EARLY PROTEROZOIC (1.9 GA) THROMBOLITES OF THE ROCKNEST FORMATION, NORTHWEST TERRITORIES, CANADA

by

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Abstract

Thrombolitic fabrics of the Rocknest Formation, Northwest Territories, Canada (Hoffman, 1975; Grotzinger and Hoffman, 1983; Grotzinger, 1986a, 1989b) were disputed by Kennard and James (1986) and Kennard (1989) and classified as cryptomicrobial boundstones. Under close re-examination, these rocks reveal mesoscopic and microscopic fabrics which are indeed thrombolitic when considered in the context of the recent tripartate microbialite classification scheme developed by Kennard and James (1986) and Kennard (1989).

Thrombolitic fabrics from the Rocknest Formation demonstrate conclusively that, in cases of pervasive dolomitization, palimpsest fabrics can continue to provide evidence for the depositional environment of microbial communities. These thrombolites are significantly different from younger Proterozoic thrombolites (Aitken and Narbonne, 1989) and their Phanerozoic counterpoints (Kennard and James, 1986; Kennard, 1989), containing far less detrital sediment and greater amounts of marine cements, which suggests rethinking of models pertaining to the origin of thrombolites, as well as how microbial communities interact with their environment in the formation of characteristic diagenetic fabrics. Additionally, Rocknest thrombolites indicate that development of diagnostic, clotted fabrics may result from microbially-induced "inorganic" calcification of microbial communities, rather than by *in situ* calcification of microbial sheaths (Kennard and James, 1986; Kennard, 1989). This suggests a stronger reliance on physical and chemical aspects of depositional environments in the formation of thrombolitic fabrics than previously suggested.

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Introduction

Aitken (1967) introduced the term **thrombolite** to classify "cryptalgal structures related to stromatolites but lacking lamination and characterized by a macroscopically clotted fabric". Controversy followed and various authors further defined these clotted fabrics as either being abiogenic, such as the tufas of many Proterozoic successions (Walter, 1987, personal communication to Kennard, 1989), or as the end result in disruption or obliteration of originally laminated structures (Hofmann, 1973). Indeed, the inherent "splotchy", "mottled", or "clotted" fabric could be the result of a number of degradative activities, such as oxidation of organic material, internal solution of laminated fabrics, and bioturbation.

Gebelein (1974) suggested that a splotchy or clotted fabric could be obtained simply by degradation of once living organic material. For example, oxidation of dead algae comprising mammilate and pustular mats of Shark Bay, Western Australia, leaves irregular, often large, voids (Logan, 1976; Dravis, 1982), which could subsequently be filled with sediment, giving the mat a clotted appearance (Monty, 1976).

Garrett (1970) and Awramik (1971) report similarities of external form between thrombolites and stromatolites and that intergradations frequently occur between the two.They proposed that thrombolitic textures were perhaps the result of bioturbation of stromatolites. This would explain not only the decline of stromatolites at the end of the Proterozoic, but also the apparent evolution of thrombolitic fabrics, for with metazoan radiation in the Phanerozoic, "bioturbated" stromatolites would certainly increase as pristine forms decreased. This argument was underscored by Walter and Heys (1985), who stated that thrombolites "owe their origin to and record the first macroscopic burrowing and possibly boring by animals".

More recent work, however, suggests that the appearance of calcareous microbes such as *Girvanella*, *Renalcis*, *Epipyhton*, and *Nuia* has been important in the development of thrombolitic fabrics (Kennard and James, 1986; Kennard, 1989). These works propose that a secular difference in the nature of the microbial community is responsible for clotted thrombolitic fabrics, rather than a disruption or modification of originally laminated fabrics. They interpret thrombolites to be characterized by a mesoscopically clotted fabric resulting from the penecontemporaneous growth and calcification of discrete colonies of coccoid-dominated microbial communities. Their origin at the Precambrian-Cambrian boundary is attributed to the first appearance of calcareous cyanobacteria (Kennard and James, 1986; Kennard, 1989).

Recent work on thrombolitic facies and fabrics (Kennard and James, 1986; Kennard, 1989; Pratt, 1982a; and Pratt and James, 1982) has contributed to revived interest in microbial buildups and their origin (Noble, 1985; Burne and Moore, 1987). However, with the exception of Kennard's (1989) intensive study of Cambrian and Ordovician thrombolites, there has been no systematic analysis of thrombolite occurrences in the rock record. Although the existence of Precambrian thrombolites has been noted (Schmitt, 1978; Cheng and Zhung, 1983; Grotzinger and Hoffman, 1983), these Proterozoic occurrences remain especially controversial. Bertrand-Sarfati (Kennard, 1989) argues that Precambrian thrombolitic/stromatolitic facies reported by Schmitt (1978) are Cambrian in age, due to proximal archaeocyathid findings. Walter and Heys (1985) regard microbialite samples reported in Cheng and Zhung (1983) to be pseudo-columnar stromatolites rather than thrombolites, and Kennard and James (1986) and Kennard (1989) consider thrombolitic fabrics of the Rocknest Formation (Grotzinger and Hoffman, 1983) to be diagenetically altered stromatolites.

The most recent report of possible Proterozoic thrombolites (Aitken and Narbonne, 1989) documents both thrombolitic clasts in debris flow deposits of the Blueflower Formation (Ediacaran/Vendian) and reefal specimens from the Little Dal Group pinnacle reefs (Riphean), both from the MacKenzie Mountains, Yukon Territory, Canada. This new information has called attention to the need for careful re-examination of recorded Proterozoic thrombolite fabrics, and has provided additional evidence for existence of true Proterozoic thrombolites.

In this study, the controversial thrombolitic fabrics of the 1.9 Ga Rocknest formation are re-evaluated and interpreted as thrombolitic in nature, making them the oldest documented thrombolites to date. This necessitates reconsideration of environmental aspects of stromatolite and thrombolite growth. In particular the complex interaction between depositional environment and growth of microbial communities is examined in terms of generation of diagnostic fabrics, and implications regarding microbial evolution.

Methods of Study

A single sample, collected by John P. Grotzinger was obtained from the core of a thrombolite mound in the inner shelf facies of the Rocknest Formation (1.9 Ga), Northwest Territories, Canada. Descriptions were made from weathered surfaces and from six slabbed and polished sections. Slabs were cut parallel to the weathered surface to display vertical cross-sections of the mound. Tracings were made of micritic and sparry void fillings, silicified portions, and laminated areas to evaluate relationships between various fabric elements. Mesoscopic analysis at low magnification (1-10x) was used to determine the relationships between fabrics on the slabbed sections. Microscopic analysis of 25 large thin-sections (4x7cm), both at medium magnifications (10-40x), and at higher magnifications (40-100x), assisted with evaluation of microstructure. However, the most useful analyses of fabric relationships were gained through examination of thin sections with a microfiche reader at magnifications of 25x and 50x. This unorthodox method provided a greatly increased field of view compared to that obtained with conventional microscopes.

Terminology

The terminology used in this study follows primarily that defined in Kennard (1989):

Microbialite: any microbial deposit, regardless of internal fabrics (Burne and Moore, 1987), including stromatolites, thrombolites, and other microbial mats

Thrombolite: cryptomicrobial mound consisting of an irregularly clotted fabric (*sensu* Aitkin, 1967)

Stromatolite: cryptomicrobial mound consisting of superimposed laminae of sediment and cryptomicrobial fabric (*sensu* Kennard, 1989)

Thromboid: individual macroscopic clots, mms-cms in size, within a thrombolite (Kennard and James, 1986)

Stromatoid: individual lamina within a stromatolite (*sensu* Kennard, 1989).

It is important to note that the definition of **thrombolite** followed in this study is that of Aitken (1967), in contrast with that of Kennard and James (1986) and Kennard (1989). In this definition, genetic connotations of the term **thrombolite** are dismissed. There are no restrictions placed on the specific type of microbial community, its form of preservation, or the abilities of the community to adapt or conform to a particular environment of deposition. Instead, usage is preferred to be purely textural and descriptional.

Additionally, for simplification in description, I propose the term **thromboid head**, defined here as composed of thromboids, and which in turn are constituents of a thrombolite. Thromboid heads are described as the intermediate-sized clotted bodies, often centimeters in size, which are externally defined by sediment fill, but with very little internal sediment.

Regional Setting

The early Proterozoic Rocknest Formation is an eastward thinning carbonate platform (0-1100m thick) exposed in the foreland fold and thrust belt and autochthon of Wopmay Orogen, Northwest Territories, Canada (Fig. 1) (Hoffman and Bowring, 1984). Palinspastic restoration indicates an original extent of over 220km parallel to depositional strike, and over 200km perpendicular to strike (Grotzinger, 1986a, 1986b, 1989b). The Rocknest Formation is the uppermost formation in the passive margin sequence (Epworth Group) of the Coronation Supergroup. Age of the Rocknest is bracketed between 1.92-1.885 Ga by U-Pb zircon dates from volcanic tuffs in the underlying Odjick Formation and the overlying Recluse Group (Bowring and Grotzinger, 1989).

The Rocknest Formation is a dolomitic, cyclic shelf sequence flanked by a barrier reefal rim and shoal complex. Stratigraphic relationships indicate long term progradation and aggradation of the shelf, interrupted by several episodes of incipient drowning associated with glacio-eustatic sea level oscillations, followed by a final, terminal drowning associated with rapid subsidence during collision (Grotzinger, 1986b).

Stratigraphy of the Rocknest Formation consists of shallowing-upward cycles of slope, outer shelf, shoal, and inner shelf facies. The cyclic inner shelf sequence, or lagoonal sequence, occurs over most of the shelf region and is exposed in the eastern and central thrust sheets, the autochthon of Wopmay Orogen, and in the Peacock Hills area of the Kilohigok Basin (Grotzinger, 1986a). It consists of asymmetric, upward-shallowing cycles of subtidal, interstratified carbonates and siliciclastics that shoal into upper subtidal and intertidal stromatolitic dolomites. These cycles are classified according to cycle-base lithologies, which in turn reflect their paleogeographic position on the shelf (Grotzinger, 1986a).

