

SILICICLASTIC MICROSTROMATOLITES IN A SANDSTONE CAVE: ROLE OF TRAPPING AND BINDING OF DETRITAL PARTICLES IN FORMATION OF CAVE DEPOSITS

Michał GRADZIŃSKI¹, Maria Jolanta CHMIEL², Anna LEWANDOWSKA¹
& Beata MICHALSKA-KASPERKIEWICZ³

¹ Institute of Geological Sciences, Jagiellonian University, Oleandry 2a, 30-063 Kraków, Poland;

e-mail: michał.gradzinski@uj.edu.pl, anna.lewandowska@uj.edu.pl

² Department of Microbiology, University of Agriculture in Kraków, Aleja Mickiewicza 24/28, 30-059 Kraków, Poland;

e-mail: mjchmiel@poczta.onet.pl

³ KTJ Speleoklub Bielsko Biala, 1-go Maja 45, 43-300 Bielsko-Biala, Poland; e-mail: beata_michals@poczta.onet.pl

Gradziński, M., Chmiel, M. J., Lewandowska, A. & Michalska-Kasperkiewicz, B., 2010. Siliciclastic microstromatolites in a sandstone cave: role of trapping and binding of detrital particles in formation of cave deposits. *Annales Societatis Geologorum Poloniae*, 80: 303–314.

Abstract: The article deals with finely laminated microstromatolites composed of detrital siliciclastic particles, mainly quartz, feldspars and clay minerals, lining the walls of W Sopotni Wielkiej Cave (Polish Outer Carpathians). Newly precipitated mineral phases do not contribute to their growth. The microstromatolites cover vertical and overhanging walls of the cave. They form subhorizontal ripples and tongue-shaped stepped microterraces. The stromatolites are constructed by bacteria and Actinomycetes. Seven morphotypes of micro-organisms have been distinguished. Trapping and binding of detrital particles result in the microstromatolite growth. The growth is influenced by the relatively close distance to the soil cover which provides detrital mineral particles and by the presence of gravitationally widened fissures which guide the water transporting mineral particles down to the cave. The particles are transported only during wet periods. The episodic supply of the particles results in visible lamination of microstromatolites. The microterraces form in zones of increased water-flow. The lack of autochthonous components most probably reflects too low saturation of water to precipitate any minerals.

Key words: bacteria, Actinomycetes, biofilm, speleothems, Outer Carpathians.

Manuscript received 18 September 2010, accepted 18 November 2010

INTRODUCTION

Constructive role of micro-organisms in speleothem formation is a focus of growing interest (see review by Northup & Lavoie, 2001; Jones, 2001, 2010; Taborosi, 2006 and references quoted therein). A great body of literature exists on the importance of bacteria and fungi for precipitation of carbonate speleothems, especially for the growth of moonmilk, cave pisoids and some subaqueous formation (e.g., Gradziński *et al.*, 1997b; Gradziński, 2000; Melim *et al.*, 2001; Jones, 2009a; Curry *et al.*, 2009). The plausible direct or indirect influence of these micro-organisms on the crystallization of needle-fibre calcite in cavern environment is commonly discussed (Blyth & Frisia, 2008; Richter *et al.*, 2008). The precipitation of speleothem-forming manganese and iron oxides, opal and phosphates is also mediated by biological activity (e.g., Gradziński *et al.*, 1995; Manolache & Onac, 2000; Aubrecht *et al.*, 2008; Jones, 2009b).

Conversely, little attention has been drawn to trapping and binding of detrital grains of various mineral composi-

tion as a constructive mechanism in speleothem growth. Such mechanism has been mentioned on the occasion of studying the microbially driven precipitation of diverse speleothems in cavern environment. However, it has only been regarded as a subordinate contribution to speleothem growth. Jones and Motyka (1987) showed that algae trap and bind carbonate micrite, which eventually leads to formation of the well visible lamination. Cyanobacteria, representing *Gleocapsa* sp., are capable of trapping air-born quartz grains and insect fragments, which collectively contribute to the formation of crayfish-like profile stalagmites located in entrance parts of Australian caves (Cox *et al.*, 1989a, b; James *et al.*, 1994). Jones (1995) noted some examples of trapping and binding of detrital grains to the substrate by organic filaments in the biofilm covering walls in twilight zones of caves. Cunningham *et al.* (1995, fig. 7) illustrated binding of corrosion residuum by filamentous micro-organisms in Lechugilla Cave (New Mexico). Cañaveras *et al.* (2001) mentioned trapping and binding of

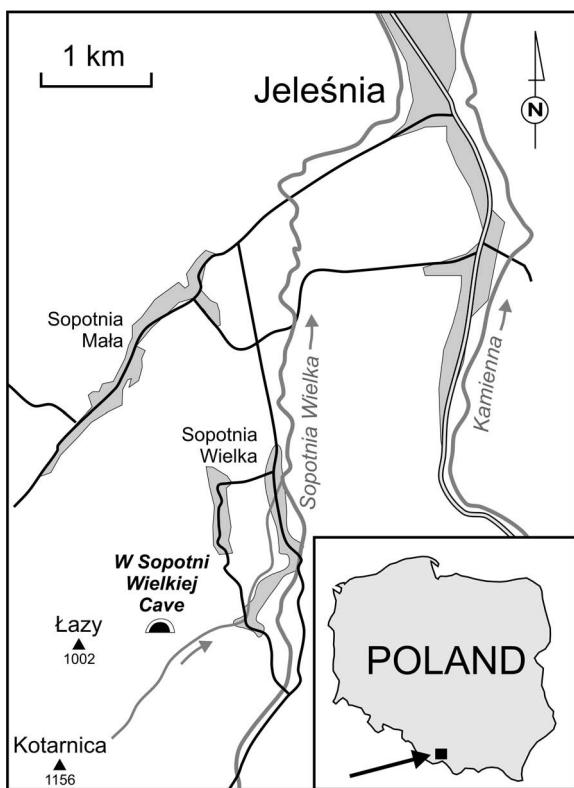


Fig. 1. Location of W Sopotni Wielkiej Cave

micritic grains resulting from substrate breakdown in the famous Altamira cave. Gradziński and Holubek (2005) found detrital silicate and dolomite grains incorporated into subaqueous cottonball speleothem in Zlomiská Cave (Slovakia); the cottonballs presumably originated under biological mediation. Baskar *et al.* (2006) suggested that detrital grains organically trapped and bound are incorporated into carbonate speleothems in Borra Caves (India). Also, biologically mediated opal speleothems from Venezuelan caves contain some grains trapped and bound by micro-organisms (Aubrecht *et al.*, 2008). Detrital grains contribute greatly to formation of some speleothems in sandstone caves in the Polish Outer Carpathians (Urban *et al.*, 2007). In some cases they compose deposits whose relief imitates the morphology taken by speleothems. Some of these forms are cemented with opal.

Clastic formations built of sand- and silt-sized grains are present in many caves (Hill & Forti, 1997, p. 219–221 and references therein). Some of them are akin to carbonate speleothems in their shape and dimension although they are only cemented by carbonate minerals (*e.g.*, Baker, 1942). In fact, many of them represent erosional remnants after accumulation of cave clastics (*e.g.*, Gradziński & Radomski, 1960) and they do not share their origin with typical speleothems. Vermiculations represent another type of cave formation composed of siliciclastic material (Hill & Forti, 1997, p. 221–223). They are found on cave walls or ceilings as irregular spots or bifurcating stripes. Their array gives the overall impression of a group of warms or a tiger or leopard skin. In the majority of papers no suggestions have been made on the possible role of micro-organisms in the origin of the above clastic cave formations, excluding special type

of vermiculation in sulfidic caves. Although Bini *et al.* (1978) considered influence of bacteria on formation of vermiculation, ultimately they ruled out this influence.

This paper documents the presence of microstromatolites composed of detrital siliciclastic particles lining the walls of a sandstone cave. The significance of micro-organisms to trapping and binding detrital particles, and therefore to forming the microstromatolites in question, is discussed. A hypothesis is put forward on a similar constructive role of micro-organisms in formation of clastic-rich laminae within carbonate speleothems.

GEOLOGICAL AND SPELEOLOGICAL SETTING

Siliciclastic microstromatolites were found in W Sopotni Wielkiej Cave (Jaskinia w Sopotni Wielkiej) and reported during a local symposium (Gradziński *et al.*, 2001). The cave is located in the Beskid Śląski Mts. From the geological point of view this region belongs to the Outer Carpathians, which are built predominantly of Cretaceous–Palaeogene flysch (Fig. 1). The cave is formed in the Eocene thick-bedded sandstones of the Magura beds belonging to the Rača Unit of the Magura Nappe (Golonka & Wójcik, 1978). The sandstone is fine grained. An X-ray diffractogram of the sandstone reveals the presence of quartz, alkali feldspars and two groups of phyllosilicates, with a major order layer separation of 14.5 Å and 10.0 Å (see Figs 4A, 5A). The 14.5 Å minerals are either chlorite or smectite, although further analyses are necessary for exact identification. The 10.0 Å peak may indicate the presence of illite or micas. Observations in optical microscope revealed the presence of muscovite and biotite micas (see Fig. 5A); a confirmation of the illite presence requires <2 µm fraction separation.

