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Famennian microbial reef facies, Napier and Oscar Ranges, Canning Basin, western Australia

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ABSTRACT

Following the Frasnian–Famennian mass extinction, which eliminated most skeletal reef-building fauna, the early Famennian reefs of the Canning Basin were constructed primarily by reef-framework microbial communities. In the Napier and Oscar Ranges, the Famennian reef complexes had high-energy, reef-flat depositional environments on a reef-rimmed platform that transitioned into low-energy, deep-water reefs growing in excess of 50 m below sea level. High-energy, reef-flat depositional environments contain doming fenestral stromatolites that grade into porous thrombolites and are associated with coarse-grained sandstones and grainstones. The reef-margin subfacies contains mounds of microdigitate thrombolites, which are more delicate than the reef-flat thrombolites and locally contain abundant red algae, *Girvanella*, renalcids and sediment-filled tubes. Within the thrombolites, the red algae are in upright growth positions, suggesting that the thrombolites are largely composed of carbonate that precipitated *in situ*. Reefal-slope environments are dominated by *Wetheredella* and *Rothpletzella* with locally abundant *Girvanella*, renalcids and *Uralinella*. In reefal-slope strata, delicate fans and microdigitate stromatolites of *Wetheredella* and *Rothpletzella* are often oriented horizontal or diagonal to bedding and are interpreted as syndepositionally toppled over. Most mesoscale microbial community structures contain several species of microbial fossils, and no single microbial species appears to have controlled the morphology of the community structure. Therefore, the depositional environment must have determined the distribution and morphology of the stromatolites, thrombolites and other microbial community structures. The adaptability of microbial communities to various reef environments allowed them to fill ecological niches opportunistically after the Frasnian–Famennian mass extinction.

Keywords Canning Basin, Famennian, microbe, reef, stromatolite, thrombolite.

INTRODUCTION

The Late Devonian mass extinction temporarily eliminated most reef-building skeletal fauna from reef ecosystems (Copper, 1986; McGhee, 1996; Webb, 1996; Copper, 2002). Consequently, early Famennian reefs were constructed primarily by microbial communities (Playford, 1980; Kerans, 1985). Remarkably, in spite of losing most skeletal

reef-framework fauna, the early Famennian reefs thrived and prograded in the Canning Basin (Playford *et al.*, 1989). These reefs provide an excellent opportunity to study the reorganization of a reef ecosystem following a mass extinction. However, no study has specifically surveyed the morphology of the microbial community structures in various Famennian reef depositional environments.

The Canning Basin has beautiful exposures of well-preserved Frasnian and Famennian reefs (Playford *et al.*, 1989) (Fig. 1). Located about 15°

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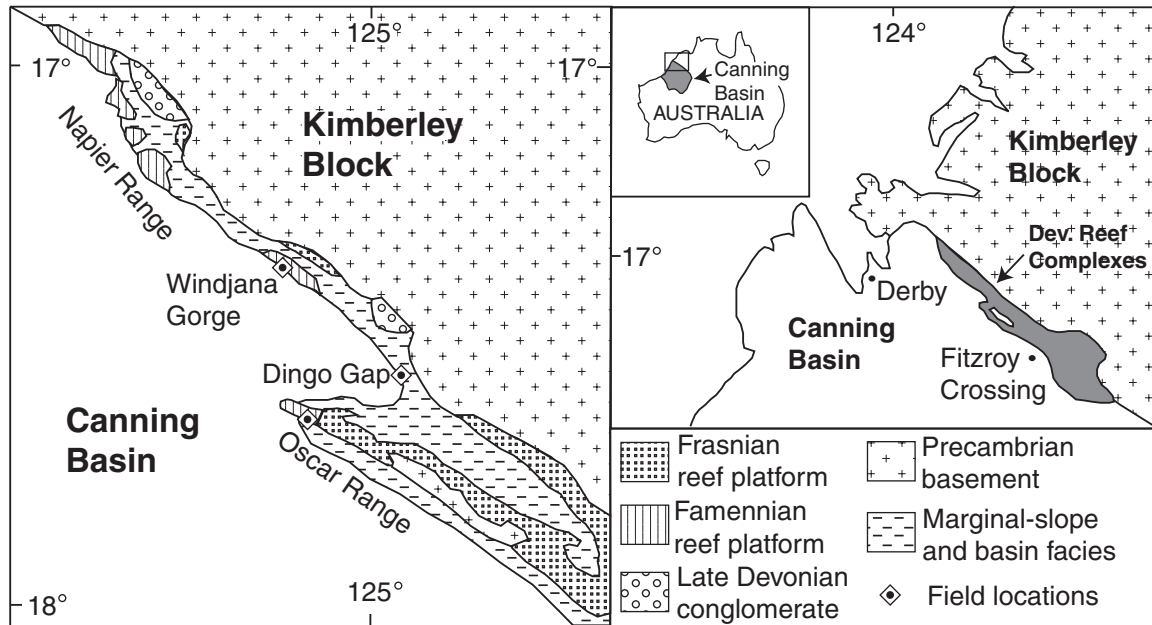


Fig. 1. Location of field area, modified from Playford (1980).

south of the equator during Middle to Late Devonian time, the northern rim of the Canning Basin was ideally situated for reef-building processes, resulting in a 350 km north-west–south-east trending reef (Playford, 1980; Hurley, 1986). Detailed mapping of the reef complexes was performed by the Western Australian Geological Survey in 1962–63 (Playford & Lowry, 1966), and new maps have refined this database (Playford & Hocking, 1999). Playford (1980, 1984) provides a general overview of the faunal distributions in the Frasnian and Famennian reefs, showing fossil assemblages for some facies. Previous studies have shown that microbial communities in the early Famennian reef complexes of the Canning Basin are diverse and dominated construction of the reefs (Playford, 1980; Kerans, 1985; Wood, 2000a). Although most microbial fossil types found in the Famennian reef strata are also present in the Frasnian reefs, the microbial reef communities were more abundant and often filled more diverse palaeoecological niches during Famennian time (Wray, 1967; Kerans, 1985; George, 1999; Wood, 2000a,b; Playford *et al.*, 2001). This paper will examine the microbial textures with respect to their palaeoenvironment and reveal the diverse palaeoecology of microbial communities in the lower Famennian reefs of the Canning Basin.

Facies types

In reef literature, many different terms have been used to describe facies in reef complexes. This

paper will use the terminology of Playford (1980) and Kerans (1985). The three major facies are platform, marginal slope and basin, which are recognized by the water depth of the depositional environment and the depositional dip of the strata (Fig. 2). The platform facies is composed of horizontally deposited strata from a shallow-water depositional environment and can be further subdivided into backreef, reef-flat and reef-margin subfacies. Backreef subfacies comprises most of the reef platform; these strata are well-bedded and horizontal. Reef-flat and reef-margin subfacies form narrow, commonly discontinuous zones on the edges of reef platforms. The reef-flat subfacies represents both reef-crest and reef-flat depositional environments (Kerans, 1985 and references therein). Strata of the reef-flat subfacies are thickly bedded and horizontal. The reef-margin subfacies was deposited at the edge of the platform, and these strata include massive bindstones and framestones. The marginal-slope facies is recognized by steep depositional dips and separates the reef platform from the basin facies. The marginal slope consists of reefal-slope and forereef subfacies. The reefal-slope strata contain abundant *in situ* bindstone and framestones with poorly developed bedding and very steep depositional dips. The forereef strata are primarily allochthonous carbonates and sandstones that interfinger with the reefal-slope subfacies. The forereef strata have depositional dips as high as 35–40° near the reefal slope, and these dips shallow downslope as the forereef grades

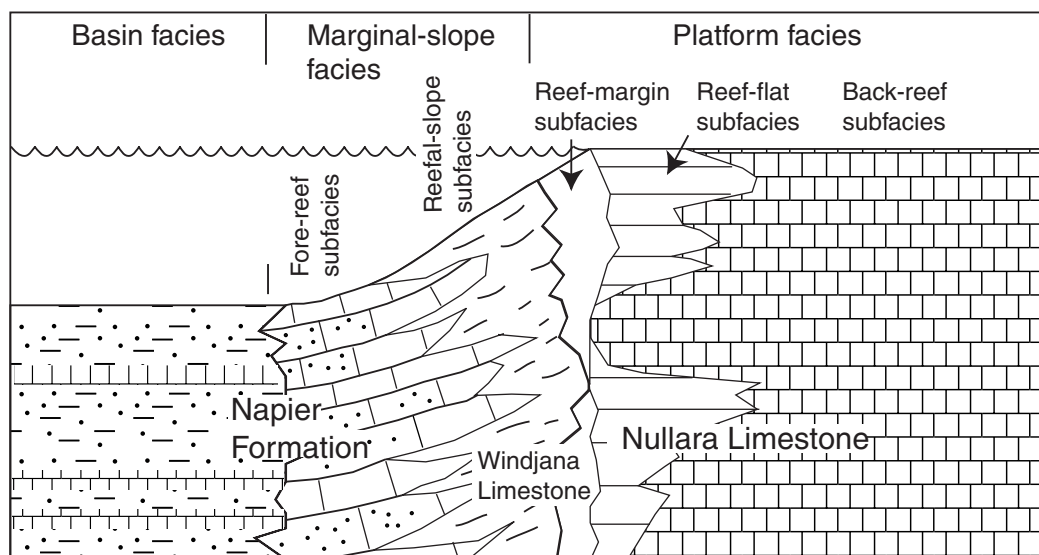


Fig. 2. Division of reef facies and subfacies (Playford, 1980).

into basin facies (Playford, 1980). Basin facies were deposited horizontally in deep-water depositional environments.

Famennian backreef and reef-flat subfacies in the Napier and Oscar Ranges comprise the Nullara Formation (Playford, 1980) (Fig. 2). The Windjana Limestone contains the Famennian reef-margin and reefal-slope subfacies (Playford, 1980). Frasnian and Famennian forereef and basin strata compose the Napier Formation (Playford, 1980). The basin facies, however, will not be discussed in this paper.