The shale-based, shallowing-upward cycles of the Rocknest inner shelf display the most diversity of lithologic facies, and include: 1) intraclast grainstone/packstone facies; 2) mixed siliciclastic and carbonate facies; 3) thick laminated dolosiltite facies; 4) stromatolitic and thrombolitic facies; 5) cryptalgal facies; and 6) tufa facies. The stromatolitic and thrombolitic facies consists of partially linked to linked stromatolites (10-150cm base diameter) with smooth to fenestral laminated fabrics (Hoffman, 1975; Grotzinger, 1986a). Thrombolitic fabrics, although occurring rarely, have external morphologies that form domes, columns, and branching columns. Paleoenvironmental data shows that these facies shoaled from subtidal to intertidal zones, with thrombolitic fabrics forming in areas of greater wave agitation than linked and domal stromatolites. Wave energy was not of sufficient intensity to cause elongation of the heads (Grotzinger, 1986a). Additionally, thrombolitic fabrics are easily distinguishable in the field, are regionally extensive, and thus provide strong guides for areal cycle correlation. A sample from these thrombolites, which reveals a "massive" and "clotted" fabric (Grotzinger, 1986a, 1989b), was collected from an outcrop at the north end of Kikerk Lake and forms the basis of this study. Other possible occurrences of thrombolites in the Rocknest Formation are found in shelf-edge reefal facies, where they interfinger with contemporaneous stromatolites (Grotzinger, 1989b). These thrombolites are not considered in this study.

Descriptions

Mesoscopic Structure

The Rocknest sample studied consists of a large portion of a single mound measuring one meter in height and 2 meters in diameter. The sample measures 13cm x 21cm in cross-sectional area and displays no less than 5cm of synoptic relief. The fabric consists of five distinct elements: 1) a dark grey (pale grey weathering) dolomite, with a macroscopically clotted texture; 2) a dark grey (pale grey weathering) drusy dolomite with a laminated texture; 3) a medium to pale grey (orange weathering) micritic dolomite; 4) a white (orange weathering) blocky dolomite spar; and, 5) a clear (black in appearance within slabbed sections) resistive and dark weathering silica (Fig. 2). These five elements combine to form a composite internal structure, involving episodes of accretionary growth marked by episodic development of renucleation surfaces. For example, laminated fabrics encrust clotted regions, which are in turn encrusted by clotted fabrics. Commonly, however, micritic dolomite, which appears primarily as a void filling fabric, interrupts the accretionary growth of clotted regions. Above these horizons, clotted, accretionary growth continues along renucleation, or regrowth surfaces. The composite structure of the sample is shown through growth of two main clotted regions, which primarily accreted vertically, but, through a series of renucleation events, coalesce into a single body. Synoptic relief during a particular stage of growth was determined by measuring the maximium vertical relief displayed by the basal surface of a single colony of renucleated thromboids.

The framework is composed of densely packed 1-3mm lobate to digitate thromboids, distributed individually or forming 3mm-4cm thromboid heads. These heads tend to accrete vertically rather than grow elongate, and are generally domal, lobed, or vaguely club shaped. The thromboid heads commonly coalesce to form an irregularly massive framework of clots and associated voids (Fig. 3). These clots commonly display pendate bases, though laminar bases often occur at renucleation surfaces. These renucleation surfaces are restricted within the sample to the portions of the thrombolite crest with the highest synoptic relief. Laminated regions are found primarily encrusting vertical margins of the thrombolite, encrusting individual thromboids, or internally lining void spaces. Encrustation of thromboids gives the thromboid heads a vague, internally arcuate lamination. Under low magnification, encrustations of individual thromboids are seen to be composed of an isopachous drusy cement. Thromboid material and laminated cements compose 70-75% of the sample, and 100% of the framework components. Interframework components, comprised entirely of micritic sediments, compose 25-30% of the sample. The micrite is often very finely laminated, with laminae primarily horizontal. Occasional concave-upward laminae, suggest compaction, and concave-downward laminae around regions of blocky, dolomitic spar, suggest displacement by the growth of the void-filling cement. Rarely, geopetal fills are seen in the interframework voids.

Silicification within the framework is selective, and generally selectively replaces thromboid material rather than isopachous cements. Silicification of material within the micritic void fillings is not observed. Silicified regions are primarily found scattered irregularly within the interior of the heads, but the highest concentrations of silica appear within or near the margins of the thrombolite heads. Diagenetic silica comprises perhaps 5% of the framework mass. In contrast to the silica, the blocky, dolomitic spar occurs only within micritic interframework sediments, is not associated with thromboids, and only rarely is observed in thromboid heads. Within thromboid heads, blocky spar dominates small, internal sediment pockets. The spar comprises perhaps 10% of the interframework material.

Microscopic Structure

Many microstructural details of the thromboid material within thromboid heads and larger clots have been obscured due to pervasive dolomitization. Thrombolitic material now consist of a mosaic of anhedral dolomite crystals. However, detailed examination of discrete grain size changes and subtle textural changes reveal clues to the previous fabric.

Thrombolitic material is easily distinguished from interframework sediments through a distinct grain size difference. Thromboltic material is generally 50-75µ in size, while micrite averages 25µ in size. Grain size within thromboid heads is commonly slightly larger at the thromboid-micrite interface. There are also minor grain size differences and textural differences within the thromboid heads, as seen through extinction patterns of oriented crystals. Within the dolomitic mosiac, marginal laminations of drusy cements can be defined by a slight pink-to-orange color and a distinct to vague isopachous, bladed crystal alignment. These cements most commonly encircle micrite filled voids within the thrombolite framework. Faint lobate to cellular structures can be differentiated by grain sizes and extinction patterns and the presence of isopachous, drusy cements. These structures generally range between spherical and lobate forms.

Spherical end-member forms generally consist of a 100-500µ microcrystalline dolomite spheroid with an outwardly radiating fringe of bladed cement, 200-500µ wide. Lobate morphologies consist of grouped sub-sperical, microcrystalline dolomite forms (100-500µ in diameter), with a bladed, drusy rim (50-70µ thick), and a darker, cryptocrystalline outer rim (20-50µ thick). These forms at times display a definite cellular character, with microcrystalline dolomite or isopachous cements defining walls within the lobate morphology. Intermediate forms consist of darker, finely crystalline to microcrystalline dolomite nuclei, with a vague to distinct isopachous cement rims (Fig. 4, Fig. 5). This form constitutes the dominant fabric within the thrombolite framework material, imposing a splotchy to mottled fabric on the thrombolite microstructure.

Interframework sediment fills are microscopically a mosaic of anhedral, microcrystalline dolomite. The micrite/thrombolite interface is frequently defined by a rim of isopachous drusy cement (see Fig. 4, Fig. 13). In laminated fills, laminae can be distinguished on the basis of a grain size change. Laminae commonly warp downward, suggesting compaction, or become displaced, when in close proximity to blocky spar.

Dolomite spar is found exclusively within the micrite-filled voids and displays a bladed to dentate rim that grows inward to large, blocky, euhedral crystals (Fig. 6, Fig. 7). The bladed fringe is composed of crystals with a low length-to-width ratio (commonly 75μ:125μ), suggesting dolomitization of primary high-magnesian calcite. Large, euhedral internal crystals range in size from 0.25-1.5mm. Individual dolomite rhombs occur discontinuously at the interface between the blocky spar and the crystalline, bladed fringe. Rarely, twin planes within the dolomite spar display a distinct curvature and exhibit the sweeping extinction indicative of saddle dolomite (Fig. 8). Blocky spar is additionally found filling tiny cracks that run through the entire sample.

Solution seams are found both within the micrite in interframework voids, and within the thromboid material itself. The solution seams are quite pervasive within the micritic interframework matrix of the thrombolite, but rarely extend for more than the width of the filled void. Only rarely do solution seams incorporate thromboid material. In these cases, solution seams most commonly occur at interfaces between blocky spar and thromboid material (Fig. 9). Morphological relationships observed between framework and interframework constituents suggest that little material has been removed from these regions. Solution seams also occur along the margins of micrite and thromboid material. These solution features occur primarily at the *upper* margin of the micrite (Fig.10), but only rarely are found along vertical or lower margins . Finally, solution seams occur discontinuously within the thromboid heads, predominantly along the interfaces between siliceous regions and thromboid material.

Siliceous regions within the thrombolite are composed of a mosaic of microcrystalline to cryptocrystalline silica, with occasional incomplete, bladed boundaries. Siliceous regions appear to nucleate preferentially within the interior of the thromboid heads, forming small, irregular patches. Silica found at the margins of thromboid heads is in elongate patches, often following the contours of drusy cements. Microcrystalline regions commonly contain carbonate inclusions of undefined composition, which define two characteristic fabrics when viewed under plane light. The first is interpreted as parallel laminated, encrusting cements (Fig. 11). This form occurs predominantly at the external margins of thromboid heads, and less commonly defines thromboids within thromboid heads. The fabric is continuous with the isopachous, marginal laminations within dolomitized regions. Within silicified portions, however, relict isopachous blades are not preserved. The second form represents a spheroidal structure, with individual spheroids ranging from 50-100µ in size. This structure is seen predominantly in silica found internally within thromboids, and more rarely near the margins. In marginal areas, the spheroidal form is often found in close association with the laminated structure (Fig. 12). At the margins of thromboids, drusy cements encrust regions of inclusion-defined spheroids. Thromboid material in this case is often silicified, while encrusting cements are not, displaying the preference of silica for thrombolite material (Fig. 13).

Diagenetic Sequence

Deposition and Early Cementation

Growth of the thrombolite was contemporaneous with the precipitation of encrusting cements. The end of most accretionary growth stages within the head appear to be marked by encrustationof the growth surface by drusy cements. Rapid cementation and preservation of the thrombolite fabric resulted from these precipitated, subaqueous crusts. The isopachous habit of the bladed cements, an elongate crystal fringe growing perpendicular to the substrate, is indicative of marine deposition, and is common in reefal subtidal to intertidal environments (Harris, et al., 1985; James, et al., 1976).

