a sequence of intertidal cryptalgal carbonate structures from Bonaire, Netherlands Antilles, that grow in normal marine waters and exhibit variations in degree of early cementation causing variation in their preservation potential.

PREVIOUS WORK

In order that cryptalgal structures can be fossilized intact in the rock record, they must have a preservation potential greater than the physical and biological erosive forces that act against them even after they are established. Cryptalgal fabrics can be destroyed by eroding tides and waves (Neumann, et al., 1970), bioturbating (Garrett, 1970) or grazing (Schwarz, et al., 1975) metazoans and so never enter the rock record. On the other hand, cryptalgal structures may be preserved if they are present in areas not subjected to strong attack by tidal currents and waves. Bioturbation of algal laminites and fenestral fabrics can be eliminated if metazoans are restricted by environmental conditions which are too rigorous, such as hypersalinity or desiccation. Sudden burial, such as in periodic storm sedimentation, can act as an agent of preservation. However,

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preservation potential is greatly enhanced by early and rapid cementation and lithification Table 1 outlines previously reported examples of early cementation of, or in, recent cryptalgal structures. A feature common to all previous examples is that the structures occur in hypersaline, brackish, or fresh water environments—none are found in normal marine conditions, although intertidal cementation in sand-sized sediment is relatively common on many tropical and some temperate shores.

SETTING

Samples described in this study were collected from the Boca Jewfish area of a large shallow lagoon, the Lac, on the island of Bonaire, Netherlands Antilles (Fig. 1). The Lac is protected from the open sea by a fringing coralgal reef; the shore of the Lac is a complex of shallow embayments, mangrove swamps, and intertidal flats. The climate of Bonaire is semi-arid; nevertheless, water circulation from the open sea is sufficient to maintain normal marine salinity 35‰) in the Lac (Wagenaar Hummelinck and Roos, 1969). Hypersaline conditions are approached only in some of the mangrove swamps (Wagenaar Hummelinck and Roos, 1969; van der Meer Mohr, 1972). The tidal range is approximately 30 cm.

The benthos of the Lac has been studied by Wagenaar Hummelinck and Roos (1969) and van den Hoek, et al., (1972). The sediments are dominantly sand-sized, and are extensively bioturbated. Gelatinous oncolites and stromatolites similar to those from Florida (Ginsburg, 1960; Frost, 1974), Bahamas (Monty, 1965) and Bermuda (Gebelein, 1969) are found in very shallow areas of the Lac. In protected areas in the mangrove swamps, the bottom is covered by a loose flocculent algal mat similar to that described by Bathurst (1967) from Bimini Lagoon, Bahamas.

The Boca Jewfish is the largest bay of the Lac, and is separated from the main lagoon by a sand spit. This spit is between 50 m and 100 m in width and has prograded over mangrove peats. The sequence of cryptalgal structures studied is found on this spit. The windward (northeast) and leeward shores are separated by a low supratidal ridge of sand (Fig. 2).

TABLE 1.—*Previous studies of early cementation in Recent cryptalgal structures*

Location	Reference	Salinity	Description
Shark Bay, Western Australia	Logan, 1974	hypersaline	aragonite cementation and lithification of stromatolites of various shapes
Trucial Coast, Persian Gulf	Evamy, 1973	hypersaline	aragonite cementation and lithification of intertidal algalaminites
Laguna Mormona, Baja California	Horodyski and Vonder Haar, 1975	hypersaline	aragonite precipitation in algal mats on submerged substrate irregularities
Gulf of Aqaba, Red Sea	Friedman et al., 1973; Krumbein et al., 1977	hypersaline	aragonite and high-Mg calcite precipitation as laminae in submerged algalaminites
Baffin Bay, Texas	Dalrymple, 1965	hypersaline	aragonite precipitation within submerged algalaminites
Lobos, Canary Islands	Rothe, 1970	(supratidal)	aragonite precipitation on algal mats which then desiccate and curl to form "algal lapilli"
Bahamas, Florida Everglades	Monty and Hardie, 1976	fresh to brackish	low- and high-Mg calcite precipitation within algalaminites and stromatolites, submerged to exposed settings, with lithification of exposed heads
Marion Lake, South Australia	Von der Borch et al., 1977	brackish	aragonite cementation and lithification of exposed stromatolites and oncolites
lakes and streams	e.g., Dean and Eggleston, 1975	fresh	low-Mg calcite cementation and lithification of submerged cryptalgal "reefs"
Boca Jewfish, Bonaire	this study	normal marine	high-Mg calcite cementation and lithification of intertidal "nodules," carbonate cementation on algal filaments