Microbial nomenclature

Many of the microbial communities discussed in this paper have been referred to by various names. This paper will use the terms *Rothpletzella* and *Wetheredella*, instead of *Sphaerocodium*, and the term renalcids to describe the *Renalcis* group. *Sphaerocodium* originally referred to fossilized algae that were later determined to be a mix of different microbial fossils (Wood, 1948). From the various microbial fossils within '*Sphaerocodium*', *Rothpletzella* was defined as fan-like arrays of 20–35 μm diameter filaments, and *Wetheredella* was defined as oblong 'tubes' $\approx 100 \mu\text{m}$ in diameter (Wood, 1948). Although Wray (1967), Playford *et al.* (1976), Playford (1980, 1984) and Kerans (1985) use the term *Sphaerocodium* to describe these fossils, more recent papers have used *Rothpletzella* and *Wetheredella* (George *et al.*, 1997; Wood, 2000a,b), and this paper will follow that trend.

Members of the *Renalcis* group have also been given various names. Wray (1967) classified members of the *Renalcis* group as *Renalcis devonicus* and *Renalcis turbitus*. However, Riding (1991) classified these two fossils as *Shuguria* and *Izhella*. In recent papers on the Canning Basin, Wood (2000b) and Stephens & Sumner (2002) used Riding's (1991) classification. This paper will use the term renalcids to refer in general to members of the *Renalcis* group and will use Riding's (1991) classification for specific morphologies.

Other common fossils in the Famennian reef complexes include red algae, green algae, *Girvanella*, calcispheres and *Uralinella*. In the Late Devonian of the Canning Basin, *Solenopora* is the most common form of red algae followed by *Parachaetetes* (Wray, 1967). *Solenopora* and *Parachaetetes* both form nodular to subhemispherical masses averaging 3 mm across (Wray, 1967). They are typically found in reef-flat and reef-margin environments (Kerans, 1985). Halimedacean (codiacean) and dasycladacean green algae are reported from thin sections from the Canning Basin (Wray, 1967) but are found primarily in lagoonal environments (Wray, 1972; Tsien & Dricot, 1975). *Girvanella* are 20–30 μm round, hollow filaments that resemble the calcified remains of modern filamentous cyanobacterial sheaths (Wray, 1967; Riding, 1991). *Girvanella* are common in many microbial reef environments (Tsien & Dricot, 1975; Riding, 1991; Pratt, 2001). Calcispheres are 40–190 μm diameter spherical bodies of uncertain origin but may

represent the spores of shallow-water algae (Wray, 1967; Maurin & Noel, 1975). *Uralinella* are classified as encrusting foraminifers (Sabirov, 1974) and are often found with *Rothpletzella* (Kerans, 1985).

Microbialites, stromatolites and thrombolites are organosedimentary deposits, usually created by several types of microorganisms. A microbialite is any sedimentary structure of microbial origin (Burne & Moore, 1987). The term 'stromatolite' refers to an internally laminated carbonate of probable microbial origin, and thrombolites are non-laminated microbial structures, composed primarily of clotted micrite (Riding, 2000 and references therein).

SETTING

Windjana Gorge National Park, the Oscar Range and Dingo Gap were selected as field sites for this project (Fig. 1). Natural polishing of the canyon walls by the Lennard River makes Windjana Gorge an ideal location to examine reef textures in outcrop. Windjana Gorge has well-exposed outcrops of intact Famennian reefal-slope strata, which interfinger with marginal-slope strata at the western entrance of the gorge (Playford, 1981). The Oscar Range was selected as a field site

because of well-exposed outcrops of intact Famennian backreef, reef-flat, reef-margin and reefal-slope strata (Figs 3 and 4). Thus, the combination of Windjana Gorge and the Oscar Range provides a wide spectrum of deposition environments for the Famennian reef.

Dingo Gap was studied for its sand-filled, allochthonous reef blocks, which provide a unique look at Famennian reef textures and reef growth. Although the *in situ* Famennian reef at Dingo Gap has been lost to erosion, 1–50 m reef blocks, which spalled off the prograding Famennian reef margin, are preserved in the forereef strata (George *et al.*, 1997). Some of the blocks have bedding features that can be used to interpret the original depositional environment. With other blocks, the depositional environment must be determined by looking for specific fossils or reef fabrics. During the growth of the Famennian reef, Dingo Gap was an area where siliciclastic sand periodically spilled onto the actively growing reef (George *et al.*, 1997) and filled the reef porosity, capturing the progressive encrustation of thrombolites and other microbialites. The petrographic contrast of the siliciclastic sand in the microbial limestone highlights the mesoscale porosity and aids in determining the morphology and palaeoecology of the microbial communities.

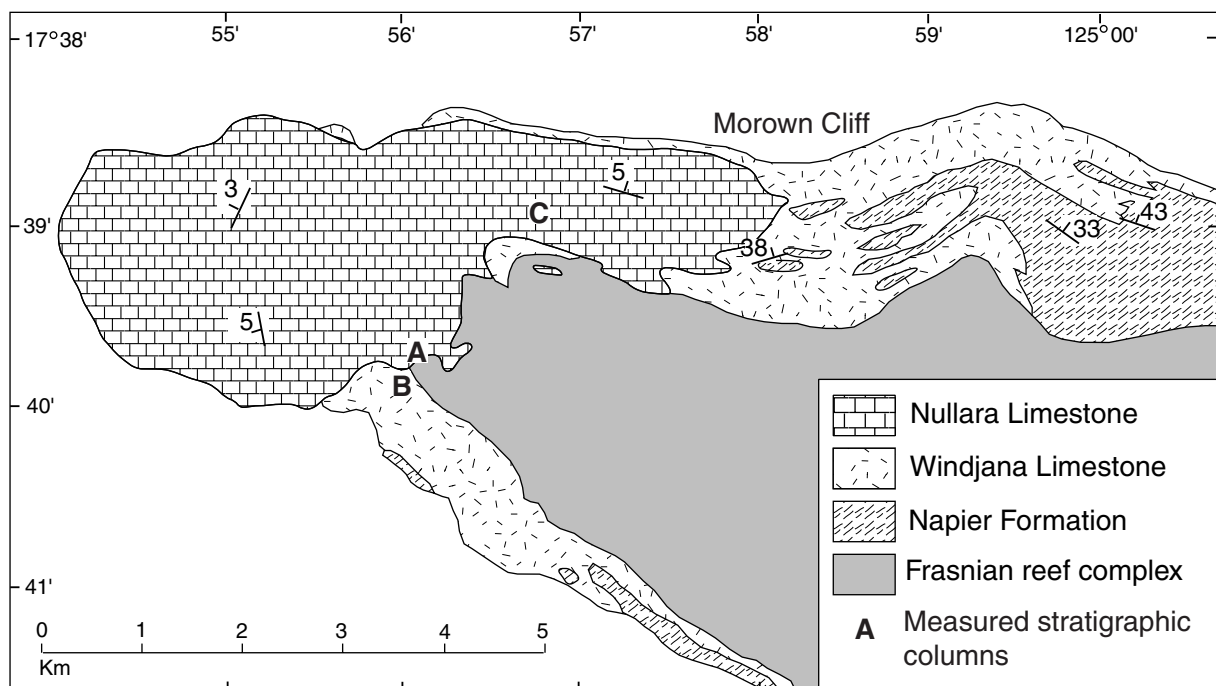


Fig. 3. Map of north-western Oscar Range, modified from Playford & Hocking (1999).

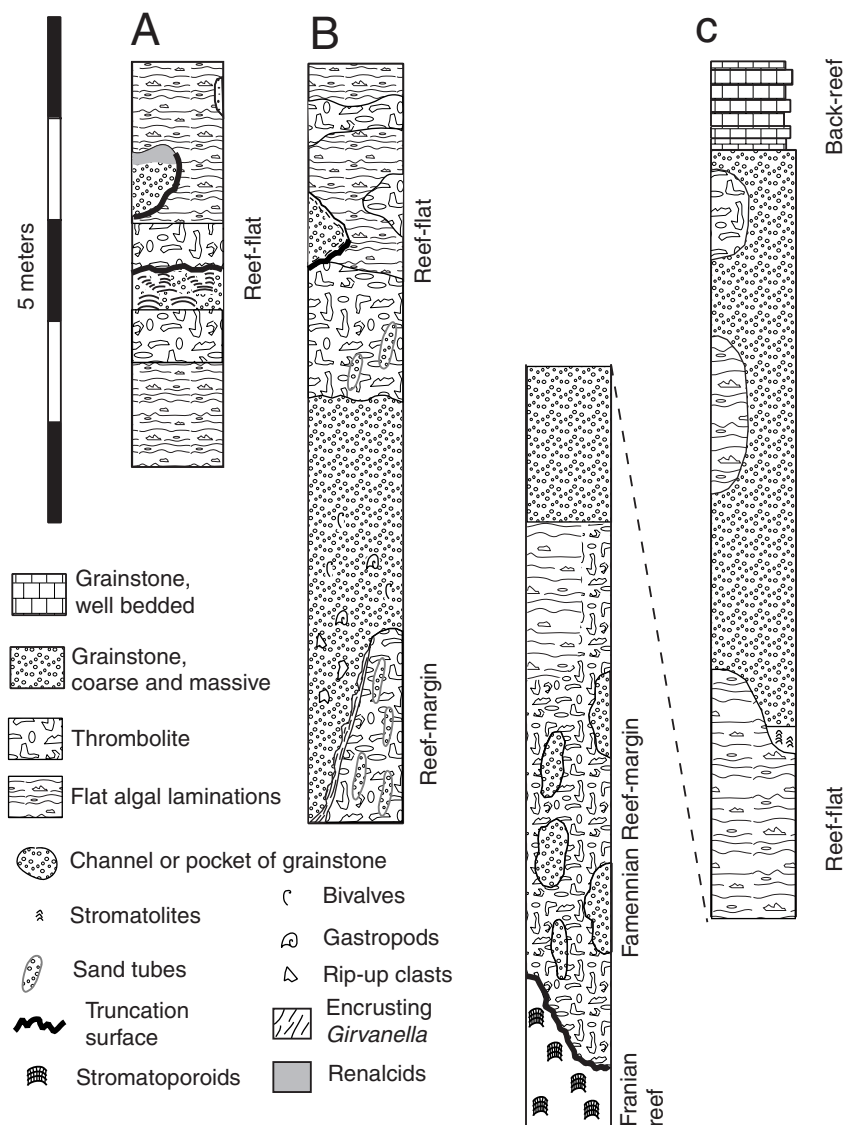


Fig. 4. Stratigraphic columns from Oscar Range. See Fig. 3 for location.

