

Calcmicrobial stromatolites at the Permian–Triassic boundary in a western Tethyan section, Bükk Mountains, Hungary

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Abstract

Basal Triassic carbonates of the Gerennavár Formation (Bükk Mountains, Northern Hungary) were studied. The succession was deposited in an open marine deep ramp environment of the western Tethys, and can be divided into three parts on the basis of the dominant microfacies. The lowermost 0.5 m-thick interval is made up by thin-bedded and bioturbated mudstones which contain ostracods and *Earlandia* along with relict skeletal fragments. The successive 8 m-thick deposits consist of planar stromatolites with well-preserved microfabrics. The most characteristic microfabric elements are sphere clusters in a dense micrite groundmass, bushy aggregates of micrite clots, bundles of prostrate micrite threads, and peloids. The formation of the spheres and the surrounding dense micrite is attributed to calcification of a coccoid–cyanobacteria dominated mat community. The tufted micrite clot clusters crudely resemble *Angusticellularia*. A filamentous microbial origin is likely for the thread bundles. The peloids are interpreted either as reworked pieces of calcified mat, or rolled microbial clumps. The reduced preservation of microfabric components in the upper unit refers to less favourable condition for mat development which is probable due to deepening of the depositional environment. The overlying mudstone unit is very poor in fossils. The preservation of microbial microfabrics in the stromatolites indicates that early lithification by carbonate precipitation was widespread and intense even in open marine environments following the end-Permian boundary events. This supports the assumption that significant changes took place in geochemistry of seawater during the Late Permian–Early Triassic time interval.

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1. Introduction

Microbialites are regarded as a prominent feature of the aftermath of end-Permian mass extinction, and their occurrence could reflect an ocean-scale event (Kershaw et al., 2002). Microbial carbonates forming sheets, mounds and biostromes, or crusts of ambiguous origin, above the fossil-rich uppermost Permian beds have been reported from several Tethyan shallow shelf sections (summary by Baud et al., 2005a,b). Elimination of grazing, burrowing, and substrate-competing organisms

allowing generalist and opportunists, including microbial communities, to occupy large parts of the shelves after the end-Permian boundary event (Schubert and Bottjer, 1992). Otherwise, Riding's (1997, 2000) microbial calcification model stressed that microbial carbonate formation depends mainly on early lithification irrespective of competitive interactions. Calcite precipitation within a polymer biofilm is facilitated either by bacterial-mediation or environmentally driven controls (Merz, 1992; Chafetz and Buczynski, 1992; Knorre and Krumbein, 2000; Merz-Preiß, 2000; Riding, 2000; Dupraz et al., 2004; and references therein). Grotzinger and Knoll (1995), and then Kidder and Worsley (2004) drew attention to the possibility of significant changes

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of marine geochemistry during Late Permian–Early Triassic, which may have promoted calcite precipitation (Kershaw et al., 2002). According to Riding and Liang (2005), combination of reduction in metazoan diversity and rising seawater saturation state could explain the changes observed in microbial carbonate abundance after the end-Permian mass extinction.

A wide spectrum of microbialite types has been described from peritidal to open shelf settings at the base of Lower Triassic formations. Stromatolites in peritidal carbonates are reported from Germany and Poland (Kalkowsky, 1908; Peryt, 1975; Paul and Peryt, 2000), Italy (from the Southern Alps, Noé, 1987; Twitchett, 1999), and from Hungary (Transdanubian Range, Haas et al., 2004). Various types of open marine stromatolites, thrombolites, and massive or clotted micritic mud-mounds are documented from Turkey, Armenia, NW and Central Iran, and Oman (Baud et al., 1997, 2005a,b; Heydary et al., 2000; Milroy et al., 2000; Baud and Richoz, 2004; Richoz et al., 2005). Microbial-like digitate forms of ambiguous origin forming crusts were reported from China

(Kershaw et al., 1999, 2002). The crust was resampled and studied in other localities by Ezaki et al. (2003) who interpreted the thrombolitic crusts as microbial in origin. Thrombolites and stromatolites were reported from China (Wignall and Twitchett, 1999; Lehrmann et al., 1998, 2003; Lehrmann, 1999; Adachi et al., 2004), and Japan (Sano and Nakashima, 1997). The latter is generally associated with large amounts of calcite cement.

Microbial carbonates were recently recognised in basal Triassic carbonates in the Bükk Mountains, Northern Hungary. The aim of this paper is to describe the mudstone beds and planar stromatolites in this carbonate succession formed above the Permian–Triassic event boundary, and to document an open marine microbial carbonate occurrence in the western Tethyan realm.

2. Geological setting

The Bükk Mountains are located in Northern Hungary, to the south of the Western Carpathians (Fig. 1).

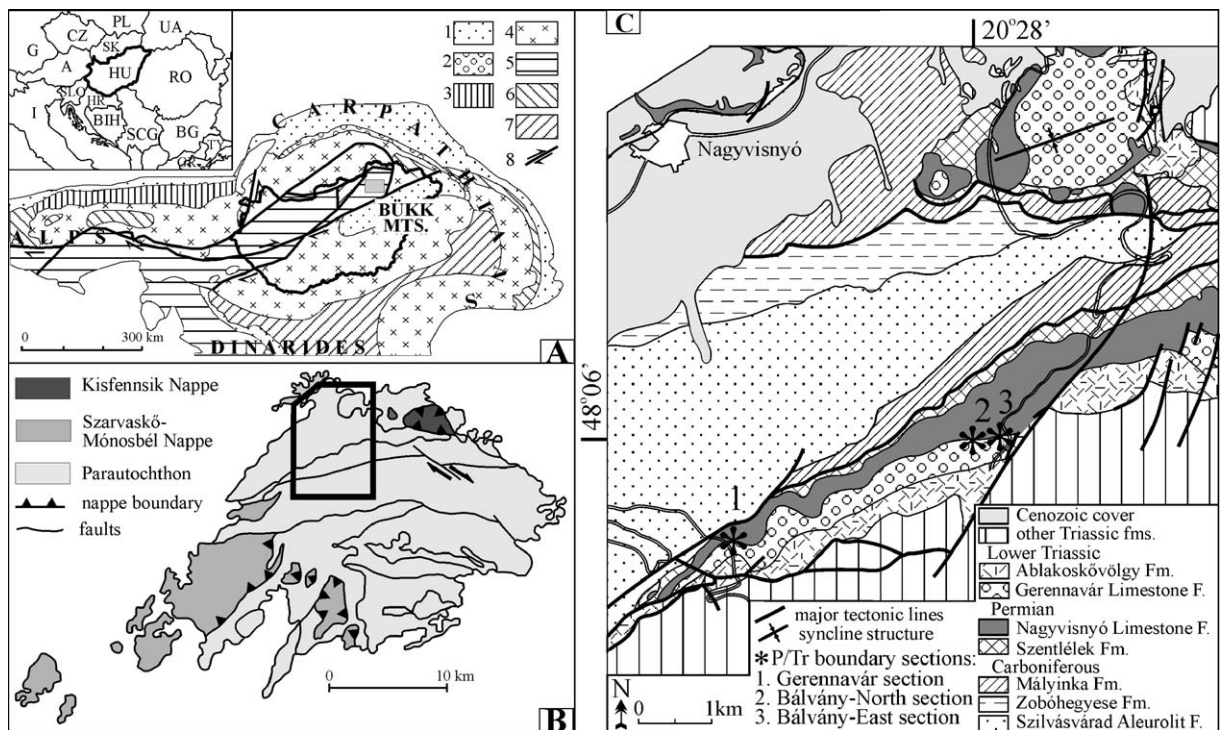


Fig. 1. Geologic map of the studied area. A: Schematic terrain map of Circum Pannonian Region with location of the Bükk Mountains (grey rectangle) (Kovács et al., 2000), 1. Flisch Belt, 2. Klippen Belt, 3. Northern Calcareous Alps, 4. Early Alpine units related to European continental margin, 5. Early Alpine shelf sequences related to the Apulian (Southern Alps and Outer Dinarides) continental margin, 6. Ophiolites of the Penninic Ocean, 7. Ophiolites of the Vardar Ocean, 8. major strike-slip zones; B: simplified geologic map of the Bükk Mountains, without Cenozoic cover (after Less et al., 2002); C: geologic map of the northern part of the mountains (rectangle on B) with locations of the sections studied (after Less et al., 2002).

