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Fabrics and sequences of submarine carbonate cements in Holocene Bermuda cup reefs *)

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With 12 figures

Zusammenfassung

Verschiedene synsedimentäre $CaCO_3$-Ausfällungszemente säumen oder füllen Hohlräume und umgeben Sedimentpartikel in den rezenten Algenriffen am Rande der Bermuda-Plattform. Es handelt sich um aragonitische Nadel-, Spheruliten- und Leistenzemente sowie kalzitische Mikrit-, Palisaden-, Schuppen- und Blockzemente (aufgezählt jeweils mit abnehmender Häufigkeit). Die Zemente zeigen keine systematische Verteilung; sie kommen in verschiedenen Kombinationen von drei oder vier Zementen in fast jeder Probe oder jedem Dünnschliff vor.

Faktoren, die Zusammensetzung und Gefüge der Zemente bestimmen, können aus Art und Weise ihres Vorkommens abgeleitet werden:

1. Morphologie, Zusammensetzung und Belag des Substrates.
2. Direkter oder indirekter Einfluß von Organismen, wie Algen, Muscheln und Crustaceen.

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3. Mikro-Milieu, speziell Größe und Permeabilität, Menge des durchfließenden Wassers sowie Einflüsse von Substrat und Organismen innerhalb des Mikro-Milieus.

Verschiedene beobachtete Abfolgen von zwei oder drei Zementen werden auf Änderungen des Mikro-Milieus zurückgeführt; das Eindringen von endolithischen Algen in teilweise zementierte Hohlräume ist die einzige evidente Ursache einer solchen Änderung.

Die vorgelegten Ergebnisse tragen zum Verständnis submariner Zementation bei und bieten Vergleichsmaterial für die Interpretation von Zementen in fossilen marinen Ablagerungsbereichen, speziell in fossilen Riffen.

Abstract

A variety of precipitative synsedimentary $CaCO_3$ cements lines or fills cavities and surrounds sediment particles within Recent algal cup reefs which dot the rim of the Bermuda platform. These include aragonite needle, spherulitic, and lath cements as well as calcite micrite, palisade, scale, and blocky cements, listed according to respective relative abundances. No distribution pattern of cements is apparent; various combinations of three or four cements are found in almost every sample or thin section.

From the occurrence of various cements, factors determining composition and fabric are deduced:

1. Morphology, composition, and coating of the substrate.
2. Direct or indirect influence of organisms such as algae, pelecypods, or crustaceans.
3. Micro-environment, specifically size and permeability, rate of sea-water circulation through the micro-environment, substrates and organisms within the micro-environment.

Various sequences of two or three precipitative cements result from changes in micro-environment; the only cause of such change recognized is the entrance of endolithic algae into partly cemented cavities.

This study provides some insight into the origin of submarine cements and a basis for comparative interpretation of cements in fossil marine environments, especially fossil reefs.

Résumé

Divers ciments de précipitation intraformationnels ($CaCO_3$) bordent ou remplissent des cavités et entourent des particules de sédiment dans les récifs d'algue récents en bordure de la plate-forme des Bermudes. Ils comprennent autant des ciments aragonitiques aciculaires, spherulites et en baguettes de même que de ciments calcitiques, micritiques, en palissades, en écailles et en blocs. Ces ciments ne présentent aucune répartition systématique; ils se rencontrent en combinaisons diverses de trois ou quatre ciments dans presque chaque échantillon ou lame mince.

Les facteurs déterminant la composition et la structure sont déduits de l'apparition de ciments divers:

1) Morphologie, composition ou dépôt du substratum.
2) Influence directe ou indirecte d'organismes tels qu'algues, coquillages, crustacés.
3) Micro-milieu: grandeur et perméabilité, quantité de l'eau circulante ainsi que des influences du substratum et des organismes à l'interieur du micro-milieu.

Des séries observées de deux ou trois diverses ciments, resultent de la transformation du micro-milieu; la pénétration d'algues endolitiques dans des cavités en partie cimentées est la seule cause évidente d'une telle transformation.

Les résultats présentés contribuent à la compréhension de la cimentation sous-marine et offre des matériaux de comparaison pour l'interprétation des ciments dans les dépôts marins fossiles, en particulier dans les récifs fossiles.

Краткое содержание

Полости и частички седиментов в современных водоросличных рифах по краю платформы **Bermuda** заполнены, или обрамлены различными выпавшими известняками. Здесь установлены в порядке убывающего количества цементы: арагонитовые, в виде игол, сферулитов и лейст, а также кальцитовые, в виде палисад, чешуек и блоков. Эти цементы не проявляют никакой системы в их распределениях и часто комбинируются по три, или четыре в каждой пробе, или каждом шлифе. Факторы, определяющие состав и строение цементов, можно вывести из типа последних: 1) морфология, состав; 2) Прямое, или косвенное влияние таких организмов, как водоросли, мягкотелые, ракообразные; 3) микросреда, именно величина и проницаемость, количество протекающей воды и влияние субстрата и организмов в самой микро-среде. — Наблюдающиеся чередования различных цементов по 2 и 3 относят за счет изменений микросреды. Внедрение водорослей в только частично заполненные цементом полости составляет единственную причину таких изменений. Результаты исследований помагают понять процессы подводной цементации и дают материал для сравнения при интерпретировании цементов в ископаемых отложениях, именно в рифовых образованиях.

Introduction

Reefs are sites and products of the complex dynamic interplay between construction and destruction by organisms, sedimentation, cementation, and mechanical breakdown. Except for cementation, these processes have been known to go on in the marine environment for a long time; however, only recently cementation in reefs has been recognized to be a submarine process (Ginburg et al., 1967, 1969). This discovery was confirmed by studies of reefs of the Barbados (MacIntyre et al., 1968, 1969), of Jamaica (Land & Goreau, 1969), of Mexico (Hoskin, 1969) and of the Red Sea (Amiel et al., 1971). Inspite of these observations, submarine reef cementation is still poorly understood, and the mechanisms of this process have remained largely a matter of speculation. This deficiency prompted a separate detailed investigation of reef cements despite their intimate interrelationships with ecological and sedimentological processes; therefore the study of Bermuda cup reefs, which was begun by Ginburg et al. (1967, 1969) and carried on by Ginsburg et al. (1971), Shinn (1971) and Schroeder (1972), was intensified. As a result, several different carbonate cements were found and are reported in this paper. Their occurrence in relatively small reef structures provided a basis for deduction of factors determining composition, fabrics, and sequence of cements.

Location and framework

The edge of the Bermuda platform, particularly in its N, NE, and SE portions, is dotted by reef structures characterized by irregular circular to ellipsoid plan view and vase or cup-shaped profiles. Their common dimensions are 10—30 m in diameter and 8—12 m in height. Locally these structures are called "boilers" or "breakers" because they reach the lower portion of the intertidal, and thus break waves. To distinguish these "boilers" and "breakers" from others of different nature found elsewhere, they were called cup reefs by Ginsburg & Schroeder (1969) with reference to their profiles.

Primary framebuilders are coralline red algae and the hydrozoan *Millepora*; secondarily, the gastropod *Dendropoma irregulare* and the foraminifer *Homotrema rubrum* contribute to the frame.