The cave main entrance is located at the altitude of 840 m (Klassek, 1997). The cave is composed of a series of passages up to 2 m wide and 5 m high, with total 101 m in length (Fig. 2). The passages display rectangular or triangular cross-sections. Their floors are littered with sandstone debris. The cave originated due to widening of fractures under the action of downslope creep of sandstone blocks towards the neighbouring valley. Hence, it represents a crevice type cave (*sensu* Palmer, 2007, p. 7). The cave is protected as a ‘nature monument’.

The microstromatolites cover the walls of the Komora Trójkątna (Triangular Chamber) located *ca.* 12 m from the cave entrance. They were noted by Mikuszewski (1973) and Klassek (1997) but recognized as carbonate flowstones. The chamber is completely dark; its walls are covered by drops of condensation water. The internal temperature is 5.5 °C (Klassek, 1997). The thickness of the roof rock over the Triangular Chamber is estimated at 6–8 m. The area over the cave is forested.

MATERIAL AND METHODS

Morphology and internal structures

Microstromatolites were documented in the Triangular Chamber (Fig. 2). Sampling was limited to the minimum due to the cave protection. Samples were collected from

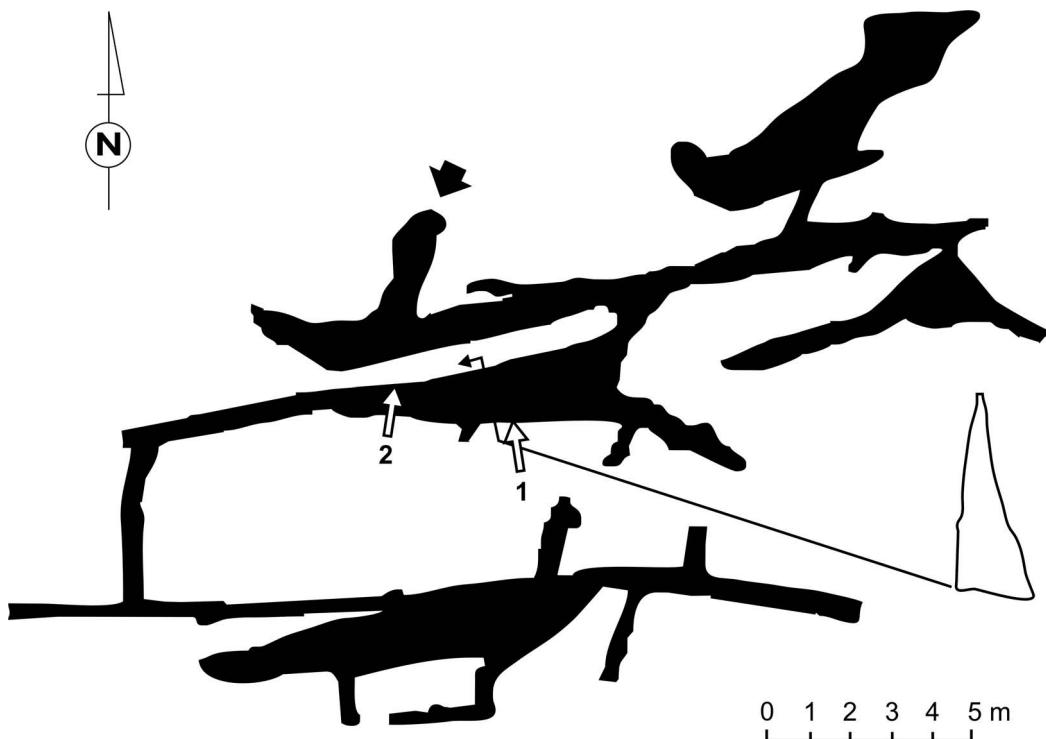


Fig. 2. Simplified map of W Sopotni Wielkiej Cave (after Klassck, 1997); sampling sites are indicated (white arrows), big black arrow shows the cave entrance

both sides of the chamber, preferably from hidden places. A thin section was made from one sample sunken in a box filled with ARALDITE. Internal structures of the microstromatolites were observed under petrographic and scanning electron microscope (SEM) JEOL 5410, coupled with a microprobe (EDS) Voyager 3100 (Noran product). The samples were mounted on SEM holders with silver glue and coated with C or Au. Samples were lyophilized prior to coating to prevent collapse of the organic structure.

Mineral composition

Samples were analysed by the powder X-ray diffractometry (XRD) using a vertical XPert APD Philips goniometer (PW 1830). Infrared absorption spectra (IR-FT) were obtained at ambient temperature and with 2.0 cm^{-1} resolution using a BIO-RAD Fourier Transform Spectrometer (FTS 135).

Microbiology

Samples were aseptically collected to sterile glass flasks, transported to laboratory and suspended in physiological salt solution, shaken and inoculated in liquid and agar media. They were incubated at 20°C and 35°C from 1 to 21 days. The growth of micro-organisms was systematically monitored. The following microbiological media were used for isolation: Beef Extract – Nutrient Broth – Merck, Trypticase Soy Broth (Soybean-Casein Digest Medium) – BioMerieux, Nutrient Agar – Merck, TSA (Trypticase Soy Agar) – BioMerieux, Soil Extract Agar (Atlas & Parks,

1997), Iron Bacteria Isolation Medium (Atlas & Parks, 1997) and Actinomycetes Isolation Agar (Atlas & Parks, 1997). After incubation the clean cultures of bacteria were isolated on agar media (Pepper & Gerba, 2004). Morphology, Gram stain and biochemical properties of bacteria were analyzed to identify micro-organisms. Species identification was based on Bergey's Manual of Determinative Bacteriology and Bergey's Manual of Systematic Bacteriology (Holt, 1989, 1994). Since there are no standard biochemical tests for the majority of isolated genera, the biochemical tests were individually selected according to diagnostic manuals.

RESULTS

Relief

The microstromatolites display a soft, pasty consistency and contain a substantial amount of water. They cover the vertical and overhanging walls of the Triangular Chamber (Fig. 3A, B, D). The dip of rocky walls covered with the microstromatolites ranges from 90° (vertical) to 110° (overhanging). The microstromatolites occur also on vertically oriented convex bends of a cave wall, which overhangs with an angle between 93° and 120° (Fig. 3A, B). Recently, they coat around 0.5 m^2 of the southern wall of the chamber (A in Fig. 2) and around 1 m^2 of its opposite wall (B in Fig. 2). However, it is very plausible that they formerly occupied a much bigger area and have been destroyed by visitors. On the vertical walls, they form more or less horizontal ripples with relief (distance between the wall and the crest), up to