BACKREEF SUBFACIES

Description

The Famennian backreef subfacies in the north-western corner of the Oscar Range (Fig. 3) consists of horizontally deposited, well-bedded strata composed of oolites, oncolites, peloidal grainstones and silty peloidal packstones. The Oscar Range reef complex was physically separated from the mainland and has only minor amounts of siliciclastic grains, unlike other Famennian backreef deposits in the Canning Basin (Kerans, 1985; Hurley, 1986). Medium to coarse grainstones with rip-up clasts are poorly sorted and subangular, whereas the oolite is typically well to moderately sorted and well

rounded. Planar cross-bedding is found locally in the oolite. Wackestones and packstones are more common in the centre of the platform than near the edge (Kerans, 1985). Locally abundant columnar backreef stromatolites are 2–5 cm wide, up to 15 cm high and well laminated with 1 mm scale laminations (Fig. 5). Famennian backreef stromatolites in the Oscar Range are similar to Frasnian backreef stromatolites reported from Windjana Gorge (Playford *et al.*, 1976; Wood, 2000b). Some oncoids have stromatolitic caps. Small tens of centimetres scale bioherms and possible biostromes are locally common. Flat and irregular fenestral porosity is very common in backreef strata. Kerans (1985) described 'bubble fenestrae', or round fenestrae, associated with the oolite and interprets these

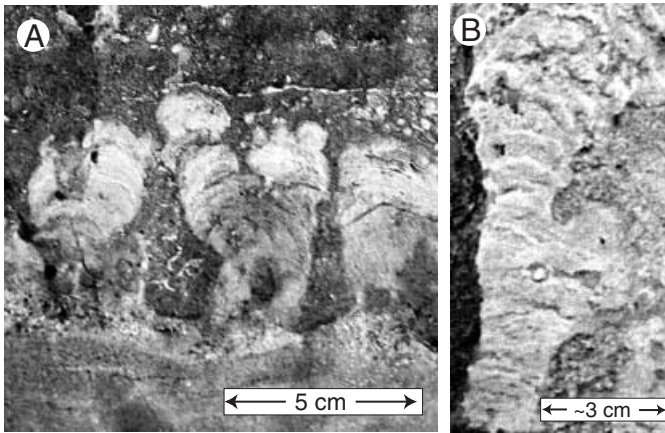


Fig. 5. Field photographs of Oscar Range stromatolites from backreef subfacies (A) and reef-flat subfacies (B).

pores as having been stabilized by cyanobacteria. Tepee structures with tens of centimetres of relief are locally common (Hurley, 1986). Kerans (1985) described pendant and meniscus cements and suggested that these resulted from marine vadose conditions during deposition of the backreef strata.

Interpretation

At the Oscar Range, coarser grain sizes and a paucity of micrite demonstrate that the backreef subfacies near the edge of the Famennian reef platform were in a higher energy environment than the equivalent facies in the platform interior. The cross-bedded oolite at the edge of the Oscar Range platform also suggests a high-energy environment, which was probably similar to modern oolitic shoals from the Bahamas (Imbrie & Buchanan, 1965). Backreef oncoids in the Canning Basin are similar to those reported from the Famennian platforms in Alberta, Canada (Whalen *et al.*, 2002). In the Oscar Range backreef strata, the poorly sorted coarse grainstones are interpreted as episodic storm deposits. Fenestral wackestones and packstones near the centre of the platform may represent a more lagoonal environment (Tucker & Wright, 1990). The meniscus cements and tepee structures may have resulted from episodes of subaerial exposure on the platform (Demico & Hardie, 1994). The backreef stromatolites are interpreted as having grown in moderate- to high-energy environments where sediments were constantly swept across the platform. Backreef stromatolites from the Oscar Range are probably similar to Canadian Famennian stromatolites, which were interpreted as having grown in peritidal environments on carbonate platforms (Whalen *et al.*, 2002).

REEF-FLAT SUBFACIES

Description

The reef-flat subfacies is locally well developed in the Oscar Range (Fig. 4) and consists of fenestral stromatolites, fenestral laminated mats, thrombolites and beds of coarse grainstone. Grainstone layers and channels truncate the microbial textures, and interbeds of coarse grainstone give the reef-flat subfacies its thickly bedded appearance. Channels filled with grainstone are up to several metres across and have abundant large gastropods and megalodont bivalves. They run perpendicular to the platform margin and, locally, younger channels of grainstone cross-cut older ones. The grainstone is massively bedded, moderately to poorly sorted, coarse to very coarse grained and locally reverse graded. Grain types include peloids, ooids, intraclasts, oolitic grapestone, red algae and occasional green algae.

Stromatolites in the reef-flat range from broad, decimetre-diameter domes to small, 2 cm diameter columns (Figs 5–7). The 0.2–1.0 cm thick,

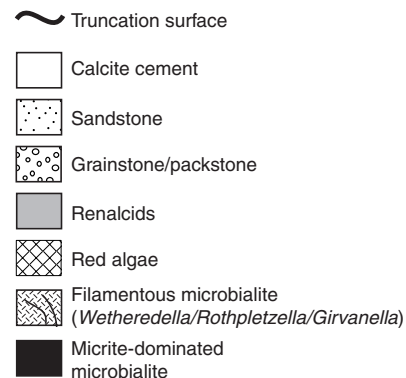


Fig. 6. Symbols used in tracings.

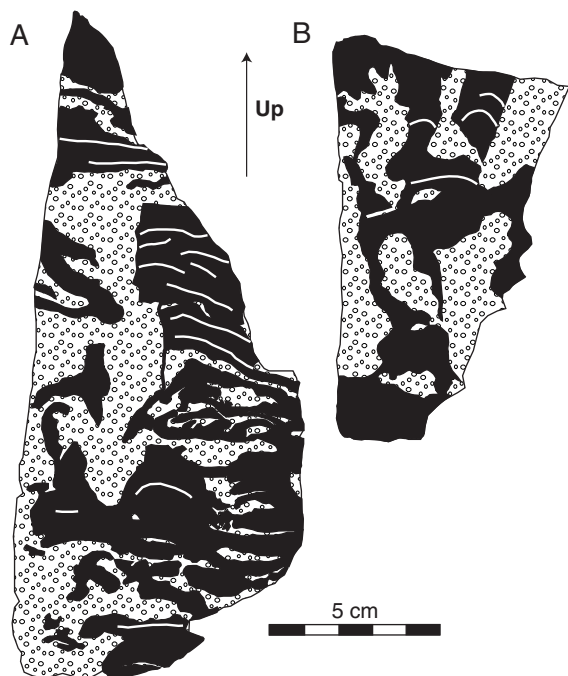


Fig. 7. Tracings from polished hand samples of fenestral stromatolites from the Oscar Range reef-flat subfacies. The lower portion of sample B is thrombolitic. White lines show internal laminations. See Fig. 6 for key.

stromatolitic laminations are irregular and composed of alternating layers of micrite and moderately to poorly sorted, coarse grainstone. Typically, reef-flat stromatolites are more coarsely laminated than backreef stromatolites. Troughs between stromatolite columns are filled with coarse to very coarse, poorly sorted grainstone. The fenestral algal mat textures are petrographically identical to the stromatolitic textures, except that the laminations are flat instead of domed. Within the reef-flat stromatolites and algal mat textures, fenestral pores are very common below the micritic laminations and typically range up to a few centimetres in length and up to 10 mm in height. In the stromatolitic laminations, no algal filaments were observed, but calcispheres are locally abundant.

Fenestral stromatolites grade into thrombolite textures, which locally form biostromes within the reef-flat subfacies. Compared with the stromatolites, the thrombolites lack internal laminations, do not have fenestral pores and are typically associated with a more diverse assemblage of microbial fossils. Reef-flat thrombolites are composed of 1.0–1.5 cm thick clumps and ribbons of micrite, which are separated by 1.0–2.0 cm wide pores filled with encrusting micro-

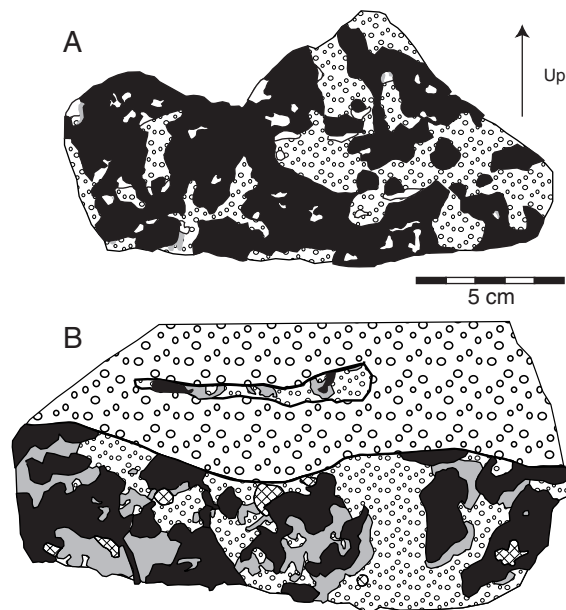


Fig. 8. Tracings from polished hand samples of coarse thrombolite textures from the Oscar Range reef-flat subfacies. Notice the truncation surface and rip-up clast in (B). See Fig. 6 for key.

bial communities and reef detritus (Fig. 8). Porosity accounts for 30–40% of the thrombolite in the reef-flat subfacies. In the Oscar Range, pores within the reef-flat thrombolite textures are typically filled with coarse grainstone and locally abundant encrusting renalcids. Clusters of red algae are occasionally found within the micritic matrix of the thrombolites (Figs 8 and 9).

Interpretation

The reef-flat subfacies was part of a discontinuous rim on the Famennian reef platforms. Because the grainstone in pores, channels and discrete beds is coarse and poorly sorted, sedimentation probably occurred mostly during episodic high-energy events, such as storms. Truncation surfaces suggest proximity to sea level and episodic planing of the microbial fabrics. Channels through the reef-flat may have funnelled much of the backreef detritus away from the microbial communities on the reef flats and down the reef slopes. Thus, microbial communities in the reef-flat environments probably grew close to sea level in an environment free from detrital sediment except during storm events.

