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RED STROMATACTIS LIMESTONE OF PALEOZOIC
CARBONATE MOUNDS

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A MODEL FOR THE ORIGIN AND PETROGENESIS OF THE RED STROMATACTIS LIMESTONE OF PALEOZOIC CARBONATE MOUNDS

PIERRE-ANDRÉ BOURQUE¹ AND FRÉDÉRIC BOULVAIN^{2*}

¹ *Département de Géologie, Université Laval, Québec Qc G1K 7P4, Canada*

² *Département des Sciences de la Terre et de l'Environnement, Université Libre de Bruxelles, Brussels, Belgium*

ABSTRACT: From study of the Devonian "récifs rouges" of Belgium and the Silurian mounds of the Québec Appalachians, we propose that deposition of the red stromatactis limestone facies of Cambrian-Devonian carbonate mounds was controlled by sponges and that the red color and stromatactis result from early diagenesis within a few meters below the substrate-water interface in the deep-marine environment.

The common presence of sponge body fossils, as well as various stages of sponge preservation, ranging from easily delineated to indiscernible bodies, in the Belgian "récifs rouges" support the conclusion that a large part of the red finely crystalline limestone originated from early cementation of sponge communities or spicule-rich organic mats derived from degradation of sponge communities. The role of bacteria and other microbes, although widely advocated as the main primary builders of carbonate mounds, is difficult to assess. Microbial communities may have contributed to mound accretion as primary builders and/or mud producers, but their presence cannot be documented. We suggest that they may have acted as agents for concurrent sponge putrefaction and early cementation (biodiagenesis) during the sulfate-reduction phase under alkaline pH and anoxic conditions.

We interpret stromatactis as a spar body that resulted from early marine cementation of a cavity network created by excavation of uncemented material in partly indurated, decaying sponges and spicule-rich organic mats derived from degradation of sponge communities through circulation of interstitial water in the uppermost few meters of the sediment. This cavity network was connected to sea floor and flushed by oxic waters that changed the diagenetic environment from anoxic to oxic, converting amorphous iron sulfide to hematite and giving the facies its red color.

Recognition of the dominant role of sponge communities in the construction of red stromatactis limestone mounds of the Cambrian-Devonian time interval has important implications for the geological record. This community was the main deep-water mound-building community during this time, but is difficult to recognize because of its variable but often poor preservation.

INTRODUCTION

Stromatactis, first described by Dupont (1881), is a spar body embedded in finely crystalline limestone. It is present in many but not all Paleozoic carbonate mounds. As defined in this paper, it is mainly Paleozoic, suggesting biologic control of some sort. It is found in two main types of Paleozoic mounds: the gray Lower Carboniferous Waulsortian mounds recognized in various part of the world (Lees and Miller 1985) and the predominantly red mounds, called "récifs rouges" in the Devonian of Belgium, known from the Cambrian to the Devonian. Examples of the latter group are known from: the Lower Cambrian of the Flinders Ranges of southern Australia (James and Gravestock 1990); the Ordovician of central Sweden (Bathurst 1982; Middleton 1988); the Upper Silurian of the Québec Appalachians (Bourque and Gignac 1983); and the Devonian of western Australia (Kerans 1985; Kerans et al. 1986), southern Australia

(Wallace 1987), southern France (Bourrouilh 1987), and the Belgian Ardennes (Lecompte 1936; Tsien 1983; Boulvain and Coen-Aubert 1989).

The origin of stromatactis and its host facies remains controversial (see reviews by Bathurst 1982 and Lees 1988). For decades it has been regarded either as a fossil (Dupont 1881), as a permineralized unfossilizable organism (Lecompte 1937; Tsien 1983), or as recrystallized patches of the host lime mud (Black 1952; Orme and Brown 1963; Ross et al. 1975). Most carbonate workers now agree that it is the result of centripetal cementation in a cavity or cavity system, but there is still little agreement on the origin of the cavity and of the host limestone.

Among the mechanisms proposed for the cavity or cavity system are: dewatering of a thixotropic mud (Heckel 1972); excavations between layers of early-cemented crusts on the sea floor (Bathurst 1980); slumping and creeping of partially cemented mud on a mud mound (Bathurst 1982); vertical water escape in organic or inorganic material (Wallace 1987); action of roots (Bechstädt 1974) or burrowing organisms (Shinn 1968); sheltering of sediment by bryozoan sheets (Schwarzacher 1961); winnowing of sediment between microbial mats on the sea floor (Pratt 1982, 1986); and collapse of material within organic tissue of probable microbial origin (Lees 1964, 1988; Lees and Miller 1985) or in sponge tissue during decay and partial cementation of organic matter (Bourque and Gignac 1983, 1986). As for the origin of the host finely crystalline limestone, some propose inorganic accumulation of lime mud (Black 1952; Orme and Brown 1963; Shinn 1968; Heckel 1972; Bechstädt 1974; Ross et al. 1975; Bathurst 1980, 1982) and others favor accretion controlled by microbial communities (Lees 1964, 1988; Monty et al. 1982; Pratt 1982, 1986; Lees and Miller 1985) or sponges (Bourque and Gignac 1983, 1986; Kerans 1985).

We propose a model for the origin and petrogenesis of the red stromatactis limestone facies of Paleozoic mounds based on the Devonian "récifs rouges" of Belgium and the Silurian red stromatactis mounds of the Québec Appalachians. The model integrates the origin of stromatactis with that of the host limestone. Bourque and Gignac (1983, 1986) concluded that the Silurian red stromatactis mounds of the Québec Appalachians were built by sponges, that the sponge network underwent early marine cementation, and that stromatactis originated from early marine cementation of cavities created by collapse of unlithified sponge tissue. This model has been severely questioned (Pratt 1986), mainly because of the absence of a regular spicular network and of easily delineated sponge body fossils in the Québec limestone. This paper reports on the common presence of sponge body fossils and spicular networks in the Belgian Devonian mounds, which represent the facies from which stromatactis was originally described (Dupont 1881), and describe several stages of sponge preservation; these two elements give additional support to the model proposed by Bourque and Gignac. We also address the origin of the red color of the limestone, not addressed by Bourque and Gignac, because it is a feature common to most Cambrian to Devonian stromatactis facies.

THE NATURE AND DEFINITION OF STROMATACTIS

Before discussing the petrography and origin of the red stromatactis limestone, it is necessary to clarify the nature of the striking feature of that facies: stromatactis. In the last century, spar bodies with flat bases and digitate tops in the Frasnian (Devonian) and the Waulsortian (Car-

* Present address: Service Géologique de Belgique, rue Jenner, B-1040 Brussels, Belgium

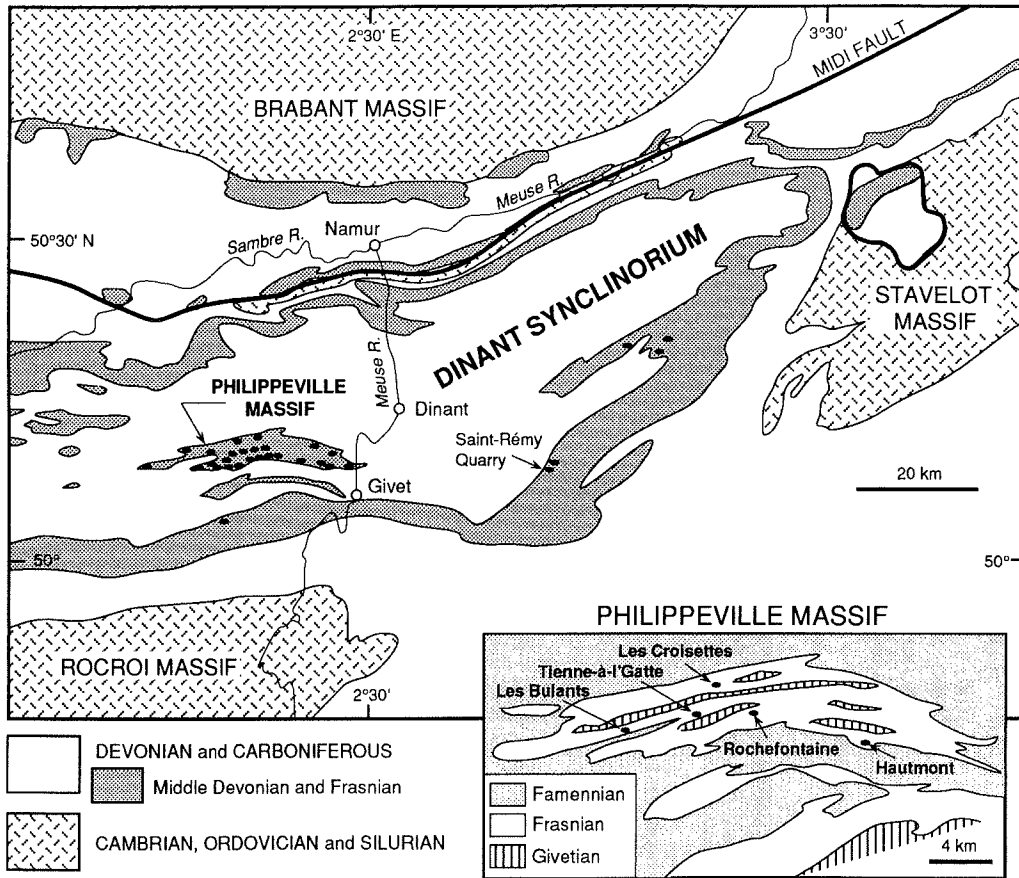


FIG. 1.—Index map of Dinant Synclinorium and location of main outcropping “récifs rouges” (black dots) in the Belgian Ardennes and selected examples in the Philippeville Massif (inset).