Evidence for negligible influx of clastic carbonate during thrombolite growth is implied by encrustation of voids with isopachous marine cements. Deposition of marine cements within void space is dominantly controlled by the accessibility to circulating pore fluids. Internal voids thus remained empty of detrital or precipitated sediment for a sufficient amount of time to allow encrustation by drusy cements before sediment entrapment. The noticeable absence of detrital sediment during the growth period of the thrombolite suggests an environment with low sedimentation rates and/or rapid growth and precipitation rates. When sedimentation occurred more rapidly, thrombolite growth was inhibited. At these interfaces, drusy cements do not occur.

Silicification

The continuity of thrombolite fabrics between silicified regions and the unsilicified portions of the surrounding components indicate a diagenetic replacement origin for the silica. The preservation of original structures suggests that the replacement of thrombolite material with silica occurred before any severe disruption of the original fabric through dolomitization or other ubiquitous diagenetic events. In this respect, silicification appears to have occurred rather early in the mound's diagenesis, probably as precipitation as chert. Silica selectivity during the replacement of thromboid material relative to encrusting marine cements may have been promoted by the organic nature of microbial colonies. It is known that silica has an affinity for organic material as nucleation surfaces (Leo and Barghoon, 1976; Knoll, 1985), and implies replacement prior to organic degradation of the microbial colonies.

Dissolution and Precipitation of Void Cements

Effects of dissolution are dependent upon textural aspects of constituent fabrics as well as the chemistry of diagenetic fluids. The most abundant evidence for solution of material is found within the micritic interframework void fillings. Solution may have occurred here preferentially due to a greater initial porosity than the early-cemented thromboid material. Interframework sediment retained sufficient porosity to allow slight compaction, as evidenced by the concave-upward geometry of the micritic laminae, while negligible porosity would remain in zones of isopachous cements precipitated directly onto thromboid boundaries. Stylolitization along the upper micrite-thromboid interfacial boundary may have occurred in response to porosity or grain size contrast. The inter-thromboid solution seams, primarily found at the silica-thromboid interfaces, could also reveal a discrimination between fabric elements due to porosity differences or material solubility contrasts.

Precipitation of blocky, magnesian calcite and high temperature saddle dolomite occurred preferentially within micritic interframework sediments possibly due to void spaces or other inhomogeneities developed during dissolution, or again, due to the greater porosity of micrite relative to that of thromboid material. It is not known when solution and chemical compaction begin, but they are influenced by both of water chemistry and depth of burial (Harris, et al., 1985). The precipitation of high-magnesium calcite in voids suggests solution began in an intertidal to subtidal environment, whereas the presence of saddle dolomite indicates a second stage of solution occurred in a high temperature, i.e. subsurface, environment.

Dolomitization

The final stage of diagenesis was ubiquitous dolomitization of the sample. Dolomitization may have occurred contemporaneously with dissolution and precipitation of saddle dolomite, as a result of the same pore fluid chemistry. Alternatively, dolomitization may have occurred through the influx of meteoric fluids at a shallow depth, at a time earlier or later than the subsurface precipitation of saddle dolomite. Early dolomitization is preferred; the strong preservation of original fabrics makes it unlikely that dolomitization occurred after a period of deeper burial. In either case, the dolomitization clearly discriminated between the original elements within the thrombolite, as shown by preservation of primary heterogeneities between crystal sizes and fabrics. The preservation of distinctive fabrics characteristic of marine cements is important, for example, for the recognition of aspects which define and accentuate the possible lobate forms of former microbial communities.

Classification

Following Kennard's classification scheme for microbialites (Kennard, 1989; Kennard and James, 1986), mesoscopic framework components are taken into account and volumetrically categorized as stromatoid, thromboid, or undifferentiated microbial fabrics. It is the relative proportions of these components that give the microbialite its classification. Inorganic features, such as marine cements, pebble aggregates, and skeletal material, if a predominant framework building component, are used to modify the fabric classification.

Massively clotted fabrics of the Rocknest microbialite consist of 100% thromboids, and thus warrants classification as a true thrombolite. Due to the drusy cement's syndepositional relationship with the growth of the thrombolite and the primary role of cements as a framework component, the Rocknest thrombolite would be classified as cement-bearing. The Rocknest thrombolites can further be classified as disrupted, cement-bearing thrombolites. Kennard and James (1986) denote the adjective "disrupted" to describe microbialites with minor stromatoids or thromboids, primarily composed of cryptomicrobial fabrics which are probably stromatolitic or thrombolitic in origin but have been modified or destroyed by organic or inorganic processes. In the case of the Rocknest Formation, pervasive dolomitization has resulted in recrystallization over-printing, though not complete destruction, of the primary fabric.

Discussions

Rocknest Thrombolites

Investigations of the mesoscopic and microscopic structure of the Rocknest "clotted" microbialites indicate that they are not simply diagenetically altered laminated stromatolites (Kennard, 1989), but rather true thrombolites in the context of Kennard's classification (Kennard, 1989; Kennard and James, 1986). Kennard and James (1986) and Kennard (1989) considered the irregular fabric of the Rocknest thrombolites to be an early diagenetic, rather than a primary microbial fabric. However, closer study reveals that recrystallization during diagenesis did not severely alter the original fabrics. The silicification, as an early diagenetic replacement feature, helped to preserve the microscopic characteristics of the thromboid heads, both by preserving evidence of the encrusting cements and by enhancing the relict "mottled" or "splotchy" internal characteristics of the thromboid heads. The dolomitization, though pervasive, was discriminatory enough to preserve remnants of the original fabric. There is little doubt as to the mesoscopic or microscopic distinction between interframework and framework components, and palimpsest microscopic fabrics remain.

Both mesoscopic and microscopic structures within the thrombolite give indications as to its environmental setting and growth regime. Thromboid heads, composed of lobate thromboid bodies and synsedimentary marine cement, with little internal micritic sediment, indicate that the microbial community that formed the thrombolite was non-trapping and binding, and formed primarily through accretionary growth and marine cementation.

Pendate bottoms to the anastomosing heads are common throughout the structure, and indicate that the thrombolite had open void space, provide evidence for irregular surface growth, and further define a clotted mesostructure. If internal solution of laminated microbial structures were the cause of the clotted mesostructure, a distinct break in laminae should be found where material has been dissolved away. Not only is this not found, but the stylolites actually occur in positions where they cannot be considered viable evidence in favor of severe dissolution. Stratigraphic and diagenetic evidence suggest that the unlaminated fabrics of some of the Rocknest Formation's microbial mounds were formed in a reasonably active, subtidal environment. This positioning argues against Gebelein (1974) in that the fabrics were not a result of voids left by the degradation of laminated mats. It is true that a vaguely unlaminated fabric can occur under these conditions, but these are documented as supratidal occurences (Logan, 1976; Shinn, 1968), while all evidence in the Rocknest thrombolites suggests formation in an active subtidal to intertidal environment.

Comparison with Younger Thrombolites

While evidence argues that the Rocknest thrombolites are definitely not disrupted stromatolitic fabrics, they also are quite different from younger, documented thrombolites. They contain, proportionally, a far greater ratio of framework to interframework components than do Kennard's Cambrian and Ordovician thrombolites (1989), and also a much greater volume of framework-building marine cements. However, in general form, the major constituents and fabrics are quite similar, even though preservation does not allow for microfossil characterizations. Lacking microfossils, it is impossible to accurately determine the microbial composition of the thromboids. However, two questions have yet to be resolved in the study of microbial structures. It remains to be determined whether distinct microbial forms are necessary to produce distinct microbial fabrics, and to what extent depositional environment is responsible for the growth habit of microbial communities and the resulting fabrics.

Both Aitken (1967) and Kennard (1989) indicate the minor presence of filamentous cyanobacteria within thromboids, yet it has also been documented that unlaminated microbial growths are primarily the product of coccoid cyanobacteria (Gebelein, 1974). The lack of lamination, and the general impression of spherical-to-lobate-to-cellular forms of the Rocknest thrombolite microfabrics suggest that a coccoid-dominated community generated the clotted fabric. This feature parallels conclusions of Kennard and James (1986) concerning the original microbial make-up of the community in Cambro-Ordovician thrombolites. Kennard and James (1986) and Kennard (1989), however, interpreted the thrombolitic microbial fabrics to have been formed through the *in situ* calcification of the microbial community. The thrombolitic fabrics from the Rocknest Formation provide no evidence of *in situ* calcification. This is of little surprise, considering it has been noted (Riding, 1982) that no cyanobacteria is an obligate calcifier. Kennard (1989) and Kennard and James (1986) suggest that the calcification of cyanobacteria evolved at the base of the Cambrian due to pressures from the explosion of metazoan life. However, there is an increasing amount of evidence that the ability for *in situ* calcification may have evolved in the late Proterozoic (John P. Grotzinger, personal communication, 1990). Therefore, this change to *in situ* calcification in the late Proterozoic/early Phanerozoic most likely occurred as a reaction to some stimulus other than the evolution of metazoans, for example, a reaction to changes in the chemistry of seawater. Therefore, at a time such as the early Proterozoic, where calcification is not stimulated by outside forces microbial communities may not calcify, but instead become cemented in a different manner, either by early cementation of trapped and bound sediments, or by the precipitation of encrusting marine cements.

Gebelein (1974) states that coccoid algae, which primarily form non-laminated fabrics, can trap and bind sediments. Detrital sediments are easily trapped within pockets between coccoid cell clusters, and are held by the sticky mucilaginous sheaths. This would provide a mechanism for building microbial communities without the presence of an obligatory calcifying microbial organism. Early cementation of the trapped and bound sediments would depend, however, upon local seawater chemistry. Along similar lines, Pratt (1982) and Pratt and James (1982), have emphasized the effects of rates and regularity of sedimentation on various microbial buildups. They proposed that irregular sediment influx rates would provide the environmental conditions necessary for formation of a clotted to reticulate, rather than laminar, framework formed by the trapping and binding properties of microbial growth.