In reef-flat and backreef environments, Famennian stromatolites are similar to modern stromatolites and may have formed in similar ways. Famennian stromatolites from the Oscar Range

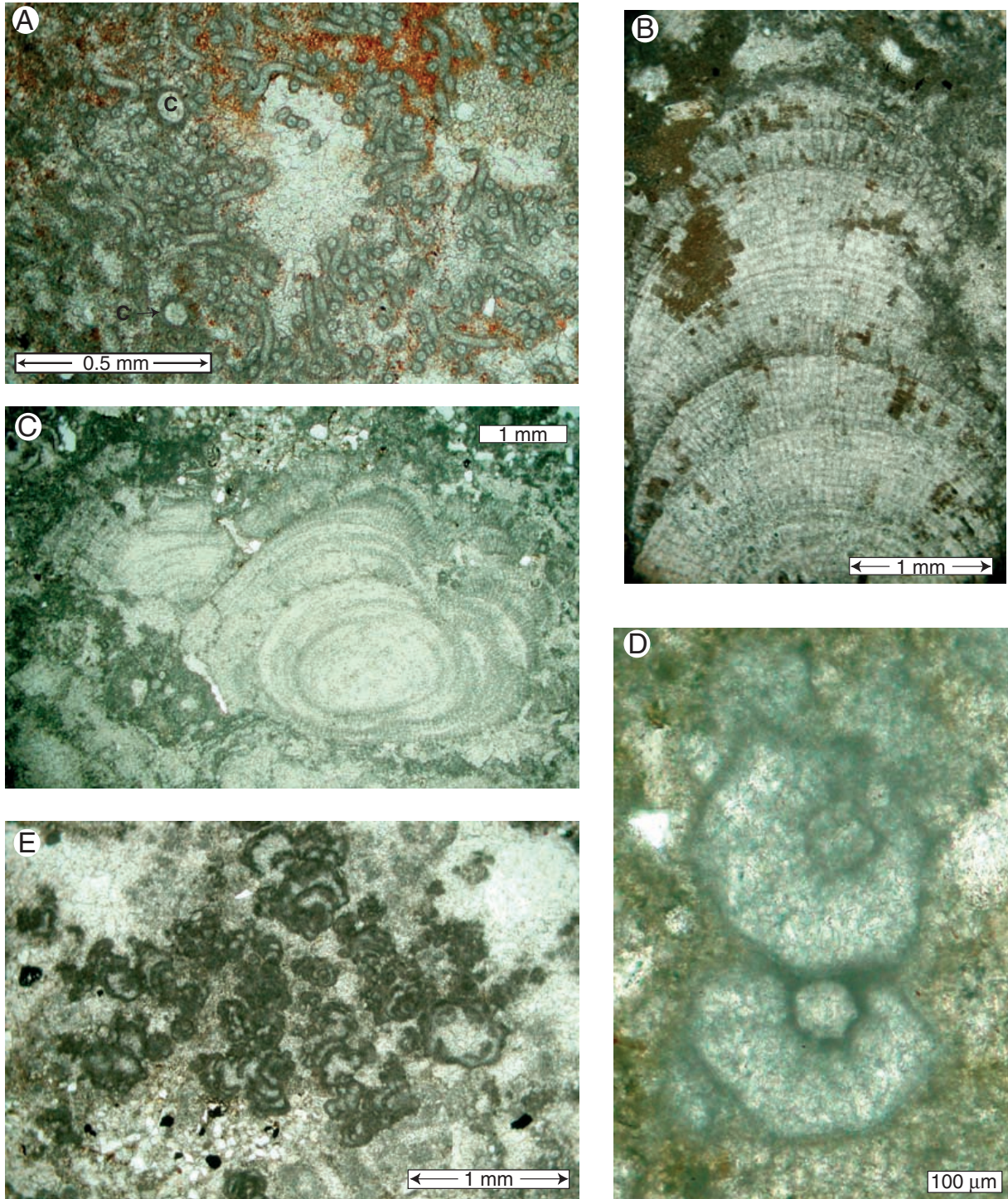


Fig. 9. (A) *Girvanella* from Dingo Gap reef-margin subfacies. Calcispheres are labelled (c). (B) *Parachaetetes* red algae from Dingo Gap, upper reefal slope. (C) *Solenopora* red algae in upright growth position, Dingo Gap reef-margin subfacies. (D) *Uralinella*, encrusting foraminifera, from lower reefal slope, Windjana Gorge. (E) Renalcids from Dingo Gap.

and modern Bahamian stromatolites are both composed of laminations of micrite and grainstone (Feldmann & McKenzie, 1998; Reid *et al.*, 2000; Riding, 2000). The micritic layers in

modern Bahamian stromatolites are formed by photosynthetic biofilms, and the grainstone laminations are bound together by extracellular bacterial polysaccharides and endolithic coccoid

cyanobacteria (Reid *et al.*, 2000). The Famennian stromatolites may have formed by similar microbial processes, although the petrographic evidence for such activity is not, nor is expected to be, preserved (Stolz *et al.*, 2001). Calcispheres in the stromatolitic laminae may be preserved algal spores, and the micritic layers may be calcified biofilms with the poorly preserved remains of shallow-water bacteria and algae (Maurin & Noel, 1975; Feldmann & McKenzie, 1998; Reid *et al.*, 2000). In the Oscar Range, backreef stromatolites are more finely and more evenly laminated than reef-flat stromatolites; the coarsely laminated reef-flat stromatolites grade further into unlaminated thrombolites towards the reef margin. The degree to which these stromatolites were laminated may have been controlled by the energy of the environment and by the frequency of detrital coatings of sediment. The micrite in the thrombolites and stromatolites is petrographically identical and may have formed by similar means. Compared with stromatolites, reef-flat thrombolites are more delicate structures and may represent periods of deepening, where wave energy was not as intense.

REEF-MARGIN SUBFACIES

Description

Famennian reef-margin strata are observed *in situ* at various places in the Oscar Range and are found in some allochthonous blocks at Dingo Gap (George *et al.*, 1997). The reef-margin subfacies consists of mounds of microdigitate thrombolites and encrusting organisms, including *Girvanella*, *Wetheredella* and renalcids. In the Oscar Range, the mounds of thrombolites are several metres across and surrounded by coarse, unbedded grainstone. Encrusting organisms observed along the side of a thrombolite bioherm on the southern margin of the Oscar Range included abundant *Girvanella*, renalcids and rare encrusting bryozoans (Fig. 4B). The grainstone infilling and surrounding the thrombolite mounds is medium to very coarse, moderately to poorly sorted, rounded to subangular with peloids, ooids, gastropods, bivalve shells and angular rip-up clasts of reef material (Fig. 4B). At Dingo Gap, the thrombolite structures are associated with coarse to very coarse, poorly sorted, quartzo-feldspathic sandstone. Whether these thrombolites are bioherms or biostromes could not be determined because of the restricted size and exposure of the

allochthonous reef blocks at Dingo Gap. Large, 2–3 cm gastropod shells are found within the grainstone and sandstone at both Dingo Gap and the Oscar Range.

In the reef-margin subfacies, the thrombolites are 0.5–1.0 cm ribbons of structureless, laminated and clotted micrite, which locally contains microbial filaments, quartz silt, ostracods, red algae and calcispheres. Some of the Canning Basin thrombolite textures are similar to reported reef-margin thrombolites from Alberta, Canada (Whalen *et al.*, 2002). In the Canning Basin, pores are irregular, commonly 0.5–2 cm across and account for 40–50% of the rock (Fig. 10). *Solenopora* is the most common red alga associated with the

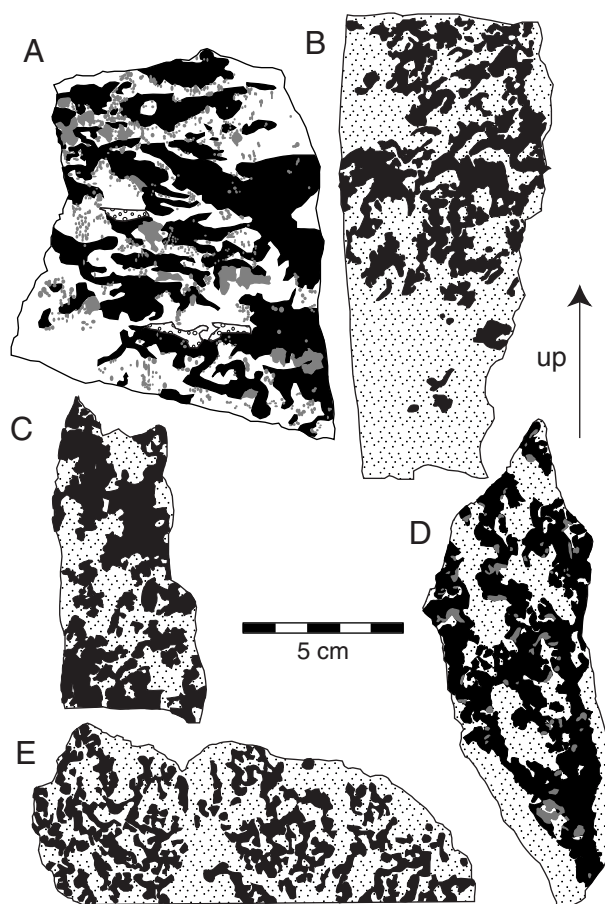


Fig. 10. Tracing of fine thrombolite textures from the Oscar Range and Dingo Gap reef-margin subfacies. The siliciclastic sand, which filled the pores of (B), (C) and (E), prevented encrustation of the thrombolite framework. Sample (D) has minor occurrences of renalcids in the pores, suggesting that sand filled the porosity of the thrombolite after encrustation had begun. In (A), pores contain little allochthonous material, and renalcids are very common in the pores of the thrombolite. See Fig. 6 for key.

thrombolites; however, *Parachaetetes* is present as well. Where red algae are present, five to 10 semi-hemispheres of red algae are typically observed in thin section and commonly trend stratigraphically upwards within the thrombolite structure (Fig. 9). Microbial filaments observed in the thrombolite include *Girvanella*, *Wetheredella* and possibly *Rothpletzella*. The percentage of red algae, *Girvanella* and *Wetheredella* within the thrombolitic micrite is variable and can be in excess of 50%.