According to palaeogeographic reconstructions (Filipović et al., 2003) the Palaeozoic–Mesozoic sequence of the Bükk Parautochthon was formed in the northwestern neighbourhood of the Sana–Una and Jadar Block (Dinarides). The Upper Permian–lowermost Triassic formations were deposited on the subtidal carbonate ramp of the Dinaridic–Alpine branch of the western Tethys (Haas et al., 2004).

The Bükk Unit approached its present-day position during the Tertiary as a result of large northeastward dextral strike-slip movements along the zone of the Mid-Hungarian Lineament. The Bükk Mountains is made up of anchi-metamorphosed Palaeozoic–Mesozoic formations that were subjected to intense deformation, and are overlain by non-metamorphic Palaeogene–Neogene formations (Árkai, 1973, 1983; Csontos, 1999; Less et al., 2002). Permian–Lower Triassic formations are known only in the northern part of the Bükk (‘northern anticline’).

3. Stratigraphy

Balogh (1980) distinguished and defined the Upper Permian Nagyvisnyó Limestone and Lower Triassic Gerennavár Limestone formations in the Bükk Mountains (Fig. 2). A more detailed subdivision was given by Pelikán (in Fülöp, 1994) for the Permian–Triassic boundary interval. He recognised a *c.* 1 m-thick silty marlstone bed (‘basal bed’), and a 5.5 m-thick thin-bedded and laminated limestone bedset (‘transitional bedset’) at the base of the Gerennavár Limestone. Hips and Pelikán (2002) first reported the stromatolite beds in the lower part of the Gerennavár Limestone, but did not deal with the details of the boundary interval. Since the microbial carbonates occur almost immediately above the silty marlstones the ‘transitional bedset’ were regarded as equivalent to the stromatolite interval. However, recent investigations of stromatolites in the Gerennavár section revealed that there is no direct

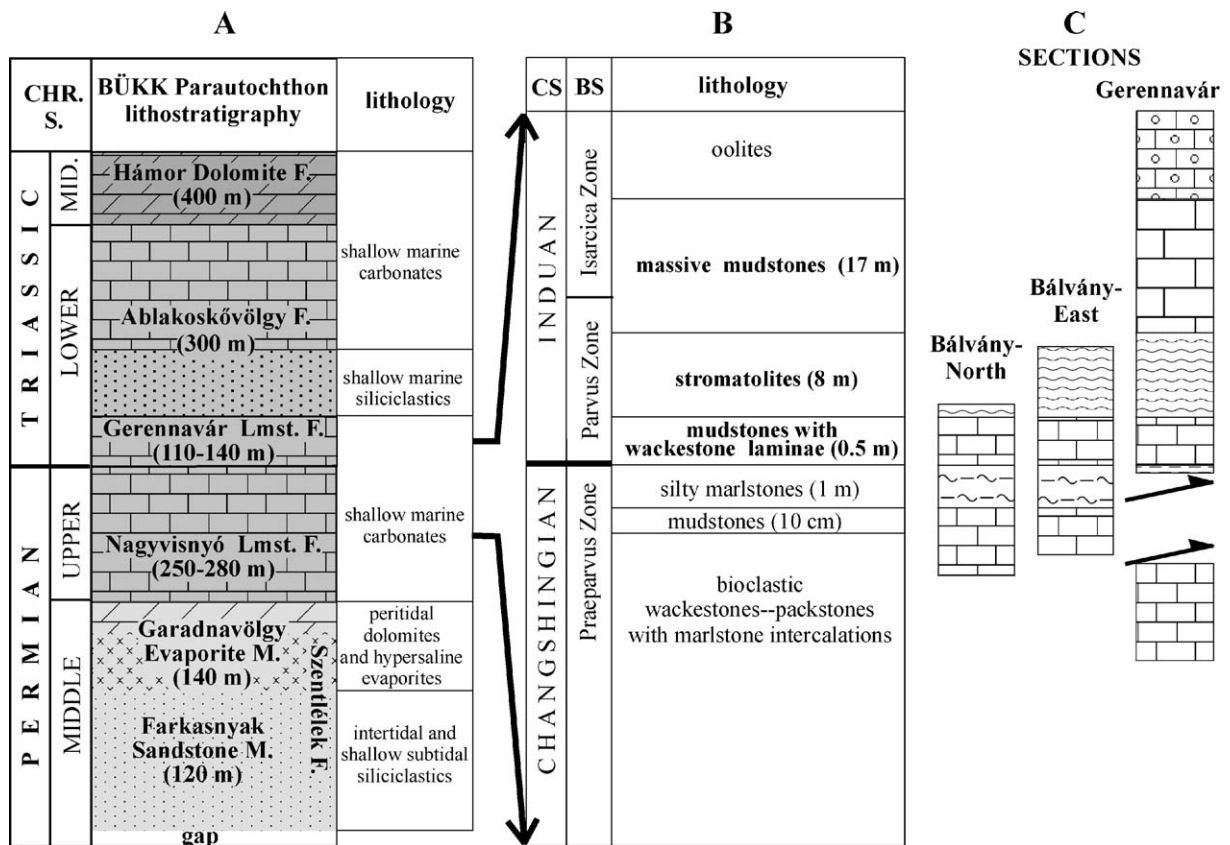


Fig. 2. Stratigraphical setting of the Upper Permian and Lower Triassic formations in the Bükk Mountains. A: General scheme of the Permian and Lower–Middle Triassic lithostratigraphy in the Bükk Parautochthon (Filipović et al., 2003), CHR.S.: chronostratigraphy; B: lithological units and biostratigraphical subdivision of the uppermost Permian–lowermost Triassic, CS: chronostratigraphy, BS: biostratigraphy; C: simplified log of the studied sections.

relationship between the macroscopically thin-bedded and laminated limestones, defined as the ‘transitional bedset’, and the stromatolites recognised mainly by microscopic studies.