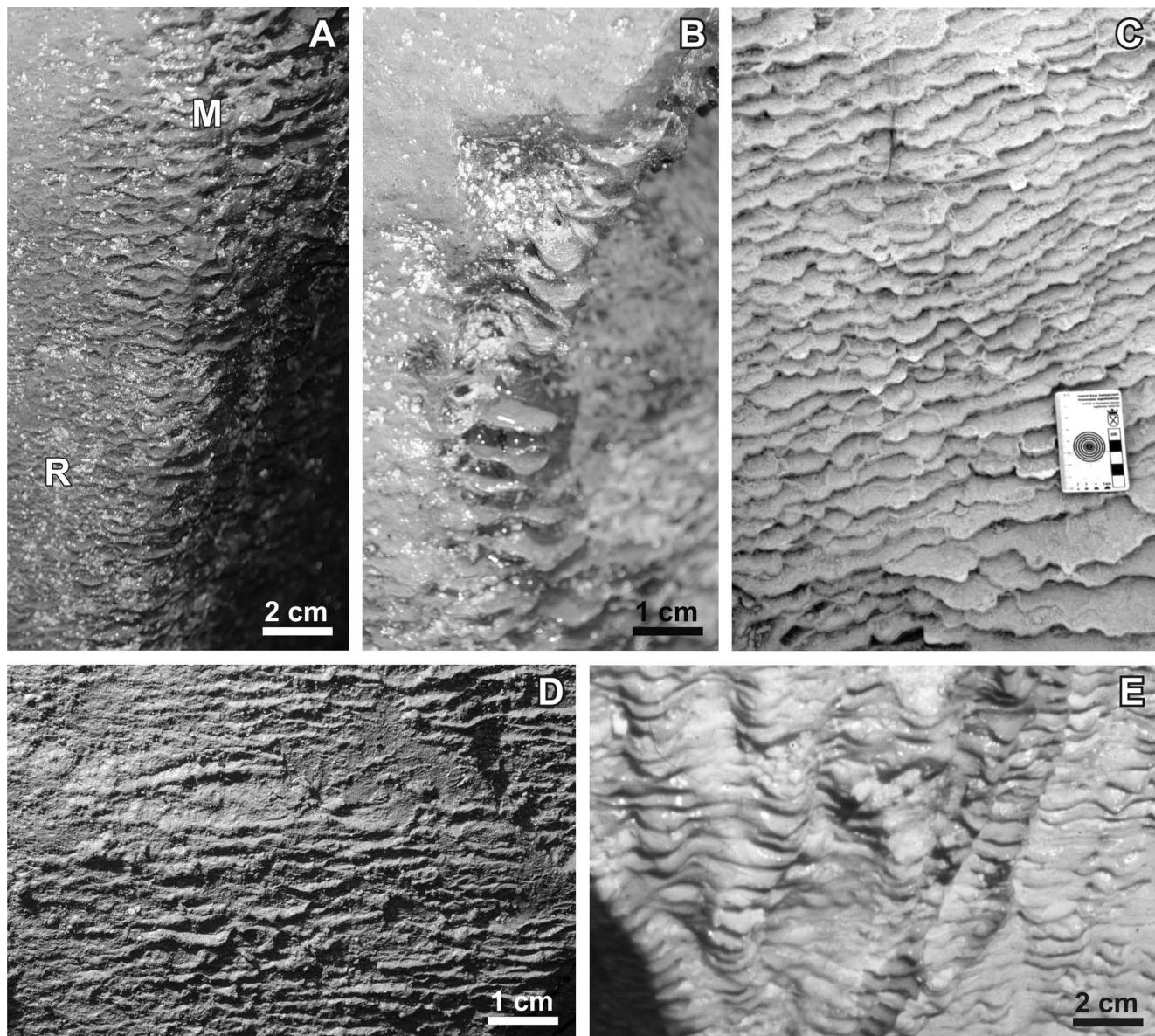


Fig. 3. Siliciclastic microstromatolites and their morphological counterparts; if no otherwise stated photographs are taken in W Sopotni Wielkiej Cave: **A** – Convex corner of cave wall covered with microstromatolite, microterracettes are developed along the corner (M), flat wall to the left is covered with ripples (R); **B** – Microterracettes with microrim fringing the micropool; **C** – Miroterracettes composed of travertine, Sivá brada, (Spiš, Slovakia); **D** – ripples covering cave walls, bifurcation of ripples is visible; **E** – Microterracettes and ripples composed of moonmilk deposits, Szczelinia Chochołowska cave (Western Tatras Mts., Poland)

2 mm (Fig. 3D). The length of particular ripples exceeds 35 cm. The neighbouring ripples bifurcate. With the wall dip changing towards more overhanging, the ripples become more sinuous and form tongue-shaped stepped microterracettes (Fig. 3A, B, D). The microterracettes overhang and their upper parts dip outward at a maximum angle of 45°. In some cases, a microrim is developed along their crest with a micropool formed behind it. Microterracettes are particularly well developed along a vertically oriented convex bends of the cave wall (Fig. 3B). The distance between the microterracette crest and rock wall reaches 1.5 cm. The vertical distance between neighbouring ripples ranges between 2 and 5 mm, whereas between microterracettes it is slightly higher and maximally reaches 8 mm.

Microbiology

Microbiological analysis reveals the occurrence of several taxa which are listed in Table 1. It seems reasonable to accept that *Arthrobacter*, *Bacilli* and *Actinomycetes* belong to indigenous microflora of the analysed microstromatolites. A scarce presence of *Micrococcus* and *Staphylococcus* in the studied samples implies that they should be considered allochthonous. A preferred environment of their growth supports the above view (Table 1).

Mineral composition

Quartz is the major constituent of the microstromatolites; the alkali feldspars and clay minerals have a smaller

Table 1

List of determined micro-organisms with their major characteristics (after Holt, 1989, 1994)

Bacteria	Occurrence	Morphology	Properties
<i>Arthrobacter</i> sp.	sample 1, sample 2	Gram positive irregular, nonsporing rods, in old cultures cocci	Aerobic, chemoorganotrophic; grows on simple media, widely distributed, principally in soils; psychrothropic arthrobacters have been reported to predominate in subterranean cave silts
<i>Amycolata autotrophica</i>	sample 1, sample 2	Gram positive, Actinomycetes, branched vegetative hyphae	Aerobic, chemoorganotrophic - facultatively autotrophic; isolated from diverse habitats
<i>Bacillus alcalophilus</i>	sample 1	Endospore forming, gram positive rods	Aerobic, chemoorganotrophic; alcali tolerant, isolated from various material in media at pH 10
<i>Bacillus megaterium</i>	sample 1, sample 2	Endospore forming, gram positive rods, cell diameter over 1 μm	Aerobic, chemoorganotrophic; found in wide range of habitats; grows in low temperatures
<i>Bacillus mycoides</i>	sample 1	Endospore forming, gram positive rods, cell diameter over 1 μm , forms filaments	Aerobic but can grow anaerobically, chemoorganotrophic; forms rhizoid colonies; widely distributed
<i>Micrococcus varians</i>	sample 2	Gram positive cocci, nonsporing	Aerobic; micrococci are common on mammalian skin, soil, air
<i>Staphylococcus xylosus</i>	sample 1	Gram positive cocci, nonsporing	Facultatively anaerobic; staphylococci are mainly associated with skin, but often isolated from food products, dust and water
<i>Streptomyces</i> sp.	sample 2	Gram positive, Actinomycetes, extensively branched vegetative hyphae	Aerobic; chemoorganotrophic; widely distributed and abundant in soil

contribution. The clay mineral content, although insignificant, is slightly higher in the microstromatolites than in the host rock. Sheet silicates show diffraction peaks at 14.5 \AA and 10.0 \AA as well as a minor peak centered at 12.0 \AA (Fig. 4A). The 14.5 \AA and 10.0 \AA peaks correspond probably to minerals present in the host rocks (smectite or chlorite and micas), whereas the 12.0 \AA peak reflects most likely the presence of mixed-layer clay minerals. This issue requires further investigation.

Additional information as to the composition of the microstromatolite sample is brought by IR absorption spectrum (Fig. 4B). A weak absorption band at 1405 cm^{-1} may point to the presence of only very small amounts of carbonates. The weak intensity of this absorption bend and the absence of appropriate diffraction peaks, that is 3.03 \AA (Fig. 4A) indicate almost negligible amount of carbonates. The microstromatolites have similar composition to the sandstone which hosts the cave (Fig. 5A). The XRD patterns are given for comparison of the mineralogy of both rocks (Fig. 4A).

Internal structures

The surface of the microstromatolites is uneven. It displays elevated clumps surrounded by depressions. The clumps show lower porosity than the depressions. Also the microrim crest is characterized by a lower porosity than the micropool fringed by it (Fig. 5B).

The microstromatolite is finely laminated, with the lamina thickness ca. 50–200 μm visible due to differentiation in mineral composition, grain size, and probably changes in microporosity (Fig. 5C). The laminae are convex outward, irregular. Some of them have confused boundaries. They are composed of particles of clay and fine silt fraction. Sporadic quartz and muscovite grains reach up to 150 μm across (Fig. 5C). Outsized quartz and muscovite grains are concentrated in thicker laminae.

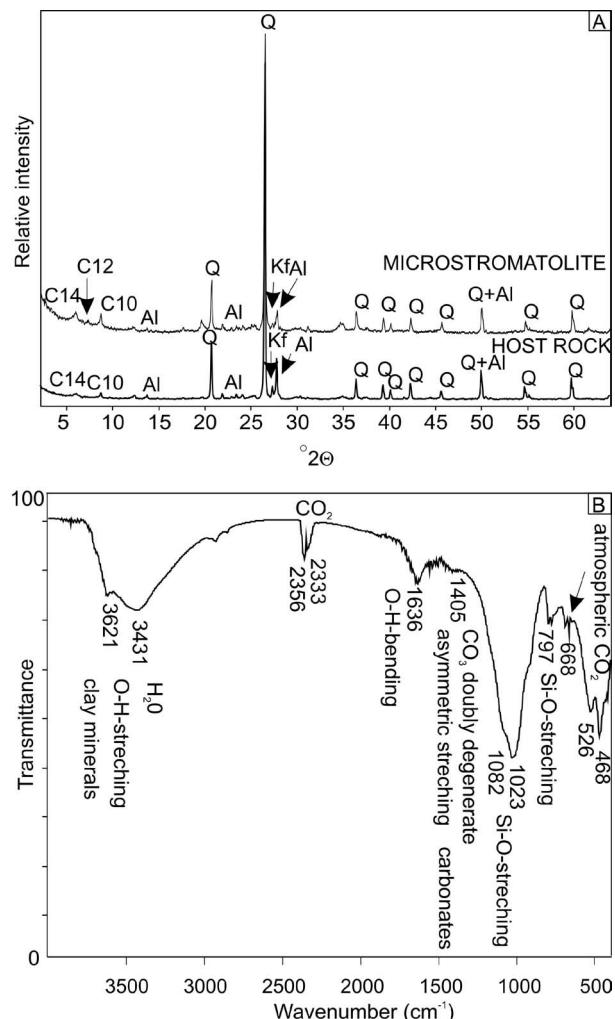


Fig. 4. A – XRD pattern of host rock and microstromatolite; Q – quartz, Al – albite, Kf – K feldspar, C14 – clay minerals with main reflection 14.5 \AA ; C12 – clay minerals with main reflection 12.5 \AA , C10 – 10.0 \AA micas or illite, B – IR absorption spectrum of the microstromatolite