The Rocknest thrombolites, however, do not appear to have been preserved by the early-cementation of trapped and bound sediments, and in fact have less internal sediment than most traditional thrombolitic facies. Evidence indicates that the preservation of the Rocknest thrombolites was due to precipitation of marine cements rather than trapping and binding sediments, perhaps due to a lack of detrital sediment in the environment during the growth of the microbial community. Within Rocknest cycles containing thrombolitic facies, stromatolites in similar intertidal environments commonly alternate sediment trapped and bound in laminae with laminae displaying encrustation by marine cements (John Grotzinger, 1990, personal communication). At shallower water depths in these same cycles, inorganically precipitated tufas are found (Grotzinger, 1986a). These factors indicate an initial seawater chemistry favorable to the precipitation of marine cements. A rate of precipitation of marine cements higher than that favored by seawater chemistry could have been induced through the extraction of CO_2 from seawater during photosynthesis. This could result in encrustation and microbial recolonization at a rate greater than sedimentation rates, and thus produce fabrics such as those observed in the Rocknest thrombolites.

Conclusions

"Splotchy", "mottled", and "clotted" fabrics of the Rocknest microbialites are distinct from stromatolitic fabrics. Although preservation of microstructural fabrics is poor due to pervasive dolomitization, relict fabrics are present. These fabrics are spherical, lobate, or cellular in morphology, and are interpreted as relict remains of coccoid-dominated microbial communities.

Existence of such fabrics, early in the Proterozoic, demonstrates a need for extensive study of environmental effects on the formation of microbial fabrics, and on the effects of indirect cementation on fabric development.

Kennard and James (1986) and Kennard (1989) interpret thrombolites to be products of the obligatory calcification of microbial communities. However, fabrics found in the Rocknest Formation suggest that development of clotted fabrics may also result from microbially-induced, "inorganic" precipitation. Rather than calcification occurring within the sheaths of the microbial community, precipitation of calcic cements occurs around the microbial sheaths. Both processes provide a means of preservation for the morphological and fabric elements of microbial communities. Precipitation would be controlled primarily by the physical and chemical environment in which microbial communities lived; however, communities themselves could initiate the precipitation by a chemical/metabolical process, such as extraction of CO_2 from seawater during photosynthesis.

Rocknest thrombolites contain a far lower percentage of interframework sediments and a far greater percentage of framework-building cements than younger thrombolitic occurrences. This difference in mode of preservation is interpreted as an effect of depositional environment on the growth of the microbial communities. The Rocknest thrombolites flourished in an environment where precipitation of marine cements as crusts around coccoid-dominated colonies dominated over the accretion of clastic carbonate sediment, due to accelerated rates of colony growth, and/or to extremely low sedimentation rates. The consequences of such rapid lithification, even under conditions of no obligate calcification, lends strong evidence to the importance of thrombolites as early reef-building constituents, equivalent to Early Proterozoic stromatolitic reefal counterparts.

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Figure 1

Regional setting of Wopmay Orogen. A) Location of foreland thrust-fold belt (zone 2), the autochthon (zone 1), and their relationship to the Peacock Hills area (P. Hills) of Kilohigok Basin. B) Simplified geology of zones 1 and 2, showing the distribution of the Rocknest Formation, included with the Odjick Formation as the Epworth Group. (Grotzinger, 1986a)

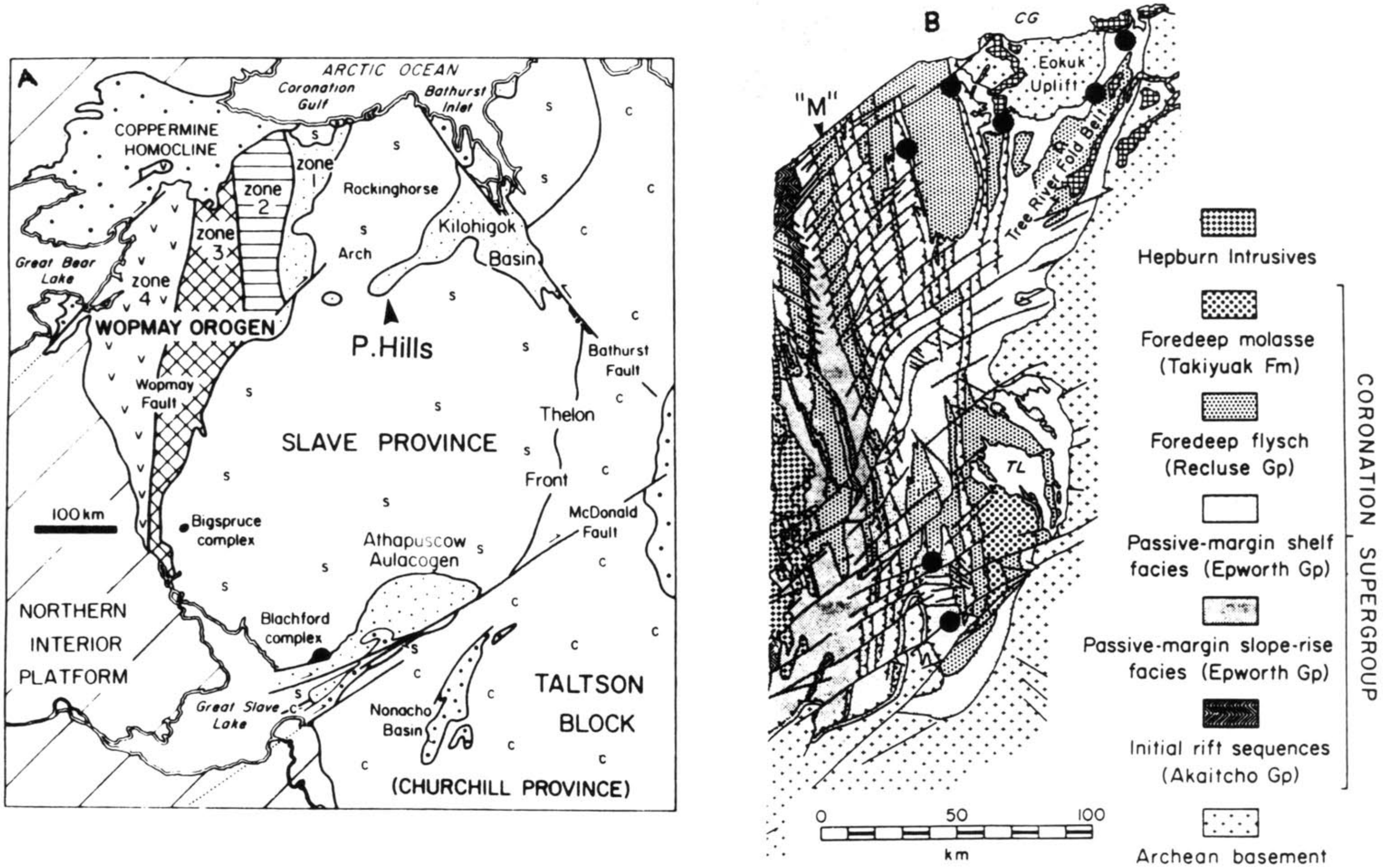

A
ARCTIC OCEAN
Coronation Gulf
Bathurst Inlet
COPPERMINE HOMOCLINE
zone 1
zone 2
zone 3
zone 4
Great Bear Lake
WOPMAY OROGEN
Wopmay Fault
Rockinghorse Arch
Kilohigok Basin
P. Hills
Bathurst Fault
Thelon Front
SLAVE PROVINCE
McDonald Fault
100 km
Bigspruce complex
Athapuscow Aulacogen
Blachford complex
NORTHERN INTERIOR PLATFORM
Great Slave Lake
Nonacho Basin
TALTSON BLOCK
(CHURCHILL PROVINCE)
B
CG
"M"
Eokuk Uplift
Tree River Fold Belt
TL
0
50
100
km
Hepburn Intrusives
Foredeep molasse (Takiyuak Fm)
Foredeep flysch (Recluse Gp)
Passive-margin shelf facies (Epworth Gp)
Passive-margin slope-rise facies (Epworth Gp)
Initial rift sequences (Akaitcho Gp)
Archean basement
CORONATION SUPERGROUP

Figure 1

Figure 2

Rocknest thrombolite sample displaying relationships between thrombolitic materialand marine cements (dark grey), micritic sediments (pale grey), blocky dolomitic spar (white), and diagenetic silica (black). Note the clotted to splotchy fabric, the vague arcuate laminations, and the zones of recolonization. Scale bar is 2cm, arrow indicates up.

Figure 2

Figure 3

Distribution of thrombolite material (white) and micrite filled voids (black). This "reversal" of color schemes (cf. Pratt and James, 1982; Webb, 1987) is used to emphasize the massive framework of the thrombolite. All sections are the same scale (scale bar is 3cm), and represent vertical cross-sections through the sample. Figures are sequential through the sample, representing sections approxiamately 1 cm in thickness. Note the overall irregularity of the fabric. The relative absence of micritic sediments during thrombolite growth contributed to the coalescence of thromboids, and ultimately resulting in the formation of the massive, clotted thromboid heads.