In the Bükk Mountains the Upper Permian is represented by the Nagyvisnyó Limestone Formation (250–280 m) (Fig. 2), a unit equivalent to the Badiota facies of the Bellerophon Formation in the eastern part of the Southern Alps (cf. Noé, 1987) and the Dinarides (Pešić et al., 1988). The Nagyvisnyó Limestone consists of black and dark grey, thick-bedded limestones with thin marl interlayers, and dolomites at the lower part (Balogh, 1964). The beds contain a rich biota of dasycladacean algae, foraminifers, sponges, anthozoans, bivalves, gastropods, nautiloids, ostracods, trilobites, brachiopods, bryozoans, echinoderms, scolecodonts, conodonts, and chondrichthyes (Balogh, 1964; Kozur and Mock, 1977; Kozur, 1985; Pešić et al., 1988). According to Kozur (1988, 1989), the formation has an age ranging from Capitanian to Changhsingian.

At the uppermost part of the formation (70 cm below the top) the thick-bedded bioclastic limestones change to thin-bedded wackestones–packstones, containing fine sand- to silt-sized biotritus, with thin marlstone interlayers. Conodont *Hindeodus praeparvus* Kozur was found in this interval (Haas et al., in press-b). The two topmost, thin mudstone layers, 10 cm in thickness, record a dramatic decrease in biogenic components, indicating the first biotic decline (Haas et al., 2004).

The overlying silty marlstone bed, the ‘boundary shale bed’ (Haas et al., 2004) (*c.* 1 m in thickness) that is regarded as the basal bed of the Gerennavár Limestone Formation (Fig. 2), preserves the last Permian bivalve and brachiopod assemblage (Posenato et al., 2005). Disappearance of macrofossils, and sand- to silt-sized bioclasts in the upper third of this bed marks the second biotic decline (Haas et al., 2004). Carbon isotope values display a negative shift in this bed, and a prominent peak in its upper two-thirds (Haas et al., in press-a). The significant negative peak of the carbon isotope curve is considered as an isotope stratigraphic marker (review in Bowring et al., 1998). Based on these data, the Permian–Triassic event boundary can be drawn within the silty marlstone bed.

Upwards, the Gerennavár Limestone Formation is made up by limestones 110–140 m in thickness. The lowermost *c.* 8.5 m-thick interval of the carbonate succession contains the stromatolites (Fig. 2). Only small quantities of microfossils were found in this interval, including fragments of dasycladacean algae, foraminifers, molluscs, ostracods, spirorbid worms,

holothuroidea sclerites, ophiuroid fragments, and conodonts. Among the foraminifers simple and persistent *Earlandia* dominate. However, a few foraminifers characteristic of Changhsingian strata were also encountered. Recently, *Hindeodus parvus* (Kozur and Pjatakova) together with *H. praeparvus* Kozur were found in the lowermost limestone beds (Haas et al., in press-b). It is crucial, because the definition of the GSSP for Permian–Triassic boundary was based on FAD of the conodonts *H. parvus* (Yin et al., 1996, 2001). Upsection, about 17 m of massive mudstones very poor in fossils occur. Along with ostracods, an advanced form of the conodont *H. parvus* (Kozur and Pjatakova) was found at *c.* 14 m above the lower boundary of the Gerennavár carbonates (from the core drilling Mályinka-8, Kemesnye Hill, det. Kozur) indicating *Isarcica* Zone (Induan). Upsection, thin bioclastic grainstone layers, and oolites make up the bulk of the formation (Hips and Pelikán, 2002).

4. Studied sections

There are a few sections in the Bükk Mountains which expose the Permian–Triassic boundary interval and basal Triassic carbonates (Figs. 1, 2). These sections show the same facies trend and the basic characteristics are similar; however, there are differences that are due to subsequent tectonic disturbance (Haas et al., 2004). The stratigraphic data presented above and the results of sedimentary studies reported in this paper summarize observations collected from all the sections studied.

The palaeontological and geochemical investigations revealed that the Bálvány–North section most completely records the event boundary interval. However, the interval exposed here is not more than 3 m thick (Haas et al., 2004). This forest road-cut section is located near the top of Bálvány Peak, 1 km NW of Bánkút, in the northern Bükk Mountains, and exposes the uppermost beds of the Nagyvisnyó Limestone and the lowermost beds of the Gerennavár Limestone. No significant tectonic disturbance was observed in the section measured. Recognition of the Permian–Triassic event boundary is based on biostratigraphic data (Haas et al., 2004, in press-b; Posenato et al., 2005), and the significant negative carbon isotope peak measured in this section (Haas et al., in press-a). The basal Triassic carbonates–46 cm of thin-bedded and laminated limestones with thin shale interlayers, and a 20 cm-thick basal part of the stromatolites–are exposed at the top of the section.

The nearby complementary Bálvány–East section is located 500 m from the Bálvány–North section.

However, because of the oblique cut with respect to the bedding there is almost twice the virtual thickness of beds in the lower part of the section compared to the previous section. This section exposes a much thicker stratigraphic interval, including the microbial beds, in the lower part of the Gerennavár Limestone. However, the 7 m-thick stromatolite beds are slightly disturbed here by a small structural fold.

With regard to the microbial beds, the best section is found at Gerennavár cliff. This section is situated at the foot of a cliff on the steep slope of the Leány Valley that exposes almost the entire succession of the Gerennavár Limestone, *c.* 100 m in thickness. In the lower part of the section the uppermost beds of the Nagyvisnyó Limestone and the prominent ‘boundary shale bed’ are tectonically reduced (Haas *et al.*, 2004). In contrast, the overlying thin-bedded mudstones (0.5 m) and the stromatolite interval (8 m) seem to be undisturbed. The stromatolite interval can be divided macroscopically into two parts: a thin-bedded, 4.3 m-thick lower part and a thick-bedded, 3.7 m-thick upper part. The description of the basal Triassic carbonates is mainly based on the study of Gerennavár section.

5. Depositional facies of basal Triassic carbonates

Sedimentary and microfacies features of the carbonates in the lower part of the Gerennavár Limestone are summarized below. Three consecutive microfacies types were recognised: mudstones with wackestone laminae, stromatolite boundstones, and massive mudstones (Fig. 2). According to Zhu and Chen (1992), and Riding and Sharma (1998) a distinction can be made between the overall small-scale appearance and arrangement of stromatolite laminae, which is the microstructure, and their internal microscopic compositional details that is microfabric. This paper follows these definitions.

5.1. Mudstones with wackestone laminae

The silty marlstone bed is directly overlain by dark grey, thin-bedded and evenly laminated limestones, *c.* 0.5 m in thickness. The typical microfacies is mudstones with a few scattered microfossils (*Earlandia*, foraminifers which commonly occur in Changshingian strata, and ostracods). Along with these components small fragments of dasycladacean algae, molluscs, brachiopod shells and spines, together with sand-sized quartz and mica grains were encountered in a few thin interlayers. The most characteristic textural feature is bioturbation patches ranging up to a few millimetres

in diameter. Burrow margins are diffuse suggesting a soft substrate. These patches are preferentially dolomitized or contain scattered dolomite rhombs. One thin spongiostrome micrite lamina was also found in this interval.

5.1.1. Facies interpretation

The mudstones were deposited in a low-energy environment. The fine bioturbation in the wackestone interlayers may have been redeposited by storms below storm wave-base. The majority of the fragmented bioclasts could be reworked relict Permian elements, except of the simple persistent foraminifer *Earlandia* and the relatively abundant ostracods. Between storm events the benthic fauna slightly disturbed the laminated sediments. However, preserved thin-bedding suggests that the depth of bioturbation did not generally exceed a few centimetres. The spongiostrome micrite implies that microbes had already started to colonize the seafloor.