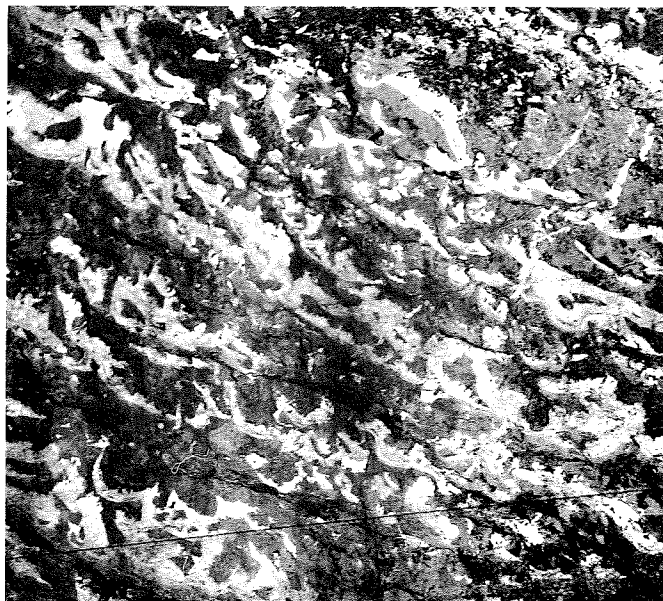


FIG. 2.—Cross section of stromatactis network on wire-cut quarry wall showing that the spar network is preferentially aligned along the bedding planes (here dipping at 40°) with some vertical connections. Width of photograph is 1.5 m. Saint-Rémy quarry, near Rochefort, Belgian Ardennes.

boniferous) carbonate mounds of Belgium were mistaken for fossils and named *Stromatactis* (Dupont 1881, 1883). According to material in the Musée d'Histoire naturelle de Belgique in Brussels, the type stromatactis was described by Dupont from three quarries: in Saint-Rémy near Rochefort (Fig. 1), in Malplaquet at Merlemont, and in Sautour. Of these, only the Saint-Rémy quarry still exists, although it is not operating. One might accept that stromatactis from that quarry should constitute the basis of stromatactis definition.

Most carbonate workers now agree that stromatactis is a spar body that originated from centripetal cementation of a cavity by mostly isopachous crusts of fibrous-looking cement, regardless of the origin of the cavity. There is, however, an aspect of stromatactis to which sufficient attention has not been paid: its three-dimensional nature. This is because reference to stromatactis is usually made with respect to individuals. Serial sectioning in the Silurian stromatactis red limestone of Québec for three-dimensional reconstruction (P.-A. Bourque, work in progress) has shown that stromatactis spar is a network. No serial sectioning was done in the red stromatactis limestone of the Saint-Rémy quarry of the Belgian Ardennes, but this limestone is so similar to the Québec limestone that it is difficult to imagine that the Saint-Rémy stromatactis is not a spar network like that of the Québec example.

We therefore consider that the network nature of stromatactis is an important aspect and that it should be part of its definition. To better reflect the structure originally described by Dupont (1881) in the Saint-Rémy quarry in Belgium, we propose the following definition of stromatactis: a spar network, whose elements have flat to undulose smooth lower surfaces and digitate upper surfaces, made up principally of isopachous crusts of centripetal cement and embedded in finely crystalline limestone. Quarry-wall exposures in Québec as well as in Belgium (particularly

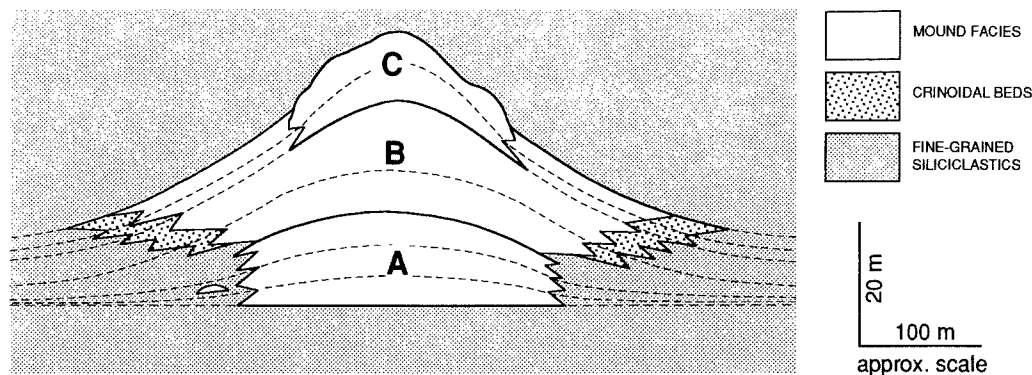


FIG. 3.—Facies distribution (upper half), main biotic assemblages (lower left), and environmental setting (lower right) of typical Frasnian “récifs rouges” of the Belgian Ardennes. Dotted lines in upper figure are time lines. (A) red stromatactis limestone; (B) pink coral limestone; (C) gray microbial, algal, coral and stromatoporoïd framestone. Stacking of facies is water-depth-dependent.

in the Saint-Rémy quarry) show clearly that the spar network is preferentially aligned along the bedding planes with some vertical connections (Fig. 2). An individual network can be continuous for tens of meters in any direction along bedding planes and can have thicknesses of some tens of centimeters to a few meters. Clearly, stromatactis is a much larger structure than originally intended with the name.

THE FRASNIAN “RÉCIFS ROUGES” OF BELGIUM

Lithology

The Upper Frasnian “récifs rouges” of the Dinant Synclinorium in the Belgian Ardennes (Fig. 1) have received much attention since their first description by Dupont (1881), particularly from a paleontological and stratigraphical standpoint (see review by Boulvain 1990). Sedimentological studies have been few, focusing on the origin of stromatactis (Bathurst 1982) or of the lime mudstone (Monty et al. 1982), or both (Bourque 1983; Bourque and Gignac 1986; Boulvain 1990). The following description is based on observations on several mounds exposed in quarries in the Dinant Synclinorium. Although they are traditionally called “récifs rouges” in Belgium, these structures are better termed mounds than reefs (*sensu* James and Bourque 1992). Moreover, they are not wholly red: they contain a variable proportion of pink and gray lime mudstone. Three broad facies, each making up a variable proportion of an individual mound, are mappable (Fig. 3; Bourque 1983; Boulvain and Coen-Aubert 1989).

Facies A is a massive to crudely bedded, deep red, finely crystalline limestone devoid of tractional sedimentary structures and with crude bedding enhanced by stylolites and alignment of stromatactis. Ubiquitous presence of stromatactis is the signature of this facies (Fig. 2). The whitish-gray stromatactis spar constitutes up to 40% by volume in places. Biotic diversity of this facies is particularly low. Except for scarce corals, pelmatozoan ossicles, and rare brachiopods, the only macrofossils are sponges. The petrography of the facies is discussed below. Where relationships of the red limestone with surrounding argillaceous facies are observed, commonly the two lithologies interfinger. Lenses of red stromatactis lime-

stone are present locally in the flanking beds (Figs. 3, 4). In general, it appears that the relief above sea floor at that stage of the mound was low (Fig. 3), although the angle between geopetals and bedding planes suggests local paleoslopes of up to 10°.

Facies B is a light-red to pink and pinkish-gray, fossiliferous, finely crystalline limestone, locally rich (up to 25% by volume) in platy and less commonly branching corals and platy stromatoporoids, along with pelmatozoans and brachiopods. Fragmented fenestellid bryozoans, *Renalcis*, and encrusting *Sphaerocodium* are seen in thin section. The skeletal metazoans are scattered in the mud rather than forming a framestone. The branching coral colonies are reworked in places, and several of the platy corals and stromatoporoids are overturned. The facies is dominantly finely



FIG. 4.—Stromatactis limestone lens in flanking beds of Facies A on wire-cut quarry wall. Width of picture is 1 m. Note angle between base of stromatactis cross sections (center of photograph) and trace of bedding plane, suggesting depositional paleoslope of about 20°. Alternative hypothesis is that this angular relationship originated from syndepositional sliding. Hautmont quarry, Vodelée, Belgian Ardennes.