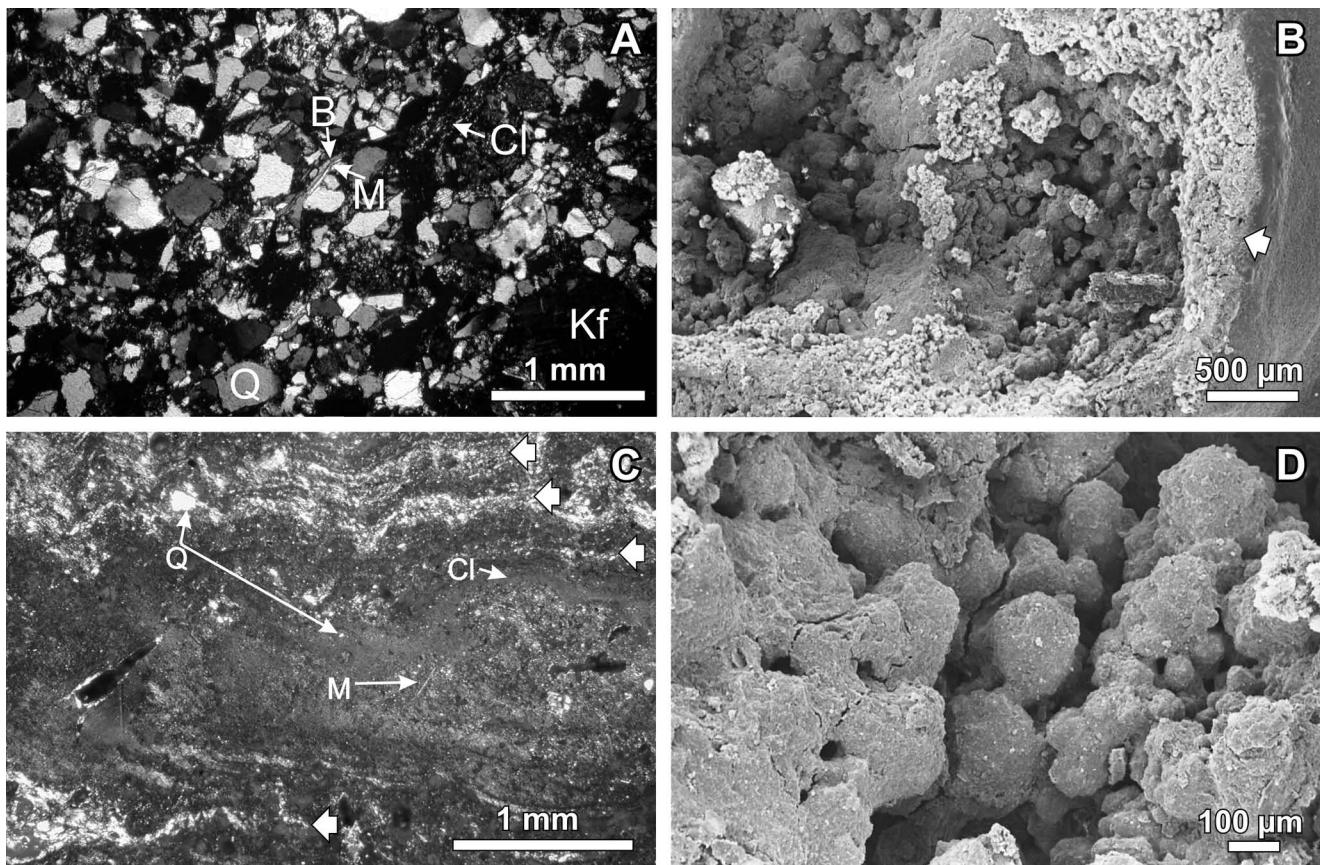


Fig. 5. A – Host sandstone: quartz and alkali feldspar grains accompanied by biotite and muscovite flakes present in the host sandstones, Q – quartz, Kf – potassium feldspar, M – muscovite, B – biotite, Cl – clays, thin section, crossed polars; B – Irregular clumps forming a microstromatolite surface, more compact arch structure to the right side is crest of microrim (arrow) seen from above, granular, more porous material fill the micropool, SEM photo; C – Finely laminated crust of the microstromatolite is composed mainly of clay minerals (Cl), with larger muscovite flakes (M) and variable size quartz (Q) grains, laminae rich in coarser-grained quartz are indicated with big arrows, thin section, parallel polars; D – Clumps devoid of micro-organisms from deeper part of microstromatolite, SEM photo

Observation under SEM reveals the internal structures of the microstromatolites. They are composed of mineral grains, micro-organisms and their extracellular polymeric secretions (EPS).

Clay minerals compose clumpy aggregates, up to 200 µm across (Figs 5B, D, 6A). The aggregates also comprise some admixtures of bigger mineral grains. Mica grains display angular shape and tabular habit (Fig. 6B). They contain Al,

Table 2

Characteristics of distinguished morphotypes

Morphotype	Shape	Dimensions	Branching	Morphology	Cell arrangement	Comments	Figure
1	coccoid to short rods	$\varnothing - 0.8 \mu\text{m}$ length < 1.5 µm	no	smooth	chains or three-dimensional colonies covered with EPS		6C, 7A-D
2	rods	$\varnothing - 0.8 \mu\text{m}$ length - 2-3 µm	no	smooth	straight or zig-zag chains		7E
3	spindle-shaped rods	$\varnothing - 1 \mu\text{m}$ length - 4-5 µm	no	granulated	chains		7F
4	coccoid	$\varnothing - 0.5-0.8 \mu\text{m}$	no	smooth	single or in linked pairs	co-occur with no 6	8D
5	irregular ovoid	$\varnothing - 6 \mu\text{m}$	no	irregular but smooth	single or in linked pairs	co-occur with no 6	8C
6	filamentous	$\varnothing - 1.1-1.3 \mu\text{m}$ length > 20 µm	yes	spinose	filaments slightly curved	co-occur with no 4, 5, 7, forms dense mat of intertwined filaments	8A
7	filamentous	$\varnothing < 0.5 \mu\text{m}$ length > 15 µm	no	smooth	some filaments are twisted	co-occur with no 4, 6	8A-D

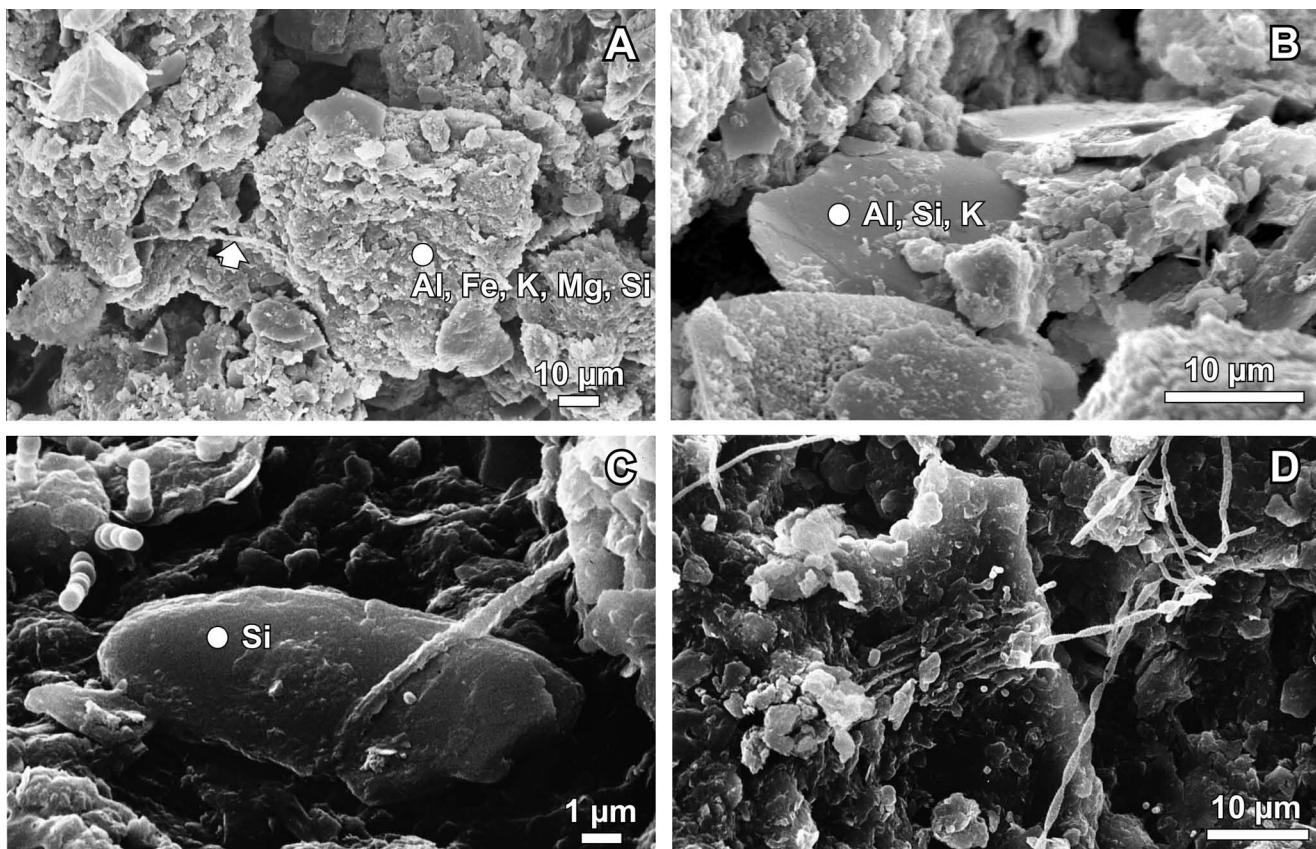


Fig. 6. A – Irregular clumps composed of clay minerals, filaments of EPS are visible (arrow), subsurface part of stromatolite; B – Muscovite flakes incorporated into microstromatolite; C – quartz grain covered with partly collapsed microbial filament, coccoid bacteria (morphotype 1) are visible to the left, D – mineral grain entombed by micro-organisms, biofilm surface seen from above; all photographs under SEM, in A–C EDS chemical composition is indicated

Si and K, which, along with the results of the XRD analysis, suggests muscovite (Fig. 6B). Quartz grains are more rounded and devoid of cleavage planes with Si as their major EDS detectable component. Mineral grains co-occur with, and are entombed by, micro-organisms which in many cases are tightly clung to them (Figs 6C, D, 7).