5.2. Stromatolite boundstones

The horizontally laminated microbial carbonates occur above the platy mudstone unit. The stromatolite interval can be divided into two parts. In the Gerennavár section the 4.3 m-thick lower unit is laminated and thin-bedded, whereas the 3.7 m-thick upper unit is thick-bedded where the lamination gradually disappears upwards.

The lamination is most pronounced where black and dark grey macrolaminae alternate in submillimetre scale, up to 2–3 mm in thickness. This occurs in some intervals of the lower unit, whereas crinkle lamination prevails in the upper unit (Fig. 3A). Neither erosional discontinuities below or above the stromatolite unit, nor evidence of subaerial exposure within the stromatolites was found.

The stromatolite microstructures are characterized by dark, dense or clotted micrite exhibiting various distinct microfabrics and light, massive, finely crystalline detrital deposits. They most commonly compose alternating dark–light lamina couplets (Fig. 3B). Otherwise, lighter detrital carbonates commonly fill the space among the dense micritic elements. Some of the dense micrite laminae form simple wrinkled crusts, whereas others exhibit very complex internal microfabrics (Fig. 3B). The dense or clotted micrite, which is the most typical stromatolite texture, is interpreted—on the basis of the various microfabrics described below—as precipitates within microbial mat. Both microfabric preservation and small crystal size suggest relatively rapid crystalli-

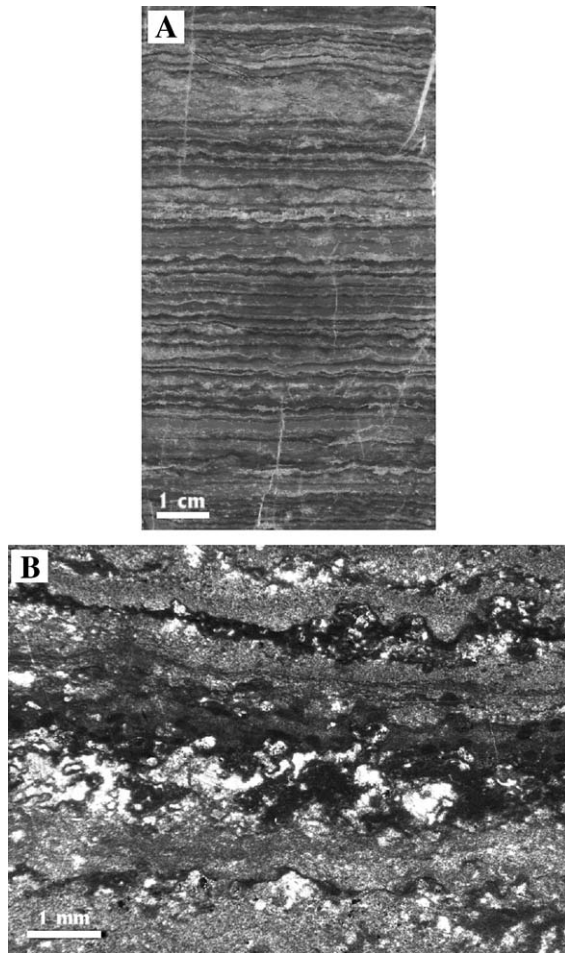


Fig. 3. Macro- and microlamination of the stromatolites studied. A: Crinkle macrolamination from the upper stromatolite unit. B: Typical microstructure of alternating dense microbial and light detrital laminae. Note thickness variation of the microbial laminae.

zation rate. The distinctive microfabric elements are interpreted as syndepositional calcified remains.

The succession of microbial precipitates is punctuated by detrital carbonate laminae or interlayers. They are most commonly typified by massive micrite, without any internal fabric and having smooth upper surfaces. They appear as very thin micritic films or laminae up to several millimetres in thickness. The thicker detrital laminae may contain single reworked elements of dense micrite laminae, e.g. mudstone flakes, articulated shells surrounded by a thick micrite mantle, and single spheres with micrite envelopes. Some centimetre-thick interlayers in the uppermost part of the lower stromatolite unit consist of graded successions of bioclastic grainstones–wackestones–mudstones. In one level of the lower unit (*c.* 80 cm above the basal layer) bioturbation also occurs.

The basal layer of the stromatolite unit consists of round micrite peloids and dense micrite flakes. The peloidal texture grades into micrite or clotted micrite groundmass. Otherwise, there is gradual transition in the upper stromatolite unit to the overlying massive mudstones together with a gradual diminishing of the dense micrite laminae. Additionally, reworked mat chips disappear upsection.

5.2.1. Facies interpretation

The planar stromatolites represent laterally extensive and most likely a continuous sheet of microbial mats. In the area studied, no lateral facies differentiation was observed within the stromatolite unit. Similarly to the underlying Upper Permian subtidal ramp deposits, the basal Triassic carbonates exhibit fairly uniform features over the whole area of the Bükk Parautochthon. A relatively low-energy open marine environment on a deeper ramp may have been the site of formation of this facies. Loose fine sediments of the intercalating detrital laminae were most likely transported by weak bottom currents of storms. In the upper part of the lower unit, recurrent accumulation of lamina triplets reflects slightly enhanced current activity.

5.3. Massive mudstones

The stromatolites are overlain by thick-bedded massive mudstones, 17 m in thickness. A single thin lamina is enriched in disarticulated ostracods compared to the mudstones, which are generally very poor in fossils. In the lower part of the interval silt-sized detrital carbonates of probable bioclastic origin are abundant. The mudstone unit is overlain by a few thin bioclastic layers, and by a thick oolite packstone–grainstone unit.

5.3.1. Facies interpretation

Mudstones without any definitive sedimentary structure may have been deposited in a low-energy environment below storm wave-base. The lamina with ostracods is interpreted as distal tempestites, in which the bioclasts were reworked by storms. The overlying thick oolite packstone–grainstone succession suggests high-energy shallow subtidal deposition leading to the building of oolite shoals (Hips and Pelikán, 2002).

6. Stromatolite microfibrics and microstructures

Regarding the fine, microscopic features in the dense micrite laminae of the stromatolite unit, in addition to the trapped particles and cavernous voids, four basic

distinct micritic elements could be distinguished. These are sphere clusters, bushy aggregates of micrite clots, prostrate micrite threads, and peloids.

6.1. Dense micrite laminae

Most of the dark laminae are composed of basically massive micrite. In addition to recognisable bioclasts, this contains significant amount of relatively large-sized sparry calcite and occasionally dolomite rhombs. The calcite spars have either sharp or diffuse boundaries, and based on this observation two different modes of their formations are interpreted. The former type is most likely composed by diagenetically altered sand-sized skeletal fragments, which were trapped in the mat. Aragonite precursors of the detritus are inferred. The spars with diffuse boundaries probably formed via dissolution (cf. Golubic, 1976) or winnowing where the secondary vugs were filled by spar cement. The upper surfaces of laminae are commonly sharp and irregular or wavy, and in cases show evidence of erosion.

6.2. Sphere clusters

This microfabric is typified by clusters of micrite-walled hollow spheres up to *c.* 50 μm across. Their most common size ranges between 30 and 40 μm . It is a general feature that the spheres are close-packed and embedded in dense micrite matrix. The spheres most commonly adhere to each other by dense micrite, forming grape-like clusters of various sizes and shapes (Fig. 4A). The clusters are commonly arranged in thin, dissected and irregular laminae. However, many winnowed or eroded single spheres rimmed by a thin micrite halo are scattered in detrital laminae. In a few levels, larger aggregates of loosely piled clusters also occur.