Figure 3a,b

Figure 3c,d

Figure 3e,f,g

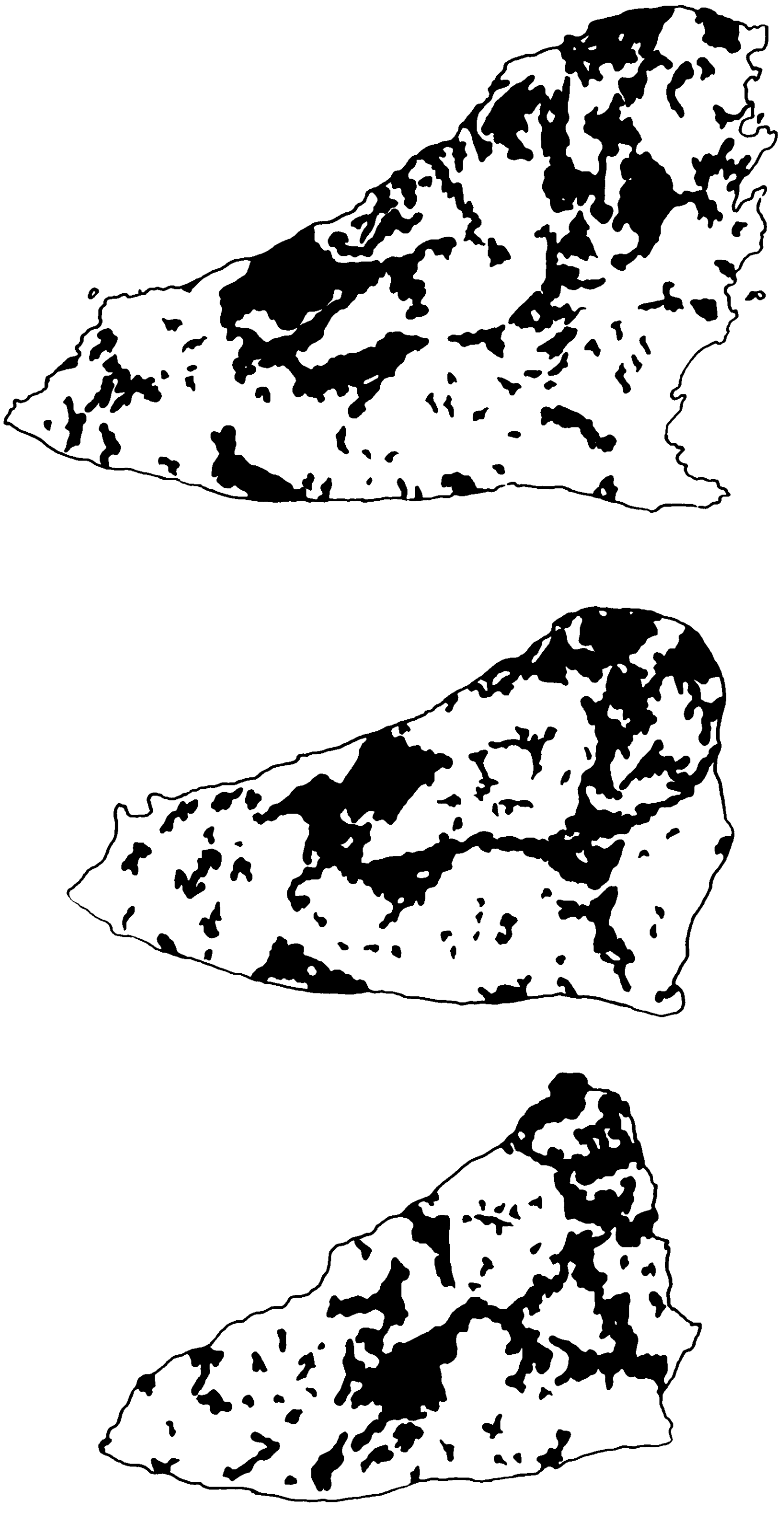


Figure 4

Thromboid microstructure, displaying lobate to spheroidal crystalline bodies encrusted by isopachous cements. Ovoid body of cement at right shows the intrusion of a thromboid from the third dimension. In the following illustrations, "T" denotes thrombolitic material, "M" denotes micrite, "V" denotes void fillings of blocky dolomitic spar, and "C" denotes isopachous encrustations of drusy cements. All photos taken under plane light unless otherwise stated. Scale bar is 0.5mm.

Figure 4

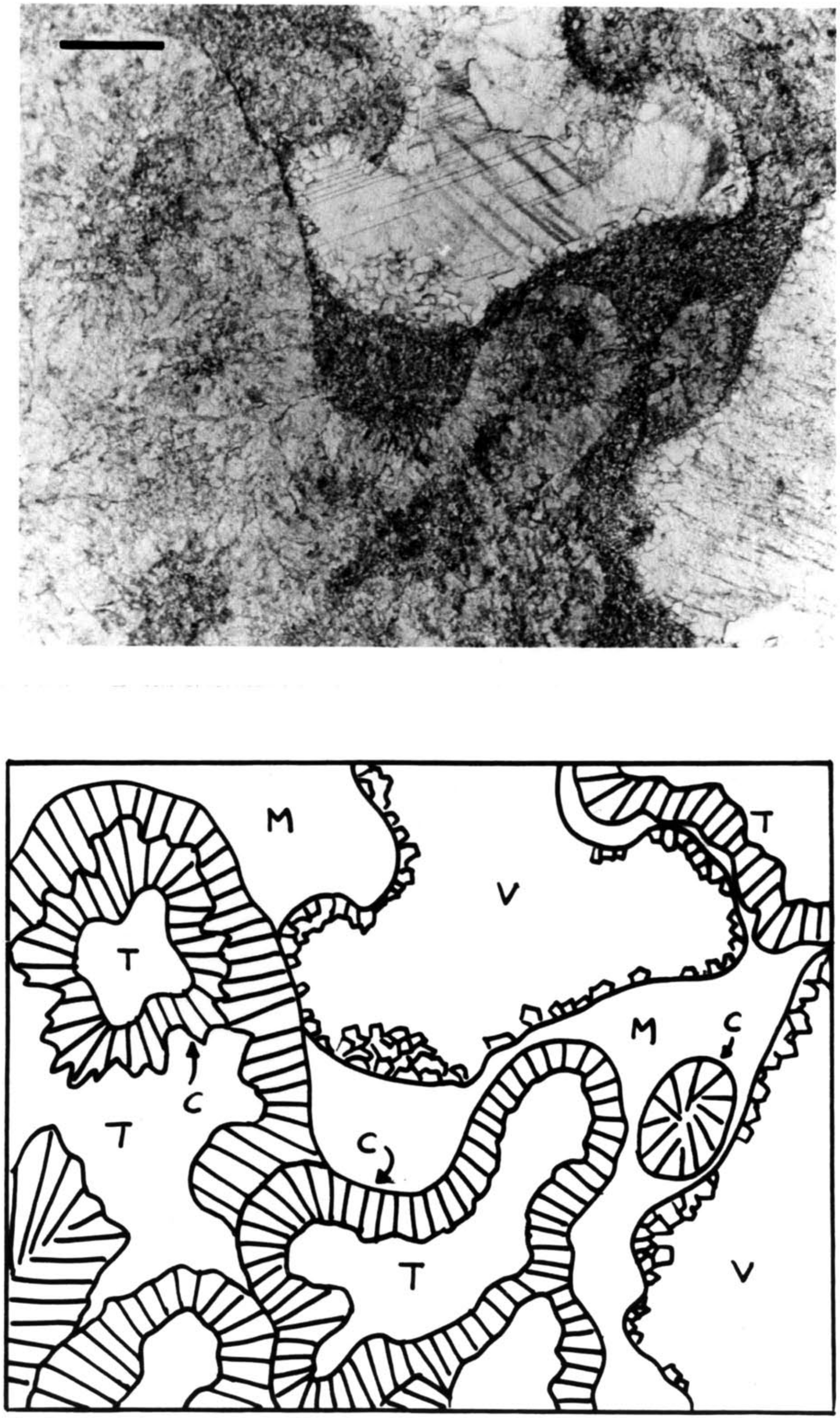


Figure 5

Dolomitic mosaic of thromboid material showing a mottled fabric resulting from vague arcuate laminations of encrusting cements around finer grained relict microbial (?) communities. Scale bar is 0.5mm.