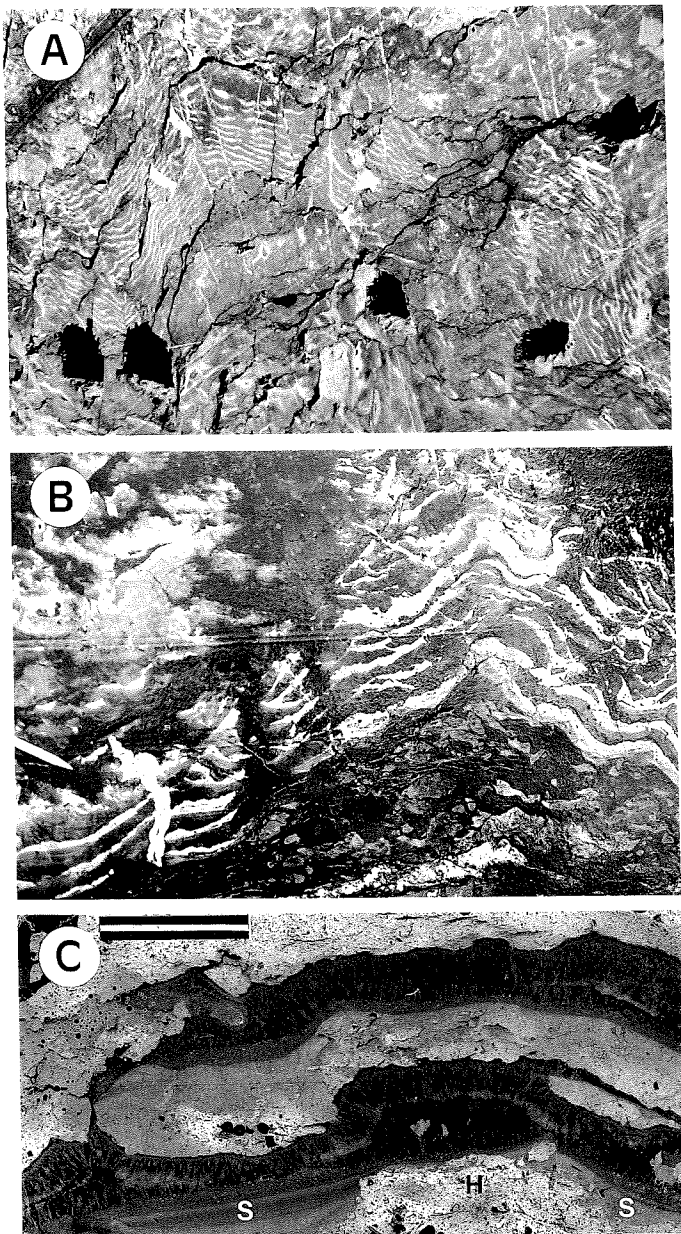


FIG. 5.—Zebra spar sheets in red stromatactis limestone facies of the Belgian Ardennes. A) Quarry-wall photograph showing association with contorted bedding (slumping). Tiers Cocrai quarry, near Saint-Rémy quarry near Rochefort. Width of picture is about 3 m. B) Zebra spar sheets associated with slump. Les Bulants quarry, Neuville. Tip of pencil (left) for scale. C) Negative print of an acetate peel (bubbles in left) showing matching walls of sheet cracks if internal sediment (S) is distinguished from host facies (H). Note brecciation related to cracking. Scale bar is 2 cm. Les Maquettes quarry, Villers-le-Gambon.

crystalline limestone. The angle between geopetals and bedding planes indicates local paleoslopes steeper than in facies A, up to 35°.

Spar bodies termed stromatactis by some workers (e.g., Tsien 1983) are mostly underneath platy skeletons. They likely resulted from cementation of shelter cavities formed during deposition, or of cavities formed by collapse of the mud underneath a rigid object acting as an umbrella during water escape and mud compaction. In most instances, three-dimensional field observations indicate that these cavities were not interconnected.

The massive gray limestone that forms Facies C is better termed a coral-algal-microbial bindstone. The frame is open and forms 30–40% of the

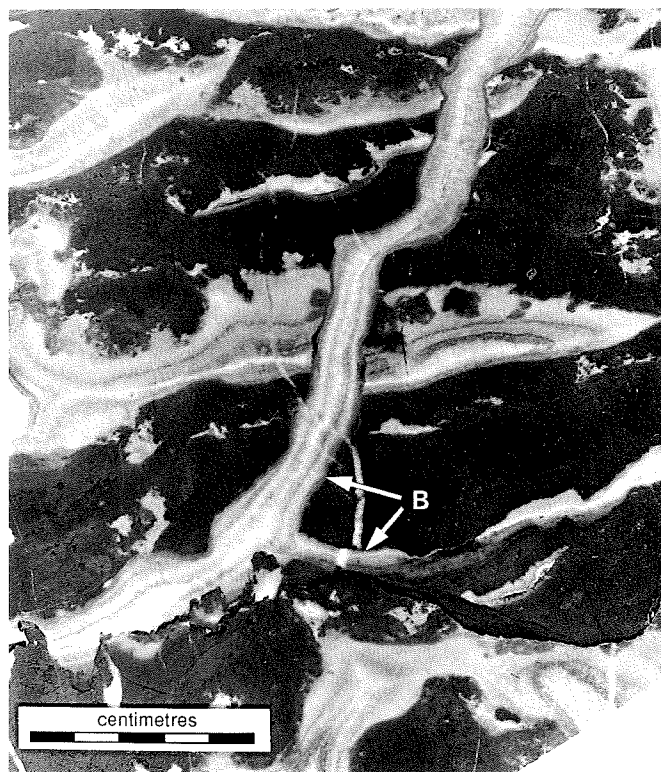


FIG. 6.—Polished slab of red stromatactis limestone of facies A showing a fissure that bifurcates (B) to cut across stromatactis, indicating that this type of fissuring postdated formation of stromatactis. Cement filling of the fissure has the same morphology and composition as the stromatactis it cuts. Les Maquettes quarry, Villers-le-Gambon.

facies by volume. It is composed of corals, less common fenestellid bryozoans, and structureless to laminoid pelletoidal spar and microspar (thrombolitic and stromatolitic material) commonly interpreted as microbial (Monty et al. 1982; Pratt 1982). The calcimicrobe *Renalcis* (Pratt 1984) is common and is associated with the pelletoidal spar and microspar. Bedded Udoteacean-rich packstones are present in places. This facies is devoid of stromatactis. As in facies B, geopetal and bedding-plane relationships indicate paleoslopes of up to 35°.

Altogether these three facies constitute a pure limestone body enclosed, with some degree of interfingering, in fine-grained siliciclastic-dominated facies composed of shale and argillaceous lime mudstone and wackestone, with variable content of brachiopods, corals, and bryozoans (Fig. 3). Although absent in the mound facies, bioturbation is common in the surrounding facies. Proportions of the three facies A, B, and C in an average mound are 30%, 50%, and 20% by volume, respectively.

Zebra Spar Sheets and Neptunian Dikes in Facies A

Besides the stromatactis cavity network, other types of cavities subsequently filled by marine cement also developed in Facies A. These are: (1) millimeter- to centimeter-scale cracks and fissures, commonly but not exclusively parallel to bedding planes and hence to the stromatactis network, and whose cementation gave rise to flat elongate spar bodies often referred to as laminar stromatactis (Pratt 1982) or as zebra stromatactis (Ross et al. 1975) when they are clustered to form striped limestone (Fig. 5); (2) decimeter- to meter-scale open fractures whose filling by early marine sediment and cement has produced what is usually referred to as neptunian dikes. Both types of cavities are also observed in Facies B and C.

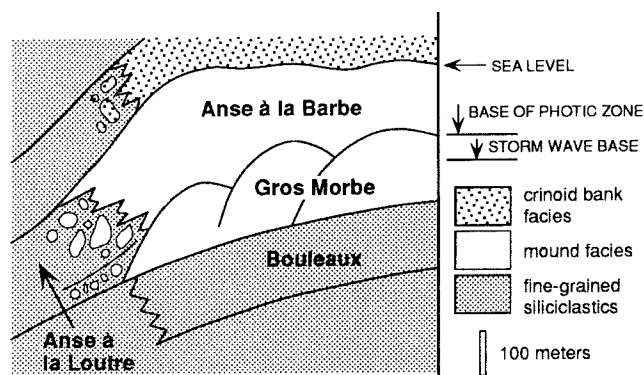


FIG. 7.—Facies succession in Silurian mounds of southern Gaspé Peninsula, northern Appalachians, Québec. The Bouleaux Member is an early-cemented mixed siliclastic and limestone unit, the Gros Morbe Member is a red stromatactis limestone, the Anse à la Barbe Member is a gray microbial limestone, and the Anse à la Loutre Member is a debris unit coeval with both the Gros Morbe and Anse à la Barbe. The Bouleaux–Gros Morbe–Anse à la Barbe succession is a shallowing-upward sequence. Modified from Bourque et al. (1986).

Zebra stromatactis and laminar stromatactis are improper terms, because they designate spar structures that are different from the typical stromatactis. Zebra stromatactis is better termed zebra spar sheets. These are often associated with slumps (Figs. 5A, 5B). In several examples, provided that internal sediment is distinguished from host facies (a distinction not always easy to make), opposing walls of the original cavity are seen to match like a jigsaw puzzle, so that they represent pull-apart walls (Fig. 5C). Cavities of this kind likely originated as cracks that opened during slumping (sheet cracks) and were later filled with internal sediment and cement. Other isolated laminar spar bodies (laminar stromatactis) are associated with and parallel to stromatactis, and often look like stromatactis. In some instances, however, this laminar structure bifurcates to cut across and pull apart stromatactis (Fig. 6), indicating that this type of fissure postdated formation of stromatactis. All these sheet cracks and fissures were filled by the same kind of internal marine sediment and cement that compose stromatactis. Isopachous fibrous-looking cements (Figs. 5C, 6) have yielded carbon and oxygen stable-isotope values identical to those of stromatactis (PAB, work in progress).

Neptunian dikes are large, commonly meter-scale, structures composed of alternating marine sediment and cement. Marine sediments range from homogeneous lime mud to crinoidal sand and gravel. Marine cement is commonly in thick isopachous crusts of fascicular optic calcite, locally containing hematitic peloids and/or microstromatolites. Neptunian dikes cut across all three facies of the mounds.