Intra-skeletal as well as inter-skeletal cavities of the structure, cavities bored by pelecypods, worms, sponges, and other organisms, as well as inter-particle and intra-particle pores of internal sediments provide the sites where cements are precipitated. As a result of cementation, these structures are composed of well indurated reef rock which accounts for their rigidity and wave resistance. (A more detailed report on the Bermuda cup reefs will be given shortly by GINSBURG & SCHROEDER [in preparation].)

Methods

Some cup reef structures were dissected by means of small charges of explosives; samples were collected from newly made submarine outcrops by skin and scuba diving. Specimens were studied by Scanning Electron Microscope (SEM), by petrographic microscope, and by electron microprobe.

For SEM study, samples were fractured or sawed to provide access to cavities; loose material was removed by ultrasonic cleaning. Samples were not ground, polished, or etched, but the unetched surface was coated with gold to provide the conductivity required. A Cambridge Stereoscan Mark II A was used; an accelerating voltage of 10 KV or 30 KV was applied.

Thin sectioning procedures included embedding in epoxy or polyester resins, but otherwise were standard.

For microprobe work thin sections were polished and carbon coated. An ARL microprobe, type EMX, was used; the accelerating voltage was 15 KV, the specimen current 20n amp. Counts were taken for ten seconds both at selected spots and with moving sample. In addition, traverses were run across selected sample portions and the results recorded graphically.

Mineral composition was determined by means of petrographic microscope including universal stage, by means of microprobe following the method of GLOVER & PRAY (1969) or by means of SEM on the basis of crystal habit. X-ray diffraction analysis was applied only where sufficient amounts of pure material could be obtained.

Description of the cements encountered

Aragonite cements

The aragonite needle cement (Fig. 1) described from these reefs briefly by GINSBURG et al. (1971) is composed of bladed or, more frequently, of fibrous crystals which exhibit well defined crystal faces and often are twinned (Fig. 1 d). Their width varies between 0.2—15 μ and their length between 1 and 400 μ. The needles are found predominantly in intra-skeletal cavities, but they also occur in others; some aragonite shells are syntaxially overgrown (Fig. 11 center). This cement forms either a dense crust (Figs. 1 a, f) or less dense brush-like aggregates (Figs. 1 b, c, d, e). In the crusts, crystals are oriented normal to the substrate, but may deviate by about 10° from this direction. With decreasing density of the aggregate, crystal orientation becomes more oblique with respect to the substrate and to adjacent crystals.

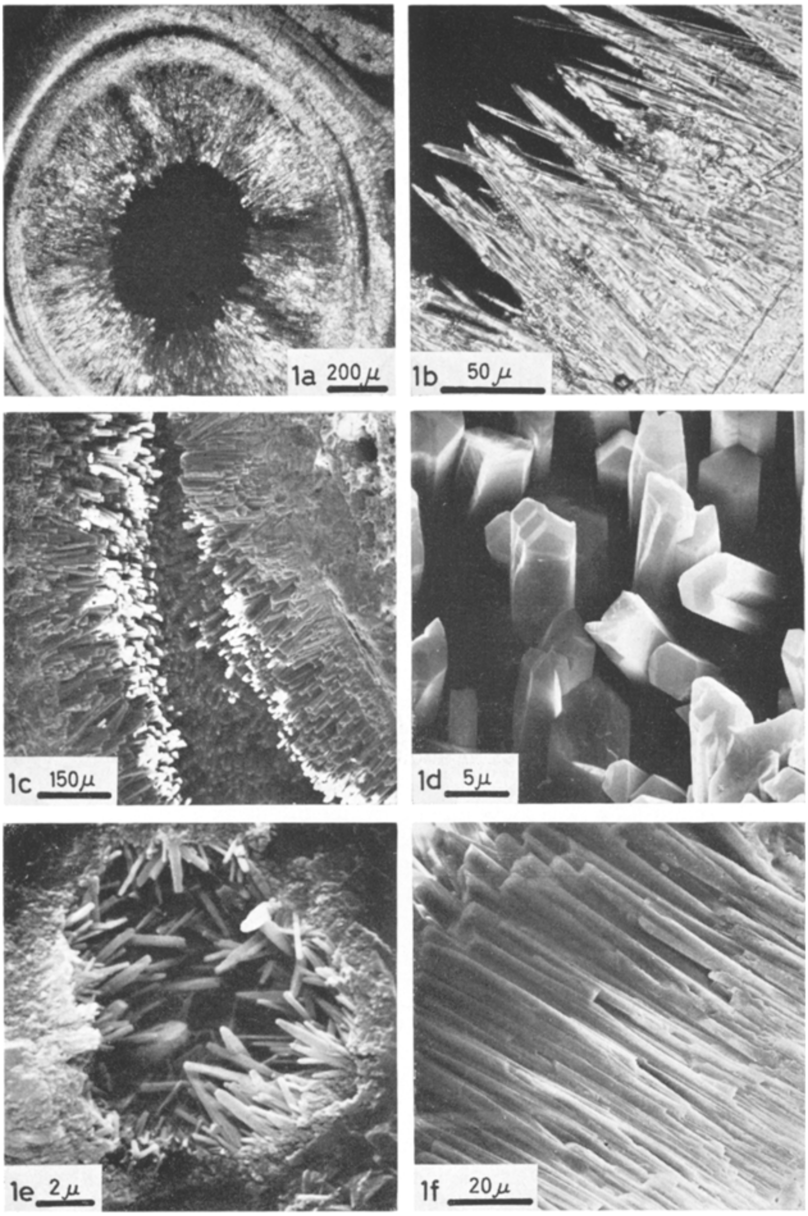

Fig. 1. Aragonite needle cement (Note different scales!). a) Crustose rim within a gastropod shell (Thin section; × nicols). b) Same as a, different sample. Note ragged outline toward cavity center (upper left), deviations in needle orientation, and algal borings (upper right) (Thin section; × nicols). c) Crustose rim within gastropod shell (Scanning Electron Microphotograph). d) Detail of c showing well defined crystal surfaces, twinning, and intergrowth of aragonite needles (SEM). e) Minute cavity with brush-like aggregate of small aragonite needles. Note the lack of orientation with respect to cavity wall and adjacent crystals (SEM). f) Tightly packed needles paralleling each other almost without deviation (SEM).

The aragonite spherulitic cement (Fig. 2, 3) consists of fibers, 1—5 μ wide and 60 to 400 μ long. These fibers radiate from the center of a sphere; generally only cone shaped sectors of a sphere are found (Fig. 2 a) which in section look like fans (Fig. 2 b). Common opening angles of these fans range from 60° to 180°, but any other angle has been observed. Some of these aggregates exhibit sub-concentric growth lines between 2 and 5 μ apart which are thought to indicate discontinuous growth. This cement is abundant in cavities between successive layers of red algae (Fig. 2 b) or Millepora or in intraskeletal cavities of Millepora (Fig. 2 a). In a given cavity the tips of the cones may be oriented toward either or both the roof and the floor.

