The formation of stromatactis-type fenestral structures during the sedimentation of experimental slurries – a possible clue to a 120-year-old puzzle about stromatactis

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Abstract. A critical analysis of stromatactis-type fenestrae, including the unaltered composition of the host carbonate sediments and other circumstances, led to the formulation of the hypothesis that swarms of stromatactis might originate during the process of rapid, uninterrupted sedimentation. The rationale behind this possibility concerns several points. First, the stromatactis sediment has the characteristics of particulate materials that are typically polydisperse (with polymodal frequency distributions). Also the shapes of the particles are extremely diversified and complex – the grains are often subangular, platelet-like or acicular, porous, soft, or irregularly indented. This seems to be valid not only for relatively coarse banks with stromatactis (with visible amounts of sand- and even fine gravel-sized grains), but surprisingly also for the finest available varieties, which consist rather of calcisiltites than of muds and also provide a large variety of shapes and internal fabrics (alterations), even in the finest fractions. These sedimentary materials have unusual mechanical properties, of which high coefficients of internal friction (in a dry state) and presumably high dynamic viscosities in contrast to low mass density (in dense aqueous suspensions) are the most important. The latter attributes (in suspension) can be enhanced by the occurrence of filamentous organic muds, where living bacteria significantly contribute to the production of microbubbles. The swarms of stromatactis fenestrae are often developed in the lower/middle parts of relatively homogeneous or mottled beds, being underlain by a coarser, graded base. The finest, uppermost parts of these beds are almost devoid of stromatactis. There are also other constraints, for example, that stromatactis formation can be traced from just below the fair-weather wave base to middle slope environments, and stratigraphically reach the deep Proterozoic sequences. This is a very general occurrence. Sedimentation experiments with artificially prepared slurries of comparable complexity have resulted in the production of structures that are nearly identical to stromatactis, including the details of typical stromatactis formations and the changes in the surrounding sediment. These consistently repeatable experiments show clear cause-and-effect relationships between the processes and resulting fabrics.

Key words: carbonate sedimentology, stromatactis, fenestral structures, mud mounds, polydisperse suspensions, sedimentary experiments

Introduction

The limestone facies with horizontally spreading layers of stromatactis-type fenestral structures, as introduced by Dupont (1881) and defined by Bathurst (1982), are often studied to determine their origin. A number of papers have been published on these relatively large, flat bottomed and reticulate pores with digitate roofs, and the current leading opinions in this field contain useful information concerning a link with bacterial mud mounds (Monty et al. 1995, Reitner and Neuweiler 1995, Riding 2002). However, the problems of the mechanism of their formation have not yet been resolved. In addition, there is emerging evidence that at least several facts do not fit the current polymud mud-mound accretion hypotheses (e.g., long rows of stromatactis

fabrics in planar beds with no domical topography, stromatactis-type swarms of fenestrae occurring in coarse grained crinoidal limestones, and the tendency of these swarms to occupy the levels between the lower third or one half of a single bed). An analysis of the stromatactis question has not only theoretical significance, but also practical and regionally important relevance for the chemostratigraphic and magnetic-susceptibility stratigraphy studies that are currently in progress in the limestone sections of the Barrandian area (Figs 1 and 2 – location and appearance of stromatactis fabrics exposed in quarry faces).
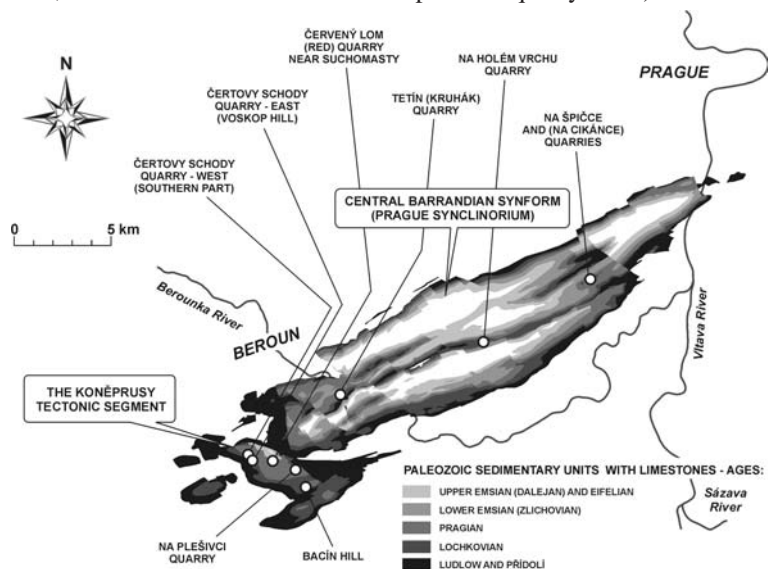