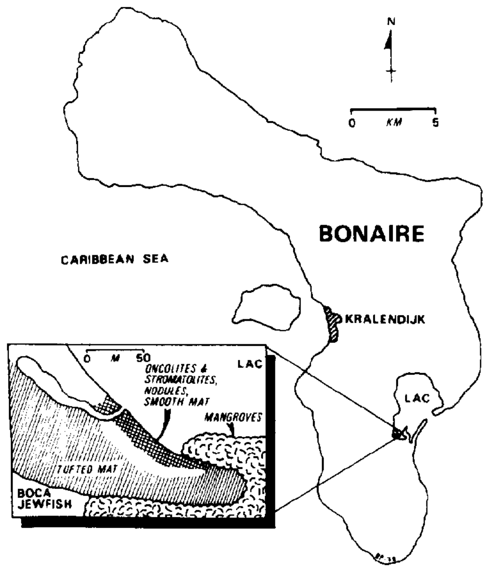


FIG. 1.—Map of Bonaire showing location of the study area.

INTERTIDAL CRYPTALGAL STRUCTURES

The intertidal cryptalgal structures are distributed on both the windward and protected leeward sides of the Boca Jewfish spit, as shown in Figure 2. The structures are described in Table 2. The smooth mat, nodules, and stromatolites and oncolites occupy a 15 m by 75 m strip of the windward shore. Wave agitation is important here, eroding the smooth mat and disturbing the stromatolites and oncolites. Sediment influx is more regular and the cryptalgal structures here are laminated. The tufted mat has the greatest areal distribution but is protected by a supratidal ridge of sand and mangroves from significant destructive wave agitation and regular sediment influx. The lowermost intertidal areas of the tufted mat are sporadically burrowed by fiddler crabs. The mat-forming algal "species," though not investigated taxonomically, were found to vary with the different cryptalgal structures; thus, environmental and biological parameters interact to produce the zonation of cryptalgal structures. The cryptalgal crust occurs as a brecciated pavement and is found in protected supratidal areas of the Boca Jewfish. It is similar to previously reported supratidal examples (e.g., Shinn, et al., 1965; Hardie, 1977).

EARLY CEMENTATION

Carbonate cement is present in the nodules and in the smooth and tufted mats. The nodules are lithified by pervasive cementation, but cements are rare in the smooth and tufted mats, and these structures are still soft.

Cements in the cryptalgal nodules are seen in thin section to fill intraskeletal pores and to form fringes around carbonate sand grains. The fringes encase algal filaments and are pendent on the lower surfaces of grains (Fig. 4A). The cement crystals are submicron-sized scalenohedra between 0.1 μm and 0.2 μm in diameter (Fig. 4B). They also occur as rinds or crusts on the external surfaces of blue-green algal sheaths (Fig. 4C). The

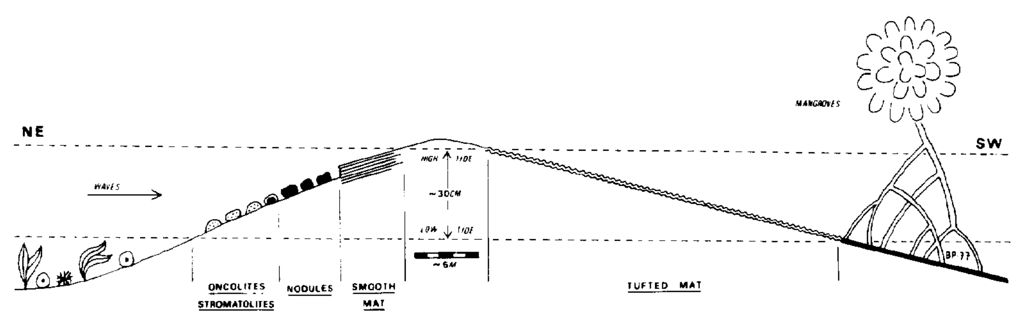


FIG. 2.—Diagrammatic cross-section across the Boca Jewfish sand spit, showing sequence of intertidal cryptalgal structures. The windward and leeward sides of the spit are separated by a low supratidal ridge of carbonate sand. The Lac subtidal benthos includes *Thalassia*, gelatinous oncolites and stromatolites and coralline algal clusters (rhodoliths). In the protected subtidal Boca Jewfish, the sediment among the mangroves is stabilized by a flocculent algal mat.