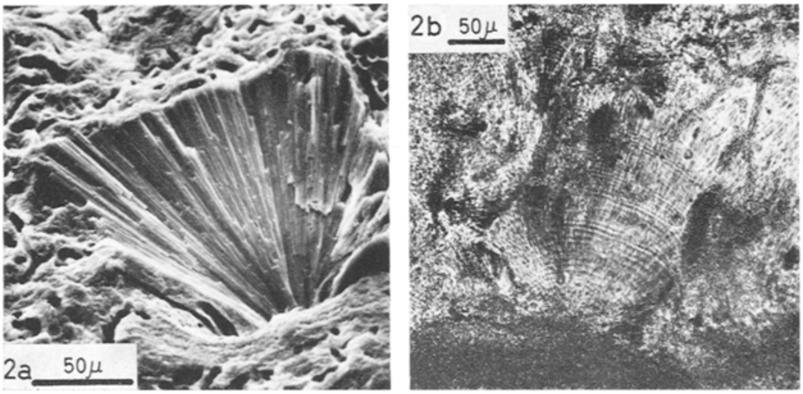

Fig. 2. Aragonite spherulitic cement. a) Within a large intra-skeletal cavity of the hydrozoan *Millepora* (SEM). b) In a sheet cavity between subsequent crusts of coralline red algae. Note algal borings in upper right. (Thin section; × nicols).

A distinct variety of aragonite spherulitic cement is recognized in the aragonite coatings of boring pelecypods (Fig. 3), which also are composed of cones of radiating fibers. The diagnostic feature of these coatings is the arrangement of the cones in larger aggregates, and this arrangement, in turn, is characteristic of the species of boring pelecypod. In the cup reefs the holes of *Spenglaria rostrata*, *Gastrochaena hians*, and *Lithophaga bisulcata* have been found to be partly or completely coated; the coating of the species mentioned last is described and illustrated here. Only the dorsal portion of the date-shaped hole is coated (Fig. 3 a). The fibrous cones are arranged in layers with the cone axes toward the center and the tips toward the wall of the hole. The combination of cones results in an undulate surface at the top of the layer. Similarly, the growth lines of the fibrous cones combine to a faint undulate micro-lamination (Fig. 3 b). Several, commonly 10 to 20 layers of 20 to 300 μ thickness represent various growth stages of the mollusc. With increasing age and size of the mollusc, the curvature of the borehole decreases both with respect to its long and short axis, and consequently the curvatures of the layers composing the coating decrease. Their decrease results in a series of layers onlapping in all directions (Fig. 3 a). This characteristic onlapping pattern is easily recognized in section. Coatings of pelecypod boreholes have been recognized by paleontologists long ago; Otter (1937) for example, described coatings of several *Lithophaga* species. However, their significance with respect to reef cementation has not obtained the attention it deserves.

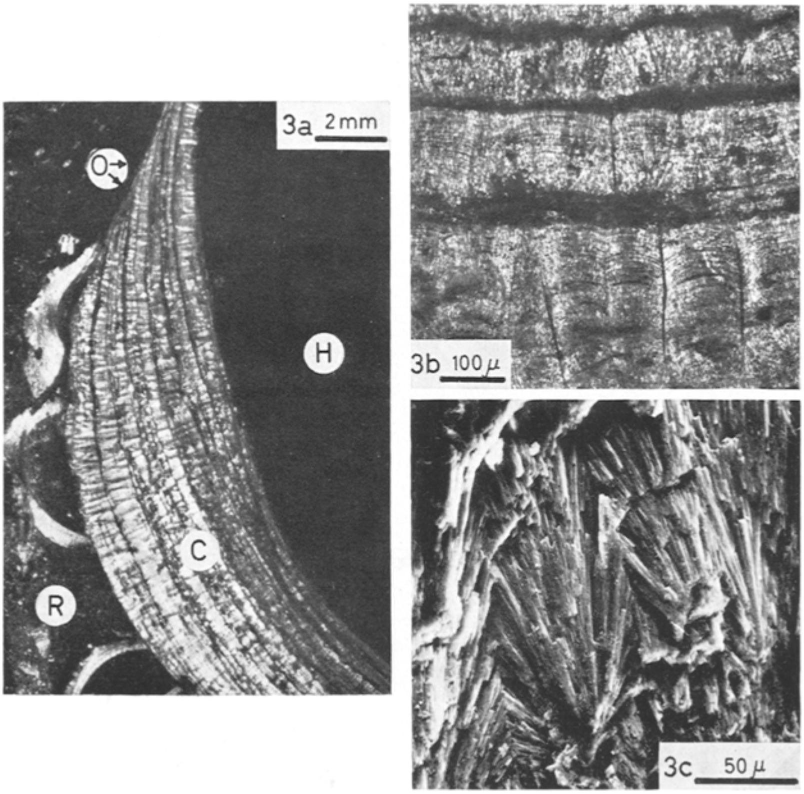

Fig. 3. Aragonite spherulitic cement in coatings of pelecypod boreholes. a) Portion of the borehole (H) with coating (C) and adjacent reefrock (R). Note truncated gastropod shells at the contact between coating and reefrock. Also note the onlapping pattern (O) formed by successive layers of the coating (Thin section; × nicols). b) Detail of a, oriented with the borehole wall down. Note layered arrangement of the fibrous cones and microlaminations within individual layers (Thin section; × nicols). c) Coalescing fibrous cones of a pelecypod borehole coating. The tips of the cones point toward the borehole wall (SEM).

The aragonite lath cement (Fig. 4) commonly is composed of lath-shaped crystals up to 2 μ thick, 2 μ wide and up to 20 μ long, but rod-shaped (Fig. 4 a) and board-shaped (Fig. 4 b) crystals also occur. Characteristic is the lack of any apparent orientation with respect to the substrate and to adjacent crystals. Crystals intergrow and penetrate each other frequently (Fig. 4 a) without showing any characteristic pattern or angle. The aggregates render the impres-

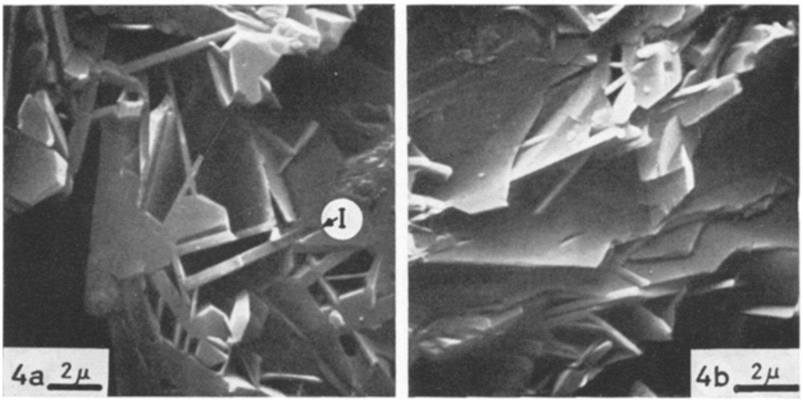

Fig. 4. Aragonite lath cement. a) Irregulary scattered rod and lath-shaped crystals; note intergrowth (I) (SEM). b) Irregularly piled-up board-shaped crystals with some rods and laths (SEM).

sion of irregularly piled-up crystals. This cement has been studied only by means of SEM and has not been studied in thin section, where it possibly is confused with brush-like aggregates of aragonite needle cement. The mineral identification is based on morphology only and therefore should be considered preliminary.