Figure 1. The principal occurrences of stromatactis structures in limestones SW of Prague, Czech Republic. These occurrences are concentrated on the slope of Koněprusy paleoheight, in the Koněprusy tectonic segment, also extending in the direction to Prague, but mainly bordering the Koda fault system on its northern side, between the Tetín and Na Špičce quarries. The thicknesses of these limestones do not exceed a few metres or a little more than ten metres in maximum, and the succession of beds is only slightly domed, or not at all. The most significant stratigraphic levels are early middle Pragian and the uppermost Emsian. The latter concerns mainly the Červený lom (Red) Quarry near Suchomasty (where decorative stromatactis marbles were quarried for several hundred years), where stromatactis beds of the lowermost Eifelian also exist.
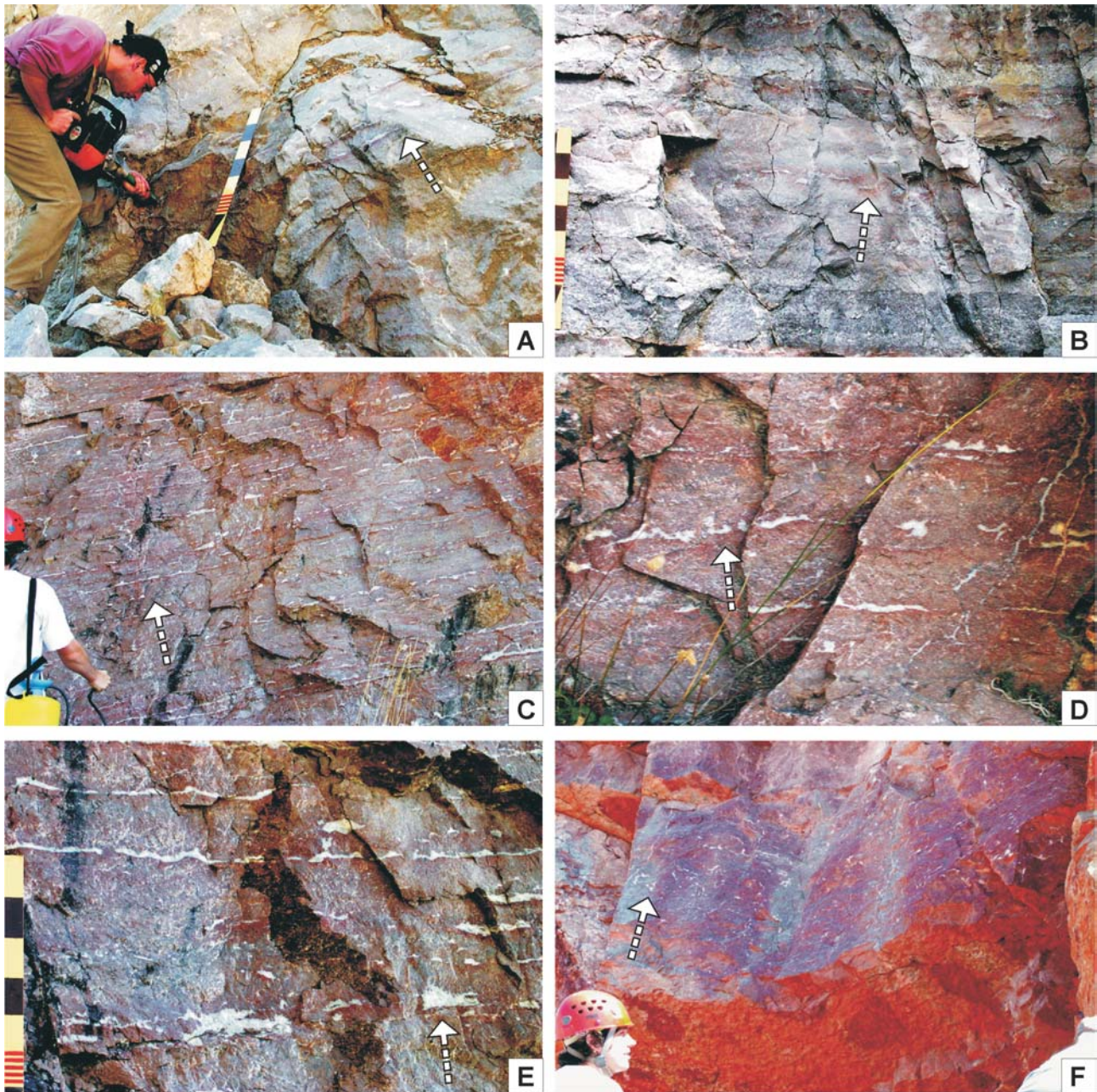
Figure 2. Examples of the Lower Devonian (Pragian) stromatactis beds from limestone quarries between Prague and Beroun. A – Koněprusy, Čertovy schody West Quarry, S wall. B – Měňany, Na Plešivci Quarry, NE corner. C–E – Tetín, Kruhák Quarry, N wall. F – Trněný Újezd, Na Holém vrchu Quarry, S wall. The bright objects marked by arrows are stromatactis fenestrae filled by calcite cements.