Figure 5

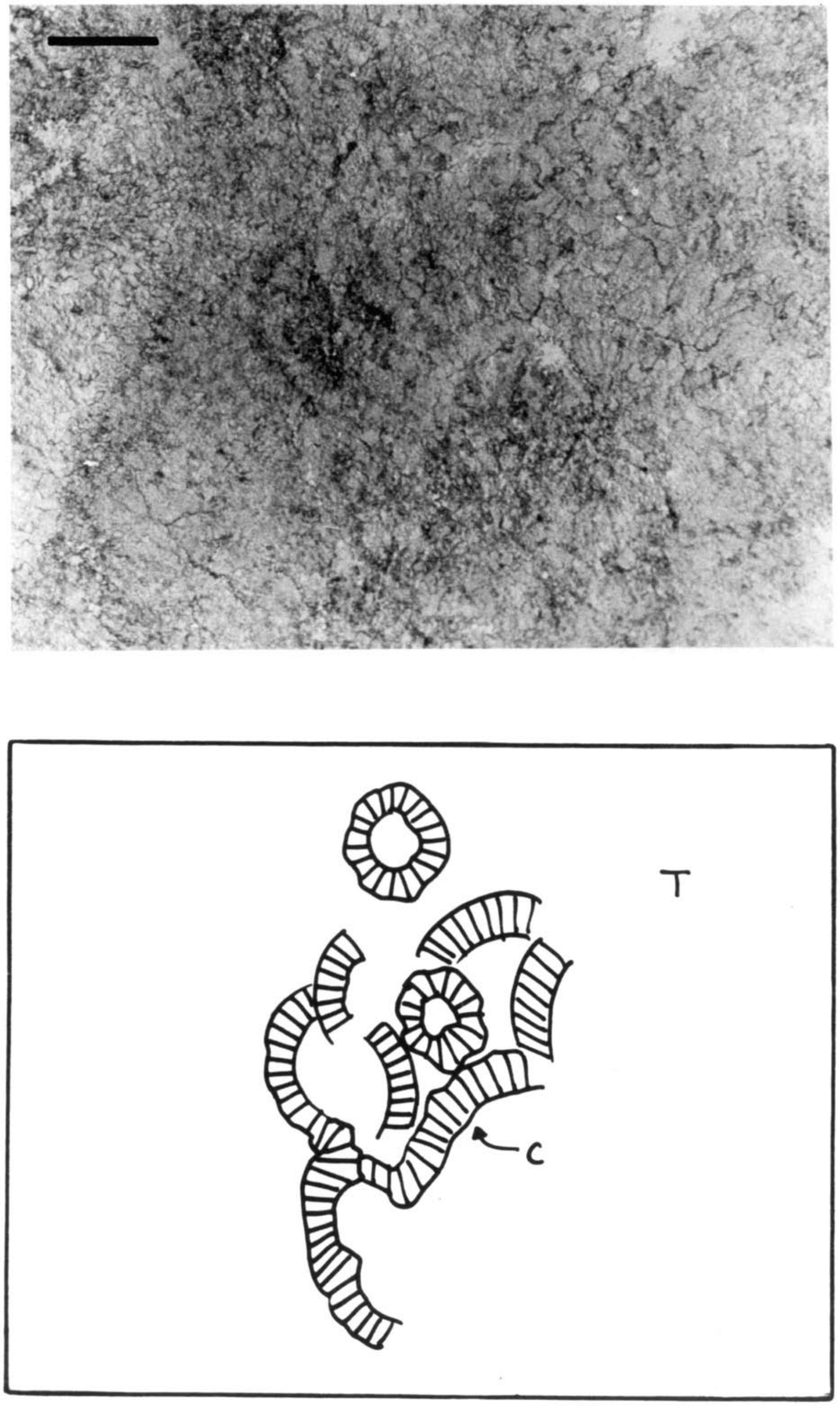
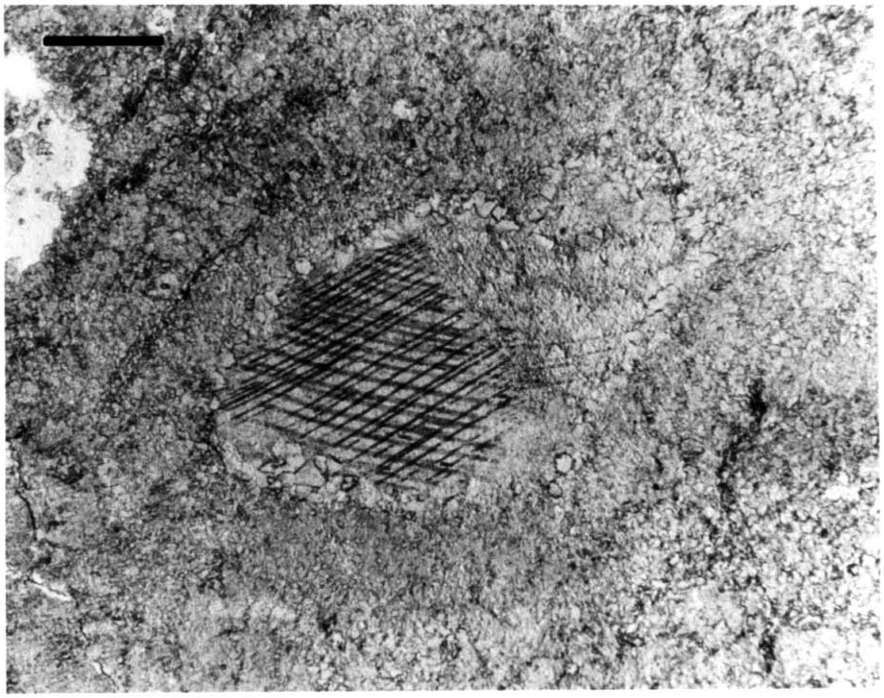


Figure 6

Void filled with dolomitic spar displaying a bladed to dentate rim with the low length-to width ratio and scalanohedral terminations indicative of primary deposition as high-magnesium calcite. Scale bar is 0.5mm.

Figure 6



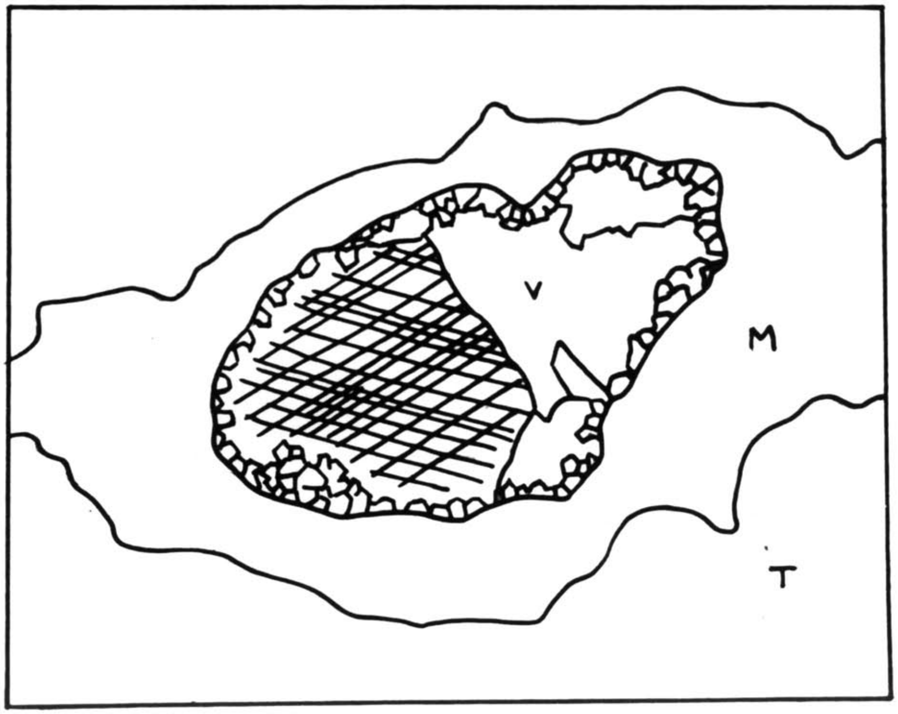


Figure 7

Closer view of the bladed to dentate rim of a blocky spar void filling. Note the pendate bottom of upper thromboid. Scale bar is 0.5mm.

Figure 7

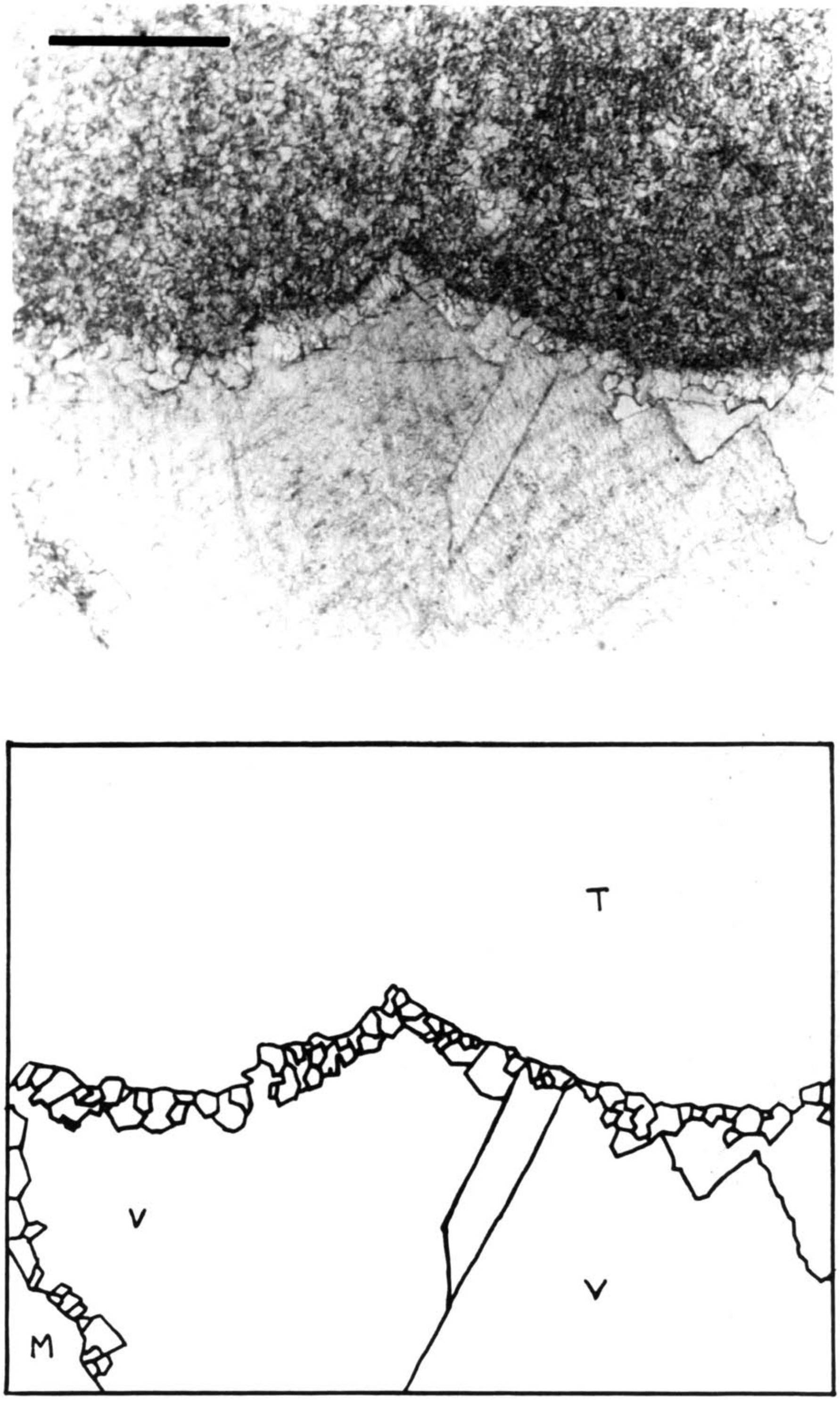


Figure 8

Dolomite void filling showing the curved twin planes and sweeping extinction indicative of the primary, high-temperature precipitation of saddle dolomite. Photo taken with crossed-polars. Scale bar is 1mm.