Seven morphotypes of micro-organisms have been distinguished. Their characteristics are listed in Table 2. All morphotypes are built exclusively of organic matter. Neither EDS analyses nor observation under SEM reveal any traces of cell mineralization. Micro-organisms show three-dimensional morphologies, only some of them are collapsed. The micro-organisms and their EPS occur on the surface of microstromatolites and in their shallow subsurface where they form an active biofilm. Deeper on, their amount radically decreases (Fig. 5D).

Affinity of the particular morphotypes is hard to be determined even in the light of the results of microbiological analyses. The morphotypes 1 to 3 most probably represent bacteria (Fig. 7A–C). Chains of coccoid cells, such as those of the morphotype 1, are typical two-dimensional colonies of coccoid bacteria developed due to cell divisions (Fig. 7A–C). Similarly, chains of rods characteristic for the morphotypes 2 and 3 are the effect of cell division (Fig. 7D, E). The morphotype 2 may be assigned to *Arthrobacter* genus, taking into account the list of determined micro-organ-

isms and their shape and size (Table 1). Moreover, it forms a zig-zag chain of cells typical of this genus (*cf.* Carlile, 1979). The filamentous morphotypes 6 and 7 resemble Actinomycetes. The morphotype 6 is particularly akin to ‘hyphae morphotype 5’ described and illustrated by Jones (2009b, fig. 7A–C) from the Grand Cayman speleothems. This morphotype forms extensive three-dimensional, porous network (Fig. 8A–D). The coccoid morphotype 4 and ovoid morphotype 5 may represent both bacteria and spores of Actinomycetes (Fig. 8C, D). However, their close spatial relationship with the morphotype 6 strongly suggests the latter possibility. Although the EPS form irregularly twisted filaments or a dense layer which covers micro-organisms, none of the morphotypes is associated with a copious amount of EPS.

DISCUSSION

Trapping and binding of detrital particles cause the growth of the studied microstromatolites. Two mechanisms are evoked to entrap detrital grains into a stromatolite – adhesion by sticky EPS and baffling by complicated three-dimensional microbial community (Riding, 1991). In the discussed case the latter mechanism seems to be decisive, since the SEM examination of the studied samples has not re-

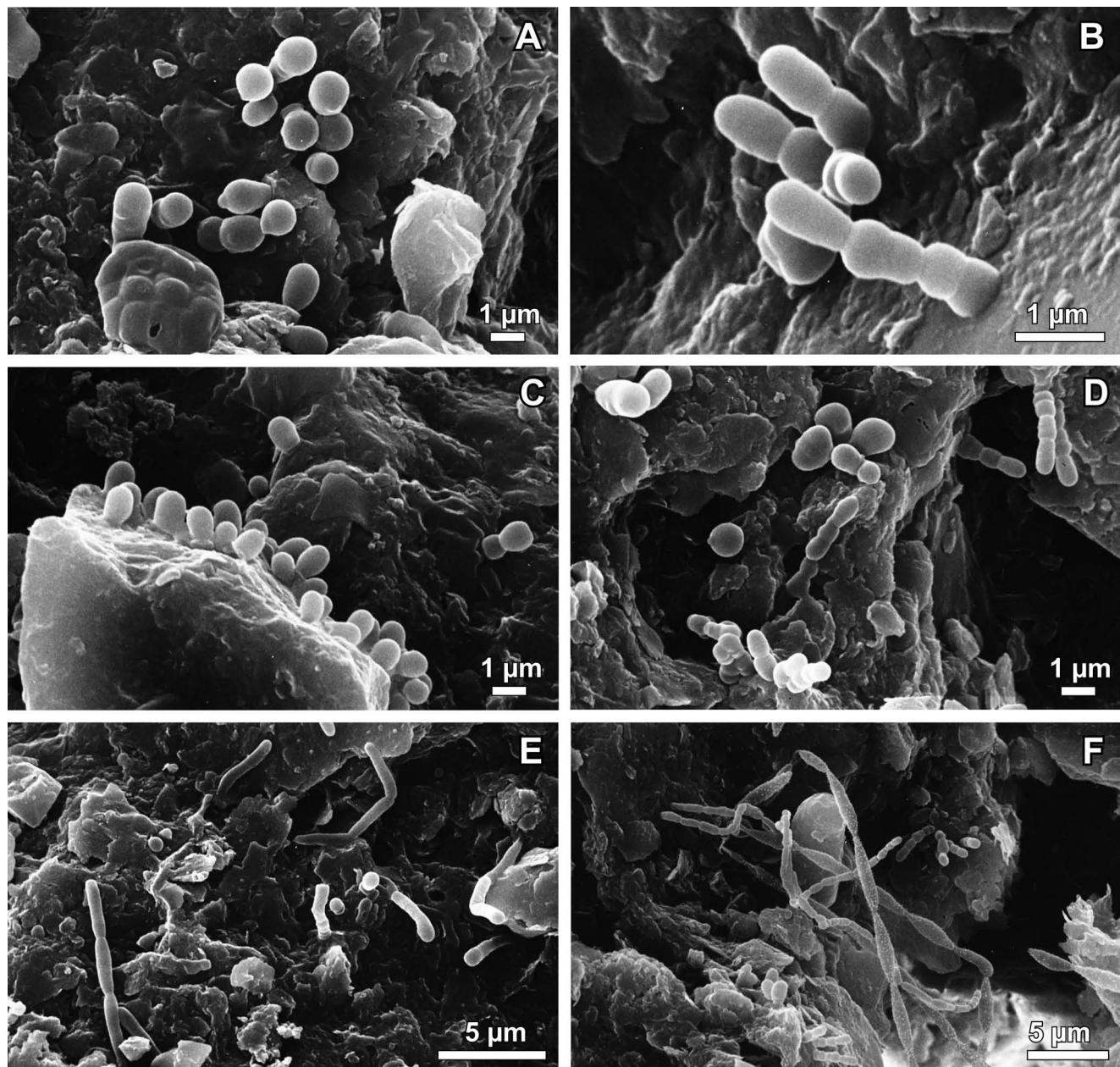


Fig. 7. A–D – Morphotype 1 representing bacteria, elongated chains developed due to cell divisions; E – Chain of rod-shaped cells (morphotype 2) probably representing *Arthrobacter* sp., F – Morphotype 3 formed elongated chains of spindle-shaped cells with granulated wall; all photographs under SEM

vealed copious amounts of EPS. Highly branched cells of Actinomycetes *Amycolata* and *Streptomyces* species act as a dense three-dimensional network capable of baffling the detrital particles. Nevertheless, *Arthrobacter* and *Bacillus* cells can excrete some slimy substances, hence the former mechanism may also work, but only to a limited extent.

Newly precipitated mineral phases seem not to contribute to the microstromatolite growth. Bearing in mind their growth mechanism, the microstromatolites in question represent agglutinated stromatolites *sensu* Riding (1991). In this aspect they bear a strong resemblance to some modern stromatolites in marine (Schwarz *et al.*, 1975) and lacustrine settings (Squyres *et al.*, 1991) as well as to several fossil examples (Martin *et al.*, 1993; Braga & Martin, 2000 and references therein). Martin *et al.* (1993) coined the term silici-

clastic stromatolite which adequately reflects the composition and mode of growth of the studied examples. The size of entrapped siliciclastic grains differentiates cave microstromatolites from the hitherto described marine and lacustrine ones. Non-spelean forms are composed mainly of sand grains with some admixtures of coarser material (Martin *et al.*, 1993); however, some silt-rich siliciclastic stromatolites are also known (Bertrand-Sarfati, 1994). Jones and Kahle (1985) introduced the term microstromatolites in order to describe microbolites, formed of fine carbonate particles and displaying fine lamination, recognized in cave sediments from the Cayman Islands. The term microstromatolite seems to be appropriate to the studied deposits. The mode of growth distinguishes the described forms from any other hitherto known microbial cave deposits being con-