Paleoenvironmental Setting

The stratigraphic relationship of the three facies of the Belgian “*récif rouge*” is usually one of superposition (Fig. 3). A complete succession is A-B-C, giving rise to mounds up to 70 m thick, but some mounds, like that of the St. Remy quarry near Rochefort (Fig. 1), are made up entirely of Facies A. The mounds are surrounded by, and to some extent interfinger with, shales and argillaceous limestones, testifying that they grew in a siliclastic-dominated environment. While Facies A had a relatively low synoptic relief (see above), higher relief was achieved in Facies B and C where paleoslopes of up to 35° were reached and relief is estimated at some tens of meters.

The succession A-B-C is the expression of a shallowing-upward sequence. Very low diversity of biota dominated by sponges, absence of current-generated or wave-generated sedimentary structures, interfingering with shales, and absence of algae in Facies A point toward deposition in a low-energy environment, below storm wave base and likely below

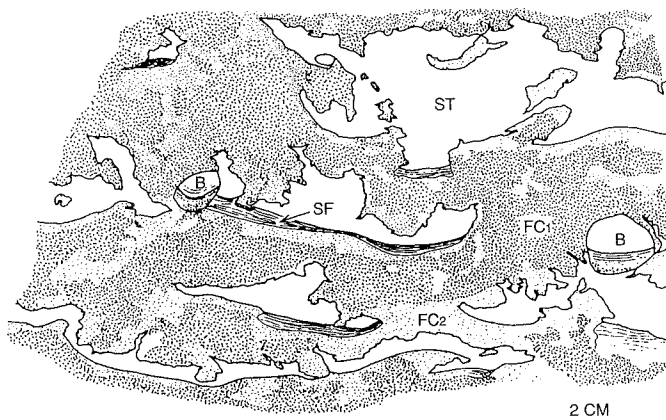


FIG. 8.—Polished slab and corresponding tracing showing the three basic components of a typical red stromatactis limestone: (FC) uniform structureless finely crystalline red limestone forming the bulk of the facies; (ST) stromatactis; (SF) laminated red lime mudstone underneath stromatactis corresponding to sedimentary filling in stromatactis cavity. Original shape of stromatactis cavity corresponds to SF+ST. (B) identifies brachiopods filled with same sediment and cement as stromatactis cavities. The structureless finely crystalline red limestone shows two aspects: (FC1) deep red limestone and (FC2) slightly lighter red limestone. In thin section these two aspects of the limestone are indistinguishable. Contrast is due to a slight difference in iron-oxide content. Although lighter limestone seems preferentially located around stromatactis in this example, this relationship is not consistent in the whole facies. Saint-Rémy quarry, in vicinity of Rochefort.

the photic zone. High diversity of biota, presence of a rigid frame, and abundance of microbial and algal communities in Facies C indicate deposition in a higher-energy environment, probably in well oxygenated waters in the photic zone. Facies B is an intermediate facies that developed when the mound reached storm wave base, as indicated by reworking of many platy corals and stromatoporoids and pelmatozoans bioclasts.

THE SILURIAN MOUNDS OF THE QUÉBEC APPALACHANS

Lithology

Mounds that form the foundation of the thick Upper Silurian West Point carbonate buildup of the Gaspé Basin in the northern Appalachians have been described in detail by Bourque and Gignac (1983), Bourque et al. (1986), and Bourque and Raymond (1988). These are carbonate bodies composed of two facies (Fig. 7): a lower, red stromatactis finely crystalline limestone (the Gros Morbe Member), and an upper, gray massive finely crystalline limestone (the Anse à la Barbe Member). These overlie a mixed siliclastic and limestone unit (the Bouleaux Member). A debris unit (the

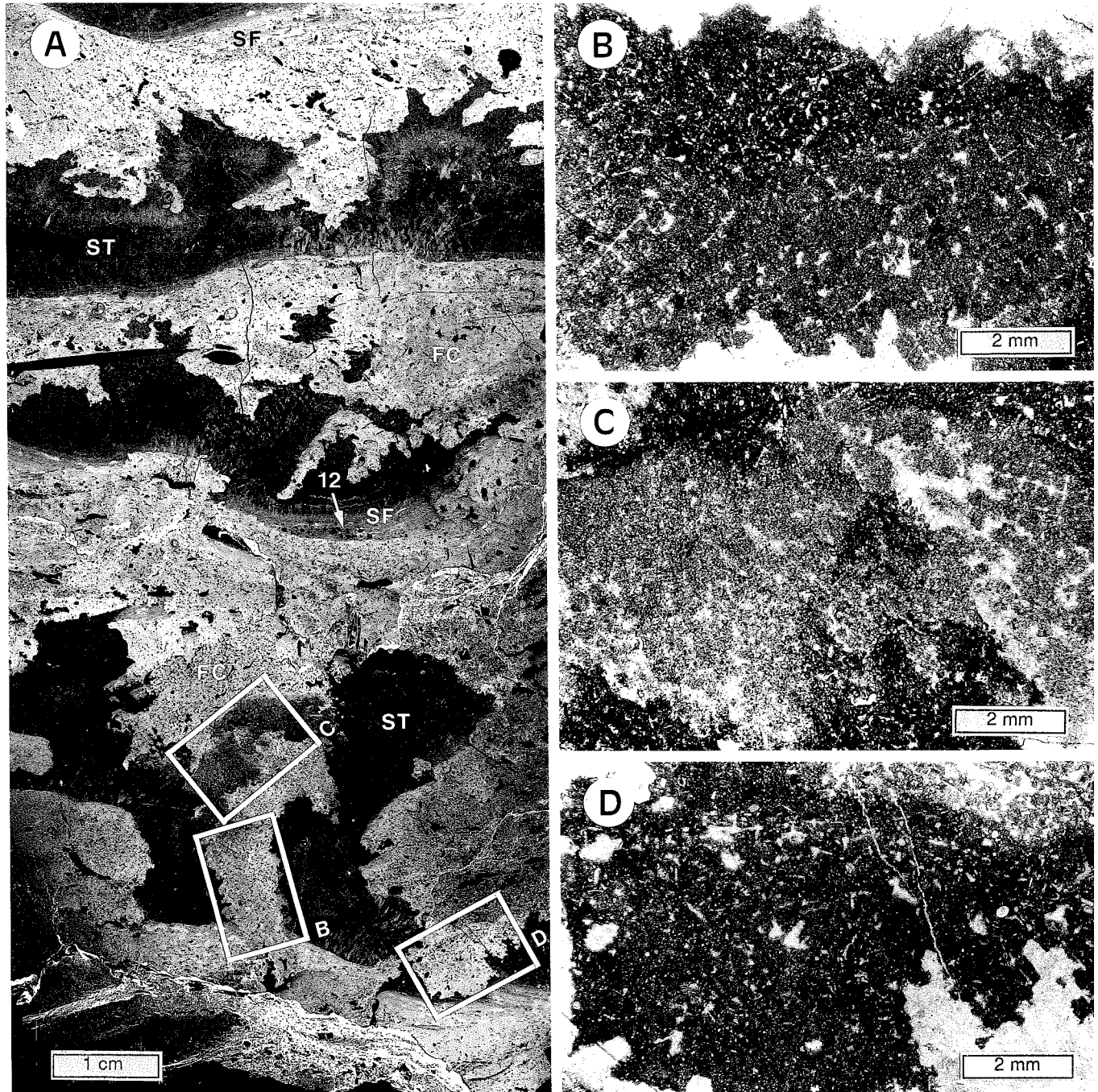


FIG. 9.—Microfacies of the red stromatactis limestone of Facies A, Les Croisettes quarry, Vodecée, Belgian Ardennes. A) Negative print of a large thin section showing the three basic components of the facies. FC, ST, and SF are as in Figure 8. Arrow indicates location of Figure 11. B) Photomicrograph showing still partly preserved spicular network adjacent to stromatactis. (C) Photomicrograph of a pelletoidal microspar (lighter gray) with mostly obliterated but still detectable spicular network (particularly in lower left and upper right quarters) surrounded by same material (darker) as in B. (D) Photomicrograph showing finely crystalline limestone with rather disorganized but still preserved sponge spicules adjacent to stromatactis.

Anse à la Loutré Member), coeval with the mounds, is composed of basinal fine-grained siliciclastics containing limestone debris ranging in size from millimeters to tens of meters and derived from both the Gros Morbe and the Anse à la Barbe members. Like the Belgian mounds, the Québec mounds developed above and are entirely surrounded by siliciclastic facies.