Formulating the working hypothesis

Basic features of stromatactis fenestrae

The stromatactis-type fenestrae (Figs 3–6) have relatively smooth and sharp (horizontal or slightly bent) bases, but the roofs are clearly arched and have friable fabrics. The upper sides of individual stromatactis chambers are densely ornamented by cuspate or digitate protrusions. The stromatactis can be found separately, but many of them comprise interconnected, sub-horizontally spreading, or reticulate to maze-like caverns, in which some specimens can also form obliquely climbing channels. The well separated and relatively high fenestrae (with height to length ratios of approximately 1 : 3) differ from the more interconnected and relatively low forms (less than 1 : 6). The latter are usually bent and form dish-like shapes, and their roofs are locally depressed to the cavity floors. Nearly every stromatactis formation, albeit generally arranged sub-parallel to bedding, is regularly placed inside a relatively thick carbonate bed which has considerably massive (or mottled) structures. Stromatactis directly bordering the bed boundaries are extremely rare. The stromatactis levels mainly occupy the intervals from the lower third up to half of the sedimentary bed's height. The floors of the stromatactis cavities are nearly always covered by a thin layer of upward

fining internal sediment that precipitated as a "snow" of ultra-fine particles. This concerns only the earliest sedimentation inside these fenestrae, with no direct connection to any planar structures in the sediment around the stromatactis. This "snow" had formed earlier than any other component of the geopetal fill.

The above description emphasizes the attributes of possible primary (and mostly still preserved) stromatactis shapes, i.e. those of the primary stromatactis cavities instead of those that are related to subsequent alterations and fills. Nonetheless, Bourque and Boulvain (1993) have suggested that stromatactis is a spar network of these morphologies, and thus could also be considered as a phenomenon of the later stages of early diagenesis.

It will be instructive to briefly consider the sedimentary systems in which these typically shaped stromatactis commonly occur, as they cannot be understood separately from their host rocks. The currently prevailing interpretation is that stromatactis-type structures were coupled with ancient deep-water reefs called mud mounds, or near by off-mound sediments (e.g., Pratt 1982, Bosence and Bridges 1995, Boulvain 2001). The depositional environments were traditionally interpreted as being related to places of relatively slow, complex sedimentation, with the occurrence of microbial mats (e.g., the polymuds by Lees and Miller 1995). However, the polyphase/polygenetic polymuds with various micrite clots and fills are not necessarily indicative of in-situ carbonate build-ups, but they may point to highly selective mechanisms related to internal sediments/precipitates in any unusually inhomogeneous and porous carbonate deposits. In particular, there are several recent publications that indicate links between stromatactis and poorly sorted crinoidal limestones (e.g., Kaufmann et al. 1999, Aubrecht et al. 2002b). The present author's opinion is that stromatactis-related sedimentary conditions could be simpler than usually stated, being connected to a specific sort of event sedimentation process rather than comparable to the growth of a bacterial reef.