The spheres themselves are filled by diagenetic equant, drusy microspar akin to that of the microcrystalline groundmass. Because of the surrounding dense micrite, their micrite walls are not always distinctly visible. Where they are clearly visible they commonly consist of a single concentric microcrystalline cortex (Fig. 4B). However, in some cases the walls are composed of multiple microcrystalline cortices that are most commonly asymmetric to one side. Moreover, there are clusters where dense micrite clots of similar size occur among the spheres. The micrite-walled spheres are considered to be calcified microbial remains that were preserved due to early mineralization.

In the laminae with spheres, there are irregular pores with protruding micrite flakes that are occluded by

calcite spar (Fig. 4C). The pore-walls are generally not sharp. These pores were most likely created through either early dissolution in the lithified crust, or winnowing of the dense micrite precipitates, which is indicated by their irregular shape. The sparry calcite filling the voids is regarded as subsequent diagenetic precipitate. Otherwise, part of the sparry calcite patches, especially those having round outlines, suggest recrystallization or differential calcification of the spheres.

6.3. Bushy aggregates of micrite clots

The microfabric of dense micrite laminae is most commonly characterized by upward-expanding tufted aggregates, up to about 2 mm tall, of spheroidal to very irregular micritic clots ranging between 50 and 200 μm in diameter. The tiny spherical clots are commonly close-packed and coalesced to form larger, more irregular knots (Fig. 5A). The arborescent clumps of irregular knots straddle interstitial framework voids which are filled by microspar grading to spar or partly probable detrital carbonates (Fig. 5B). However, even larger thromboids (2 mm) formed by amalgamation of knot clusters are found. These micrite clots and larger clumps are also regarded as early calcified microbial remnants. Some of these morphotypes might be referable the calcimicrobe *Angusticellularia* (Riding pers. com., 2004; cf. Riding, 1991).

Where the microstructure is typified by light–dark lamina couplets, the thickness of the dark, clotted micrite laminae can range from 50 μm to 2 mm, and can vary according to the evolutionary stage of the mat. Prominences make their upper surface rough, and where the laminae thin out they may become dissected. The thicker laminae of micrite clots exhibit reticulate microfabric and appear to be cavernous (Figs 3B, 5C). These laminae are made up by relatively large micrite-walled chambers, which are filled by uniform micrite clots (Fig. 5D). The ‘empty’ chambers are occupied by calcite spar. Since the filled clot-chambers are comparable in size and shape to the empty cavernous space, the clearing of chambers and dispersal of dense micrite clots as loose peloids is possibly due to winnowing by weak currents. The loose peloids are accreted parautochthonously on top of dense micrite laminae (Fig. 5C). Slight truncation of the top of dense micrite laminae can be assumed in some cases. In spite of the erosion of pockets, the fabric has not collapsed which suggests its internal rigidity and early lithification. The structures preserved indicate that early lithification led to formation of a surface crust from which calcified elements could be winnowed by currents. This also implies that

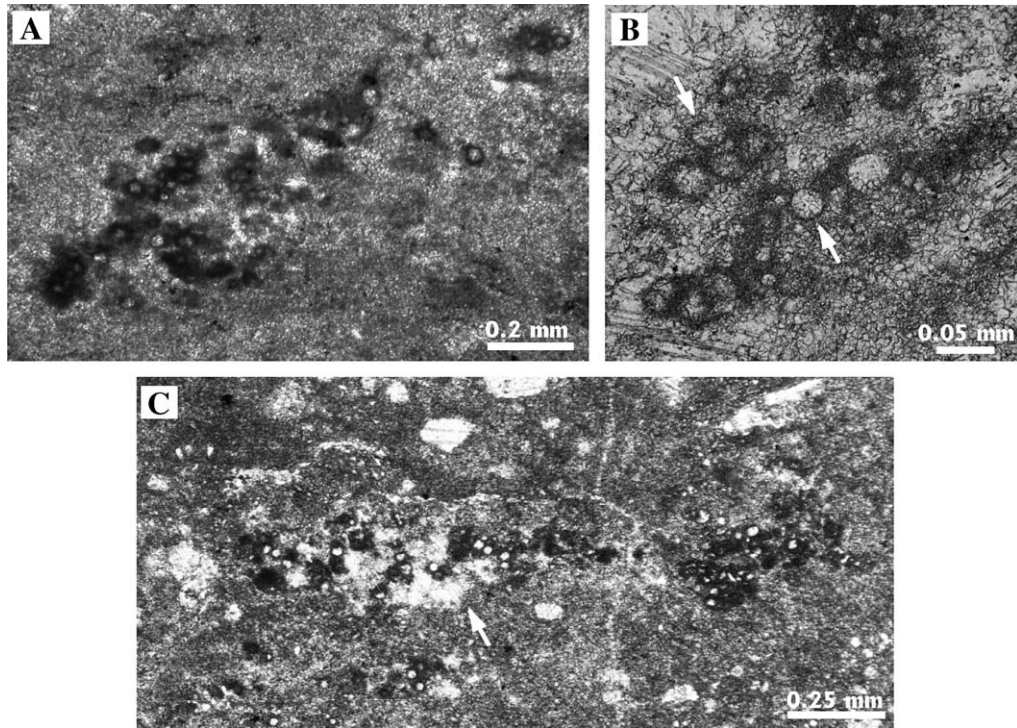


Fig. 4. Microfabrics of laminae with sphere clusters. A: Grape-like clusters of the spheres involved in dense micrite. B: Details of sphere clusters. Note microspar filling and thin micrite rim of the spheres (arrows). Close-packed spheres are visible on left side. C: Sphere clusters and related spar-filled vugs (arrow). Note diagenetically altered sand-sized biodebris (top).

at least a part of the detrital carbonates originated from the calcified laminae.

6.4. Prostrate threads

This fabric type is typified by wrinkled, shorter or longer micritic threads arranged more or less parallel to the lamina surface. Single threads rarely occur, and have spiral or crinkle forms and are mainly scattered in detrital laminae (Fig. 6A). Bundles of threads can form laminae which commonly exhibit scallop structures or pustular surfaces (Fig. 6A, B). Otherwise, the threads are commonly associated with micrite clots (Fig. 5B, C). In the upper stromatolite unit obscured dissected, crinkle threads and clots within a finely crystalline detrital groundmass are characteristic. A filamentous microbial origin is inferred for this distinct microcrystalline component (cf., e.g. Monty, 1976).

6.5. Peloids

The peloidal microfabric only occurs at some levels. The laminae are composed by peloids of various shapes and sizes, ranging 100–500 μm in diameter. The peloids

are distinct grains with sharp margins (Fig. 5C, D). Many have an outer zone composed of denser micrite that grades inward to microspar. In these cases, it is commonly clear that the peloids are constructed by elemental spheres. A couple of fused spheres can comprise various patterns, most commonly threaded rings or spherical or elongated clumps. The peloids gradually lose their microfabric details as the sphere clusters grade into dense micrite. This might indicate that each peloid consisted originally of sphere cluster that now are only in part preserved in minute detail. Arrangement of peloids in some cases shows imbrication on top of the lamina.