Gros Morbe Member.—The Gros Morbe red stromatactis facies has a mound shape (Bourque and Gignac 1983, their fig. 2), individual mounds

reaching 115 m in thickness. In places the paleoslope of the flanks is estimated to be up to 40°. The limestone is finely crystalline, deep red, and crudely bedded, with ubiquitous white stromatactis constituting 10–30% by volume. It is very similar to the red stromatactis limestone of Facies A of the Belgian mounds. Similarly, bioturbation, common in the surrounding siliciclastics, is almost absent in the mound facies. The observed biota is scarce and consists of crinoid ossicles, tabular favositid

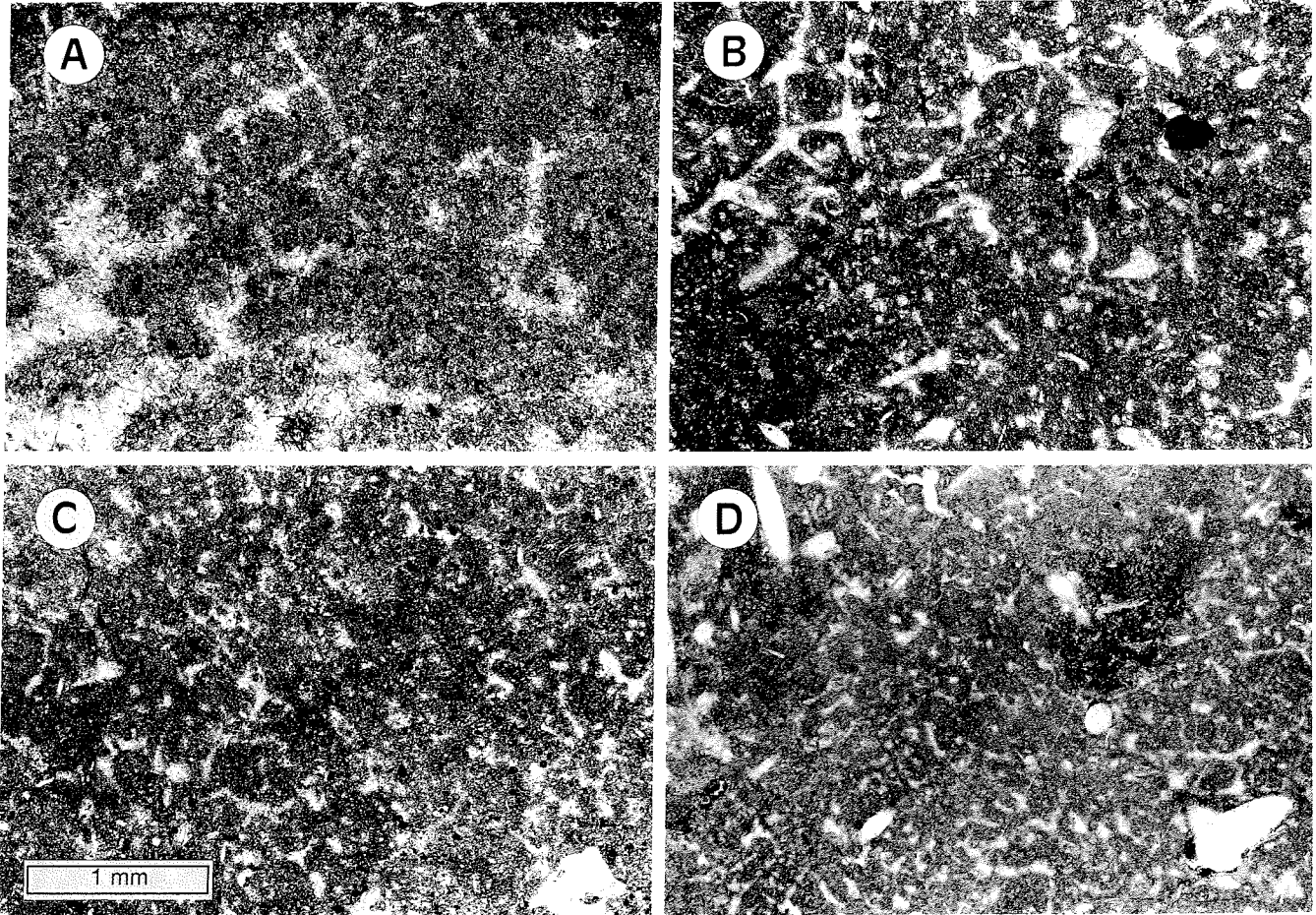


FIG. 10.—Different preservation states of spicular network in red stromatactis limestone of Facies A, Belgian Ardennes. A) Close-up view of Figure 9C showing spicular network in pelletal microspar enlarged and mostly destroyed during early diagenesis and later further obliterated by neomorphism. B) Same phenomenon as in A. This field corresponds either entirely to a single sponge spicular network that was in great part obliterated during diagenesis, or to agglomeration of individual spicules and pieces of a disintegrated sponge. C) Finely crystalline limestone showing an incipient vermiform aspect with still recognizable spicular network. D) Vermiform aspect of the finely crystalline limestone, probably inherited from diagenetic transformation of a sponge-spicule network. Spar-cemented molds of larger spicules are preserved (lower right and upper left). All figures at same scale.

coral and stromatoporoid colonies, brachiopods, and ostracodes. This biota is more common in the upper part of the member, where bedding is better developed, where crinoids are concentrated in thin lenses, and where corals and stromatoporoids are commonly overturned. This upper zone, a few tens of meters thick, contains progressively less stromatactis upsection. It constitutes a transition between the Gros Morbe and the Anse à la Barbe members. Unlike the Belgian red stromatactis limestone, no sponge body fossils are observed.

Anse à la Barbe Member.—The Anse à la Barbe Member is composed of massive gray finely crystalline bindstone. In thin section, the bulk of the limestone is pelletal spar or microspar, very similar to that of Facies C of the Belgium mounds, and also of probable microbial origin. Besides the microbial spar and microspar, fenestellid bryozoans, algae, and calcimicrobes (*Girvanella*, *Sphaerocodium*, *Wetheredella*, and *Gaspsiella*; Bourque et al. 1981) are significant contributors to the bioconstruction.

As in the Belgian mounds, zebra spar sheets (illustration in James 1983, his fig. 133) and neptunian dikes are found in the Silurian Gros Morbe Member of Québec. The zebra spar sheets are composed of early marine sediments and cements and contain hematitic peloids and microstromatolites, while the few known neptunian dikes are composed exclusively of pelmatozoan limestone.

Paleoenvironmental Setting

The succession from the Bouleaux to the Anse à la Barbe (Fig. 7) is a shallowing-upward sequence (Bourque et al. 1986; Bourque and Raymond 1988). The Gros Morbe facies is interpreted as having been deposited in quiet water, below storm wave base and probably below the photic zone. Except for some tiny dasycladacean algae in the Gros Morbe, which could be pelagic, this facies is devoid of calcareous algae and has a very low-diversity biota. The Gros Morbe and the Anse à la Barbe members represent facies and depositional environments equivalent to Facies A and C, respectively, in the Belgian mound succession.

MICROFACIES OF RED STROMATACTIS LIMESTONE

Three main components form the red limestone of Belgian Facies A: uniform, structureless, finely crystalline red limestone; stromatactis; and laminated red lime mudstone underneath stromatactis (Figs. 8, 9).

The structureless finely crystalline limestone is not as uniform in thin section as on polished slabs. It is a microspar that looks patchy (Fig. 9), with uniform or pelletal or vermiform texture (Figs. 10, 11). A striking feature of the finely crystalline limestone is that regardless of its texture

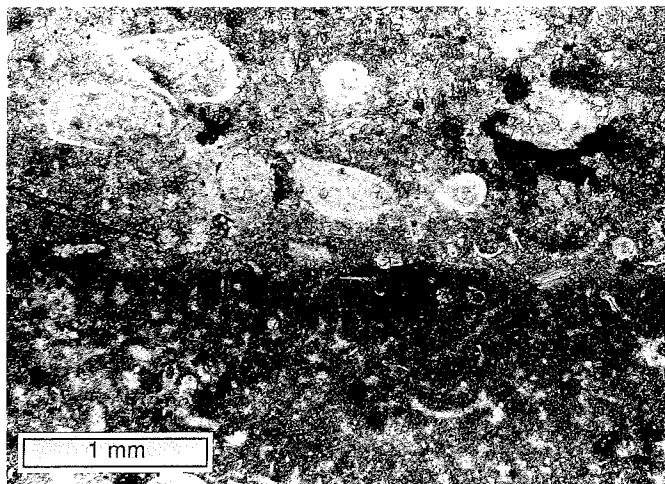


FIG. 11.—Photomicrograph showing the two zones in sedimentary filling of stromatactis cavities: a lower lime mudstone (darker) that merges downward into the underlying finely crystalline limestone with a rather diffuse contact, and an upper more uniform lime mudstone (lighter) containing small ostracodes. The contact between the zones is sharp. See Figure 10A for location.

it contains ubiquitous sponge spicules. These are commonly disorganized and scattered in the microspar, but in several instances actual spicule networks are observed (Figs. 9B, 9C, 10C), even though sponge bodies cannot be detected on corresponding polished slabs.

Underneath stromatactis are variable thicknesses of laminated lime mudstone (Fig. 9A), which can be divided into two types: a lower poorly laminated lime mudstone with about same grain size as the surrounding finely crystalline limestone and commonly containing scattered sponge spicules, and an upper, finer-grained, well laminated lime mudstone, locally containing small ostracodes (Fig. 11). The contact of the lower mudstone with the underlying finely crystalline limestone is diffuse, whereas the contact between the lower and upper mudstones is relatively sharp. These two mudstones are interpreted as the sedimentary geopetal filling of part of the cavity network before the centripetal cementation that resulted in stromatactis. The sedimentary filling may be relatively thin at the base of the cavity or, in some instances, may fill it almost entirely. In rare cases, some of the well laminated material alternates with cement crusts.

Stromatactis spar is of two kinds. The first is a number of roughly isopachous crusts of fibrous-looking cement, and the second is coarse granular cement.