The perception of the stromatactis shapes and their position in the sediment, based on the present author's field experience, is not essentially different from that presented in the most respected papers in this field. Bathurst (1982), for example, stated that stromatactis can only be identified in terms of all five of the following criteria: 1. the masses of spar (which may be perceived as evidence of cavities), 2. the smooth base, 3. the digitate roof, 4. the occurrence in swarms, and 5. the reticulate distribution. Even though the cement fills may have secondary importance (Bathurst's point 1), it is apparent that the larger forms have a volumetrically considerable, non-ferroan, inclusion-rich, radiaxial fibrous calcite, distributed isopachously over the cavity walls. This would seem to indicate the presence of cavities (as emphasized by the open-space structures by Kukal 1971). Furthermore, it was shown by Kaufmann and Wendt (2000) that these radiaxial cements must correspond to very early stages of diagenesis, particularly owing to unaltered C and O marine isotope values similar to those in unaltered brachiopod calcites.
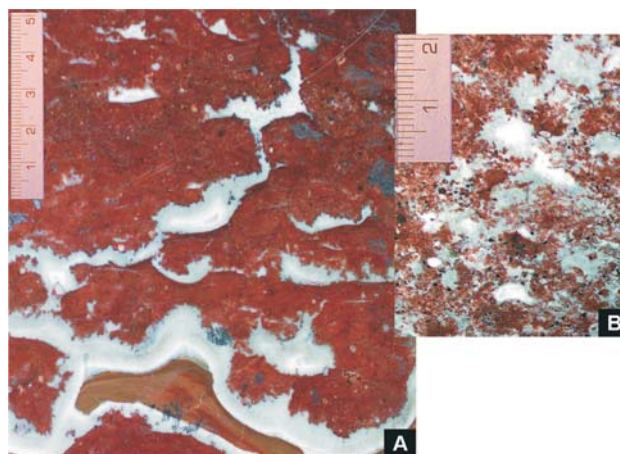

Figure 3. A closer view of the stromatactis structures. The polished sections are marble plates in the Smíchov Railway Station, Prague. A – vertical section, Radotín, Na Špičce Quarry, Slivenec Limestone, Lower Devonian (Pragian). B – cross section showing the tubular channels that developed in the upper part of a stromatactis structure, Suchomasty, Červený lom (Red) Quarry, Suchomasty Limestone, Lower Devonian (Upper Emsian). This exemplifies the reticulate and upward-climbing fabrics, with the occurrence of tubular channels. Scale: paper ruler (numbered in cm).

Incompatible opinions, or definitions of stromatactis and stromatactis-like structures, are based on a variety of flat-floored and arched cavities sitting on sutures between the beds, which can also be attached to the contacts between rocks and corals (Wood 1998), or occurring at similar interfaces (possible dissolution, Sanders 2003). However, none of these forms fulfil the above mentioned criteria, which are emphasized here as the most significant for the definition of stromatactis-type cavities.

The unity of true stromatactis fenestral shapes

Although most papers agree that stromatactis cavities have characteristic shape variations (Bathurst 1982, Bourque and Boulvain 1993), the nature of their relationships to smaller, stromatactis-like structures remains open, unknown, or even misinterpreted. For example, Neuweiler et al. (2001) and Boulvain et al. (2004) distinguished the typical (i.e. large) stromatactis structures from these small forms. This is what they call the stromatactoid fenestrae (fenestrae that are shaped like stromatactis), which are unconnected cavities usually smaller than 5 mm, cemented mostly by clear equant spar calcite. Such stromatactis-like structures have been excluded from the stromatactis concept. However, many of these small stromatactoid fenestrae are ambiguous in both form and origin (e.g., Neuweiler et al. 2001, Fig. 4C – a stromatactid cavity as a miniaturized stromatactis in contrast to Fig. 5B – the stromatactid cavities changing to a tangle of openings after bubbles, channels, and irregularly clumped sediment; or Boulvain et al. 2004, Fig. 4E – other stromatactoid fenestrae, corresponding to the above mentioned tangle of associated structures, nevertheless, quite distantly related to stromatactis).