Figure 8

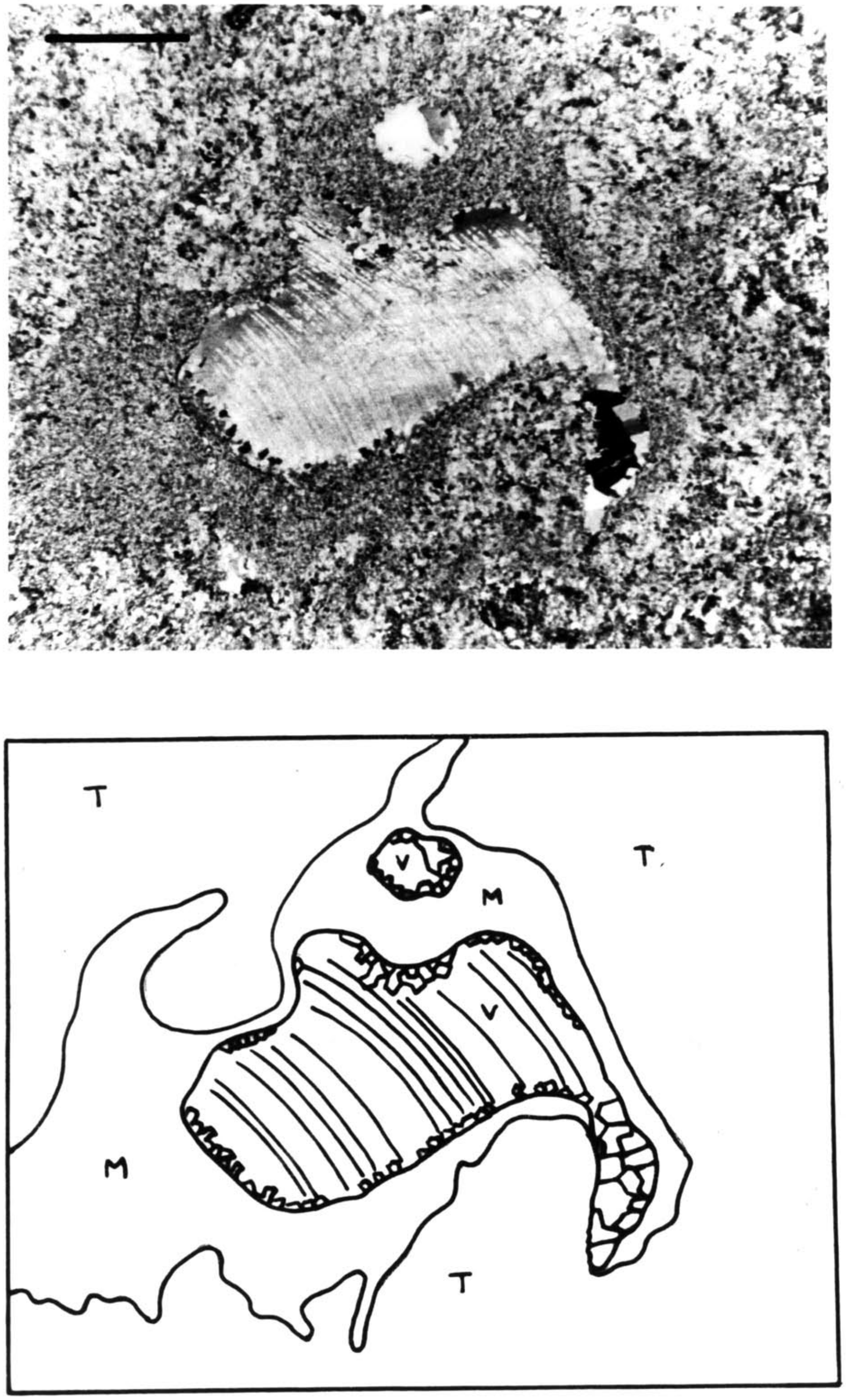


Figure 9

Distribution of dolomitic void fillings in relation to thrombolite material and micritic sediments. Stylolitic seams form at the contacts between thrombolite material and spar-filled voids, perhaps due to pressure solution, or to the textural difference at the interface. Scale bar is 1mm.

Figure 9

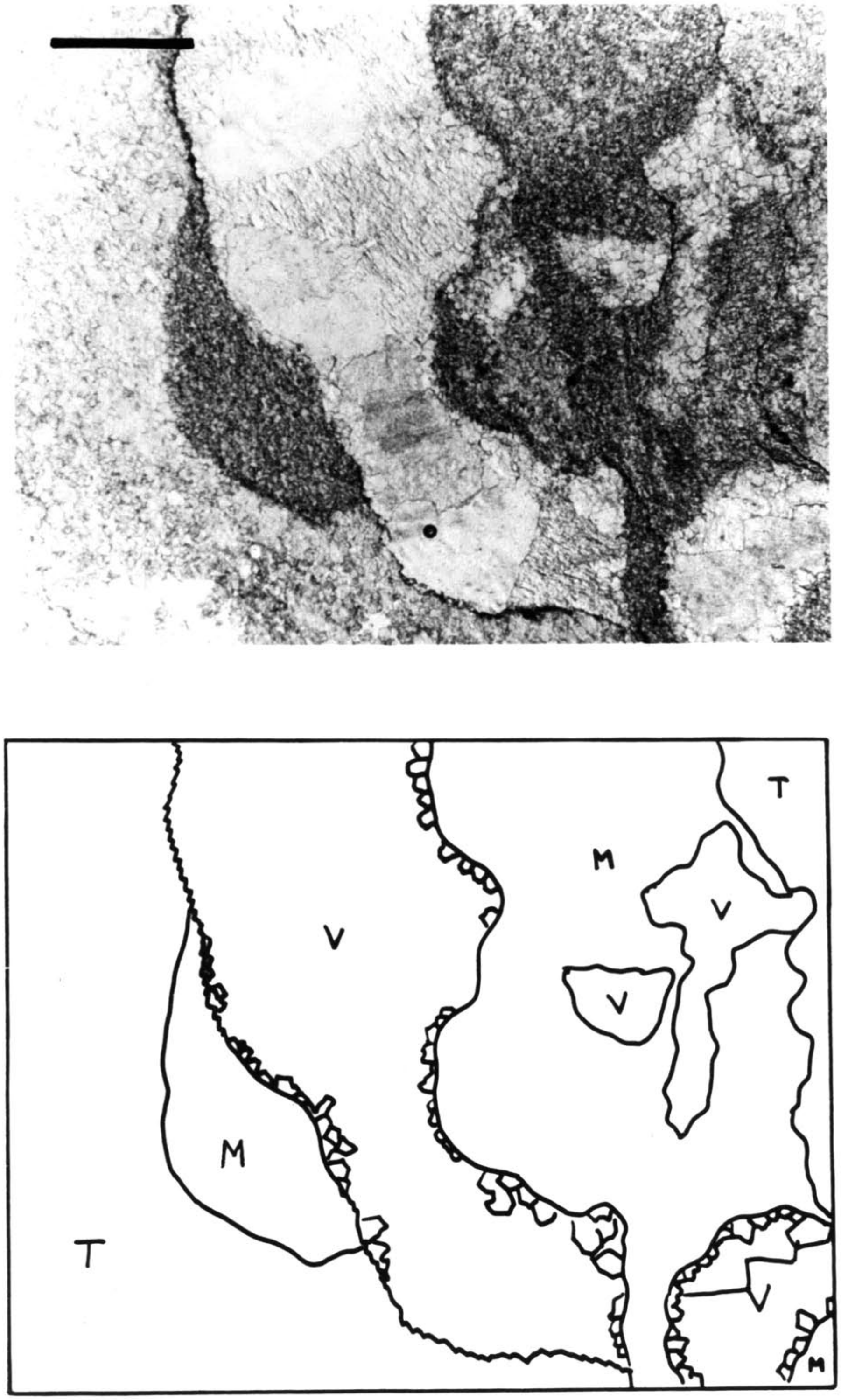


Figure 10

Solution seams forming at the *upper* boundary of micritic sediments and within the sediment infills. Only rarely do solution seams remove thrombolite material. Porosity variance between fabrics could be a possible explanation of stylolite distribution. Scale bar is 1mm, arrow indicates up.