The three main components of the Belgian Facies A also constitute the Gros Morbe red limestone of Québec. The microfacies of the uniform finely crystalline limestone consists of a mixture of a pelletoidal network and lime mudstone, both with ubiquitous sponge spicules (Bourque and Gignac 1983, their figs. 6–8). Unlike the Belgian facies, however, no actual spicule networks are observed. The finer-grained limestone underneath stromatactis is only vaguely laminated. It locally contains spicules and small ostracodes, and it alternates with cement crusts in places. Stromatactis spar is also made up of initial isopachous crusts of fibrous-looking cement followed by coarse granular spar. Visual evaluation of the proportions of the various components in 87 thin sections from a section of uniform

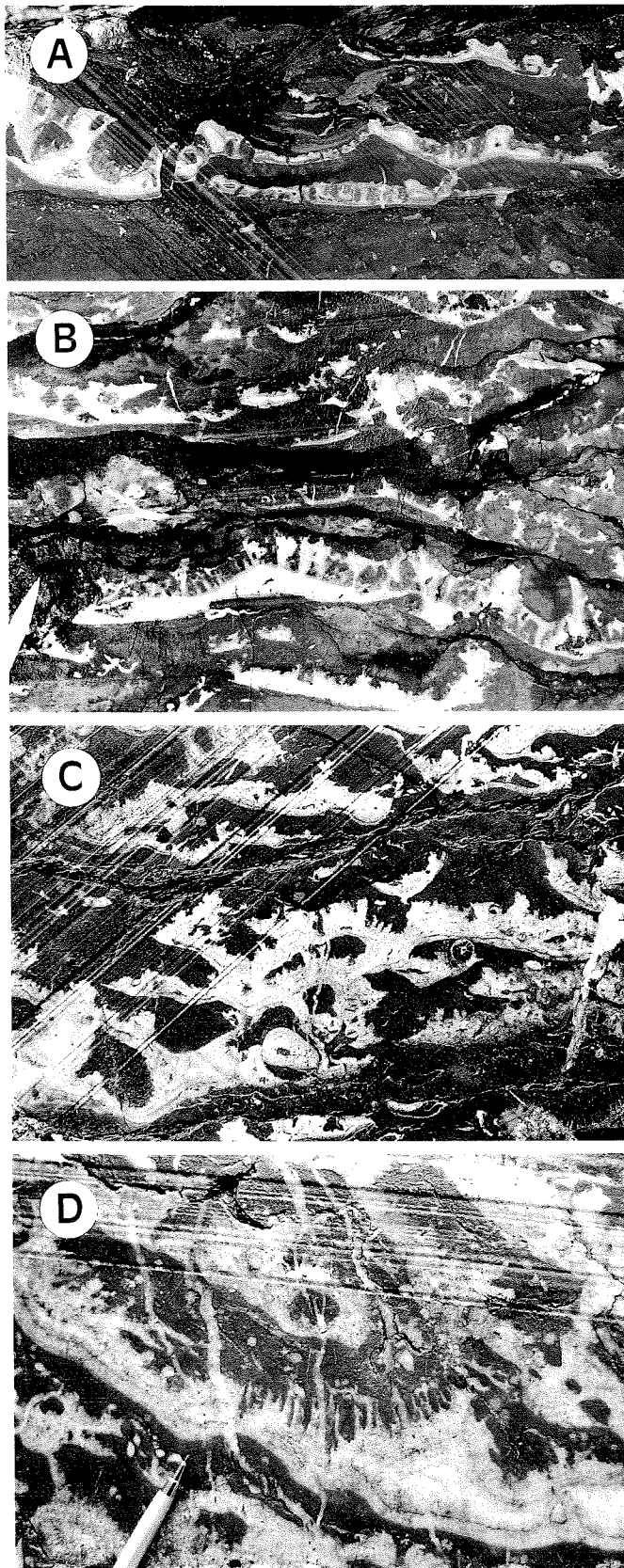


FIG. 12.—Various organizations of stromatactis cross sections, suggestive of sponge bodies, as is often observed on quarry walls in the Belgian Ardennes. A) Quarry block at entrance of Les Croisettes quarry, Vodecée. Width of picture is

50 cm. B) Les Bulants quarry, Neuville. Tip of pencil (lower left) for scale. C, D) Saint-Rémy quarry, near Rochefort. Width of picture C is 40 cm.

Gros Morbe red stromatactis limestone 110 m thick showed that the pelletaloid microspar network makes up on average 30% of the whole limestone, and stromatactis spar, 30%.

INTERPRETATION AND DISCUSSION

An adequate model for the origin and petrogenesis of the red stromatactis limestone facies must account for the origin of the three basic features of this facies: stromatactis, the sponge-spicule-rich host finely crystalline limestone, and the red color of the facies.

Origin of the Uniform Finely Crystalline Limestone

Presence of sponge spicules is characteristic of the red stromatactis facies in the Frasnian "récifs rouges" of Belgium (Boulvain 1990) and in the Silurian red mounds of the Québec Appalachians (Bourque and Gignac 1983). Sponge spicules are also reported from other Paleozoic red stromatactis limestone facies, e.g., the Lower Cambrian of the Flinders Ranges of southern Australia (James and Gravestock 1990), the Ordovician of Scandinavia (Middleton 1988), the Upper Devonian of western Australia (Kerans 1985; Kerans et al. 1986) and southern Australia (Wallace 1987), and the Middle Devonian of Montagne Noire in France (Bourque, unpublished observations).

For the Silurian red stromatactis limestone of Québec Appalachians, Bourque and Gignac (1983, 1986) proposed that the finely crystalline limestone originated from massive calcification of a sponge network and associated lime mud during bacterial decay of the sponge tissue. The spicule-rich pelletaloid network and associated lime mudstone were interpreted as a former sponge framework infiltrated with lime mud. Pratt (1986) questioned this interpretation because of the absence of observable sponge body fossils and regular spicular networks in the Québec limestone. In the Belgian quarries, however, sponge body fossils are common in Facies A (Bourque 1983; Bourque and Gignac 1986; Boulvain 1990). There, the facies shows all transitions from well preserved, easily delineated sponge bodies, to recognizable sponge bodies that can be only partly delineated, to stromatactis limestone in which sponges are indiscernible (compare Figures 12A, B, C, and D). In thin section the well preserved sponges commonly show a well preserved spicular network embedded in spar or microspar, but in some instances the network is poorly preserved or even absent. In the stromatactis limestone where sponge bodies are indiscernible, all transitions exist, from an undisturbed though only partly preserved and locally barely discernible (Fig. 9C) sponge-spicule network embedded in spar or microspar, to microspar displaying a meshwork of small canal-like structures that give a spongy appearance to the limestone (Fig. 10D; the vermiform texture of some authors, e.g., Pratt 1982), to rather uniform pelletaloid spar and microspar with scattered, variably abundant spicules, not organized in a specific network.

We view these various aspects of the macrofacies and microfacies as a continuum expressing different stages of early diagenesis of sponge communities, with the two end members of the continuum being well preserved early "frozen" sponges and early-cemented spicule-rich organic mats derived from degradation of sponge communities. The sponges are hexactinellids with subordinate demosponges and heteractinids (Termier et al. 1981). The fact that parenchymal hexactines and other spicules are invariably weakly fused, or not fused at all in hexactinellid sponges (De Freitas 1991), may account for the poor preservation in general, and the variable preservational stages observed.

Following Bourque and Gignac (1983, 1986) we conclude that sponges were significant in mound accretion. We consider, however, that the finely crystalline limestone is the result of early cementation not only of a sponge network but also of variably preserved sponges and spicule-rich organic mats derived from sponge communities.

Origin of the Red Pigment

The red color of the limestone in most of the Cambrian to Devonian stromatactis-bearing mounds is striking. In the Belgian and Québec mounds, the red color is confined to mound facies and is caused by concentrations of about 1% Fe₂O₃ disseminated in the limestone. The iron-oxide content of the perimound fine-grained sediments is much less. (Bourque and Gignac 1983 stated that the Gros Morbe stromatactis limestone is red in outcrop but gray in drill cores. Reexamination of the cores has shown that the gray color is restricted to zones adjacent to fractures or to Carboniferous karst fissures, and that it more likely originated from alteration of originally red limestone.)

A commonly held explanation for the origin of the pigment is that the iron oxide is detrital (Delhay 1908; Lecompte 1936; Reijers 1984), having been derived from the continent, deposited in low-energy mound and perimound environments, and preserved from reduction by the slight elevation of the mound above the surrounding argillaceous reducing sediments. An opposing view is that the bulk of the iron oxide of the Belgian Frasnian mounds was precipitated microbially *in situ* (Monty et al. 1982). Boulvain (1989, 1990) described sheathed and coccoidal iron-oxidizing bacteria from the Hautmont, Les Bulants, Les Croisettes, and Rochefontaine mounds. In these Belgian mounds, iron-oxidizing bacteria are found in all kinds of cavity fillings (cement or sediment), including stromatactis and the lime mudstone underneath it, zebra and laminar spar sheets, and neptunian dikes. In the Silurian Gros Morbe red mounds of Québec, iron-oxidizing bacteria were also found in sediment and cement filling of sheet cracks and of stromatactis cavity networks (Bourque, unpublished data).

Sheathed and coccoidal bacteria are scattered in the sediments filling the cavities or aggregated into 0.1–1 mm hematitic peloids concentrated in layers alternating with cement crusts, or associated with other non-iron-oxidizing bacteria in microstromatolites (Mamet and Boulvain 1988) embedded in spar cement. The best-preserved sheathed forms belong to the *Sphaerotilus-Leptothrix* group of iron-oxidizing bacteria (Fig. 13A; Boulvain 1989). They are always either associated with or overlain by internal marine sediments or entombed in marine cements.