Calcite cements

Calcite micrite (Fig. 5) from these reefs has been described by Ginsburg et al. (1971), and little is to be added to their description. It consists of rhombs, 2—8 μ in size with curved faces (Fig. 5 a). The crystals form layers up to 20 μ wide, which line all kinds of cavities including intra-skeletal ones (Fig. 5 b) and encrust sediment particles. The layers apparently consist of crystals piled up at random, some of which are intergrowing or twinning. In section this

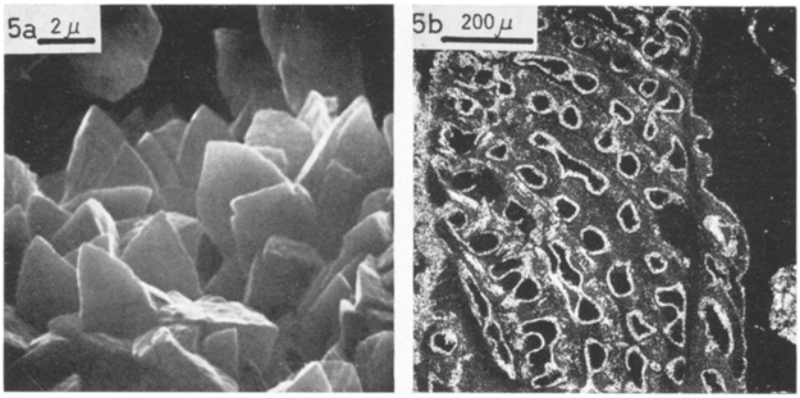

Fig. 5. Calcite micrite cement. a) Rhomb terminations of micrite crystals; note rounded faces and edges (SEM). b) Lining of intra-skeletal cavities within a foraminifer (Thin section; × nicols).

cement forms clear transparent rims. The magnesium content has been analysed to be 15 mole % $MgCO_3$.

Calcite scale cement (Fig. 6) is characterized by the size of its crystals ranging from 5 to 20 μ, by their frequent twinning parallel to the rhomb-face which results in a scale pattern, and by the oblique orientation of the c-axis with respect to the substrate. Similar to the micrite, in this cement the crystal faces tend to be curved (Fig. 6 b). However, the curvature exceeds that observed at the micritic rhombs by far: frequently crystals lack edges, and their terminations consist of a cone instead of three rhomb-faces. As shown in Fig. 6 c the orientation of the scale cement crystals and hence of the aggregate depends largely on the

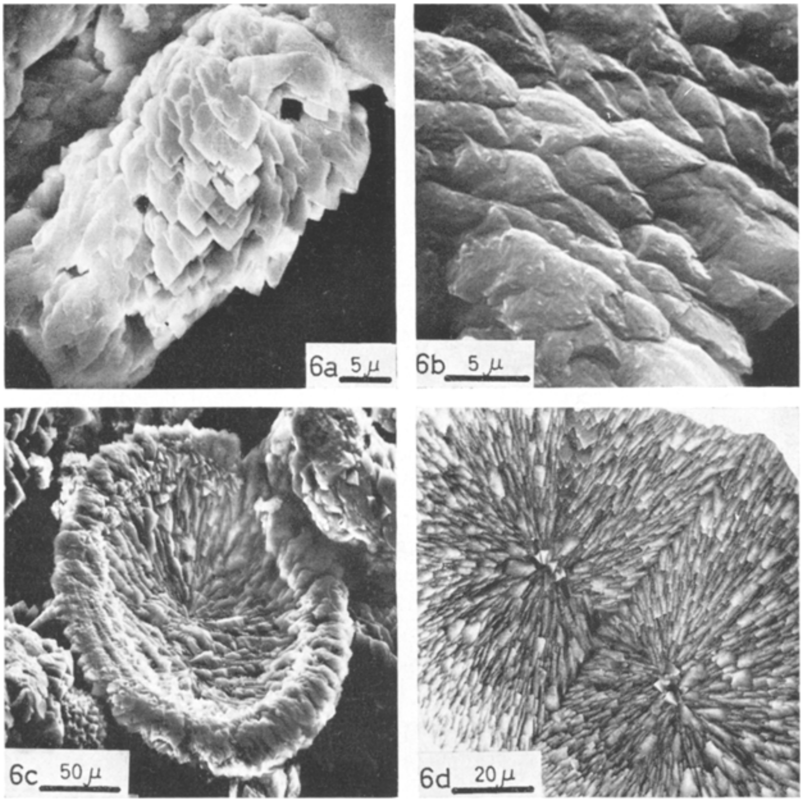

Fig. 6. Calcite scale cement. a) Encrusted particle on the surface of a cavity filling exhibiting the characteristic scale pattern (SEM). b) Crystal faces may be rounded and thus edges lacking; crystals then assume cone shape (SEM). c) Encrustation of an ostracode; note the centripetal orentation on rim and interior of the valve, and also two "centers" (SEM). d) Two ostracode valves still in contact encrusted by scale cement; each valve has its own centripetal pattern, and the contact line acts as devide between them (SEM).

morphology of the substrate. For example in the interior encrustation of an ostracode valve, the crystals form a centripetal pattern with the tips of the rhombs oriented toward the morphologically deepest portion(s) of the shell. Where both valves have been preserved in contact (Fig. 6 d) the contact line between the valves forms the devide between the respective centripetal encrustation of each valve.

Calcite palisade cement (Figs. 7, 8) is composed of bladed to fibrous crystals whose c-axis is oriented normal to the substrate. Crystals of 20 to 80 μ length and up to 5 μ width combine to crusts (Fig. 7 a). The regular parallel orientation of the constituent crystals (Figs. 7 b, c) and the correspondingly regular outline of the surface of the crust distinguishes these from the crusts formed by the aragonite needle cement with their less orderly orientation and rather ragged surface outline. Skeletal particles such as ostracode valves may be enveloped by two such crusts (Figs. 7 b, c).

A distinct variety of the calcite palisade cement is the crust of calcified algal filaments [1]), which have been described in detail by Schroeder (1972). These calcified filaments form meshworks (Fig. 8 a) or linings (Fig. 8 c) within reef cavities. They consist of a core of inward growing micrite and a crust of outward growing equant, bladed, or fibrous crystals; the mutual basis of core and crust is the thallus membrane of the endolithic green alga *Ostreobium*. In cross section calcified filaments have a peloid appearance (Fig. 8 b top), in longitudinal section they closely resemble ostracode valves enveloped by two palisade crusts (compare Figs. 7 b, c, and 8 b bottom). The crystals of the filament crust are 10 to 150 μ long and 2—10 μ wide. Due to the curvature of their substrate they widen as they grow, thus assuming the shape of a wedge (Fig. 8 b top). Where the original filaments were attached to the cavity wall, their calcification resulted in a characteristic pattern of fans with cores at the tips and with their axis normal to the wall (Fig. 8 c). Due to the micritic cores and the small width of the crust crystals at their base, this pattern takes the appearance of two different cement layers: a "dirty" or "dusty" micritic layer at the cavity wall, usually 10—20 μ thick overlain by a layer of transparent crystals up to 200 μ thick (Fig. 8 c). The nature of such lining can be recognized by SEM study; but also in thin section, where the following criteria are useful: 1. fanning crystals of the transparent layer, 2. the undulating surface outline formed by coalescing fans, and 3. individual filaments protruding from the lining into the cavity. Calcite palisade cements, both algal and non-algal, contain of 15 mole % $MgCO_3$. With respect to the algal cement, microprobe results were confirmed by X-ray diffraction analysis.

Blocky calcite (Fig. 9) forms mosaics of equant to bladed crystals, which commonly are between 20 and 60 μ in size. No preferred orientation is apparent. Nevertheless rhombs may point to the interior of the cavity, and thus similarity with the drusy fabric described by Bathurst (1964) may result; however, the essential characteristic of the drusy fabric is lacking, namely the increase in crystal size toward the center of the cavity.

The magnesium content of this cement was found to be 17 mole% $MgCO_3$.