The separation of these two extremes (i.e. the biggest and smallest stromatactis shapes, the latter with only negligible amounts of early internal sediment and fibrous
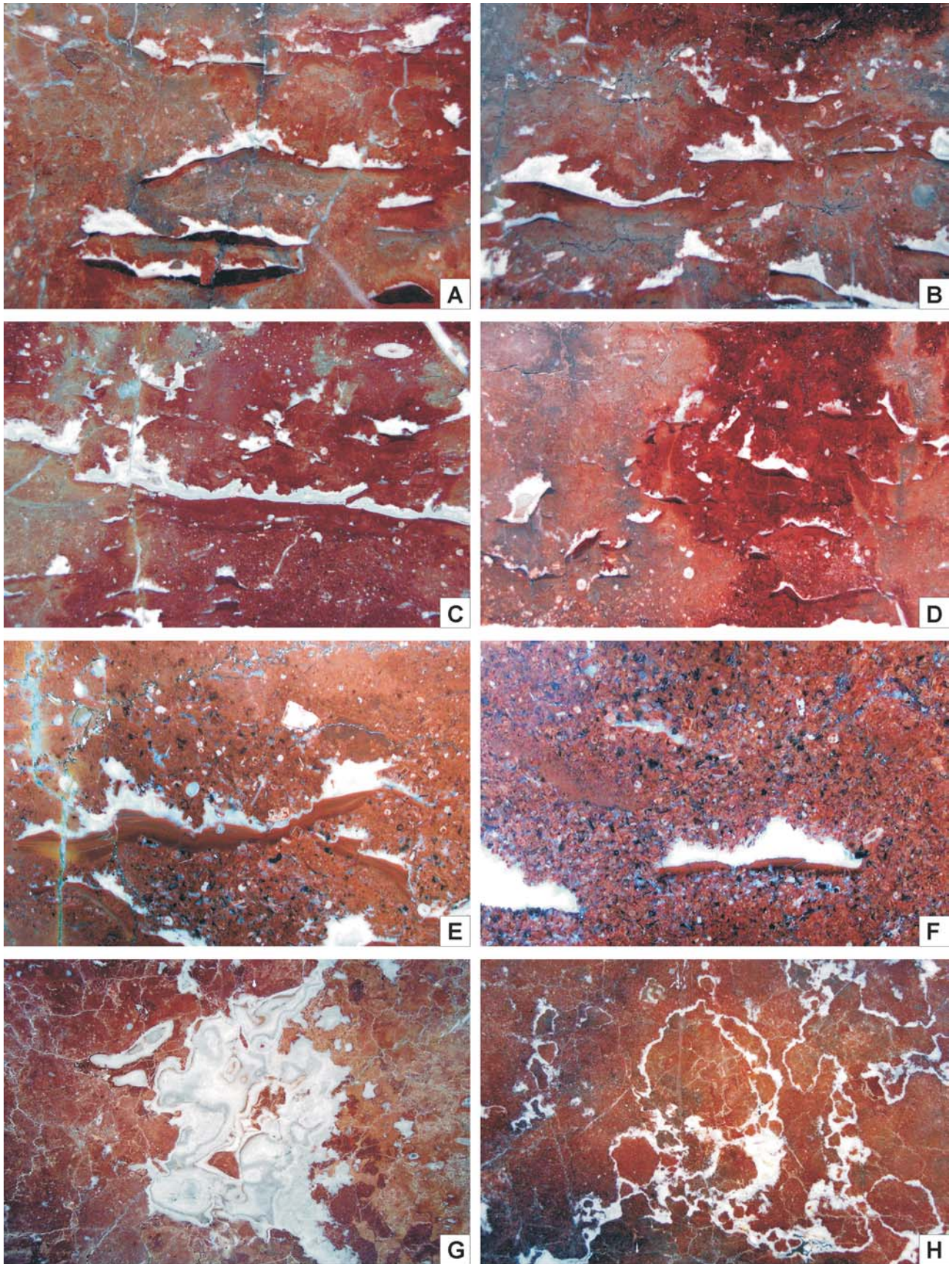
Figure 4. Stromatactis rock fabrics of the Upper Emsian Suchomasty Limestone. A–E – images of the lower/middle parts of the thick stromatactis beds, vertical sections. A – geopetal sediments of early origin are thicker in the lower (first) cavities. B – small and large cavities alternate, the uppermost cavities are very small and the higher ones are missing. C – mainly the spacious and partly collapsed (flattened) cavities branched to upper galleries. The base

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sparite) is, however, problematic. It is certainly very useful to separate the apparently similar structures of different nature and in other than typical stromatactis rocks, but it is very implausible to think that these large and small forms were strictly separated in the stromatactis sediment. In actuality, any real stromatactis formations yield a number of gradual size transitions from the largest specimens of decimetre sizes to the smallest of a few millimetres in size. The co-occurrence of many sizes of stromatactis shapes is too common to be negligible. It is true that the smallest fenestrae are more frequently filled by equant than by fibrous calcite cement (or the amount of the latter is reduced). But this transition is also observable in typical stromatactis swarms, and is not due only to differences between the stromatactis and non-stromatactis facies. Further, fine grained but unevenly mixed, wild calcilutite/calcarenite sediments with miniaturized swarms of stromatactis (including the fibrous cements) also exist. Such beds are not infrequently observed in upper to mid-slope calciturbidite deposits, and they contain the true, albeit very small stromatactis (e.g., the Lower Pragian sediments of Bacín Hill, the Koněprusy segment of the Barrandian area). The relatively shallow-water stromatactis occurrences in contact with photic-zone reef corals and stromatoporoids (Boulvain et al. 2004) are in contrast to the stromatactis swarms that occur together with deep-water corals related to hydrothermal vents (Brachert et al. 1992, Berkowski 2004). But the crinoidal limestones with characteristic mixtures of calcilutite (mud) to calcirudite grains are very often indicative of these facies.