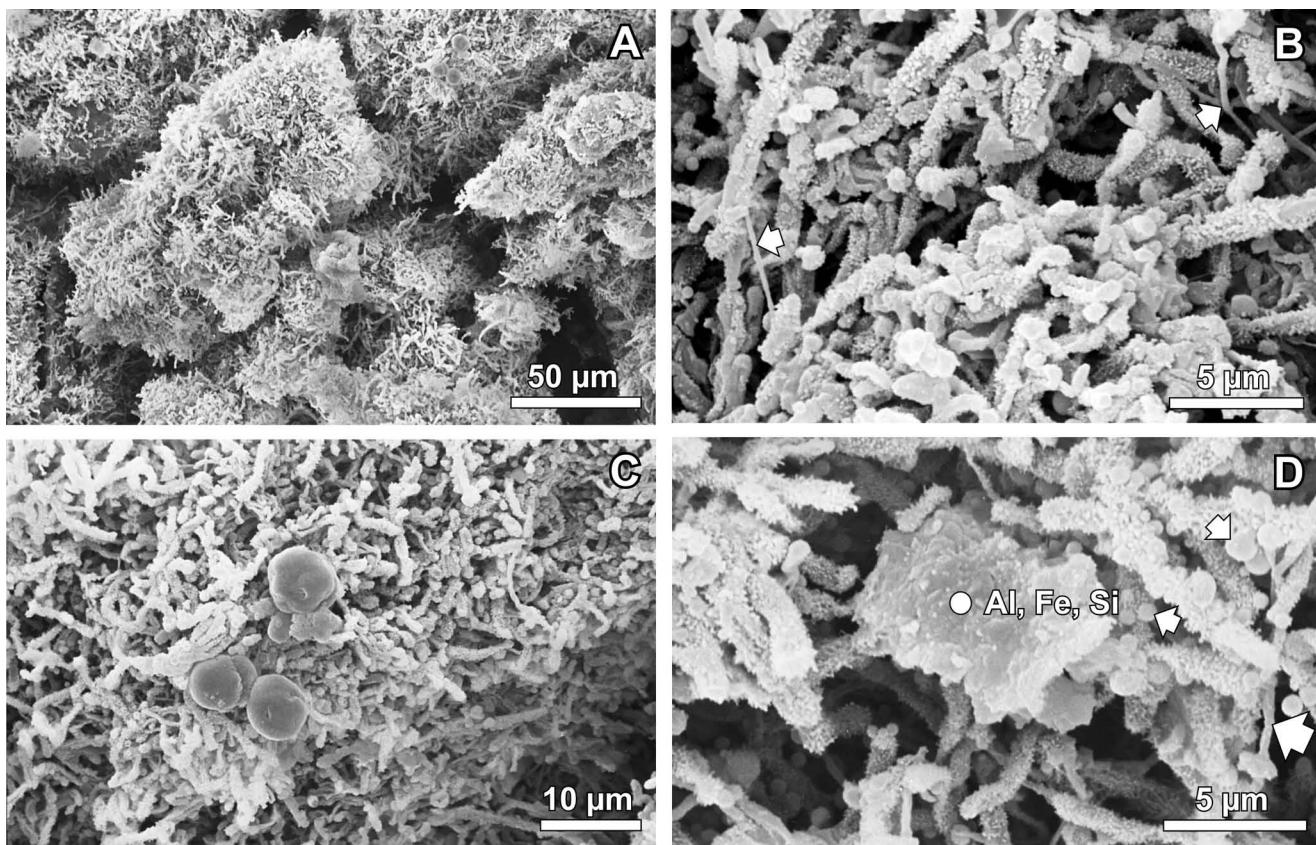


Fig. 8. **A** – Three-dimensional porous network composed mainly of morphotype 6 (Actinomycetes); **B** – Detailed view of the network, spinose-walled morphotype 6 dominate, smooth-walled morphotype 7 occur subordinately (arrows), **C** – ovoid morphotype 5 (arrows) associated with spinose-walled filamentous morphotype 6; **D** – minute coccoid bodies of morphotype 4 (spores of Actinomycetes; small arrows) associated with filamentous morphotypes 6 and 7 (big arrow), in the centre platy mineral grain entrapped within organic filaments (EDS chemical composition is indicated); all photographs under SEM

structed predominantly by minerals precipitated from solution. Although the discussed deposits mimic the relief of some speleothems (see below and Fig. 3), they cannot be included into this genetically defined group, because they contain extremely small amount of, if any, secondary mineral phases, that is minerals precipitated within a cave (*cf.* Hill & Forti, 1997, p. 45). The microstromatolites bear morphological resemblance to speleothems described from other sandstone caves in the Polish Outer Carpathians (Urban *et al.*, 2007). Many of the latter forms are composed of detrital grains cemented with opal, which is not a case in the discussed microstromatolites.

The growth of the discussed microstromatolites is influenced by several factors. The influx of detrital particles is possible due to relatively close distance to the Earth surface and the weathering zone (see Urban *et al.*, 2007). It is additionally facilitated by the presence of gravitationally widened fissures which guide the water transporting mineral particles down to the cave. The fine-grained nature of microstromatolites more probably depends on the preferential removal of such grains from soils. The particles must be transported only during the wet periods, that is during thaw or after heavy rains, since during the visits to the cave its walls were covered only by drops of condensation water and were devoid of seeping water. The episodic supply of material results in a visible lamination of microstromatolite

(Fig. 5C). The microbial biofilm covering the vertical or even overhanging cave walls trap and bind the transported detrital particles (Figs 6C, D, 8D). The capacity of bacteria to stabilize sand and finer grains has been experimentally confirmed (Meadows *et al.*, 1994; Westall & Rincé, 1994; Dade *et al.*, 1996). The particles are stabilized on the surface of microstromatolite and then covered with a newly developed biofilm (Fig. 6D). Simultaneously, an older part of the biofilm disintegrates due to senescence, which is probably facilitated by covering mineral particles. The laminae which comprise outsized quartz grains mark the especially wet episodes when relatively coarse-grained material could have been remobilized from soils and washed down into the cave (Fig. 5C). The microterraces form in zones of more intense water flow (Fig. 3A–C). It is confirmed by their preferential formation along vertically oriented convex bends of the overhanging cave wall, thus the part where water flow is concentrated due to the surface tension. The downward inclined shape of particular microterraces most probably results from plastic deformation and creeping of soft microstromatolite under the action of gravity (Fig. 3C).

The influx of seepage water is also important for the micro-organism assemblage forming the microstromatolites, which most probably depends on the input of organic matter from the surface (*cf.* Groth & Saiz-Jimenez, 1999). On the one hand, the limited energy of seeping water sorts

mineral grains and controls the fine-grained composition of microstromatolites. On the other hand, it allows delicate microbial biofilm to exist on cave walls; the higher energy of flow would cause destruction and scrubbing off of the microbial biofilm.

The lack of precipitation of minerals is most probably connected with the chemistry of the seeping water. Although direct data are lacking, we can hypothesize that the water in W Sopotni Wielkiej Cave is similar to the water in other non-karst caves in the flysch rocks of the Outer Carpathians. Zawierucha *et al.* (2005) reported that the vadose water in those caves is only slightly more mineralized than the rain water. The mean concentration of the Ca ion is only 9.5 mg/l, that is definitely lower than in karst caves. For example, the Ca content in water from selected Slovak karst caves ranges between 44.1 and 132.1 mg/l (Motyka *et al.*, 2005) whereas in the vadose zone water of karst caves on the Kraków–Wieluń Upland it is from 52 to 137 mg/l (Różkowski, 2006). Moreover, one can suppose that the water which quickly percolates down after heavy rains, as it is in the discussed case, has lower concentration of ions due to its lower residence time (see discussion in Musgrove & Banner, 2004). Thus, the water in the studied cave most probably does not achieve the appropriate saturation to precipitate carbonate minerals.

The micro-organisms detected within the microstromatolites have been reported from other caves and have been supposed to influence – actively or passively – precipitation of minerals. Living bacteria belonging to *Arthrobacter* were detected within growing moonmilk deposits (Gradziński *et al.*, 1997b) and cave pearls (Gradziński, 2000). Phosphatized microbial cells assigned also to this genus are reported from the speleothems of Grand Cayman Island (Jones, 2009b). Mineralized, commonly calcified, Actinomycetes, including various species of *Streptomyces*, are known from cave deposits of Spain (Cañaveras *et al.*, 2001), Italy (Groth *et al.*, 2001), USA (Melim *et al.*, 2008) and the Cayman Islands (Jones, 2009a, b). This leads to the suggestion that the mineralization of micro-organisms in the cavern environment is strongly dependent upon chemistry of the feeding water.

The described origin of the studied siliciclastic microstromatolites may shed some light on the formation of other cave deposits. The unconsolidated accumulations of fine-grained clastics on cave walls, including vermiculations common in many caves, can be also formed by the trapping and binding of detrital particles by micro-organisms. Several forms of speleothems recognized in some caves of the Polish Outer Carpathians may also share their origin with the discussed microstromatolites. They are also composed of siliciclastic material, display lamination and contain some laminae rich in coarser quartz sands (Urban *et al.*, 2007).

The described stromatolites have a low potential for preservation. The only one possibility for their preservation is a quick cementation with calcium carbonates or opal acting as cement or covering a stromatolite as a younger flowstone (*cf.* Urban *et al.*, 2007). Thus, clastic-rich layers occurring within flowstones and other speleothems (see Dziedzio *et al.*, 1993; Gradziński *et al.*, 1997a; Turgeon & Lundberg, 2001) may be fossil counterparts of microstromato-

lites formed during the break of crystallization and intense clastic supply. Since the micro-organisms entrapped detrital grains on the vertical and overhanging walls in the studied case, it seems plausible that they also play a role in stabilization of such grains deposited on a flowstone surface and later cemented with calcite or aragonite. Non-mineralized micro-organism cells have been decomposed and have not been preserved. Hence, the layers in question lack any traces of micro-organisms.