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[1]) In this paper, reference to "calcified algal filaments" implies reference to the palisade cement in their crusts.

Nature and environment of cementation

The cements described are clearly precipitative overgrowth cements (sensu Folk, 1965). No transition from one type of cement to another has been observed except for the micritization of spherulitic cements (Fig. 2 b), a process which is closely related to algal boring (Bathurst, 1966; Alexandersson, 1972 a).

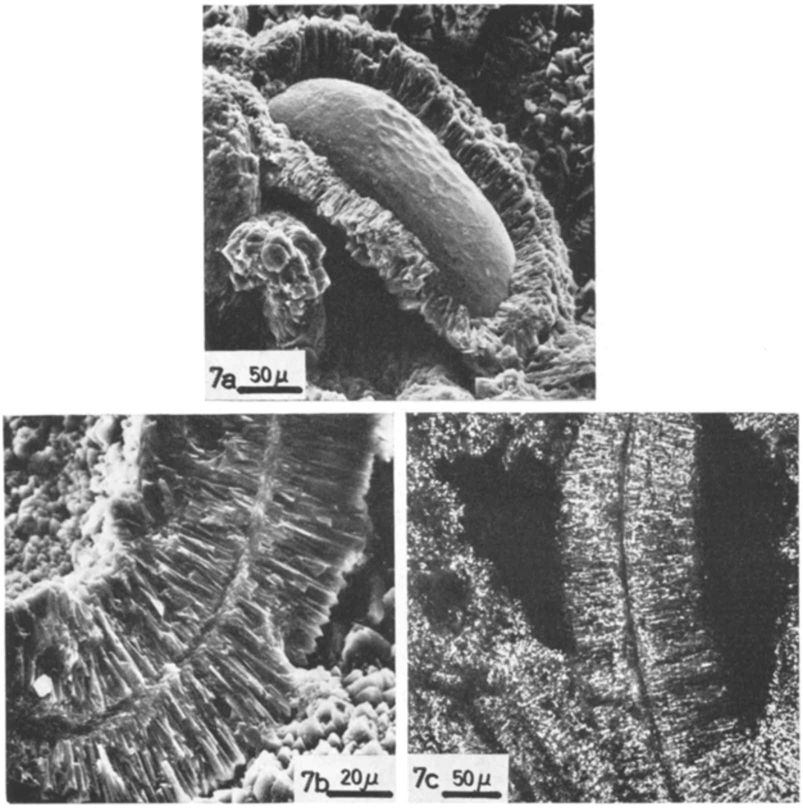

Fig. 7. Calcite palisade cement. a) Ostracode valve encrusted by palisade cement; part of the crust fell off during sample preparation (SEM). b) Ostracode valve enveloped by two crusts of palisade cement (SEM). c) Same as b, different sample (Thin section; × nicols).

With respect to the environment of cementation, by now, five years after the initial report, it appears almost superfluous to present evidence in support of marine origin of cements found in marine reefs, because submarine cementation in many marine environments is well documented and established. As to this case, both analytical (C and O isotopes) and circumstantial evidence has been presented in earlier papers on these reefs (Ginsburg et al., 1967, 1969, 1971; Shinn, 1971; Schroeder, 1972). Most circumstantial evidence can be applied

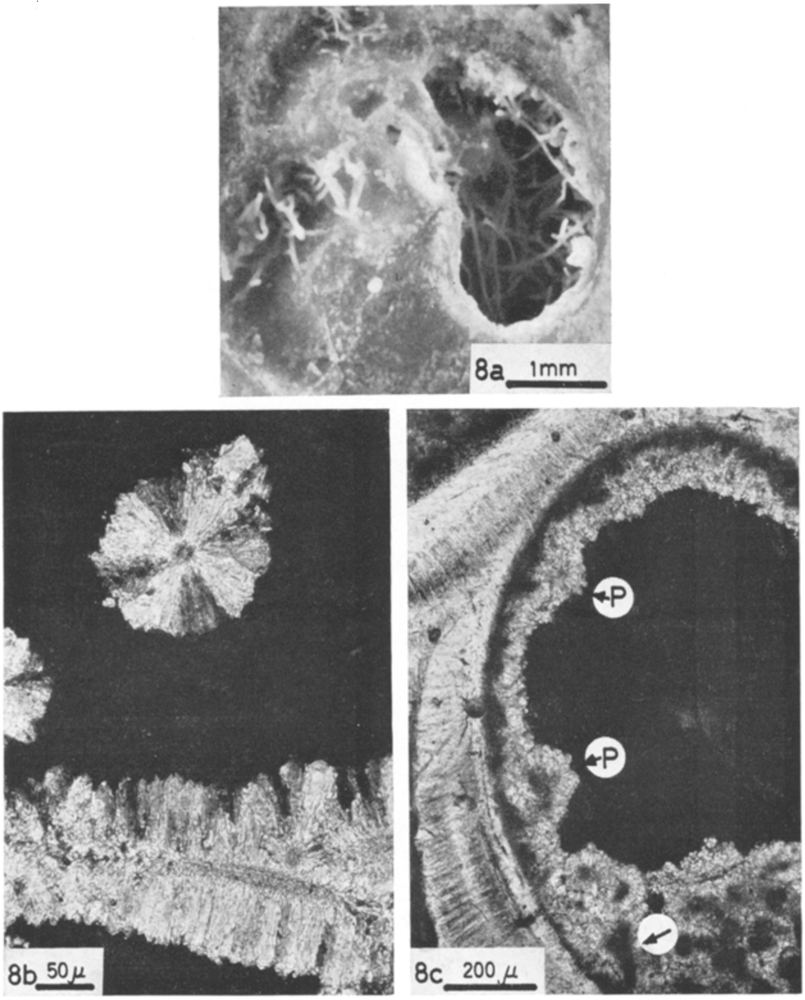

Fig. 8. Calcified algal filaments with crusts of palisade cement. a) Meshwork of calcified filaments in intra-skeletal cavities (Macrophotograph of sawed surface). b) Transverse (top) and longitudinal (bottom) section of calcified algal filament consisting of micrite core and palisade crust (Thin section; × nicols). c) Calcified filaments partly filling and lining a gastropod shell. Note the double-layer-appearence of the lining (dark micritic; light palisade cement) and the diagnostic protrusions (P) of individual filaments. Within the geopetal filling one elongate section (arrow) and several peloid cross sections of filaments are shown (Thin section; × nicols).

to all cements reported here, and therefore is summarized in the following (updated) list:

1. The lack of erosion unconformities within the reefs;
2. Initial cementation within millimeters below the growing surface;

3. New frame growth and subsequent cementation is observed at all depth to 12 m;
4. Interlayering of cements and reef derived sediments;
5. Alternation of organism growth and cementation;
6. Influence of marine organisms on cementation (algae, molluscs, crustaceans; see also below);
7. Boring of cements by marine endolithic algae; calcified filaments succeeding other cements.