It can be tentatively suggested that the distinct shapes of true stromatactis formations (as defined by Bathurst 1982, but of any size), correspond rather to distinct sediment deposition dynamics than to any other circumstances, such as various sea depths, the magnitude of bacterially mediated precipitation or binding of the sediment, or the proportions of the various organisms providing the dishevelled skeletal debris in the host rocks.

The relationships of stromatactis to other fenestral fabrics

The stromatactis fenestrae have geometries that are distinct from other open structures in the sediment, including those that occur in the same beds or in adjacent, lithologically different beds. This is particularly relevant when comparing stromatactis fenestrae with various eye-, mushroom- or umbrella-shaped empty spaces, openings created by expanding and ascending bubbles, bedding-parallel cracks, bioturbation voids, or a variety of dissolution cavities.

The gaseous products of bacterial metabolism, if accumulated in the sediment, may form bubbles that increase in size and migrate to the most porous, soft, or low-pressure locations. A variety of bulbous, bird's eye, amoebic, and tubular shapes may also form coalescing structures when many bubbles collected into an irregular layer of gas are separated by material in which cavities are relatively few. Because of the fact that the bubbles are mostly moving upward, increasing in size with reduced pressure, the particular zones of their coalescence occur under the umbrellas of impermeable membranes or lamellar objects (crusts, mats, coatings and shells). The shapes of such cavities are upside-down compared to stromatactis that protrude upwards. The cavities under the umbrellas have sharp roofs but undulating, porous, and tubular bases that were never, or only sporadically, covered by internal sediment. In addition, the crystalline fill is a very clear and coarse equant calcite.

If stromatactis and bubble structures merge together in rare but not uncommon situations, then the latter are apparently delayed or younger, and have altered or dissected the stromatactis. Also the sub-vertical cracks and subhorizontal fissures form a variety of void structures that undoubtedly originated during middle/late stages and after the process of filling the stromatactis cavities. The observations that the stromatactis fenestrae and their fibrous cement fills preceded all other suites of void structures have primary significance for the further development of the hypothesis. The stromatactis formation is, therefore, constrained to the earliest stages of the rock-forming processes, and it must be related to the deposition, settling, and earliest diagenetic stages of the host sedimentary rock.

Speculations of this type are very different than the stromatactis explanations that have been formulated during the history of the stromatactis research. The enduring history of related investigations began in 1881, as reviewed in several recent papers (e.g., Bathurst 1982, Dieken 1996, Krause 2001, Neuweiler et al. 2001). This history consists of about two hundred more-or-less related but remarkably inconsistent papers. Some of them are considered to be somewhat antiquated and/or to contain ideas that have been disproved in subsequent studies. The causes of stromatactis were seen in many possible precursors or processes; for example: a) decay of soft-bodied organisms, plants, cyanobacterial mats, biodictyons and mucilaginous clumps under the sea floor, b) sheltering and baffle effect of skeletal or soft-bodied organisms, c) openings created by roots and burrowers, d) recrystallization of former skeletons,