TABLE 2.—*Characteristics of Boca Jewfish area cryptalgal structures*

Cryptalgal Structure	Intertidal Position	Description
stromatolites and oncolites	lowermost intertidal, windward shore	gelatinous texture; internal sand and mucilagenous laminations; low domes when undisturbed, commonly coalescing, often flipped over by wave action; permanently damp (Fig. 3A).
nodules	middle intertidal, windward shore	variable shape; generally with vague internal laminations; lithified, the degree of induration increasing upward in the intertidal from unlithified stromatolites and oncolites; laminoid fenestral porosity; dry out during intertidal exposure (Fig. 3B).
smooth mat	upper intertidal, windward shore	flat and featureless upper surface; internal sand laminations; rigid but unlithified; seaward edge undercut and eroded by waves, forming intraclasts, some of which become lithified nodules; laminoid fenestral porosity; remains damp during intertidal exposure (Fig. 3C).
tufted mat	lower to upper intertidal, leeward shore	leathery texture when dry; varies, depending on intertidal position, from a desiccated, shrunken, and torn mat to a thick damp luxuriant carpet; irregular sediment influx; no internal lamination; burrowed sporadically in the lower intertidal by crabs; laminoid fenestral porosity (Fig. 3D).
cryptalgal crust	protected upper intertidal to supratidal	forms a pavement, 2 cm to 6 cm in thickness; brecciated and buckled into low-relief tepee structures; dolomitic; upper surface planar but pitted, resembling tufted mat surfaces; lower surface irregular as degree of cementation decreases downward; laminoid fenestral porosity, cement reduced; found mainly in protected parts of the Boca Jewfish, sporadically on the spit under a thin sand cover (Fig. 3E).

mineralogy of the cement is high Mg-calcite, as determined by staining (Winland, 1971). Electron dispersive X-ray analyses (EDAX) of the crystals were inconclusive owing to their small size and high background interference levels; however, elements to suggest anything other than calcium carbonate were not detected. Particles very similar to these submicron-sized cement crystals also occur on filaments and mucus in the smooth and tufted mats. In these latter cases, it cannot be proven unequivocally that they are precipitated in situ rather than simply entrapped sediment grains, as they occur rarely and are only visible at the limits of resolution of the scanning electron microscope. Their uniform size and their distribution as patches of equant particles on mucus and as rinds on some filaments do suggest, however, local calcium carbonate precipitation in situ.

Precipitation of calcium carbonate cement in the modern marine intertidal zone is well documented (e.g., Taylor and Illing, 1969; Alexandersson, 1972; Davies and Kinsey, 1973; Moore, 1973; Milliman, 1974, p. 278–286; Bathurst, 1975, p. 367–370). The scalenohedral high-Mg calcite cement in the nodules on the Boca Jewfish beach is similar to but smaller than the beachrock cement reported by Moore (1973). It is suggested that the process of lithification of the nodules is analogous to that of beachrock formation in settings free from the influence of fresh groundwater. The fact that the nodules are lithified in preference to the beach sands and the smooth and tufted mats, indicates that cementation is related partly to the rapidity of drainage in isolated cryptalgal structures: the smooth and tufted mats remain slightly damp during intertidal exposure due to capillary action but the nodules dry out. The pendent nature of the cement suggests that cementation is gravity influenced and occurs during intertidal exposure when pore water is concentrated by evaporation or diluted by rain. Precipitation may be related to pH