Thrombolite pores are filled with reef detritus, sandstone, encrusting microbial communities and/or calcite cement. *Girvanella* and *Wetheredella* are often the first stage of encrustation, and renalcids are often the final encrusting microbial communities. Renalcids in the reef-margin subfacies include both *Shuguria* and *Izhella*. Renalcids are dominantly in pendant growth position within the pores of the microdigitate thrombolites (Stephens & Sumner, 2002). However, not all thrombolite pores contain encrusting microbial communities. Variable amounts of detrital sediment also filled the thrombolite pores and, in some cases, the thrombolite pores were filled entirely by detrital sediment (Fig. 10). In some allochthonous blocks at Dingo Gap, sand lenses overlay thrombolite biostromes, and the depth of infiltration of the sand into the thrombolite pores is $\approx 4\text{--}5$ cm (Fig. 11D). In these reef blocks, the progression of encrustation can be observed, and layers of pore-lining renalcids increase in thickness with stratigraphic depth. Fibrous and equant calcite cements are often the final pore-filling materials.

Long vertical tubes, averaging 7–15 cm diameter and up to 3 m in length, are commonly associated with thrombolite textures. Because the most studied examples of these tubes are filled with siliciclastic sand, they are called sand tubes and are common in the allochthonous reef blocks at Dingo Gap (George & Powell, 1997) (Fig. 12). Reef-margin sand tubes, filled with grainstone, are also present in the Oscar Range. At the edges of the sand tubes, the microbial textures of the host rock are often truncated, but show no evidence of chemical dissolution, such as clays or metal oxides. Many tubes have fairly consistent diameters and, in some cases, sand tubes cross-cut patches of siliciclastic sand (Fig. 12B). The progression of encrustation along the sides of the sand tubes is a filamentous microbial layer – *Wetheredella*, *Girvanella* and possibly *Rothpletzella* – followed by renalcids. However, many sand tubes are not encrusted or are only encrusted by

the filamentous layer. The sand tubes are usually filled with the same type of detrital material that is within the pores of the thrombolite, and the detritus within the sand tubes is typically not bedded.

Interpretation

Compared with the reef-flat subfacies, the massively bedded reef-margin subfacies has fewer truncation surfaces, suggesting less scouring by storms and deposition in deeper water. Because the coarse grainstones and sandstones are poorly sorted and formed massive beds, these deposits are interpreted as storm events, which buried living thrombolite communities (Fig. 13). With the exception of the storm-derived detritus, most of the pores are filled with calcite cement and encrusting microbial communities, suggesting that the reef-margin thrombolites grew in a relatively sediment-free environment. However, some reef-margin thrombolites contain coarse silt and very fine sand within their matrix and within internal pores. The silt and fine sand comprise $\approx 5\%$ of the thrombolite matrix and were probably incorporated into the thrombolite during fair-weather growth conditions.

The thrombolites are *in situ* framework structures, formed by a consortium of different microbes, many of which did not fossilize. Modern Bahamian thrombolites and stromatolites contain several types of microbes, which do not form calcified body fossils but produce calcifying exopolymers (Feldmann & McKenzie, 1998; Reid *et al.*, 2000). Similarly, the micrite in the Canning Basin thrombolites may be a byproduct of microbial activity and calcification of microbial exopolymers. Alternatively, much of the clotted micrite in the thrombolites may be the altered remains of *Girvanella* and red algae. Because red algae bound within the thrombolite matrix are usually in upright growth position, the red algae probably grew *in situ* as part of a microbial community (Fig. 13). In some samples, however, the edges of well-preserved microbial textures grade into micrite, suggesting alteration. Turner *et al.* (2000) recognized that Neoproterozoic thrombolite textures from the North-west Territories were products of taphonomically altered microbial filaments. Owing to the pounding of waves, calcified microbial sheathes might be shattered within a semi-lithified thrombolite, and filaments such as *Girvanella* can easily be altered to micrite (Pratt, 2001). The clotted

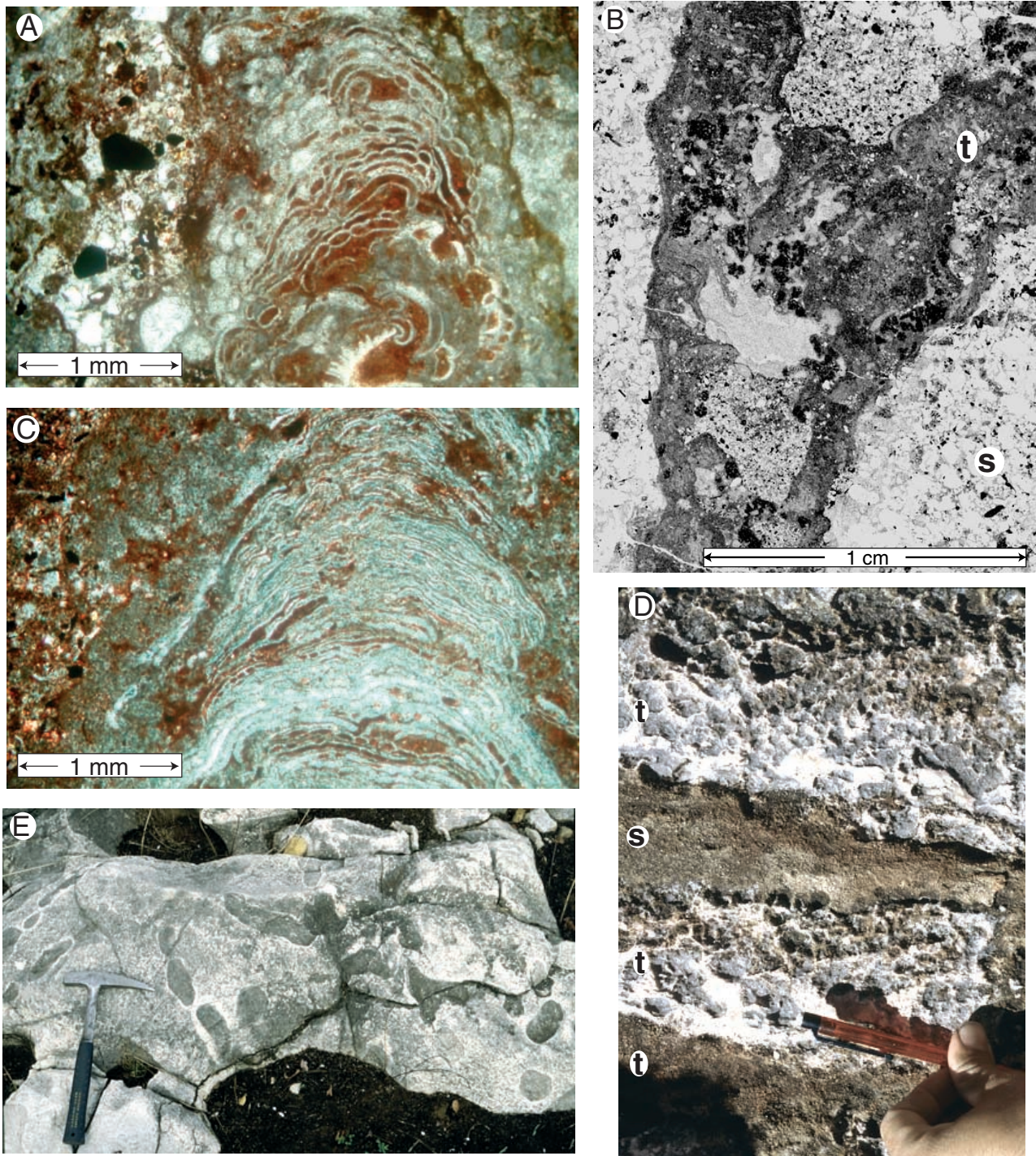


Fig. 11. (A) Microdigitate stromatolite of *Wetheredella* from Dingo Gap upper reefal-slope subfacies. *Wetheredella* are oblong filaments (B). Thrombolite (t) with sandstone (s) filled pores from Dingo Gap reef-margin subfacies. (C) Microdigitate stromatolite of *Rothpletzella* from Windjana Gorge forereef subfacies. (D) Interbedded layers of coarse sandstone (s) and thrombolite biostrome (t). The sand has filled the porosity in the upper 5 cm of thrombolite. Pencil for scale. (E) *In situ* sand tubes from the Oscar Range in reef-margin subfacies (see Fig. 4B).

micrite in thrombolites from the Oscar Range and Dingo Gap may be a combination of altered microbial fossils and calcified exopolymers.

Pores in the thrombolite texture are interpreted as original growth features of the microbial framework. The presence of encrusting microbial

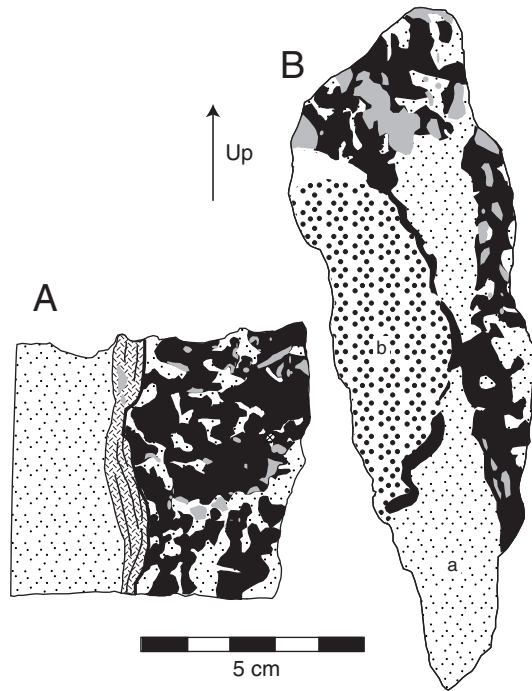


Fig. 12. Tracings of thrombolites with sand tubes from Dingo Gap. (A) The thrombolite texture is truncated, and 1 cm thick undifferentiated filamentous microbialite encrusts the wall of the sand tube. (B) A patch of medium- to coarse-grained sandstone (a) is cross-cut by a very coarse-grained sand tube (b). The sand tube contains a micritic rim. See Fig. 6 for key.

communities within the pores suggests that the pores were connected with the open ocean water, and the irregular shape of the pores does not support bioturbation as a possible origin. A rigid thrombolite framework would have allowed renalcids to grow pendantly from the roofs of the pores (Fig. 13) (Stephens & Sumner, 2002). At Dingo Gap, infilling sand, deposited rapidly over the top of the thrombolite, penetrated 4–5 cm into the thrombolite pores (Fig. 11D), suggesting

rigidity in the thrombolite framework and pore connectivity of at least 5 cm.