of a bed is much coarser (and graded) than its middle/upper part, i.e. when comparing the lower and upper edges of image D. E – sediment with large stromatactis structures is a diverse mixture of allochthonous and variously altered grains, some of them (e.g., crinoid pluricolumnals, cephalopods, brachiopods, or broken crystals) are even gravel-sized objects. F – small stromatactis fenestrae do not necessarily originate in the fine-grained fraction, though an exception to this rule is exemplified in image. G – horizontally sectioned stromatactis structures yield complementary information on the geometry of the stromatactis cavities: an example of a large, uncollapsed stromatactis cavity shows inner parts that were richly filled with fibrous milky, isopachous calcites, and equant, translucent/transparent calcite cements. H – interconnected and flattened stromatactis cavities resemble dish-like water escape structures. This bending is visible in vertical sections (D), and its nearly ideal form was found in a horizontal section. All these rocks were quarried in the Červený lom (Red) Quarry near Suchomasty in 1932–1933 (documents of Filip Migot Marble Industry Co., The National Archive, Brno), and several hundred square metres of polished marble plates cover the pillars and walls in a spacious nave of the St. Augustine Church in Brno (since 1934). Scale (width of area in image): A–E – 20 cm, F – 5 cm, G, H – 30 cm.
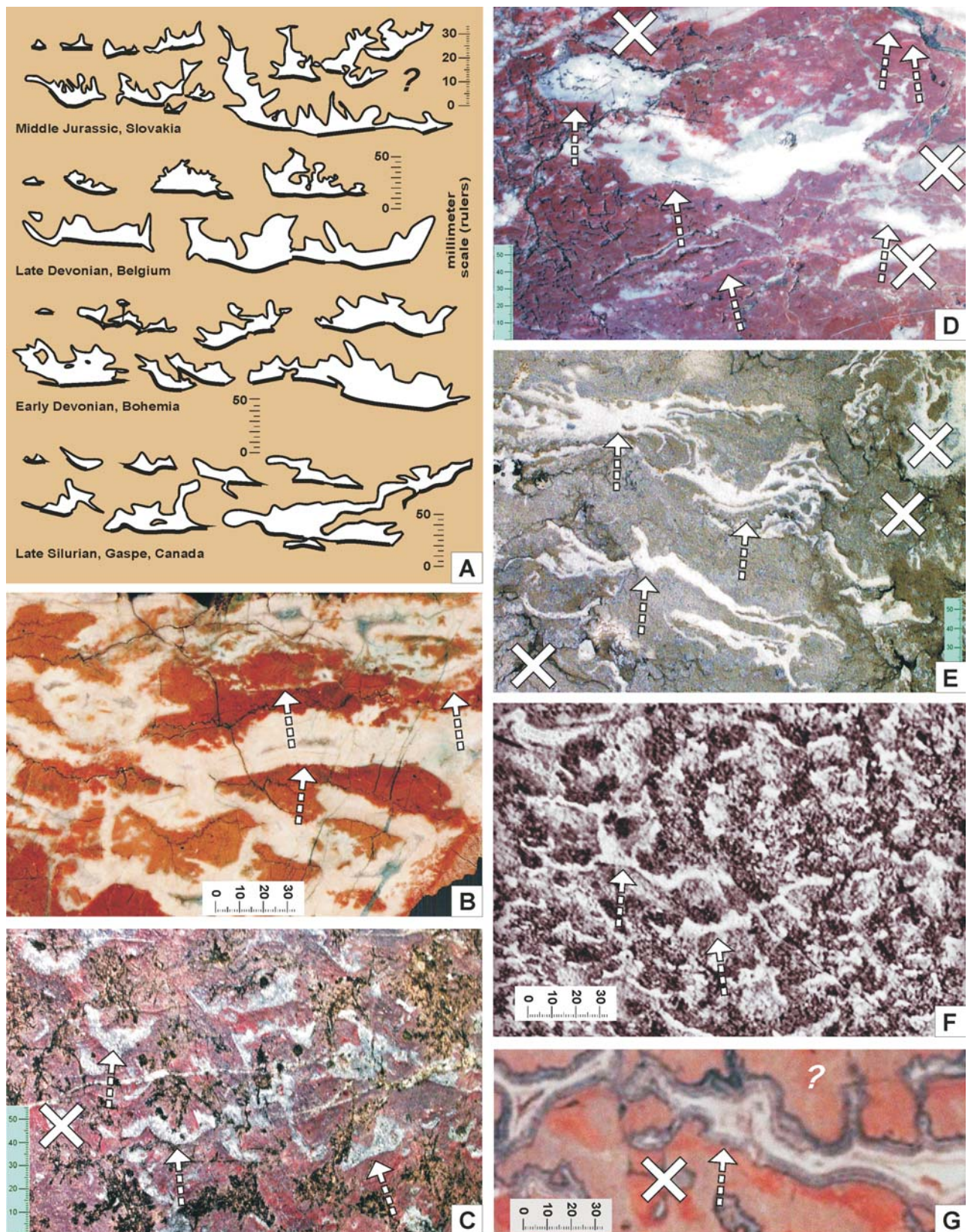
Figure 5. Several examples of the shapes of stromatactis fenestrae in limestones of very different ages and from different parts of the world. A – large and small stromatactis specimens occur most often together in a series (or randomly), but the characteristics of their shape variability become more apparent if these objects are artificially arranged according to size. Even though these archive outline diagrams are very approximate, such a collection gives a good picture on how the well-preserved stromatactis differ from other fenestral fabrics. Details: Slovakia – Slávnica-Podhorie N of Dubnica nad Váhom, Jurassic (Callovian), contributed by R. Aubrecht and J. Michalík; Belgium – Senzeille (Beauchateau?), Upper Devonian (Middle Frasnian), contributed by J. Dvořák; Czechia (Bohemia) – Koněprusy, Late Devonian (Middle Pragian); Canada – Gros Morbe, SE Quebec, Upper Silurian (Ludlow), contributed by H. Geldsetzer. B–G – although about 90 % of stromatactis are integral to the basic inventory of their typical shapes, marginal and modified forms also