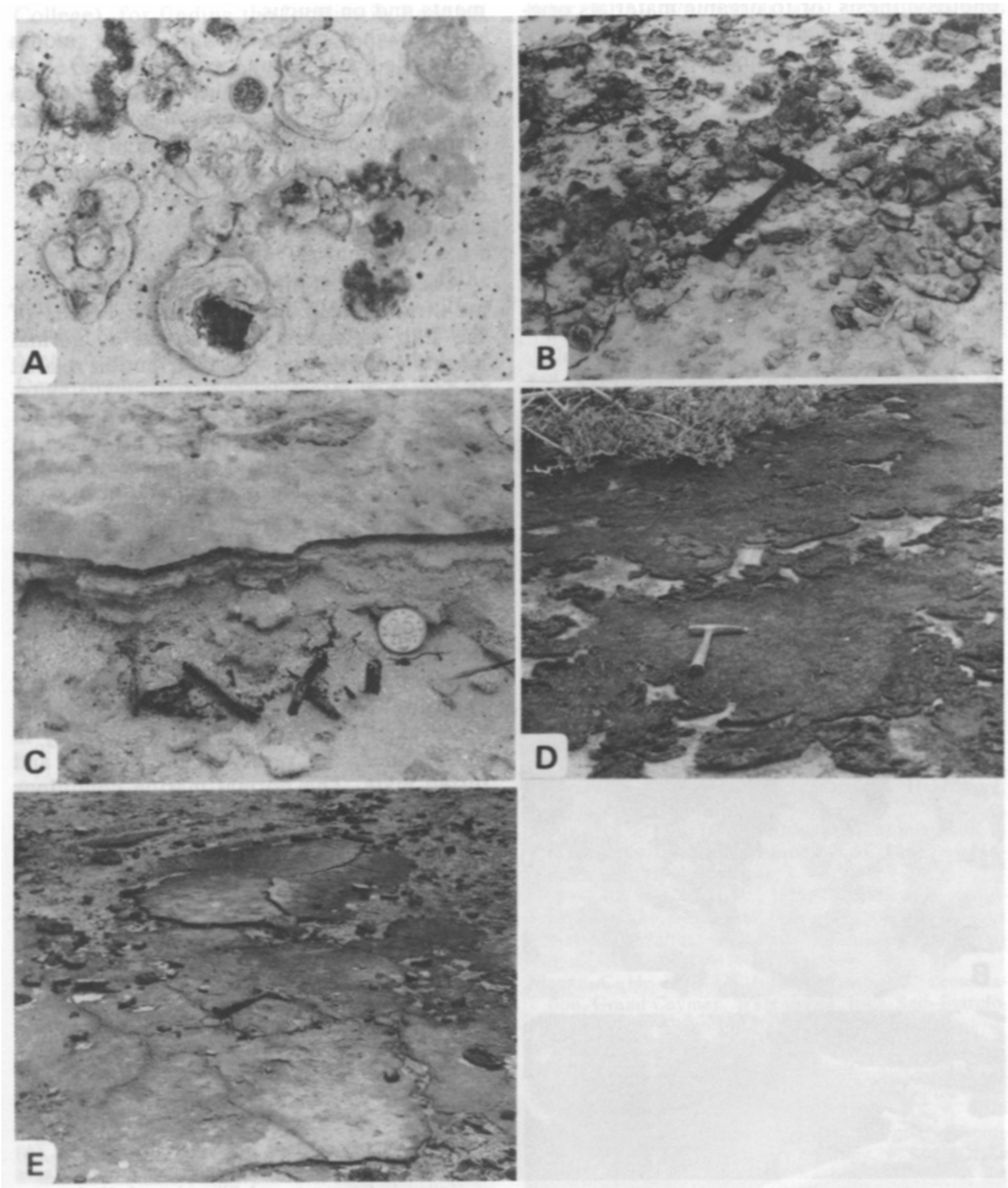
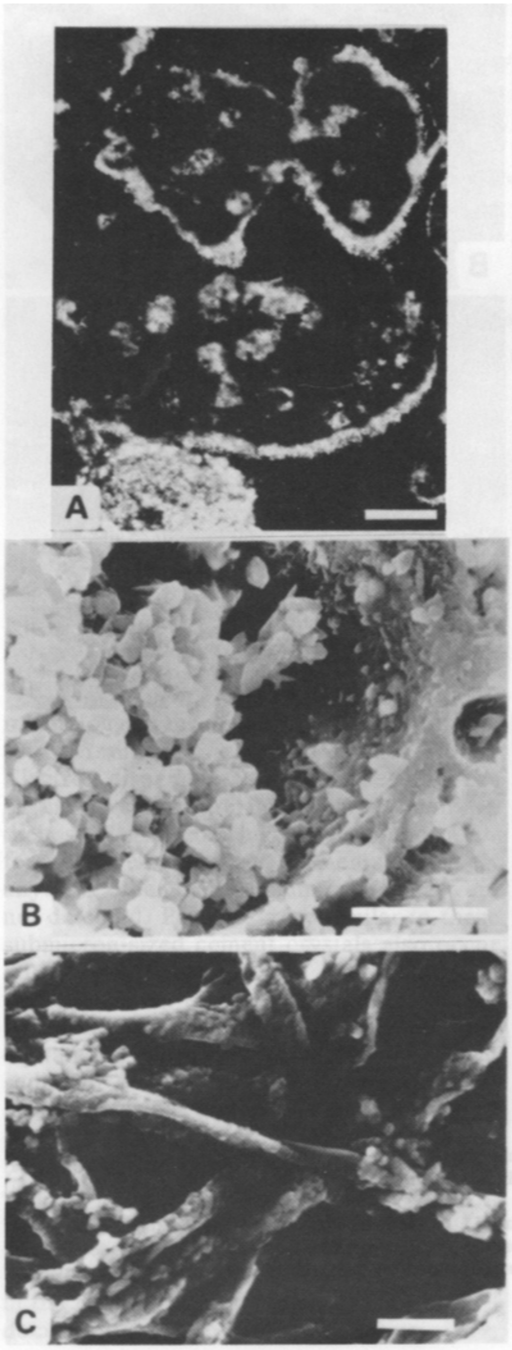