The closest modern counterparts of the described forms, both in morphology and origin, are sand ripples developing on steep sandstone crags described by Pentecost (1999) from Kent. They are composed of sand grains stabilized by algae and mosses and display relief strikingly similar to that of the described microstromatolites. The most important difference between the relief of sand ripples and the cave microstromatolites is a slightly greater lateral distance between neighbouring ripples (5.6–8.0 mm for the sand ripples). Other surface counterparts are litter dams occurring on slopes. They owe their origin due to accretion of small organic and mineral particles and their stabilization by mosses (Eddy *et al.*, 1999). The spatial arrangements and relief of the litter dams are different, mainly because of their formation on the inclined, not vertical slopes.

Interestingly, a relief analogous to the described microstromatolites characterizes surfaces of several actively growing continental deposits. The surfaces of some cave flowstones and dripstones are crenulated (Hill & Forti, 1997, pp. 71, 105) or rippled (Ford, 1988). Similar ripples are formed on the growing icicles (e.g., Ogawa & Furukawa, 2002). The cave draperies also display serrated edges composed of the stepped overhanging terracettes comparable to the terracettes formed by the described microstromatolites. Identical terracettes are composed of moonmilk deposits (Gradziński & Radomski, 1957). On the steeply inclined or overhanging walls their upper surfaces are downward inclined similarly to the terracettes of the described microstromatolites (Fig. 3E). Such orientation probably resulted from some instability of moonmilk having a pasty consistency and from its tendency to creeping down, which is in common with the discussed microstromatolites. Also travertines form similar regularly spaced terracettes. The lateral distance between the neighbouring travertine terracettes becomes shorter on steeper slopes (Hammer *et al.*, 2010). Hence, the travertine terracettes developed on vertical and steep slopes may serve as a counterpart of the described ripples and terracettes formed by the microstromatolites. Nonetheless, in contrast with the microstromatolites and moonmilk examples, the rim of travertine terracettes is almost always perfectly horizontal (Fig. 3C; Hammer *et al.*, 2010). It most probably results from the robust consistency of travertine deposits. Surprisingly, although all the above mentioned calcareous deposits originated mainly by the precipitation of crystals, not by the accumulation of detrital particles, they share their shape and geometric pattern with the discussed microstromatolites whose growth is governed by different factors. It adds a new dimension to the discussion on the factors influencing the shape and spatial arrangements of terracettes in recently growing travertines and speleothems.

CONCLUSIONS

1. The walls of W Sopotni Wielkiej Cave are covered with siliciclastic microstromatolites constructed by bacteria and Actinomycetes, which trap and bind mineral particles washed into the cave from overlying soil during wet episodes.
2. Newly precipitated mineral phases seem not to contribute to the microstromatolite growth.
3. The microstromatolites form ripples and microterraces on vertical and overhanging cave walls. Their shape depends upon the relief of a cave wall. The microterraces are located where water flow is more intense, mainly along vertically oriented convex bends of a cave wall.
4. It seems possible that trapping and binding mechanism influences the origin of clastic-rich layers within cave flowstones. Clastic grains were stabilized by micro-organisms and later were cemented with calcite or aragonite. The micro-organisms were subsequently decomposed and have been not preserved till now.
5. Sand ripples developing on almost vertical sandstone crags are a close genetic and morphological analogue of the cave siliciclastic microstromatolites.

6. Ripples (crenulations) on the speleothem and icicle surfaces, as well as stepped microterraces in speleothems and travertines share the same relief with the described microstromatolites in spite of their different origin.

Acknowledgements

MG was supported at the beginning of the study by the Foundation for Polish Science in the frame of Grant for Researchers to Professor Józef Kaźmierczak. Renata Jach and Ryszard Gradziński assisted in the field, Jaga Faber, Zuza Banach and Aleksandra Woźnicka operated the SEM, Renata Jach also prepared the figures; the authors gratefully acknowledge this help. The manuscript benefited from the reviews of Tadeusz Peryt and Jan Urban.

REFERENCES

- Atlas, R. M. & Parks, L. C., 1997. *Handbook of Microbiological Media*. CRC Press, Boca Raton, 1706 pp.
- Aubrecht, R., Brewer-Carias, Ch., Šmidá, B., Audy, M. & Kováčik, L., 2008. Anatomy of biologically mediated opal speleothems in the World's largest sandstone cave: Cueva Charles Brewer, Chimanta Plateau, Venezuela. *Sedimentary Geology*, 203: 181–195.
- Baker, G., 1942. Sand stalagmites. *Journal of Geology*, 50: 662–667.
- Baskar, S., Baskar, R. & Kaushik, A., 2006. Evidences for microbial involvement in the genesis of speleothem carbonates, Borra Caves, Visakhapatnam, India. *Current Science*, 92: 350–355.
- Bertrand-Sarfati, J., 1994. Siliciclastic-carbonate stromatolite domes in the early Carboniferous of the Ajers Basin (Eastern Sahara, Algeria). In: Bertrand-Sarfati, J. & Monty, C. (eds), *Phanerozoic Stromatolites II*, Kluwer, Dordrecht, pp. 395–419.
- Bini, A., Cavalli Gori, M. & Gori, S., 1978. A critical review of hypotheses on the origin of vermiculations. *International Journal of Speleology*, 10: 11–33.
- Blyth, A. J. & Frisia, S., 2008. Molecular evidence for bacterial mediation of calcite formation in cold high-altitude caves. *Geomicrobiology Journal*, 25: 101–111.
- Braga, J. C. & Martin, J. M., 2000. Subaqueous siliciclastic stromatolites: A case history from Late Miocene beach deposits in the Sorbas Basin of SE Spain. In: Riding, R. E. & Awramik, S. M. (eds), *Microbial Sediments*. Springer, Berlin, pp. 226–232.
- Cañaverales, J. C., Sanchez-Moral, S., Soler, V. & Saiz-Jimenez, C., 2001. Microorganisms and microbially induced fabrics in cave walls. *Geomicrobiology Journal*, 18: 223–240.
- Carlile, M. J., 1979. Bacterial, fungal and slime mould colonies. In: Larwood, G. & Rosen, B. R. (eds), *Biology and Systematics of Colonial Organisms*. Academic Press, London, pp. 3–27.
- Cox, G., James, J. M., Leggett, K. E. A. & Osborne, R. A. L., 1989a. Cyanobacterially deposited speleothems: subaerial stromatolites. *Geomicrobiology Journal*, 7: 245–252.
- Cox, G., James, J. M., Leggett, K. E. A. & Osborne, R. A. L., 1989b. Stromatolitic crayfish-like stalagmites. *Proceedings of the Bristol Speleological Society*, 18: 339–358.
- Cunningham, K. I., Northup, D. E., Pollastro, R. M., Wright, W. G. & LaRock, E. J., 1995. Bacteria, fungi and biokarst in Lechugilla Cave, Carlsbad Caverns National Park, New Mexico. *Environmental Geology*, 25: 2–8.
- Curry, M. D., Boston, P. J., Spilde, M. N., Baichtal, J. F. & Campbell, A. R., 2009. Cottonballs, a unique subaqueous moonmilk and abundant subaerial moonmilk in Cataract Cave, Tongass National Forest, Alaska. *International Journal of Speleology*, 38: 111–128.
- Dade, W. B., Self, R. L., Pellerin, N. B., Moffet, A., Jumars, P. A., Nowell, A. R. M., 1996. The effects of bacteria on the flow behavior of clay-seawater suspensions. *Journal of Sedimentary Research*, 66: 39–42.
- Dziadzio, P., Różniak, R. & Szulc, J., 1993. Origin of the Pleistocene calcite flowstones of two caves (Jaskinia Psia and Jaskinia Naciekowa) in the West Tatra Mts. (In Polish, English summary). *Przegląd Geologiczny*, 41: 767–775.
- Eddy, J., Humphreys, G. S., Hart, D. M., Mitchell, P. B. & Fanning, P. C., 1999. Vegetation arcs and litter dams: similarities and differences. *Catena*, 37: 57–73.
- Ford, T. D., 1988. Rippled speleothems. *Cave Science*, 15: 86–87.
- Golonka, J. & Wójcik, A., 1978. *Objaśnienia do szczegółowej mapy geologicznej Polski. Arkusz Jeleśnia 1:50 000*. (In Polish). Wydawnictwa Geologiczne, Warszawa, 40 pp.
- Gradziński, M., 2000. *Pizoidy jaskiniowe: uwarunkowania genetyczne i środowiskowe ich powstania*. (In Polish). Unpublished PhD thesis, Institute of Geological Sciences, Jagiellonian University, Kraków, 90 ms. pp.
- Gradziński, M., Banaś, M. & Uchman, A., 1995. Biogenic origin of manganese flowstones from Jaskinia Czarna Cave, Tatra Mts., Western Carpathians. *Annales Societatis Geologorum Poloniae*, 65: 19–27.
- Gradziński, M., Chmiel, M. J. & Michalska, B., 2001. Powstanie i rozwój detrytycznych polew naciekowych w Jaskini w Sopotni Wielkiej (Beskid Żywiecki). (In Polish). In: Gradziński, M., Mleczek, T., Pukowski, J., Szelerewicz, M. & Urban, J. (eds), *Materiały 35. Sympozjum Speleologicznego, Bartkowa, 26–28.10.2001. Sekcja Speleologiczna PTP*, Kraków, p. 20.
- Gradziński, M. & Holubek, P., 2005. Cottonballs – peculiar speleothems from Zlomská Cave (Low Tatra Mountains, Slovakia) – pilot results. *Slovenský Kras*, 43: 187–192.
- Gradziński, M., Rospondek, M. & Szulc, J., 1997a. Paleoenvironmental controls and microfacies variability of the flowstone cover from Zvoniva Cave in the Slovakian Karst. *Slovak Geological Magazine*, 3: 299–313.
- Gradziński, M., Szulc, J. & Smyk, B., 1997b. Microbial agents of moonmilk calcification. In: Jeannin, P.-Y. (ed.), *Proceedings*