Did iron-oxidizing bacteria contribute to mound accretion? The examples described above indicate clearly that the bacteria postdated development of the various kinds of cavities. Besides these examples, however, poorly preserved sheaths or cocci are observed in some cases in the red finely crystalline limestone forming the bulk of Facies A (Fig. 13B). Either they were never more abundant than now observed, and therefore were not significant contributors to mound accretion, or they are only remnants of a more abundant population and therefore can be considered as primary builders. It is also possible, however, that the bacteria developed in micropores of the finely crystalline limestone during early diagenesis, below the substrate-water interface, at the same time they developed in the sediment and cement filling of the various cavities.

An alternative explanation for the red pigmentation of the mound limestone by iron-oxidizing bacteria is that iron oxide resulted from oxidation of ferrous iron originally precipitated as an amorphous sulfide phase in micropores during sulfate reduction of organic matter. If so, then oxidation occurred during later early diagenesis through the same pore water that permitted development of iron-oxidizing bacteria in the sediment and cement filling of the various kinds of cavities. This implies a change from reducing to oxidizing conditions during diagenesis (see later).

The Role of Microbial Communities

Mound accretion is by commonly explained by microbial communities (e.g., Monty et al. 1982; Pratt 1982; Tsien 1983; Lees and Miller 1985; Camoin and Maurin 1988). A key question is the relative role of sponges versus bacteria or other microbes in mound construction (Bourque and Gignac 1986). Our contention that sponges played a determinant role in

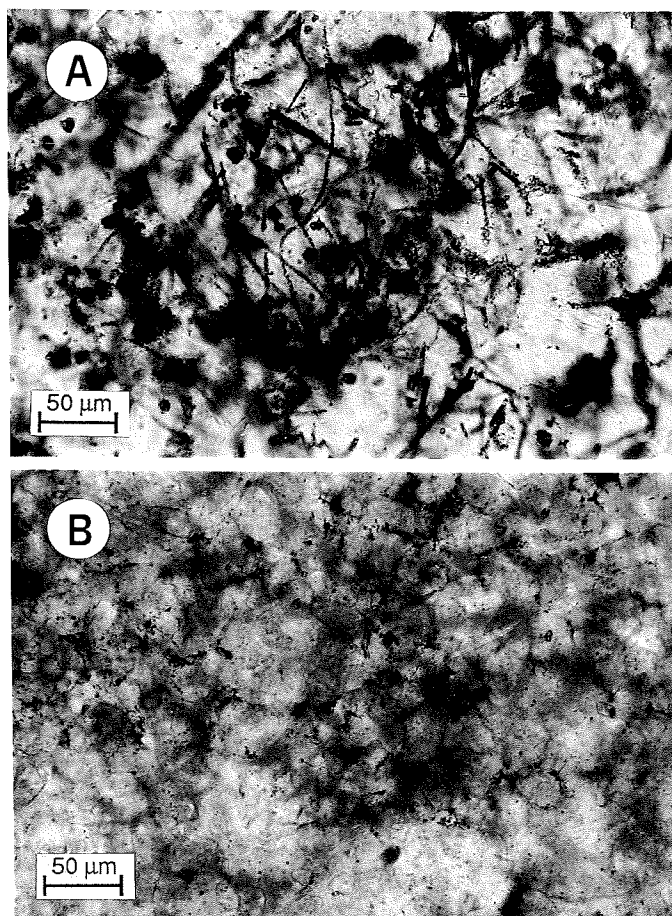


FIG. 13.—Plane-polarized-light photomicrographs of sheathed (*Sphaerotilus-Leptothrix*) and coccoid iron-oxidizing bacteria. **A**) As observed in hematitic peloids formed by a spar-cemented loose felting of bacteria. Rochefontaine quarry, Franchimont, Belgian Ardennes. **B**) Possible remnants of sheathed iron-oxidizing bacteria in finely crystalline limestone of Facies A. Les Bulants quarry, Neuville.

the initial phase of mound accretion does not necessarily deny microbial communities a role of major contributors to petrogenesis of the red stromatactis limestone, although we could not actually document their occurrence. Several hypothetical possibilities exist:

The microbes were part of the primary builders. Even if the sponges were predominant, it is possible that associated microbial communities were present at that stage of limestone genesis. However, no stromatolitic or thrombolitic structures were observed in the red limestone (whereas they are ubiquitous in the gray Facies C of the Belgian mounds and the gray Anse à la Barbe Member of the Québec mounds), nor were remnants of bacteria, except those of the iron-oxidizing group previously discussed.

The microbes were mud producers. This was advocated particularly by Monty et al. (1982), who considered that the finely crystalline limestone constituting the bulk of the Belgian mounds, including all three facies of the “*récis rouges*”, resulted from lithification of lime mud produced by microorganisms. This is widely accepted among students of so-called mud mounds (Pratt 1982; Lees and Miller 1985; Camoin and Maurin 1988). Production of lime mud by cyanobacteria is known in modern lakes (Thompson et al. 1990) and shallow-water carbonate platforms (Robbins and Blackwelder 1992) in the form of “whiting events” linked to photosynthetic metabolism of the bacteria. This kind of mud production is difficult to apply, however, to local, circumscribed deep-water concentrations (mounds) that developed below the photic zone. Obviously there

was lime mud in the mound environment, now found as lime mudstone either associated with the sponge network (Bourque and Gignac 1983) or as geopetal filling in various kinds of cavities in the facies, including the stromatactis cavity network. Even if that mud was produced microbially, production was on a much smaller scale than proposed by Monty et al. (1982). An alternative explanation is that the mud was trapped from suspension by sponges and redistributed in the cavity system by pore-water circulation after decay of the sponges. Most geopetal mud is very fine grained and represents a filtrate.

The microbes acted mainly as agents responsible for sponge putrefaction and early cementation. This is the hypothesis of Bourque and Gignac (1983, 1986), who considered that the sponge network was cemented early, during bacterial decay of organic matter. Microbially induced carbonate precipitation during sulfate reduction in organic-rich environments is well known, and sulfate reduction is identified as an important process leading to carbonate precipitation (Curtis 1983). The diagenetic environment should be one of anoxic conditions and alkaline pH. Bourque and Gignac (1983) have shown that siliceous sponge spicules must have been dissolved during early calcification of sponges. This is also true for the Belgian red stromatactis limestone. Alkaline pH would account for dissolution of the amorphous silica of the spicules.

The microbes were symbionts in the sponge tissue. An alternative hypothesis to that of sponge calcification under bacterial decay is calcification through bacterial symbionts in the sponge tissue. Fossil sponges are poorly understood (Wood 1990), and whether they had symbionts is uncertain. However, modern sponges on outer-shelf reefs commonly contain cyanobacterial and eubacterial symbionts. Cyanobacteria are known to induce precipitation of calcium carbonate (stromatolites, thrombolites, calcimicrobes), but no modern examples of sponge calcification through cyanobacterial activity are known.

Origin of Stromatactis and Laminated Mudstone

Hypotheses on the origin of stromatactis are many (e.g., Heckel 1972; Bathurst 1980, 1982; Pratt 1982; Bourque and Gignac 1983; Lees and Miller 1985; Wallace 1987). In accordance with our hypothesis of the determinant role of sponges in the facies construction and their early cementation during bacterial decay of organic matter, the making of the stromatactis cavity system can be explained by enlargement and modification of the original growth cavities of the sponge network concurrently with the decay and collapse of regions of un lithified sponge tissue (Bourque and Gignac 1983, 1986).

Early workers (Dupont 1881; Lecompte 1937; and many others), and more recently Tsien (1983), described stromatactis as organisms, and recognized well organized growth patterns. Some stromatactis networks indeed show a pattern (e.g., Fig. 12) that possibly reflects the internal structures (canals, spongocels) of sponges. One should be very cautious, however, in relating stromatactis morphology to framework geometry.

Both early calcification during decay of organic matter and creation of the stromatactis cavity network probably took place within a few meters below the substrate-water interface. The lower part of the mudstone present underneath stromatactis spar is interpreted to have been deposited in cavities formed by collapse of material, whereas the upper finer-grained lime mudstone immediately below stromatactis spar is interpreted to represent material that filtered through the facies and was deposited by water circulating in the stromatactis cavity system.