Peloids are commonly associated with bushy aggregates of micrite clots that may form the basal or other parts of the laminae among the peloids. The dense, clotted micrite also contains sphere clusters, but in these cases they have no distinct boundaries and form irregular knots. Microspar fills the pores among the peloids, and calcite spar occludes the larger voids which are most likely of winnowed origin. Compositional details of the peloidal laminae and of the peloids themselves suggest that peloids can be interpreted as calcified remains of rolled microbial clusters. Thus, their formation is akin to that of micro-oncoids.

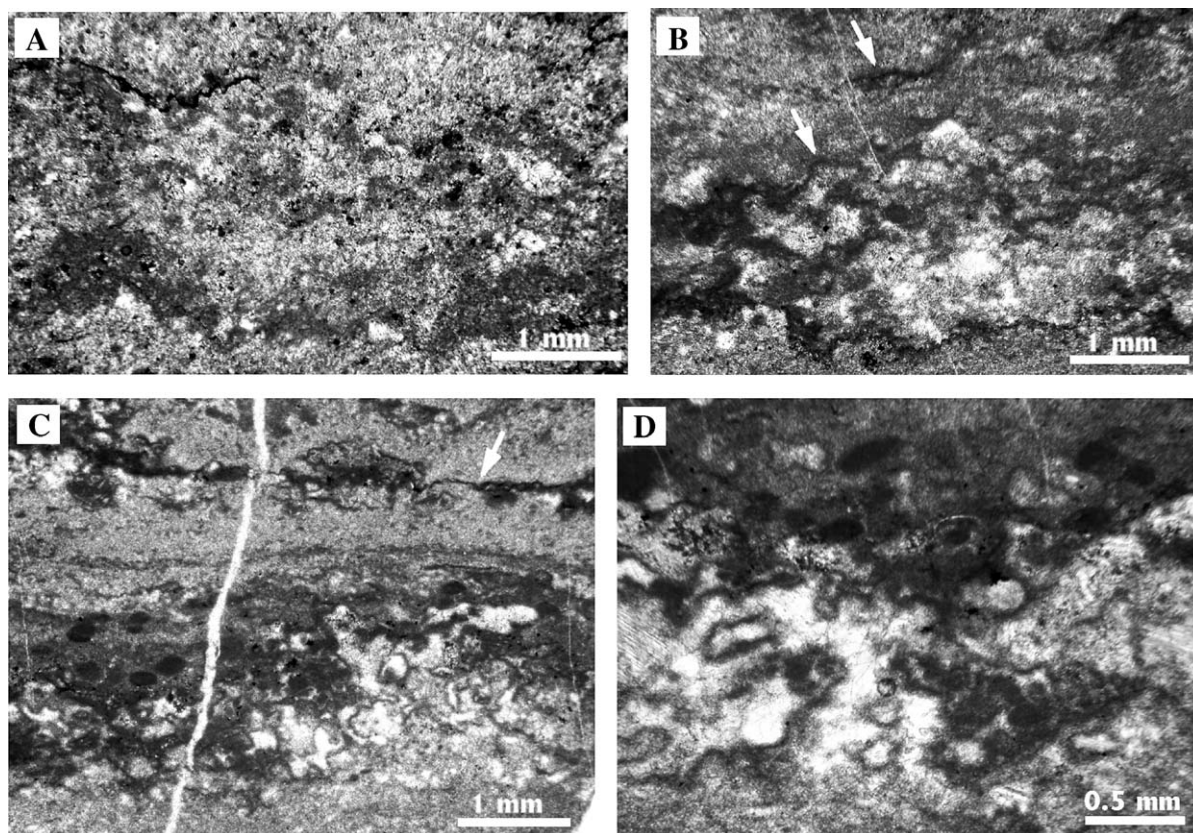


Fig. 5. Microfabrics of laminae characterized by bushy aggregates of micrite clots. A: Upward-expanding tufted aggregates of micrite clots intersected by fine detrital carbonates (lighter). Note coalesced clots forming larger knots. B: Bushy aggregates of irregular micrite clots. The framework voids are filled by coarser crystalline calcite (lighter). Note associated micrite threads (arrows). C: Reticulate pores in calcified crust and winnowed peloids (top). Note bundles of micrite threads in the upper microbial lamina (arrow). D: Details of Fig. 3B showing pockets filled by either dense micrite clots or calcite spar. Note peloids involved in micrite on top.

Single elongate and spherical micrite peloids, without any visible internal structure, occur in micrite matrix above reticulated crusts or the clotted micrite lamina mentioned above (Fig. 5C, D). They commonly rest on the crust with their largest dimension parallel to the lamina surface. Their forms and sizes are comparable to the voids of the underlying crusts. This suggests that these peloids represent either winnowed particles of the crust, or reworked chips of the microbial mat.

7. Variation in stromatolite microstructures

Overall stromatolite microstructure is characterized by alternating laminae of calcified microbial remains and detrital carbonates. According to the rate of detrital supply various microstructure patterns may have developed. Breaks in deposition allowed microbial colonization of the seafloor as long as the deposition of detrital carbonates hampered the growing of mat.

Biofilms could evolve to complex mats during relatively long-term sedimentation pauses. Accordingly, two basic microstructure types are distinguished.

The first microstructure type is typified by alternation of microbial laminae and related overlying detrital laminae that records temporal oscillations in sediment supply. In the lower of stromatolite unit, the thickness of laminae or interlayers of fine detrital carbonates gradually increase upward. In the lower part of the upper stromatolite unit the microbial laminae prevail, whereas in the upper part predominance of fine detrital carbonates is characteristic. In some intervals, relatively small clot clusters or short prostrate threads alternate with veneers of fine carbonate detritus. This suggests that small amount of fine carbonate detritus may have been incorporated into the microbial mat without terminating its growing. There are detrital interlayers, especially in the lower stromatolite unit, which contain reworked constituents of dense micritic microbial laminae, e.g. single spheres with micrite

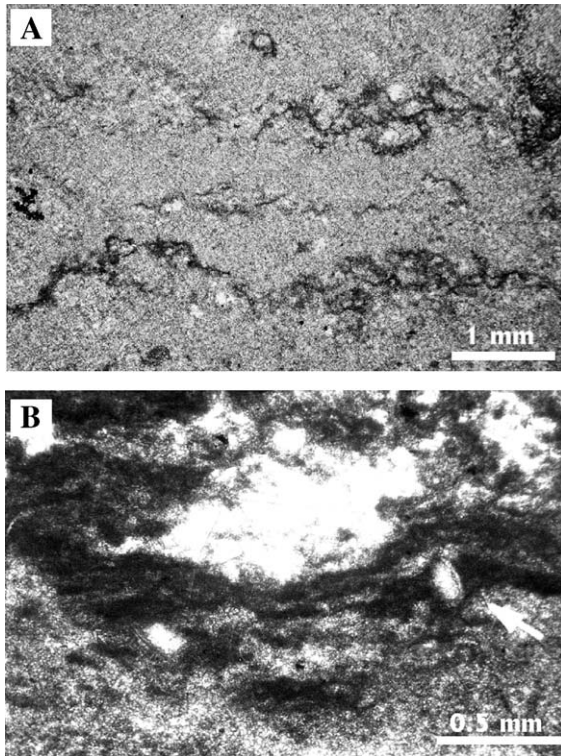


Fig. 6. Photomicrograph of prostrate threads. A: Microstructure of the upper part of upper stromatolite unit characterized by abundant microcrystalline detrital groundmass and obscured dissected thin micrite crust, composed by micrite threads. B: Bundles of closed-packed micrite threads. Note ostracod bounded in the threads (arrow), and the cavernous pore with diffuse boundary in the middle.

covers, micrite peloids, micrite flakes, or bioclasts with micrite mantles. Rip-ups from the microbial mat or calcified crust suggest stronger current activity—currents may have destroyed a part of the mat, or winnowed the calcified crust. The advanced stage of clotted microfabric development in the lower part of the upper stromatolite unit indicates prolonged periods of low sediment accretion. Accordingly the accretion pattern of the stromatolite laminae implies fluctuating detrital supply and records changes in the frequency and/or intensity of storms.