- of the 12th International Congress of Speleology, vol. 1.* International Union of Speleology, Basel, pp. 275–278.
- Gradziński, R. & Radomski, A., 1957. Cavern deposits of “rock milk” in the Szczelina Chochołowska Cave. (In Polish, English summary). *Rocznik Polskiego Towarzystwa Geologicznego*, 26: 63–90.
- Gradziński, R. & Radomski, A., 1960. Cementatory structures in the Miętusia Cave. (In Polish, English summary). *Rocznik Polskiego Towarzystwa Geologicznego*, 30: 121–125.
- Groth, I. & Saiz-Jimenez, 1999. Actinomycetes in hypogean environments. *Geomicrobiology Journal*, 16: 1–8.
- Groth, I., Schumann, P., Laiz, L., Sanchez-Moral, S., Cañaveras, J. C. & Saiz-Jimenez, C., 2001. Geomicrobiological study of the Grotta del Cervi, Porto Badisco, Italy. *Geomicrobiology Journal*, 18: 241–258.
- Hammer, Ø., Dysthe, D. C. & Jamtveit, B., 2010. Travertine terracing: patterns and mechanisms. In: Pedley, H. M. & Rogerson, M. (eds), *Tufas and Speleothems: Unravelling the Microbial and Physical Controls*. Geological Society Special Publications, 336: 345–355.
- Hill, C. & Forti, P., 1997. *Cave Minerals of the World*. National Speleological Society, Huntsville: 1–463.
- Holt, J. G., ed., 1989. *Bergey's Manual of Systematic Bacteriology*. Vol. 1–4. Williams & Wilkins, Baltimore, 2648 pp.
- Holt, J. G., ed., 1994. *Bergey's Manual of Determinative Bacteriology*. Williams & Wilkins, Baltimore, 787 pp.
- James, J. M., Patsalides, E. & Cox, G., 1994. Amino acid composition of stromatolitic stalagmites. *Geomicrobiology Journal*, 12: 183–194.
- Jones, B., 1995. Processes associated with microbial biofilms in the twilight zone of caves: examples from the Cayman Islands. *Journal of Sedimentary Research*, A65: 552–560.
- Jones, B., 2001. Microbial activity in caves – A geological perspective. *Geomicrobiology Journal*, 18: 1–13.
- Jones, B., 2009a. Cave pearls – the integrated product of abiotic and biotic processes. *Journal of Sedimentary Research*, 79: 689–710.
- Jones, B., 2009b. Phosphatic precipitates associated with actinomycetes in speleothems from Grand Cayman, British West Indies. *Sedimentary Geology*, 219: 302–317.
- Jones, B., 2010. Microbes in caves: agents of calcite corrosion and precipitation. In: Pedley, H. M. & Rogerson, M. (eds), *Tufas and Speleothems: Unravelling the Microbial and Physical Controls*. Geological Society Special Publications, 336: 7–30.
- Jones, B. & Kahle, C. F., 1985. Lichen and algae: agents of biodiagenesis in karst breccia from Grand Cayman Island. *Bulletin of Canadian Petroleum Geology*, 33: 446–461.
- Jones, B. & Motyka, A., 1987. Biogenic structures and micrite in stalactites from Grand Cayman Island, British West Indies. *Canadian Journal of Earth Sciences*, 24: 1402–1411.
- Klassek, G., 1997. Jaskinia w Sopotni Wielkiej. In: Pulina, M. (ed.), *Jaskinie Polskich Karpat fliszowych*. (In Polish). Polskie Towarzystwo Przyjaciół Nauk o Ziemi, Warszawa: 215–217.
- Manolache, E. & Onac, B. P., 2001. Geomicrobiology of black sediments in Vântului Cave (Romania): preliminary results. *Cave and Karst Science*, 27: 109–112.
- Martin, J. M., Braga, J. C. & Riding, R., 1993. Siliciclastic stromatolites and thrombolites, Late Miocene, S.E. Spain. *Journal of Sedimentary Petrology*, 63: 131–139.
- Meadows, A., Meadows, P. A., Muir Wood, D. & Murray, J. M. H., 1994. Microbiological effect on slope stability: an experimental analysis. *Sedimentology*, 41: 423–435.
- Melim, L. A., Shinglman, K. M., Boston, P. J., Northup, D. E., Spilde, M. N. & Queen, J. M., 2001. Evidence for microbial involvement in pool finger precipitation, Hidden Cave, New Mexico. *Geomicrobiology Journal*, 18: 311–329.
- Melim, L. A., Northup, D. E., Spilde, M. N., Jones, B., Boston, P. J. & Bixby, R. J., 2008. Reticulated filaments in cave pool speleothems: microbe or mineral? *Journal of Cave and Karst Studies*, 70: 135–141.
- Mikuszewski, J., 1973. Nowa jaskinia w Beskidzie Żywieckim. (In Polish). *Wierchy*, 42: 262–265.
- Motyka, J., Gradziński, M., Bella, P. & Holubek, P., 2005. Chemistry of waters from selected caves in Slovakia – a reconnaissance study. *Environmental Geology*, 48: 682–692.
- Musgrove, M. & Banner, J. L., 2004. Controls on the spatial and temporal variability of the vadose dripwater geochemistry: Edwards Aquifer, Central Texas. *Geochimica et Cosmochimica Acta*, 68: 1007–1020.
- Northup, D. E. & Lavoie, K. H., 2001. Geomicrobiology of caves: a review. *Geomicrobiology Journal*, 18: 199–222.
- Ogawa, N. & Furukawa, O., 2002. Surface instability of icicles. *Physical Review E*, 66: 041202–1.
- Palmer, A. N., 2007. *Cave Geology*. Cave Books, Dayton, 454 pp.
- Pentecost, A., 1999. A note on sand ripples developing in sandstone rock seepages of the Weald, UK. *Earth Surface Processes and Landforms*, 24: 1257–1259.
- Pepper, I. L. & Gerba, Ch. P., 2004. *Environmental Microbiology: A Laboratory Manual*. Elsevier, Amsterdam, 209 pp.
- Richter, D. K., Immenhauser, A. & Neuser, R. D., 2008. Electron backscatter diffraction documents randomly oriented c-axes in moonmilk calcite fibres: evidence for biologically induced precipitation – short contribution. *Sedimentology*, 55: 487–497.
- Riding, R., 1991. Classification of microbial carbonates. In: Riding, R. (ed.), *Calcareous Algae and Stromatolites*. Springer, Berlin: 21–51.
- Róžkowski, J., 2006. *Groundwaters of carbonate formations in the southern part of Jura Krakowsko-Częstochowska and problem with their protection*. (In Polish, English summary). Wydawnictwa Uniwersytetu Śląskiego, Katowice, 264 pp.
- Schwarz, H.-E., Einsele, G. & Herm, D., 1975. Quartz-sandy, grazing-contoured stromatolites from coastal embayments of Mauritania, West Africa. *Sedimentology*, 22: 539–561.
- Squyres, S. W., Andersen, D. W., Nedell, S. S. & Wharton, R. A. Jr., 1991. Lake Hoare, Antarctica: Sedimentation through a thick perennial ice cover. *Sedimentology*, 38: 363–379.
- Taboroši, D., 2006. Biologically influenced carbonate speleothems. In: Harmon, R. S. & Wicks, C. M. (eds), *Perspectives on Karst Geomorphology, Hydrology and Geochemistry*. Geological Society of America, Special Paper, 404: 307–317.
- Turgeon, S. & Lundberg, J., 2001. Chronology of discontinuities and petrology of speleothems as paleoclimatic indicators of the Klamath Mountains, Southwestern Oregon, USA. *Carbonates and Evaporites*, 16: 153–167.
- Urban, J., Margielewski, W., Schejbal-Chwastek, M. & Szura, Cz., 2007. Speleothems in some caves of the Beskid Mts., Poland. *Nature Conservation*, 63: 109–117.
- Westall, F. & Rincé, Y., 1994. Biofilms, microbial mats and microbe-particle interactions: electron microscope observations from diatomaceous sediments. *Sedimentology*, 41: 147–162.
- Zawierucha, L., Czop, M. & Motyka, J., 2005. Modification of precipitation chemistry in unsaturated and saturated zones of the Beskid Mały and Śląski flysch rocks. (In Polish, English summary). *Współczesne Problemy Hydrogeologii*, 12: 737–742.