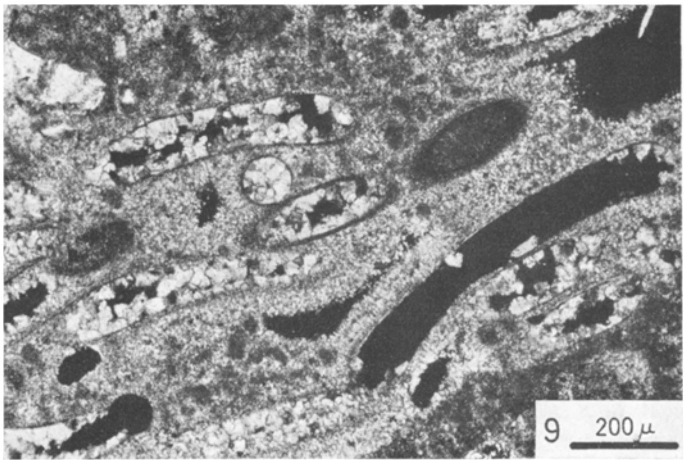

Fig. 9. Blocky calcite cement within serpulid (?) tubes (Thin section; × nicols).

Relative abundance and affinities

The cements described vary in relative abundance in the cup reefs studied: Calcite micrite is very abundant, aragonite needle cement and calcified algal filaments are abundant, aragonite spherulitic cement is common. The other cements are rare, but may be common or even abundant in given specimens or cavities.

Some affinities between the cements described certainly exist. The calcite micrite seems to be closely related to the calcite palisade cement. This is well illustrated by Ginsburg et al. (1971, Fig. 8); they show a cavity with micrite; some portions of the rim cement, however, consist of elongate crystals up to 20 μ in length, other portions are made up of equant crystals of micrite size. Palisade cement apparently grows when two requirements are fulfilled: 1. Of the crystals nucleating initially a sufficient number is oriented favorably to grow up rapidly to form palisade crystals and to suppress at the same time other crystals growing slower. This selection happens very early in the cementation process, since no crystals of different orientation are large enough to be recognized by SEM. 2. Nucleation of crystals occurs only at the beginning of the cementation process. In contrast, calcite micrite would be formed where a smaller number of nuclei is oriented favorably for rapid growth and/or as result of repetitive or continued crystal nucleation. With respect to scale cements, the conditions required for palisade cements apply except that the direction of preferred growth differs.

Occurrence of spherulitic fabric in isolated cone segments and irregular aggregates on the one hand and in the regular layers of the coatings closely related to boring pelecypods on the other, poses the question if these two are genetically closer related than apparent, or conversely, if this fabric may be produced by two (or more) entirely different mechanisms. Another example in point is the pair calcite palisade cement/calcified algal filaments; thus probably in general, multiple origin of given cement fabrics has to be considered when interpreting cements. This consideration also brings to mind the deficiency of the descriptive approach taken in this paper; however, it certainly is premature to apply any other criteria to distinguish cements.

Factors effective in cementation

Factors determining composition and fabrics of cements are deduced from observations on occurrence, coexistence, and sequences of cements.

Substrate

The nature of the substrate, be it morphology, mineralogical or chemical composition, organic coating or other properties, may determine which type of cement is precipitated. The following evidence is provided by this study:

1. The only bare skeletal surface on which blocky calcite cement has been observed is the interior of a serpulid (?) worm tube (Fig. 9): on the external surface and in adjacent skeletal cavities other cements occur. The nature of the blocky cement suggests a low rate of crystal nucleation at the inner surface of these tubes.

2. On top of a given cavity filling, that is under identical environmental conditions, ostracodes have been encrusted by different cements; one by calcite scale cement (Fig. 6 c), others by calcite palisade cements (Figs. 7 a, b). Similarly, skeletal particles of different crustacean taxa, for example an ostracode valve and a somite of an unidentified crustacean, deposited next to each other are encrusted by calcite palisade cement and scale cement respectively (Fig. 10 a). These observations suggest that substrate differences reflect taxonomic differences, and, hence, that taxonomy of a skeletal particle affects the fabrics of the encrusting cement.

3. The centripetal arrangement of scale cements (see above; Figs. 6 c, d) indicates that of the above mentioned surface properties morphology can be singled out and its influence can be traced. Another example in point is shown in Fig. 10 b; the skeletal part encrusted presumably is the terminal somite of the unidentified crustacean (see also Fig. 10 a); it has been found also without encrustation. The medial spine is encrusted by micrite or possibly palisade cement, whereas most of the posterior rim and the smooth surfaces are encrusted by scale cement.

4. The discriminating effect on mineralogical composition (GLOVER & PRAY, 1969) was seen in an aragonitic *Millepora* crust: cementation was observed within the first millimeter below the growing surface. The cements encountered include aragonite needle and spherulitic, but no calcite cement.

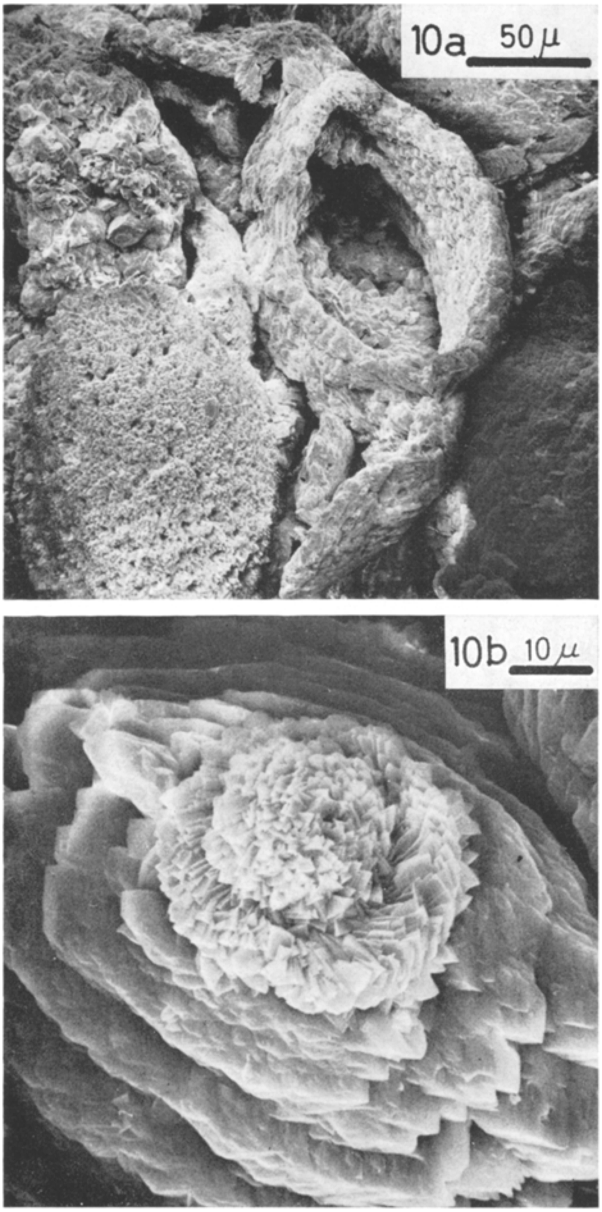

Fig. 10. Coexisting calcite cements. a) Calcite palisade cement encrusting an ostracode (lower left) and calcite scale cement encrusting a somite of an unidentified crustacean (SEM). b) Terminal somite of an unidentified crustacean. The medial spine is encrusted by micrite or possibly palisade cement, while most of the posterior rim and the remainder of the somite are covered by scale cement (SEM).

Organism involvement

Algal palisade cement as well as the spherulitic coatings of pelecypod boreholes indicate that organism activity influences cementation. Another example of this involvement are cemented walls around crustacean burrows in otherwise unconsolidated sediment, which have been found within the cup reefs. At present the nature of this involvement is wide open to speculation (and future study); there is no evidence indicating in which way organisms influence cementation and whether they do so directly or indirectly. What at first glance looks like a rather direct influence like the examples mentioned may eventually boil down to a catalytic effect of organic substrate or secreted mucus, to the product of parasitic bacteria, or other less direct influences.