The sand tubes are among the most puzzling features of the Famennian reefs. Although George & Powell (1997) described the sand tubes as karst features, Kerans (1985) and Playford (2000) suggested that these tubes are original features of the microbial limestone, and this study provides evidence that reinforces their hypothesis. Sand tubes, which are only observed in thrombolite and some *Wetheredella*-dominated textures (Figs 11E and 12), are not found in many shallower water depositional environments, such as in backreef settings, where karsting should be more abundant. *In situ* sand tubes are also not associated with evidence of exposure surfaces. Along the edge of many sand tubes, microbial textures within the host rock are only partially truncated, and sand tubes cross-cut both limestone and sandstone (Fig. 12B), which is inconsistent with a karst interpretation. The sand tubes appear to be a syndepositional feature of the Famennian reef. For example, they could be tubes formed by soft-bodied organisms, which vacated the tubes before detritus infilling of the cavity. It is suggested that they may have been formed by fluid movement, possibly as a result of tides, through the microbial communities. However, the origin of the sand tubes is still uncertain.

REEFAL-SLOPE SUBFACIES

Description

For this study, the reefal-slope subfacies is divided into upper and lower zones, based on fossil assemblages associated with progressively deeper water depositional environments. Upper reefal-slope strata are exposed in the Morown Cliff in

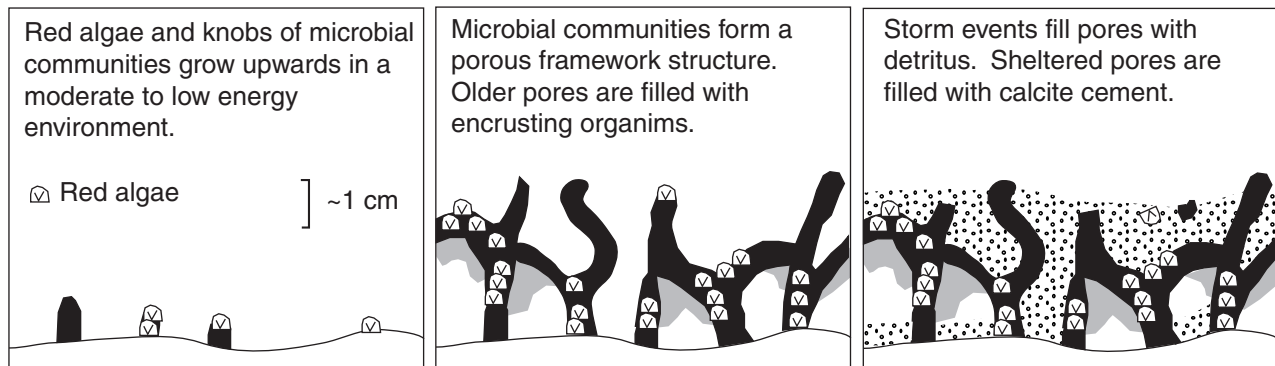


Fig. 13. Model of growth and preservation of Canning Basin thrombolites.

the Oscar Range and can be compared with adjacent reef-margin and backreef strata. The lower reefal-slope subfacies is best observed in outcrop at the entrance to Windjana Gorge. Although Wood (2000a) described the Famennian textures at Windjana Gorge as reef facies, depositional geometries preserved within the gorge demonstrate that these rocks were deposited at least 50 m below sea level. Local dips of slope strata that extend continuously up the high cliff and upright geopetal indicators demonstrate that these sediments could not have been deposited near sea level. Palaeodepth studies from other locations in the Canning Basin also support a deep-water interpretation for the Famennian fossil assemblage at Windjana Gorge (Playford, 1980; Playford *et al.*, 2001), and this assemblage is absent from demonstrably shallower facies. Upper and lower reefal-slope strata from the allochthonous blocks at Dingo Gap are subdivided based on fossil assemblages and textural comparison with the other localities.

Delicate fans and microdigitate stromatolites composed mostly of *Wetheredella* characterize the upper reefal-slope subfacies. Fans and microdigitate stromatolites often grade into each other, are 0.5–1.5 cm across and can be in excess of 15 cm long. In the microdigitate stromatolites, the *Wetheredella* filaments form thin doming layers (Fig. 11A) and, in fans, the sheets of filaments are unoriented or roughly parallel to the long axis of the microbial structure. At Dingo Gap, fans and microdigitate stromatolites often appear to be trending parallel or diagonal to bedding (Fig. 14), and some of the stromatolites appear to have had multiple stages of growth in varying directions (Fig. 14C). The direction of growth of red algae incorporated into the fans and microdigitate stromatolites is parallel to the long axis of the microdigitate stromatolites or fans, whether horizontally or vertically oriented. In the upper reefal slope, *Wetheredella* is the dominant fossil type, with some *Rothpletzella* filaments and *Girvanella* often intertwined with the coarser *Wetheredella* filaments. Renalcids and *Uralinella* commonly encrusted the fans and microdigitate stromatolites, and renalcids are often in pendant growth position.

The size of the pores and types of pore-filling material are variable in the upper reefal-slope strata. Locally, the porosity consists of irregular elongate 0.5–2 cm voids, which resemble the porosity of the reef-margin thrombolites. In other areas, voids in the microbialite can be up to 5–20 cm diameter and filled with sandstone or

grainstone. Similar to reef-margin subfacies, multiple pulses of sand appear locally to have buried the reefal-slope microbial communities. In some allochthonous reef blocks from Dingo Gap, these pulses of sand were just enough to either fill the porosity of the microbial reef or leave a thin bed of sand upon which the microbial communities were re-established (Fig. 11D). Sand tubes are not as abundant as in the reef-margin subfacies but are locally present (Fig. 11E). Stromatactis pores are also locally common. Detrital sediment in the upper reefal slope varied from medium grained and moderately sorted to coarse grained and poorly sorted siliciclastic sand or carbonate debris.

The lower reefal-slope subfacies contains bioherms of microbial bindstone/framestone. At Windjana Gorge, beds of steeply dipping, fine- to medium-grained sandstone and packstone surround the bioherms and give the lower reefal slope its poorly bedded appearance. *Rothpletzella* dominates the microbial structures, which include thin wisps of filaments, large vertical columns, encrustations and stromatolites (Wood, 2000a). Much of the microbial carbonate in the reefal-slope subfacies at Windjana Gorge consists of a highly porous framework composed predominantly of *Rothpletzella* filaments. The *Rothpletzella* microbialite is $\approx 30\%$ of the rock and consists of 0.2–0.5 cm wide, vertically trending wisps of *Rothpletzella* filaments. At Windjana Gorge, the pores associated with the wispy texture are ≈ 0.5 –2 cm wide and filled with renalcids, fine- to medium-grained finely laminated sandstone and calcite cement. Below beds of detrital sediment, many of the filaments appear to have been tilted over. The wispy texture is equivalent to the *Uralinella*–*Renalcis*–*Sphaerocodium* bindstone of Kerans (1985), who estimated that this texture comprises 60% of the Windjana Limestone. In contrast to the wisps, columns of *Rothpletzella* have very little porosity and are composed of vertical trending, layered sheets of filaments. Columns are 5–35 cm wide and can be in excess of 1 m in length (Wood, 2000a). At Windjana Gorge, some low-relief, doming, *Rothpletzella* stromatolites are also present and are similar to those described in Frasnian strata (Playford *et al.*, 1976). The *Rothpletzella* commonly encrust deep-water fauna such as sponges, bryozoans, rare deep-water stromatoporoids and rare deep-water corals (Wood, 2000a). Some *Girvanella* and *Wetheredella* are also observed intergrown with the layers of *Rothpletzella*. Renalcids and *Uralinella* are the major pore-filling microbial