Figure 10

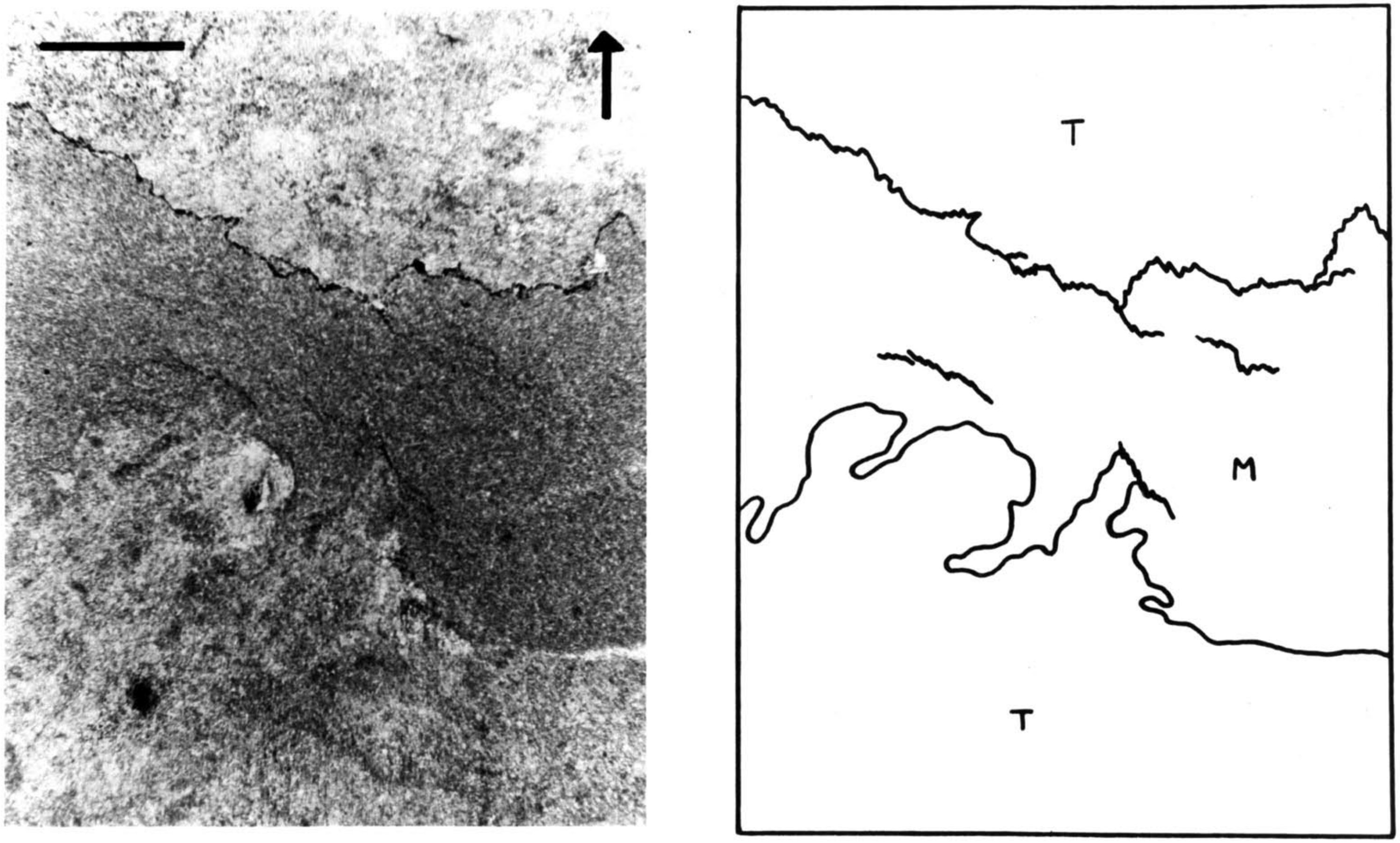
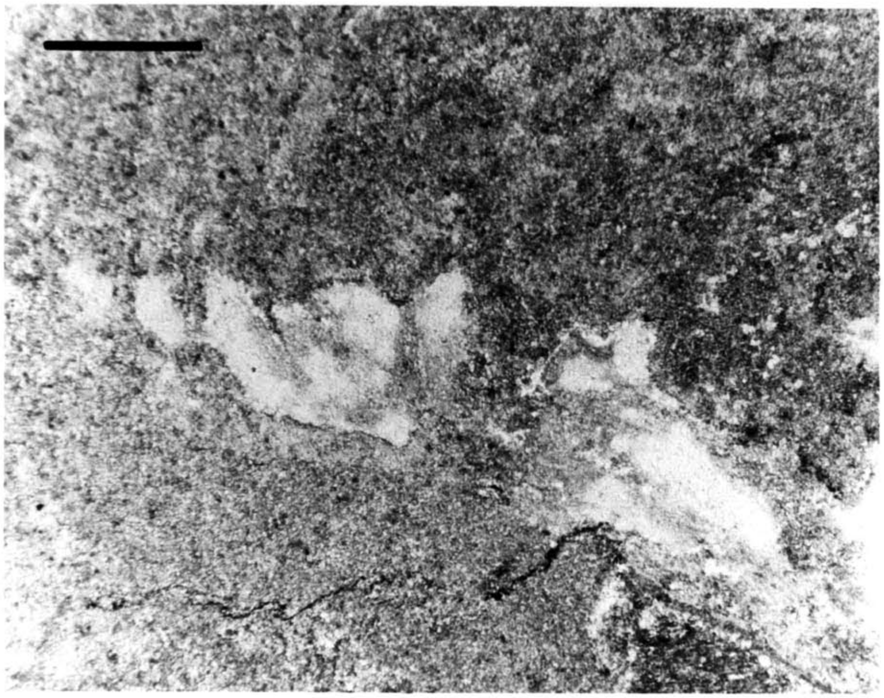


Figure 11

Diagenetic silica along the margin of a thromboid head. Dotted lines indicate extension of the encrusting cements into non-silicified thrombolite material. Note that spheroidal configuration defined by carbonate inclusions occur internally within the cement-bounded thromboid head. Scale bar is 1mm.

Figure 11



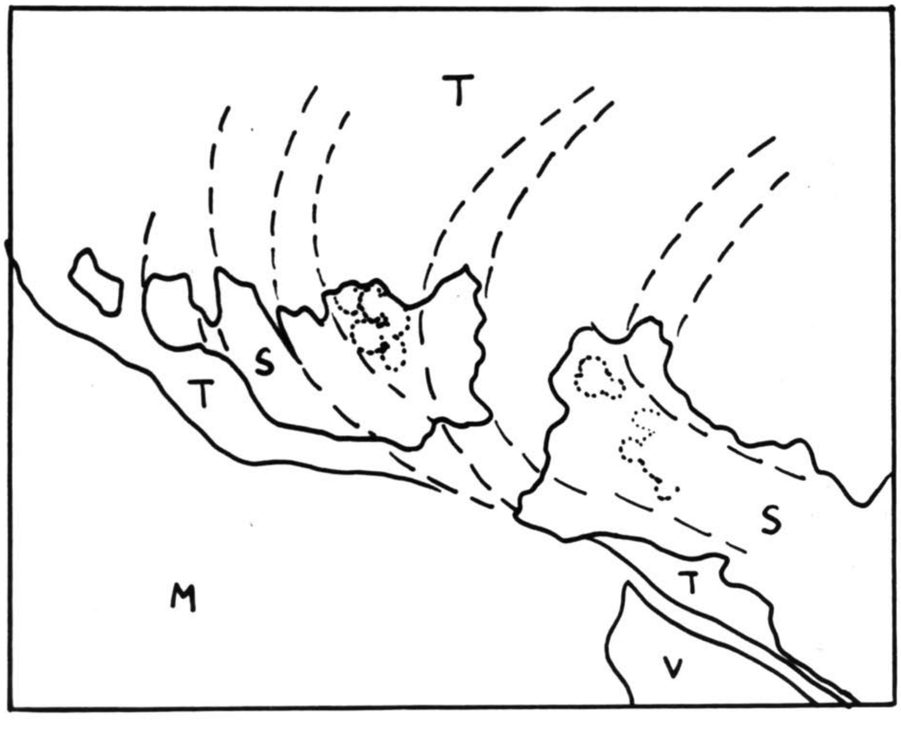


Figure 12

Diagenetic silica within a thromboid head. Note general distribution of spheroidal form, representing the possible relict fabric of coccoid-dominated, microbial (?) communities, internally with respect to the laminar form of encrusting marine cements. Scale bar is 1mm.

Figure 12

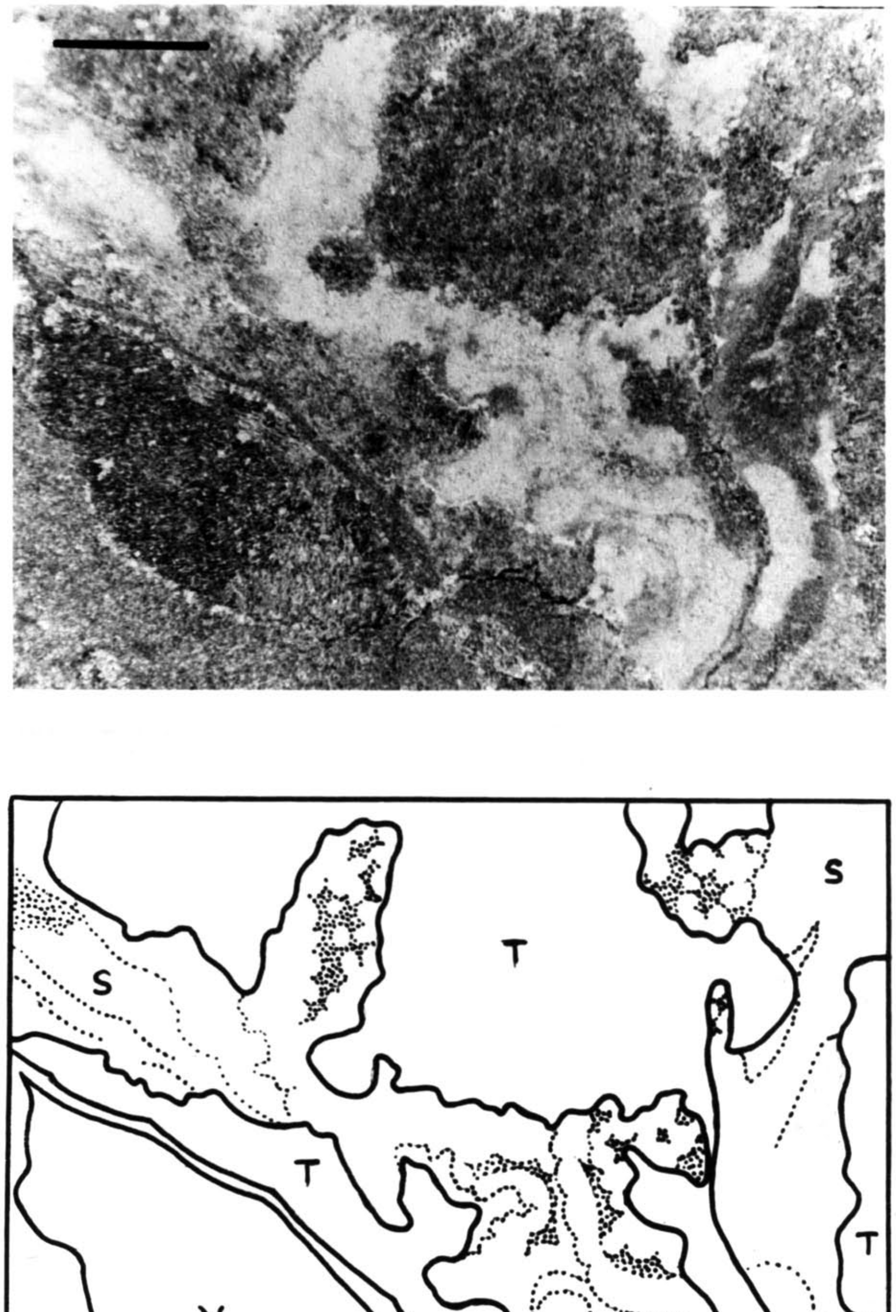


Figure 13

Inclusion-defined, spheroidal form of diagenetic silica. This form is found primarily within the thromboids and is oftern encrusted by isopachous, drusy cements. Preferential silicification of thromboid material over precipitated cements is observed. Scale bar is 0.5mm.

Figure 13