FIG. 3.—Intertidal cryptalgal structures, Boca Jewfish area, Bonaire. (A) Stromatolites and oncolites from the lower intertidal area of the beach; in-place stromatolites are on the right side of the photograph. In lower left is an oncolite with a fragment of intertidal nodule as nucleus. Coin is 2 cm in diameter. (B) Lithified cryptalgal nodules scattered over intertidal part of beach. (C) Eroded seaward edge of intertidal smooth mat. Coin is 2 cm in diameter. (D) Leathery tufted mat of the protected intertidal flats, with mangroves in background. (E) Cryptalgal crust pavement of upper intertidal and supratidal areas in the protected interior of Boca Jewfish. Pavement is buckled and brecciated, forming intraclasts.

elevation or pCO_2 reduction due to algal photosynthesis, or to organic materials originating from mucus decay or algal metabolite secretion. This is suggested by the localization of cement crystals around algal filaments and on mucus.



Although cements are rare in the smooth and tufted mats, and occur only as algal-associated rinds or patches, if cementation and lithification were to continue in these mats, a cryptalgal crust pavement could be produced, such as that present in the supratidal zone of the Boca Jewfish.

CONCLUSIONS

A sequence of intertidal cryptalgal carbonate structures in the Boca Jewfish area of the Lac, a lagoon with waters of normal marine salinity, shows a distribution related to degree of intertidal exposure, wave agitation, sediment influx and algal "species." There is, however, variability in preservation potential of these structures. The smooth and tufted mats and gelatinous stromatolites and oncolites are unlithified. This increases the possibility of alteration or destruction of their internal fabrics and outward shapes. Early lithification of the nodules enhances their preservation potential. The nodules are lithified by pore-reducing, micritic, high-Mg calcite cement precipitated during intertidal exposure. Precipitation of micrite on blue-green algal filaments occurs, abundantly in the nodules, but rarely in the smooth and tufted mats. The normal marine conditions of the Lac indicate that formation of cryptalgal structures in hypersaline, brackfish, or fresh water settings is not essential for their early cementation.

ACKNOWLEDGMENTS

This paper represents an extension of an undergraduate thesis done under the supervision of Dr. M. J. Risk, McMaster University. I would especially like to thank Dr. D. R.

FIG. 4.—Early cements in cryptalgal structures. (A) High-Mg calcite cement fringe pendent on lower surfaces of *Halimeda* fragments and filling intraskeletal pores. Scale bar is 50 μm (thin section, crossed nicols). (B) SEM photomicrograph of submicron-sized high-Mg calcite scalenohedral cement (left) partially filling an intraskeletal pore in a carbonate sand grain within an intertidal nodule. Scale bar is 1 μm (etched with EDTA solution). (C) SEM photomicrograph of patches of submicron-sized cement precipitated on the outer surface of blue-green algal filaments within an intertidal nodule. Scale bar is 1 μm (not etched).

Kobluk, University of Toronto (Erindale College), for finding the locality in Bonaire, for his help in the field and laboratory and for constructive criticism of the manuscript. Dr. M. J. Risk, Dr. N. P. James, Memorial University of Newfoundland, and Dr. Paul Enos, State University of New York at Binghamton, also reviewed the manuscript. Dr. I. Kristensen and the staff of the Caribbean Marine Biological Institute, Curaçao, helped during fieldwork. Scanning electron microscopy was done with the help of the staffs of the electron microscope facilities of the Medical Centre and Department of Metallurgy, McMaster University, and the Department of Geological Sciences, McGill University. W. Marsh, Memorial University of Newfoundland reproduced the line drawings. Financial support for the thesis was from a National Research Council of Canada operating grant to Dr. M. J. Risk, the Department of Geology, McMaster University, and an Ontario Petroleum Institute award to the author.

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