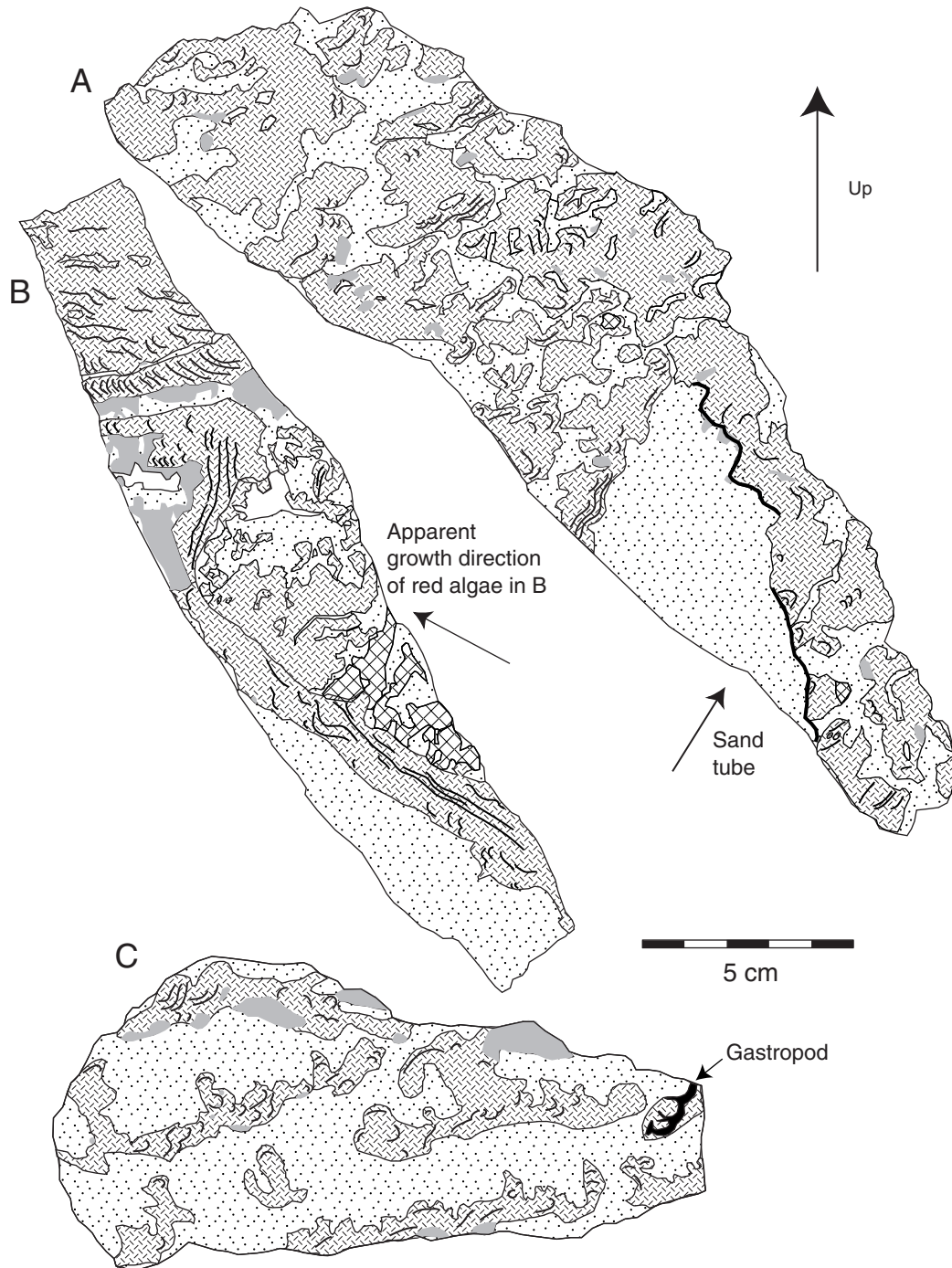


Fig. 14. Tracings of *Wetheredella* textures from upper reefal-slope subfacies, Dingo Gap. Laminations within *Wetheredella* structures are shown as lines. (A) The *Wetheredella* texture is only partially truncated around the sand tube. (B) The apparent direction of growth of the red algae is the same as the orientation of laminations in the *Wetheredella* fan below it. In (B) and (C), *Wetheredella* stromatolites appear to be trending parallel to bedding and, in (C), vertically oriented *Wetheredella* stromatolites appear to be branching off the horizontal stromatolites. Many of the *Wetheredella* structures are interpreted as having been syndepositionally toppled over. See Fig. 6 for key.

communities in the lower reefal slope (Kerans, 1985) (Fig. 9D).

Locally in the upper and lower reefal slope, porosity is in the form of stromatactis. Stroma-

tactis pores are flat bottomed and reticulate with digitate roofs (Bathurst, 1980; Kerans, 1985) (Fig. 15). Although isolated stromatactis pores can be observed, they are commonly in groups, or

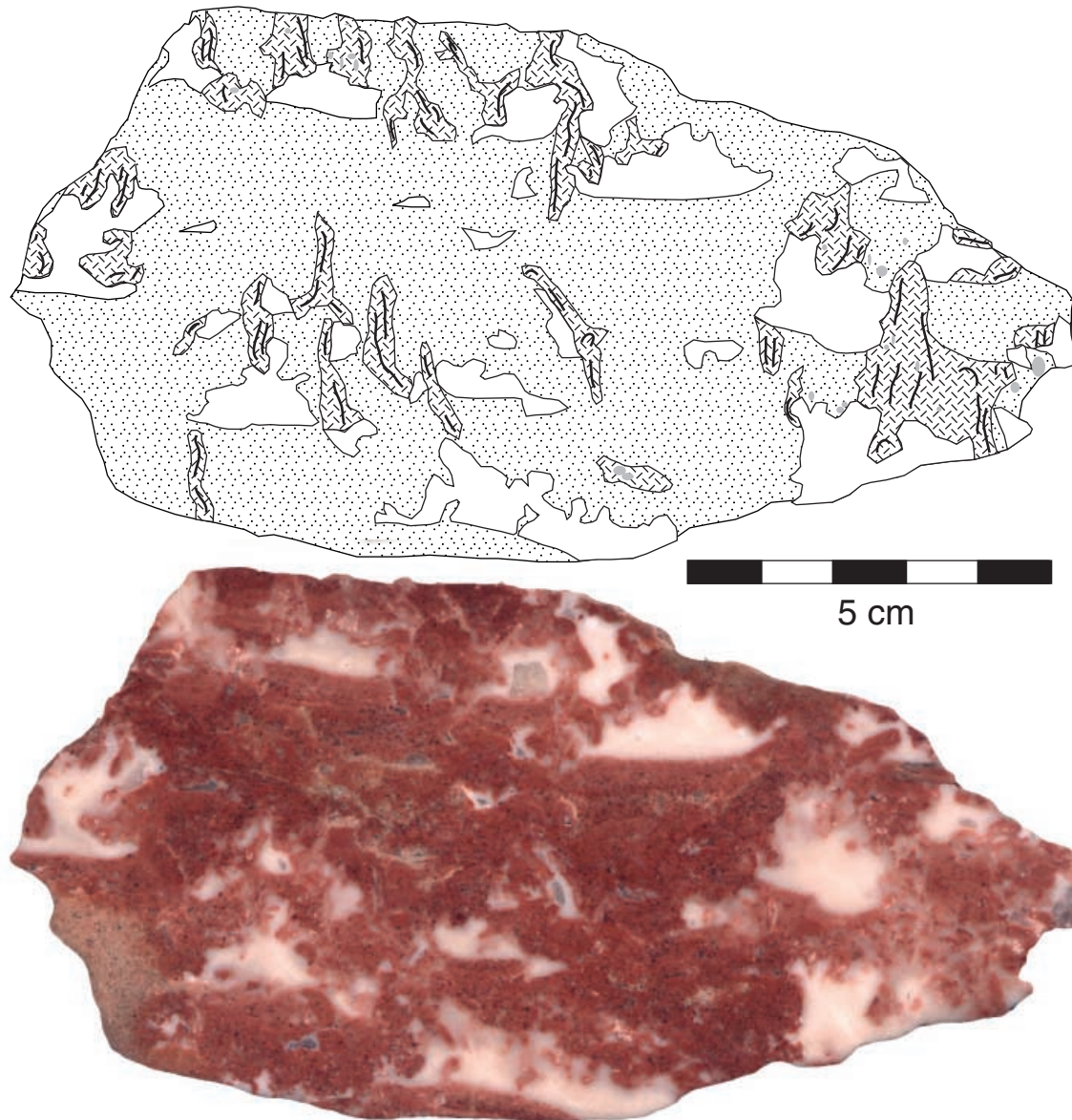


Fig. 15. Polished hand sample of stromatolite texture and tracing. Many of the stromatolite pores are associated with *Rothpletzella* filaments. This sample is interpreted as coming from a lower reefal-slope depositional environment. See Fig. 6 for key.

'swarms', locally forming a substantial percentage of the rock (Kerans, 1985). In some samples from the upper reefal-slope subfacies, subhorizontal columns and fans of microbial communities form the roofs of the stromatolite pores, and fine siliciclastic sand partially filled pores to form the flat base. At Windjana Gorge, many of the largest stromatolite pores have roofs composed of a combination of filamentous microbial communities and either sponges or bryozoans. However, many stromatolite pores do not show visible microbial framework in their roofs. Renalcids are commonly found encrusting the roofs of the

stromatolite, and most stromatolite pores are filled by both fibrous and equant cements.

Interpretation

The reefal-slope subfacies was deposited in a relatively deep-water, low-energy environment. Based on depositional geometries preserved in outcrop, the lower reefal slope was deposited at least 50 m below sea level at Windjana Gorge and may locally have been up to 300 m below sea level (Kerans, 1985). Storm events may have affected the reefal-slope subfacies by mobilizing

detrital sediment, which cascaded down the reefal slope. At Dingo Gap, coarse sandstone in the upper reefal-slope strata is similar to storm-derived beds in the reef-flat and reef-margin subfacies. In the lower reefal slope, abundant fine- to medium-grained sandstone/grainstone is interpreted as detrital sediment, which may have passed through channels on the edge of the platform.

In the upper reefal-slope subfacies, microbial communities of mostly *Wetheredella* formed delicate structures that are interpreted as syn-depositionally toppled over (Fig. 16). Within these microbialites, red algae are aligned in growth position along the long axis of the microbial structure. As stromatolitic laminations within the microbialite and *in situ* red algae are oriented oblique or parallel to bedding, they are interpreted as toppled over. In quiet-water settings, the microbial communities probably competed for sunlight by growing upwards as quickly as possible and extending delicate structures up into the water column. However, during storm events, these structures would have been knocked over and partially covered with variable amounts of coarse sand. Once the storms had passed, the *Wetheredella* re-established itself and, in some cases, the observed stromatolitic laminations of the *Wetheredella* turn from hori-

zontal to vertical, suggesting renewed growth (Figs 14 and 16). Thus, multiple storms probably produced the intermingling of sand and variably oriented *Wetheredella*-dominated structures, common in some allochthonous blocks at Dingo Gap.

At Windjana Gorge, the lower reefal slope was a low-energy environment, where competition for light resulted in vertically trending microbial filaments, many of which were unsupported or loosely supported by other microbial fossils (Fig. 16). In many of the wispy *Rothpletzella*-dominated structures at Windjana Gorge, pores between vertically trending filaments are filled with laminated, fine-grained packstone, which may have settled through the water column. Sediment may have gently rained down out of the water column or cascaded down the reefal slope as a debris flow. Some microbial structures are tilted over and covered by a thick layer of packstone, suggesting burial by cascading sediment. Some of the stromatactis pores were formed by sediment partially filling and burying a highly porous microbial framework (Fig. 15). Alternatively, some stromatactis may have developed through the decay of buried soft-bodied organisms, such as sponges and cyanobacterial clumps (Kerans, 1985; Wallace, 1987).