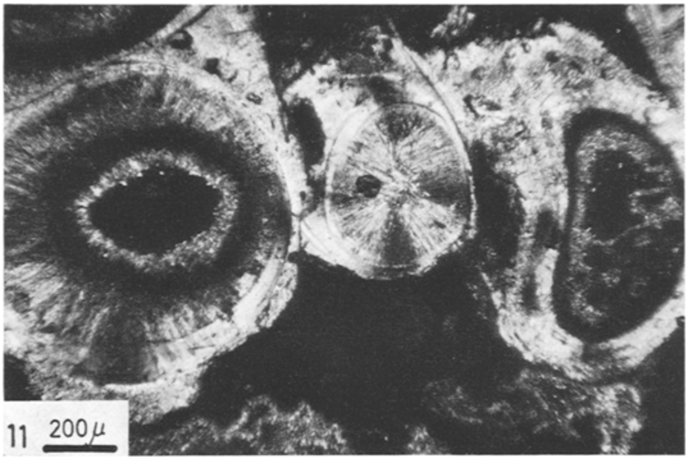

Fig. 11. Three adjacent cavities with different cements illustrating the influence of the micro-environment on cementation. The cavity on the right is lined and partially filled with calcified algal filaments; the center one is filled with aragonite needle cement; in the left one aragonite needle cement is followed by a lining of calcified algal filaments (Thin section; × nicols).

Micro-environment

GINSBURG et al. (1971) showed that different cements occur in adjacent cavities of a given specimen, and concluded "that the control (of cementation) is subtle and local". SCHROEDER (1972) drew the same conclusion from the differences in thickness of calcified algal filaments in adjacent cavities. The observations of this study confirm the earlier results; Fig. 11 illustrates this point: Three adjacent cavities are cemented in different ways. The right one is lined and partially filled by calcified algal filaments, the center one is filled by aragonite needle cement, and in the left one aragonite needle cement is followed by a lining of calcified filaments.

GINSBURG et al. (1971) and SCHROEDER (1972) have shown that generations of precipitative cements may succeed each other; SCHROEDER (1972) suggested introduction of algal filaments into cavities to be a mechanism for micro-environmental change. This study furnishes additional examples of successive precipitative cement generations (Fig. 12). Aragonite needle cement may be followed by calcite micrite (Fig. 12 a) or by calcified algal filaments; aragonite spherulitic cements may the followed by algal filaments (Fig. 12 e); calcified algal filaments may be followed either by aragonite needles (Fig. 12 b) or by blocky calcite (Fig. 12 c); calcite micrite may be followed by blocky calcite (Fig. 12 d). Aragonite needles followed by calcified algal filaments, which in turn are followed by aragonite needle cement or calcite micrite have been illustrated by SCHROEDER (1972, Figs. 17, 18). These observations on a variety of sequences of precipitative cements suggest existence of several mechanisms which change the micro-environment.

Discussion

Comparison of cements described with reports from other locations

The blessings of modern equipment such as SEM tend to turn into a curse as soon comparison with pre-SEM age work is attempted. In as much as SEM results could be supplemented by or translated into thin section observation comparison is possible [2]).

Magnesium calcite micrite is a very common submarine cement reported by many authors (LAND & GOREAU, 1969; ALEXANDERSSON, 1969, 1971; HOSKIN, 1969; ALLEN et al., 1968; SHINN, 1969; MACINTYRE & MILLIMAN, 1969; to mention only some authors). Almost equally abundant is the aragonite needle cement (MACINTYRE & MILLIMAN, 1969; ROBERTS & MOORE, 1969; MABESOONE, 1971; GLOVER & PRAY, 1969; SHINN, 1969; GEVIRTZ & FRIEDMAN, 1966; and many others). Neither calcite micrite nor aragonite needle cement seems to be restricted to or absent from any particular submarine environment.

What is elsewhere called dentate calcite (MACINTYRE et al., 1969; MACINTYRE & MILLIMAN, 1969) or fibrous calcite (MARLOWE, 1969), apparently corresponds to the calcite palisade cement reported here. These authors described the dentate or fibrous calcites to be associated with "an opaque submicrocrystalline calcite layer" (MACINTYRE et al., 1969), with "pelletoid or pseudopelletoid texture" (MACINTYRE & MILLIMAN, 1969), or with "micritic pellets" (MARLOWE, 1969). These descriptions suggest comparison with the linings of calcified algal filaments (Fig. 9 c).

SHINN'S (1969, Fig. 20) "fan druse" of aragonite probably is comparable to the aragonite spherulitic cement. His terminology was not adopted because of its reference to two-dimensional sections. ALLEN et al. (1969, Fig. 6) illustrated another comparable cement. SHINN (1971) recently reported oolites and pisolites from the Bermuda cup reefs. Although the sizes of 2 to 3 millimeters have not been observed with the spherulitic cements, a close relationship is possible. Experiments of ROZHKOVA & SOLOV'EV (1937, quoted in LEBEDEV, 1967), USDOWSKI (1963), SUESS (1971), and SCHERER (personal communication 1971) have shown that formation of oolitic fabrics does not require movement of the particles

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[2]) To limit the present discussion, comparison was restricted largely to cements of clearly submarine origin.