In the second type of microstructure, the microfabric changes within the calcified microbial lamina. Its first subtype occurs in all the distinct microfabric types. The well-preserved cryptocrystalline components progressively lose their microfabric details as they grade into ill-defined, obscure micritic masses and then microsparitic ghosts (Fig. 7). Such types of changes suggest changes in the style of calcification. The other subtype is especially common in the case of sphere clusters. The sphere clusters compose thin, discontinuous basal lamina which is capped by a massive micrite lamina. The

massive micrite is less dark under the microscope, which indicates less dense nucleation and accordingly coarser crystal size. This type of microfabric sequence suggests changes either in calcification or in the population of the microbial community.

Additionally, three successive stages of mat growth were discerned in sections where light–dark lamination is pronounced and the microfabric contains micrite clots and prostrate threads (Fig. 3B). The thin calcified crusts most likely represent the first step of surface colonization. In the second stage, thickening of the mat took place via developing mammelons which consist of tufted clot clusters. In the third stage, the fused and amalgamated mammelons composed thicker laminae that represent an advanced stage of mat growth. The reticulate appearance of these laminae can be attributed to winnowing of mat particles by weak currents.

7.1. Interpretation

Storm bottom currents transported fine detrital carbonates of which deposition determined stromatolite formation. The lamination records temporal oscillation in sediment input, and the microstructures reflect the rates of the sediment supply. Although slight erosion and reworking of parts of the mat by storm currents still occurred, sedimentary stasis allowed the microbial community to colonize the seafloor and develop over a vast area. Since bioturbation was observed only in a single horizon in the lower part of the stromatolite unit and relict skeletal fragments disappeared from the detrital interlayers, it can be assumed that along with the decrease in sediment input the microbial community overcame the burrowing organisms in competition for substrate. It is supposed that these were the local controlling factors for mat development. Although the storm activity fluctuated and periodically became enhanced, the microbes recovered soon after that the storms had calmed down.

8. Discussion

8.1. Microbial microfabrics

The planar stromatolites studied show a wide range of distinctive variation in microfabric. In the succession, the most common microbial laminae-type is simply dense micrite. One of the special forms of the microbial laminae, which was calcified in minute details, consists of sphere clusters and the surrounding cryptocrystalline mass. Their formation is attributed to

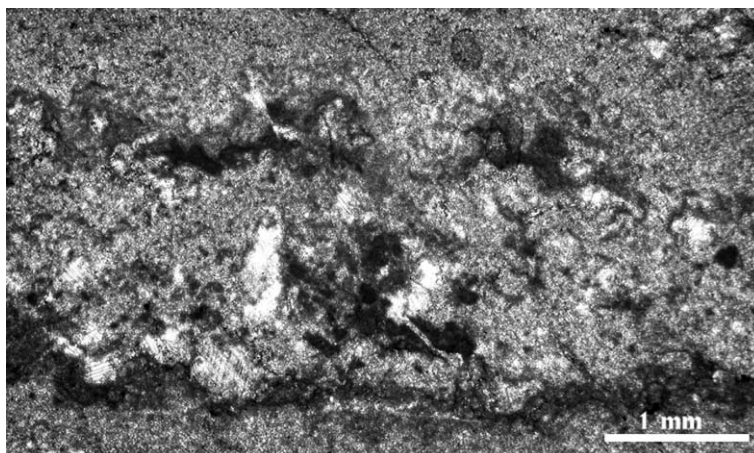


Fig. 7. Dense cryptocrystalline clot clusters grading into less dark, finely crystalline faint clusters of similar shape and size.

calcification of coccoid–cyanobacteria dominated mat community, e.g. according to the model by Dupraz et al. (2004). Micrite probable represents calcified extracellular polymeric secretions (EPS), and the sphere itself may represent the empty gelatinous envelope surrounded the cells. This spheroidal form might be comparable to the most primitive microorganisms which produce massive gel, and form gelatinous, pustular or mammillated mats and lithified stromatolites in the Bahamas, Persian Gulf and Shark Bay (cf. Golubic, 1976).

Similar calcimicrobial microfabrics were described from basal Triassic carbonates in a number of sections in South China. Ezaki et al. (2003) studied 2.5 m-thick thrombolitic crust in Sichuan Province. They reported spheroidal and ellipsoidal micritic bodies (30 μm in average diameter) which adhere to each other forming grape-like clusters. These spheres are interpreted as calcified coccoidal microbes. The illustrated microfabric composed by spheres (especially in their figs. 8E, F, G, 9C, and 10) is close resemblance of what we found in the Bükk sections. Not only are the size and shapes of the sphere clusters similar, but also their arrangements within darker dense micrite mass (cf. their fig. 9B). The associated microsparite groundmass patches, which grade into spar, are also characteristic of both microfabrics (cf. their fig. 8F). Scattered dolomite rhombs are a further similar diagenetic textural feature. The only difference is that they were encountered in thrombolites in the Chinese section, whereas they are found in planar stromatolites in the Bükk Mountains.

Similar sphere clusters are preserved in peloids that are interpreted as rolled microbial clumps in the Bükk stromatolites. Adachi et al. (2004) described peloids from thrombolites from a Chinese section (Guizhou

Province), and they also interpreted them as of microbial origin. They ranked the ‘peloids’ according to their size and preservation state. However, those that they illustrated (peloids A1.1, A2.1, A2.2) are rather comparable to sphere and clot clusters of Bükk carbonates, since the clots (on their fig. 6d, e, f) do not form distinct grains. In the Bükk stromatolites a distinction can be made between the bushy aggregates of micrite clots (comprising sphere clusters) and peloids forming grains with distinct margins. The smaller, A1.2 type peloids of Adachi et al. (2004, on fig. 6c) that occur as fillings in interstitial voids have not been recognised in Bükk stromatolites. However, reworked spheres, scattered and embedded in fine detrital carbonates, occur in several horizons.

In the stromatolites of the Bükk sections, the micrite clots are typically arranged in upward-expanding bushy aggregates resembling *Angusticellularia* calcimicrobes. According to Riding and Voronova (1982) *Angusticellularia* (= *Angulocellularia*) has a modern analogue in oscillatorian cyanobacteria. In those intervals where light–dark lamination is more characteristic, the generally thicker dark micritic microbial laminae also exhibit clotted microfabrics. These micrite clots typically fill pockets within the mammillated laminae. In many cases, prostrate threads, i.e. filamentous calcified microbial remnants, accompany the clot clusters.