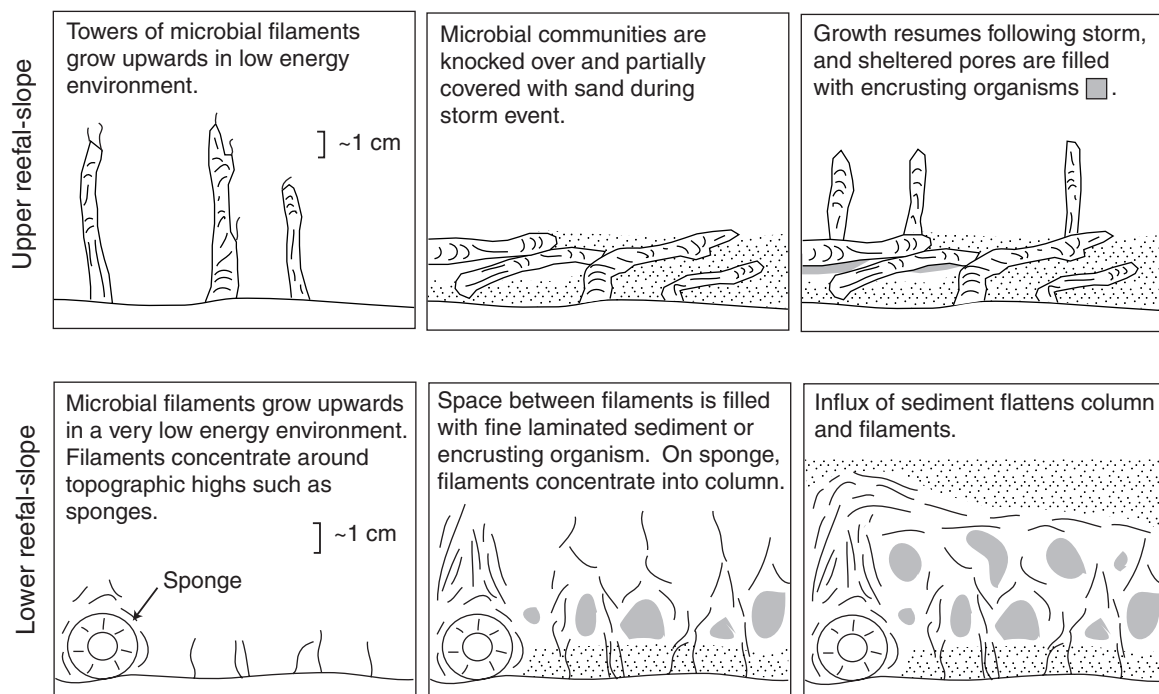


Fig. 16. Model of growth and preservation of microbial structures in the reefal-slope subfacies.

FOREREEF SUBFACIES

Description

The forereef subfacies has steeply dipping beds of grainstones, packstones and sandstones, which interfinger with the reefal-slope subfacies (Playford, 1980). These strata are typically well bedded and contain occasional brachiopods, crinoids and nautiloids. Lenses of reef-collapse breccia and allochthonous reef blocks are often interbedded within these strata (George *et al.*, 1997; George & Chow, 2002). Although *in situ* microbial communities are rare in this subfacies, deep-water stromatolites are common on the tops of allochthonous reef blocks and present as rare stromatolitic horizons (Playford *et al.*, 1976; George, 1999). Some stromatolites are composed of microdigitate laminations of *Rothpletzella* (Fig. 11C). Most stromatolites are broad domes with fine, even laminations and, in thin section, do not contain preserved microbial filaments. Detrital sediment associated with the stromatolitic horizons is commonly silt or very fine sand.

Interpretation

The forereef subfacies consists of detrital sediment, which passed over the platform or collapsed off the edge of the platform. Most of the forereef environment was probably in deep water (> 50 m). Whether the deep-water stromatolites were primarily photosynthetic or heterotrophic is uncertain. The deep-water stromatolites probably grew very slowly in environments with low levels of sedimentation (George, 1999).

DISCUSSION

The early Famennian reef complexes in the Canning Basin were constructed almost entirely by microbial communities. No skeletal reef-building fauna were present in shallow-water depositional environments and, in the deep-water reef, the proportion of skeletal fauna is minor compared with the microbial communities. During early Famennian time, reef construction may have initiated with microbial mounds stabilizing and aggrading the marginal-slope environments. Once the deep-water reefs were established, the shallow-water reefs prograded towards the basin. Rapid rates of calcification during Late Devonian time may have allowed algae and bacteria to create rigid microbial structures (Playford, 1980;

Riding, 2000). Encrusting microbial communities may have added further structural stability to the microbial framework (Wood, 2000a; Stephens & Sumner, 2002).

Wave energy was perhaps the most important factor in determining the morphology of the microbial communities. The morphologies of the microbial structures in the reef-flat subfacies are the most compact and include doming and encrusting forms. Like massive ball-shaped corals in modern reef-flat environments (James, 1983), these microbial structures were able to withstand moderate wave energy. The laminations of the stromatolites in the backreef and reef-flat environments may have formed partially in response to periodic influxes of migrating sediment, similar to modern stromatolites in the Bahamas (Reid *et al.*, 2000). The morphology of the thrombolite was also affected by wave energy. The coarsest thrombolites form in the reef flat, where the porosity of the thrombolites is about 30%. The reef-margin thrombolites are more delicate with 40–50% porosity. Thrombolite structures were rigid enough to withstand periodic storms because they are mostly observed in upright growth position. For the reefal-slope microbial communities, outcompeting each other by growing upwards was more important than wave resistance. Therefore, in the upper reefal slope, *Wetheredella*-dominated structures were long and delicate but were often knocked over during storms. In the lower reefal slope, wave energy was not a factor, and the microbial communities simply tried to grow upwards. As a result, many of the *Rothpletzella* filaments are observed trending vertically upwards in the lower reefal slope (Fig. 16).

Trends in the morphology of modern reef organisms as well as the microbial community in the Famennian reef may result from biological and physical constraints on growth. Corals and other colonial reef organisms consist of a thin living film growing on top of a dead calcium carbonate skeleton. The microbial communities were also growing on top of calcified remains of previous members of the community. In both corals and microbial communities, the morphology is a balance between optimizing photosynthesis by growing dendritically into the water column and creating a wave-resistant structure by growing as a massive low-relief community (Kaandorp, 1994). Unlike metazoan structures, however, microbial structures can rarely be attributed to a single organism. For example, thrombolites from the Canning Basin are

composed of red algae, *Girvanella* and microbially derived micrite. Modern thrombolites and stromatolites are also composed of many species of microbes (Feldmann & McKenzie, 1998; Reid *et al.*, 2000). The manner in which the microbes grew as a community was highly variable and depended on the energy of the depositional environment. A microbial filament or floc probably grew upwards until a wave or current flattened it against the community structure.

The ability of microbial communities to adopt different morphologies may have allowed these communities to flourish in shallow-water reef environments following the Frasnian–Famennian mass extinction. During early Famennian time, most reef-building metazoans dwelt in deep water and had delicate morphologies. Metazoans required millions of years to adapt their morphology to suit the shallow-water environments. However, not having predetermined mesoscale morphologies may have allowed microbial communities to colonize the shallow-water environments opportunistically. It was not until the later part of the Famennian stage that bryozoans and stromatoporoids became re-established in the

shallow-water reef environments of the Canning Basin (Kerans, 1985).

CONCLUSION

Microbial communities are able to construct robust reefs when the competition from reef-building fauna is removed. During Famennian time in the Canning Basin, microbialites of mostly *Rothpletzella* formed mounds and ledges, which stabilized sediment in the lower reefal-slope environment. High calcification rates during Late Devonian time may have facilitated the construction of the microbial framework. The microbial reefs aggraded to sea level forming reef platforms with discontinuous rims of reef-flat and reef-margin strata. Similar to modern reefs, the Famennian reefs in the Oscar Range had oolitic shoals near the edge of the platforms and channels cutting through the reef margin. Wave energy from periodic storms truncated microbial textures in the reef-flat environment and transported sediment into the reef-margin and reefal-slope environments.

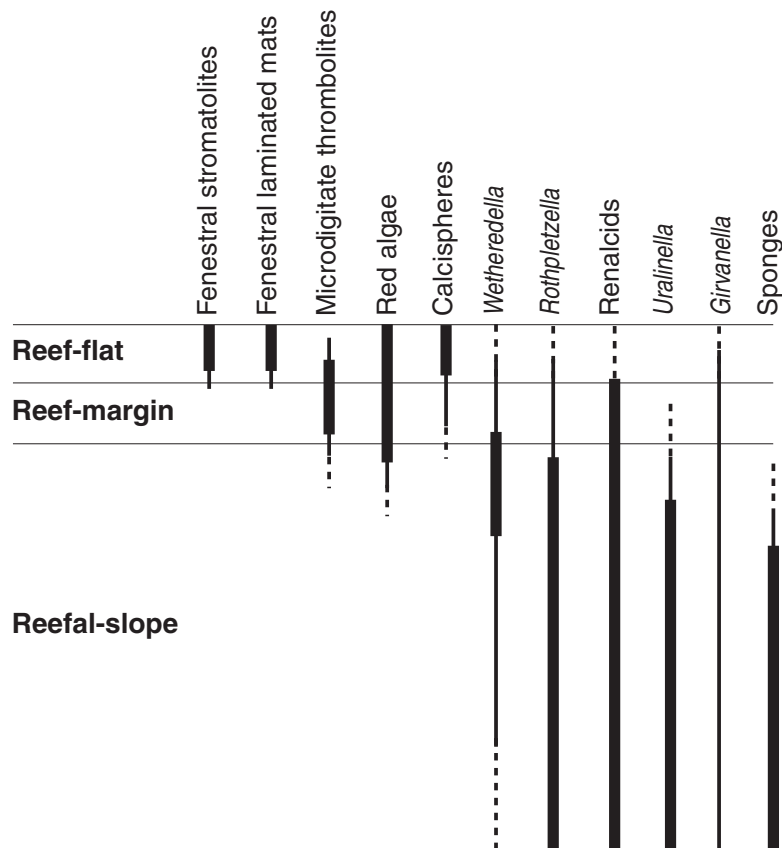


Fig. 17. Distribution of fossils and microbial structures with respect to Famennian reef subfacies.

In the Napier and Oscar Ranges of the Canning Basin, the energy of the depositional environment controlled the morphology of the microbial communities and distribution of the organisms (Fig. 17). Doming stromatolites and flat algal mats dominated the reef-flat subfacies, which was the highest energy environment. The reef-flat stromatolites were composed of alternating laminations of grainstone and micrite and may be analogous to modern stromatolites. Famennian thrombolites are micritic microdigitate structures, which were more massive in the reef-flat environments and more delicate in the lower energy reef margin. The thrombolite framestone often contains *Girvanella* filaments, and red algae within the thrombolitic matrix are commonly found in growth position. In deep-water environments, filaments of *Wetheredella* and *Rothpletzella* formed most of the more delicate microbial structures, many of which were syndepositionally knocked over.

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