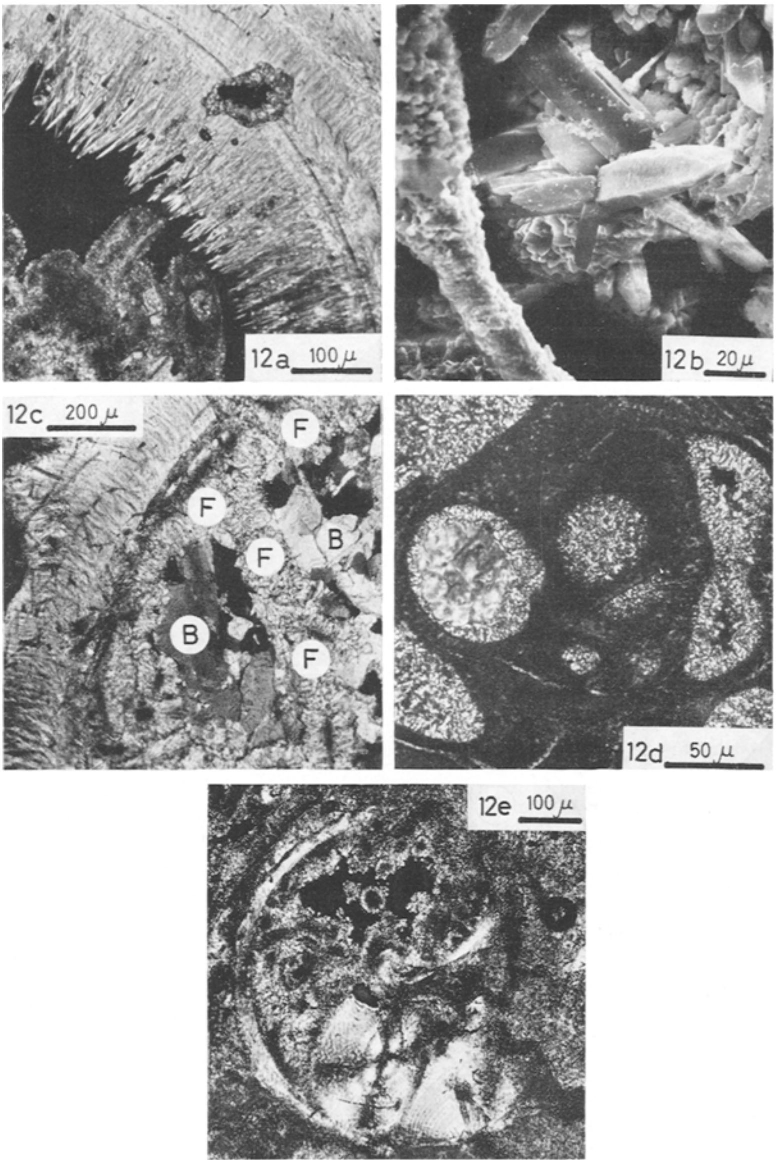

Fig. 12. Sequences of different cements. a) Aragonite needle cement lining the interior of a gastropod shell followed by calcite micrite sourrounding sediment particles and lining a boring in shell and aragonite cement (upper right) (Thin section; × nicols). b) Aragonite needle cluster on a calcified algal filament (SEM). c) Calcified algal filaments (F) lining a gastropod shell and extending into the cavity followed by blocky calcite (B) (Thin section; × nicols). d) Calcite micrite lining intra-skeletal cavities of a foraminifer followed by blocky calcite (Thin section; × nicols). e) Aragonite spherulitic cement followed by calcified algal filaments (Thin section; × nicols).

bearing the fabric; thus, a common genesis of spherulitic cement and ooids appears feasible. From comparison with known submarine cements the conclusion can be drawn that the cements known are not indicative of any depositional and, for that matter, early diagenetic, environment. It is very likely that the cements newly described from the Bermuda cup reefs in this paper will be found in other marine environments. This suggests that the genesis of any one cement can be studied in various environments; hence, factors which cannot be studied in reefs possibly can be studied in other environments; for example physico-chemical factors can be studied where the micro-environment has not such paramount influence. On the other hand, the reef may be the place to study influence and interactions of organisms.

Influence of organisms and organic matter

The influence of organisms in cementation has been suggested before, for example by ALEXANDERSSON (1969), by PURDY (1968) with reference to "burrowing organisms (shrimp?)", and by MACINTYRE et al. (1969) also with reference to burrowers. This study brings to attention several organisms involved in cementation; these are the endolithic alga *Ostreobium*, the boring pelecypods, and burrowing crustaceans. Studying the reefs off North Eleuthera, Bahamas (ZANKL & SCHROEDER, 1972) this author has found polychaets to produce cemented tubes similar to those of shrimps, but thinner. The organisms mentioned are primarily destructive; thus they play a dual role in the formation of reef rock: on one hand they destroy frame or disturb sedimentary fillings, on the other hand they directly or indirectly contribute to the rigidity of the reef by being involved in cementation.

The inhibitory effect of organic matter on carbonate precipitations has been described by CHAVE (1965), CHAVE & SUESS (1970), and SUESS (1970); also the role of organic matter in providing nuclei for precipitates (SUESS, 1971) and in determining the kind of precipitate (MITTERER, 1969 a, b) has been recognized. The study of organisms and organic material as effective in cementation is likely to improve the understanding of this process. Substrate differences related to taxonomic variation in part may consist in differences of organic matter present. However, compositional differences (GLOVER & PRAY, 1969) as well as morphological features (see above) play a role. This author has shown experimentally that the dissolution behavior of a skeletal particle depends to a large extent on taxonomically determined properties (SCHROEDER, 1969). These experimental results have received support from a recent report by SCHNEIDERMANN (1971) who found deep-sea dissolution of coccoliths to be selective with respect to species. The marked influence of taxonomically determined properties on the major diagenetic processes, cementation and dissolution, gives high priority to detailed investigations of carbonate skeletal particles.

Micro-environment

Presence and type of organic matter, and, more generally put, the type of substrate in part define the micro-environment. However, the term micro-environment comprises a large number of factors. Among those readily apparent is the access to a given cavity, i.e. permeability on a micro-scale and, in conjunction, the size of the micro-environment. Size and porosity determine to what extent the micro-environment is affected by external influences and to what extent internal influence can be effective. Cementation requires circulation of sea-water to supply ions. Sea-water contains about 400 ppm Ca^{++} (Mason 1958); according to a rough quantitative calculation, at least about 2800 volumes of sea-water are required to supply the Ca^{++} for precipitation of 1 volume $CaCO_3$; this quantity probably is much greater because the process of cementation is unlikely to deplete sea-water of all Ca^{++}. (For review see Bathurst, 1971, p. 440.) Sea-water can be circulated through the reef structure with surf and wave action serving as pumping mechanism. However, the requirement for circulation and thus for permeability conflicts to some extent with the finding that cementation is controlled by local controls of the micro-environment; local control requires at least a partly closed system unless it is exclusively a substrate effect. This conflict may account for some of the variations observed: They may represent different combinations of various circulation rates (defined by permeability) and various intensities of local control. For example, the variation in thickness of calcified algal filaments in adjacent cavities (Schroeder, 1972) may be explained in this way. Corresponding considerations may apply where ions are supplied by diffusion.

This consideration still does not provide clues toward the definition of the micro-environment: These have to come from detailed experimental and analytical work, such as the investigations on selected corals by Hubbard (1972). Long term observation of growth in field and laboratory, determination of nature, function, and internal processes of cavities, as well as comparison between living, dead, and fossil specimens of given taxa should help to understand what "micro-environment" means, and thus to understand submarine reef cementation.

Sequences of different precipitative cements so far have been reported rarely; except for the Bermuda examples (Ginsburg et al., 1971; Schroeder, 1972) only Alexandersson (1972 b) has reported some from intra-skeletal cavities of shallow-water sediments in the Mediterranean. With the lack of specific information on the micro-environment, considerations of its changes which bring about cement sequences at best offer tentative suggestions. The only evidence concerning such change are filaments of endolithic algae which have entered partly cemented cavities and have been calcified thereafter (Schroeder, 1972). In addition, on the basis of the above discussion, the following changes are conceivable:

1. Some of the substrate effects may weaken to ineffectiveness after encrustation of the substrate.
2. The relation between rate of circulation and intensity of local control may change, for example due to the reduction of effective micro-porosity as a result of cementation or organic growth.
3. Organic matter may decay.
4. (Micro-) organisms such as bacteria may enter cavities.

Conclusions

From Bermuda cup reefs, several precipitative submarine carbonate cements distinguished by composition and fabric are described to provide a basis for comparison with similar cements and for interpretation of diagenetic environments in fossil reefs.

From their occurrence the following interrelated factors determining composition and fabric of cements were deduced.

1. Substrate (both as independent and micro-environmental factor)
    a. Morphology
    b. Mineralogical composition
    c. Other properties such as organic coatings and crystal orientation.
2. Organism activity (as independent or micro-environmental factor) for example the activity of algae, pelecypods, crustaceans.
3. Micro-environment
    a. Size of the micro-environment
    b. Permeability
    c. Rate of circulation of seawater through the micro-environment.

Several sequences of precipitative cements in given cavities have been observed; these are considered the result of changes in the effectiveness of the above factors. Further study is needed to better define the factors, their effects, their interplay, and the changes of these factors.

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