Lehrmann et al. (1998), Lehrmann (1999), and Ezaki et al. (2003) documented calcimicrobial mounds and crust from Chinese sections in which framework is made up of irregular to tufted masses of chambered to clotted micrite structures referable to *Renalcis*. Adachi et al. (2004) also illustrated similar chambered microfabrics of similar size (their fig. 8b). The basic

features of these Chinese forms are remarkably similar, but comparable microfabrics have not been recognised in the stromatolites in the Bükk sections.

All things considered, the most characteristic elements of the microfabrics of the Bükk stromatolites include sphere clusters, micrite clots, and micrite threads. It seems that spheres may grade to micrite clots according to the preservation state. Otherwise, it would be a mistake to assume that all micrite clots are identical in origin in the stromatolite microfabrics, i.e. less preserved spheres. Microfabric and microstructure of microcrystalline calcite precipitates may be products of mat community composition or taphonomic effects (Monty, 1976; Pratt, 1984; Riding, 2000; Turner et al., 2000; and references therein). Although the microbial calcification is widely described and discussed, the details of the processes are poorly understood (e.g. Chafetz and Buczynski, 1992; Riding, 2000; Reid et al., 2000; Sprachta et al., 2001; Gautret et al., 2004; Dupraz et al., 2004; Ludwig et al., 2004; Visscher and Stolz, 2005). In the case of the stromatolites in the Bükk sections, complex mat populations with coccoid and filamentous cyanobacteria can be inferred and they most likely show a wide range of taphonomic preservation states.

The dense micritic calcified microbial remains are surrounded or underlain by micrite–microspar (grading to spar) groundmasses which are interpreted as diagenetic precipitates within the mat (cf., e.g. model of Dupraz et al., 2004). Outlines of the micrite–microsparite fabrics reveal similarities to the dense micrite ones. Thus, the micrite–microspar are also considered as early precipitates that postdate the calcification of dense micritic components. Additionally, coarse sparry calcite cement formation postdated the microbially induced calcite precipitation and probably took place in the shallow burial marine phreatic zone.

8.2. Palaeoenvironment

In the western end of the Palaeotethys, shallow ramp environments were established during the Late Permian. According to the relevant palaeogeographic models (Baud et al., 1993; Marcoux et al., 1993; Haas et al., 1995), in the latest Permian–earliest Triassic period the Bükk unit was a segment of the deeper part of the wide ramp (Badiota–Žažar facies belt), whereas the classic sections in the eastern Dolomites (Tesero) and the NE part of the Transdanubian Range unit in Hungary represent the inner ramp zone of the Tethys margin (Fiamazza–Tesero facies belt).

After the Permian–Triassic boundary events, the shallow subtidal skeletal carbonate ramp factory of the western Tethyan margin collapsed leading to drastic decrease in skeletal carbonate deposition on the ramp. This might suggest that low sedimentation rates, due to reduced shallow marine production, might be one of the factors that could promote microbial mat development (cf. Baud et al., 1997). However, the microbial abundance in the aftermath of the end-Permian mass extinction was most likely a function of the combined effect of drastic changes in metazoan diversity and elevated saturation state of seawater with respect to calcium carbonates (Baud et al., 1997; Riding and Liang, 2005).

After the boundary events, relict carbonate sediments were abundant on the inner part of the ramp (Haas et al., 2004). Additionally, intense marine phreatic cementation led to the formation of cemented hard-ground substrates in shallow subtidal settings. Storms reworked and redeposited the relict bioclasts and fine carbonate detritus to the deeper ramp, which was the depositional area of the Bükk unit. A thin spongio-strome micrite lamina records the first microbial colonization in the lowermost 0.5 m-thick mudstone unit. Otherwise, storm-redeposited fine carbonates and bioturbation characterize this interval. Bioturbation between the storm events indicates at least partially oxygenated bottom water.

The stromatolites were relatively shortlived in the succession of Bükk unit. The formation of microbial mat took place most likely in the photic zone of a low-energy open ramp environment. The 8 m-thick succession includes no other intercalating facies, except for relatively thin storm layers. Its basal layer exhibits storm reworking, and relatively stronger current activity is evident in the lower half of the stromatolite interval. Bioturbation almost disappeared from this level. Thus, stromatolite development might be interpreted to have roughly coincided with less frequent storm activity, which could happen in conjunction with sea-level rise.

The relatively well-preserved calcified microbial remains occur only in the lower half of the stromatolite interval, since the stromatolite lamination gradually diminishes upsection. It indicates the reducing time interval for either surface colonization of the microbial community or the calcification of the crusts. It might also indicate less intense early calcification of the mat. The limited preservation of the microbial community in the upper unit may be the consequence of changing environmental factors, e.g. drowning of the area below the photic zone as a result of sea-level rise, or increasing and/or more continuous detrital mud supply, or

changes in calcification conditions. Altogether, sea-level rise leading to shifting of the facies zones on the ramp might be the most plausible explanation for the changes in the features of the stromatolite and the overlying mudstone unit.

Otherwise, it is an open question whether oxygen-depleted bottom water affected the area of the Bükk depositional unit in the course of sea-level rise, as has been supposed in the case of the depositional area of the Dolomites (Wignall and Hallam, 1992; Twitchett and Wignall, 1996; Twitchett, 1999). Hypothetically, deposition under low oxygen seawater conditions may provide an alternative model for changes observed in the basal Triassic carbonates in the Bükk sections. Presence of benthic epifaunal invertebrates in the stromatolite laminae, which would have required some oxygen for respiration, implies that the bottom water could not be less than dysoxic in the Bükk unit depositional area. As a result of the inferred subsequent sea-level rise, more depleted seawater could have upwelled onto the ramp leading to disappearance of microfossils and calcified benthic microbial remains.

It is worth noting, that termination of stromatolite accretion in the Bükk unit roughly coincided with the end of stromatolite and domal thrombolite growth in the South Chinese sections (Sichuan and Guizhou Provinces), which occurred in the upper part of the *Parvus* Zone (cf. Ezaki et al., 2003; Lehrmann et al., 2003). However, microbial aggradation was slightly prolonged into the *Isarica* Zone in the Tianwan sections (Sichuan, China, Adachi et al., 2004).

9. Conclusions

Stromatolites were developed soon after the Permian–Triassic boundary events in a relatively low-energy environment on a deeper ramp below storm wave-base in the western Palaeotethys. However, storm bottom currents frequently reached the depositional environment of the Bükk unit. A microbial mat colonized the gently sloping seafloor from the depth where storm-transported detrital sediment supply and storm intensity became significantly reduced, down to the depth where the cyanobacterial mat community could still live.

Cessation of detrital carbonate supply was due to the very limited source, as a consequence of intensive marine cementation in the inner ramp zone. Fluctuations of minor sediment input determined the stratiform development of the microbial deposits. The lamination records the temporal oscillation in sediment input, and the microstructures reflect the changing rates of sediment supply.

The preservation of minute details of the microfabrics and that of the microbial remains imply early lithification of the mats. The coeval oolite deposits on the inner ramp also exhibit very intense early marine cementation in the Transdanubian Range unit (cf. Haas et al., 2004). Thus, altogether the western Tethyan ramp deposits reflect widespread and enhanced carbonate precipitation following the end-Permian events. This supports the assumption that significant changes must have taken place in marine geochemistry. Trend of vertical changes in microstructures and microfabrics of the stromatolites and the overlying unit suggest a gradual sea-level rise which led to disappearance of the benthic community.

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