The Red Stromatactis Limestone as the Result of Early Diagenesis of a Sponge-Constructed Facies

The model we propose for the genesis of the red stromatactis limestone facies of the Québec Silurian and Belgian Devonian mounds, and probably applicable to other examples, is built upon that proposed by Bourque and

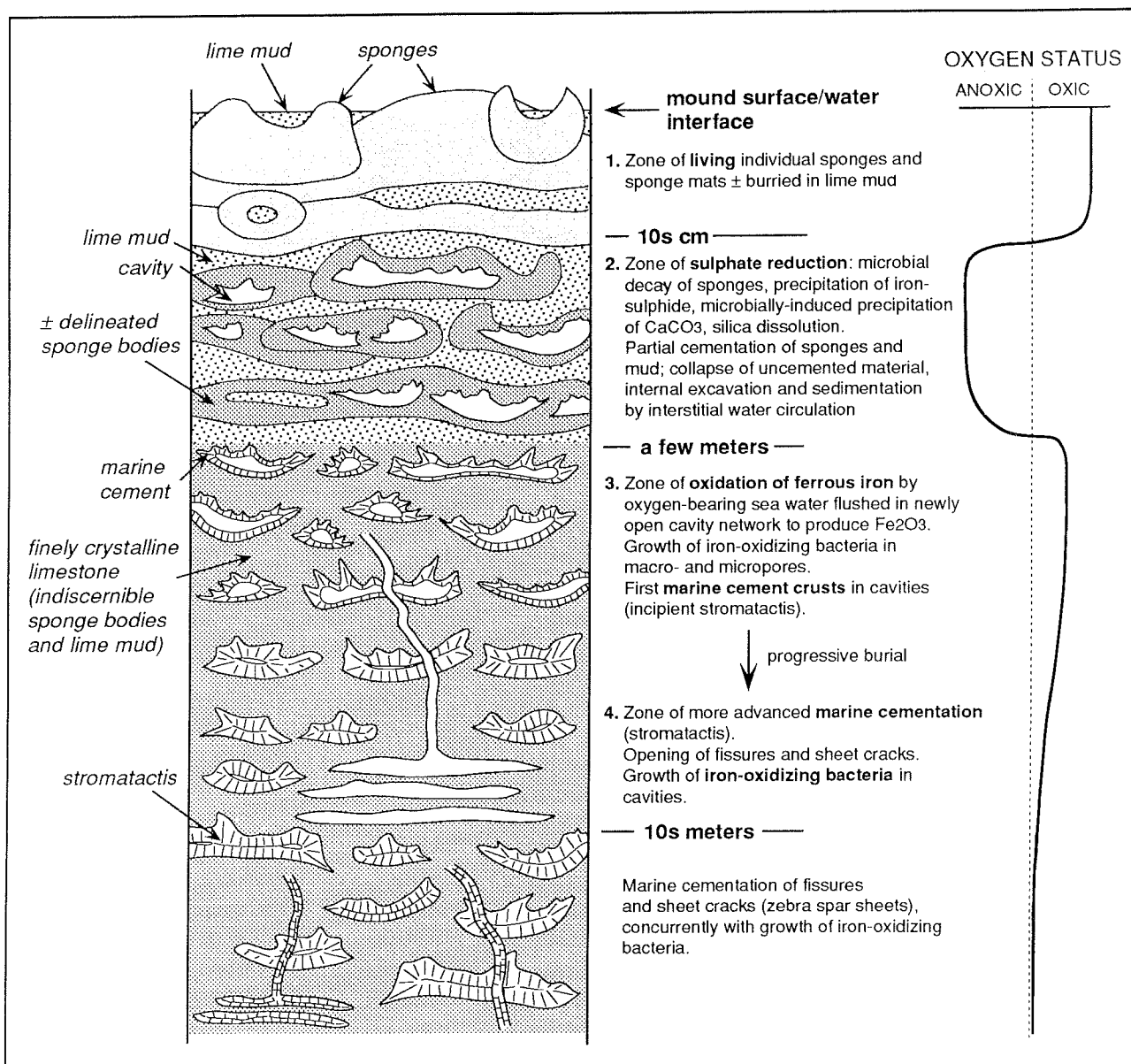


Fig. 14.—Model showing how a sponge-dominated community associated with lime mud is progressively transformed into red stromatactis finely crystalline limestone in the upper tens of meters of Paleozoic red stromatactis mounds. See text for more complete explanation.

Gignac (1983, their fig. 12). Figure 14 summarizes the diagenetic sequence that we believe led to the petrogenesis of the red stromatactis limestone. We view the sequence as a superposition of four diagenetic zones:

Zone of living community. A sponge community, represented either by individual sponge bodies or by sponge mats, dominated this zone and were responsible for mound accretion, possibly in the same way sponges now build mounds in arctic waters (Van Wagoner et al. 1989). The presence of an associated microbial community is not excluded, but in the absence of actual documentation, cannot be ascertained. Trapping of lime mud by the sponges from suspension and/or primary production by microbial activity provided mud in the environment.

Zone of sulfate reduction. As the mound accreted, previous living surfaces passed into the sulfate reduction zone, where the sponges were subjected to bacterial decay and were only variably preserved. This was a zone of alkaline pH and anoxic conditions where amorphous iron sulfide was precipitated. There ensued microbially induced precipitation of cal-

cium carbonate, partial cementation of the sponges and the spicule-rich organic mats derived from sponge material and associated lime mud, and dissolution of variable volumes of sponge spicules. Concurrent collapse of uncemented sponge and mud material and internal excavation and sedimentation by circulation of interstitial water produced the stromatactis cavity network.

Zone of oxidation of ferrous iron and incipient marine cementation of stromatactis cavities. Once established, the improved water circulation in the stromatactis cavity system brought in oxygen-bearing sea water, so that the diagenetic environment changed from anoxic to oxic, or at least to a mixed oxic/anoxic environment. The newly cemented but still porous ferrous-iron-rich combination of sponge network and lime mudstone began to be oxidized, and the iron-sulfide phase changed to an iron-oxide phase. This was made possible only by the existence of the stromatactis cavity system, which was connected to sea floor and into which marine water was flushed and circulated very efficiently. It is also possible, but

has not been demonstrated, that iron-oxidizing bacteria invaded the micropore environment. Early marine cements started to precipitate in the cavity system to produce incipient stromatactis.

Zone of marine cementation. With deeper burial, more advanced marine cementation produced stromatactis. Cracking and fissuring of the brittle mound opened sheet cracks and fissures that cut across already fully cemented stromatactis. This new cavity system was still connected to the sea floor. Marine water with low levels of free oxygen circulating in the new cavity system permitted growth of iron-oxidizing bacteria of the sheathed *Sphaerotilus-Leptothrix* group. Indeed, this group belongs to the neutral pH iron bacteria (Nealson 1983) and is microaerophilic (low level of free oxygen). At this stage, porosity was restricted to sheet cracks and fissures. With still deeper burial, marine cements precipitated in the sheet-crack and fissure cavity system concurrently with growth of iron-oxidizing bacteria.

Later on, neptunian fissures affected the red stromatactis limestone (not shown in Figure 14) and were filled by marine sediments and cements, with additional growth of iron-oxidizing bacteria.

Implications for the Geological Record

Our recognition of the dominant role of sponge communities in the construction of red stromatactis limestone mounds in the Cambrian–Devonian time interval has important implications for understanding the geological record. The first metazoan communities able to build organic relief were the archaeocyathans, and in at least one example they are associated with a red stromatactis sponge-spicule-rich facies (James and Gravestock 1990). After the demise of the archaeocyathans at the end of the Early Cambrian, the red sponge mounds persisted to the end of the Devonian, where they apparently did not survive the Frasnian–Famennian extinction, with one possible exception, the Famennian red mounds of Baelen in Belgium (Boulvain 1990). During the whole Cambrian–Devonian time interval, this community was the main deep-water mound-building community, even during the acme of the stromatoporoids (Silurian–Devonian), which occupied a wide range of water depth. The structure of this sponge community is very poorly known, however, because of the poor state of sponge preservation.

CONCLUSIONS

Contrary to common belief, Paleozoic deep-water carbonate mounds are not all monolithic bodies, but are in many cases composed of a number of distinct facies, including red stromatactis finely crystalline limestone. This red limestone facies constitutes the deepest-water facies of the Frasnian carbonate mounds of the Belgian Ardennes and of the Silurian mounds of the Québec Appalachians.

Our model for the origin and petrogenesis of the red stromatactis limestone integrates the main attributes of the facies: mound shape, ubiquitous presence of sponge spicules and, in Belgium, of sponge body fossils, presence of stromatactis composed of marine cement, and red color of the limestone. It postulates that accretion of the facies was controlled by sponges whereas the red color and stromatactis are early-diagenetic features, having been formed within a few meters below the substrate-water interface.

The presence of sponge body fossils and of various stages of sponge preservation in the red stromatactis limestone facies of the Belgian mounds gives stronger support to the hypothesis that sponges were significant in the accretion of this facies (Bourque and Gignac 1983). This sponge community is viewed as an important deep-water mound-building community during the Cambrian–Devonian time interval, but is not commonly recognized because of its often poor preservation.

The role of bacteria and other microbes as the main primary builders of carbonate mounds is widely advocated but cannot be assessed in the

two cases we studied. Microbial communities may have contributed to mound accretion as primary builders and/or mud producers, but we failed to actually document this. We suggest that they may have caused the concurrent sponge putrefaction and early cementation (biodiagenesis) during sulfate reduction under alkaline pH and anoxic conditions.

We also propose that the stromatactis cavity network was created by excavation, by circulation of interstitial water in the first meters of the sedimentary column, of uncemented material in partly indurated decaying sponges and spicule-rich organic mats derived from degradation of sponge communities. This cavity network was connected to the sea floor and was flushed by oxygenated sea waters that changed the diagenetic environment from anoxic to oxic, converting amorphous iron sulfide to hematite and giving the facies its red color. Subsequent marine cementation of the cavity network, a few meters below the substrate-water interface, produced stromatactis.

The difference between the Belgian mounds, which contain easily delineated sponge body fossils and well preserved spicular networks, and the Québec mounds, which are devoid of such fossil sponges but are rich in disorganized spicules, is viewed as representing two end members in fossilization of sponge communities. In the Belgian mounds the facies shows all transitions between well preserved sponges and spicule-rich organic mats derived from degradation of the sponges, whereas in the Québec mounds the sponges were not preserved, and the facies is represented only by the spicule-rich mats.

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