muds, and mineral crusts, e) non-uniform post-sedimentary compaction combined with dewatering, f) maturation of particulate polymer gels or syneresis of colloidal sedimentary components, g) selective dissolution during diagenesis and low-grade metamorphism, h) pressure cracking combined with dissolution, i) opening of shear fissures during gravitational sliding, j) hydrothermal vents with leaching/precipitation processes or corrosion channels caused by circulating rock brine, k) formation and melting of clathrates, gas hydrates; and many other combinations. Such a broad collection of intricate, complex, or multiple (Neuweiler and Bernoulli 2005, p. 131) solutions seem to contrast the clear and distinct characteristics of stromatactis shapes.

Constraints derived from the stromatactis record through time

The oldest stromatactis-like fabrics are found in the Proterozoic carbonate formations. The reticulate structures with geopetal fills, digitate roofs, and fibrous calcite were described from the Neoproterozoic of Namibia, but they were formed both in large thrombolite columns and in the intercolumn fills among these structures, i.e. not in platy beds (Grotzinger et al. 2000, Fig. 5, p. 343). Poorly documented stromatactis-like fabrics were also mentioned by Melezhik and Fallick (2003, p. 217) from 2.2 Ga Paleoproterozoic carbonate beds in the Pechenga Belt of NW Russia. Although these two examples are not very convincing, the chance for possible occurrence of stromatactis in these old sediments should not be underestimated. The thoroughly updated reviews of stromatactis through time (e.g., Neuweiler et al. 2001, p. 340, Fig. 2) make their record seem more continuous, but there is still much uncertainty among scientists about the possibility of finding these structures in all time windows from the Precambrian to the present. Significantly increased abundances of stromatactis are commonly observed in carbonate sediments of the Paleozoic era, especially in the Devonian and Carboniferous periods. Other common examples of stromatactis are in Mesozoic, mainly Jurassic strata.

However, the stromatactis shapes are quite consistent in carbonate rocks of different ages. This constancy is perplexing when compared with the relatively fast emergence and cessation of many faunal groups, and the variability of sedimentary systems, microfacies, and mineral composi-

tions of the rocks in which they occur. It certainly casts doubt on the validity of the simple-precursor concepts of stromatactis as moldic cavities, and suggests that the most general features and settings must be considered. Such general features that can be seen in carbonate sedimentation are, for example, those related to the mechanical formation and resedimentation of small carbonate clasts. Water depth is another consideration. Although it is very rough parameter, the inferred depths at which stromatactis form are estimated to range from several to several hundreds of meters, which would also seem to support a simple sedimentary cause.

Relationships to microbial formations

Close spatial relationships between stromatactis and occurrences of microbiolites are not uncommon. Many stromatactis structures are suspected of having been affected by bacteria (e.g., Lower Devonian, Montagne Noire – Flajs and Hüssner 1993), and their mineralized relics have been noted in thin-sections or scanning electron micrographs (e.g., possible filamentous forms – Boulvain et al. 2001, Elrick and Snider 2002). But most of the evidence for bacterial participation in stromatactis formation is based on their co-occurrence with thrombolites, algal mats, or generally any of the microbialite rock structures that display the widely documented association between stromatactis formation and mud mounds (Monty et al. 1995, Reitner and Neuweiler 1995, Riding 2002).

But there are two weak points in this coupling between stromatactis and mud mounds. The morphology of the stromatactis beds do not all bulge upward; many of them are flat or only modestly domed units (Aubrecht et al. 2002a), while others are without any swelling (e.g., Dieken 1996). The parallel beds are parts of clinoforms, being often underlain and/or overlain by common carbonate mud sediments (mostly of wackestone/packestone varieties with diagenetical nodular structure). Moreover, the stromatactis formations are also located in bedded series with coral reef debris (e.g., Wenlock, Porsgrunn, SW Oslo, Norway), or in more distant carbonate slope environments among fine-grained (calcilutite) calciturbidites (e.g., Pragian, N of Vinařice, Barrandian area, Czech Republic). The influence of bacterial processes on the composition of the rocks in these two environmental settings can hardly be higher than that of normal background conditions.

exist: B – Jurassic Slávnica fenestrae have bases with early geopetal sediment, dish-like and collapsed shapes, all of which seems to be incipiently overprinted by plates and networks of displacive, fibrous carbonate, which resembles sheet-cracks. Perhaps it represents a true stromatactis fabric that was stretched or squeezed. C, D – Late Devonian (Belgian "marble rouge") examples. The small stromatactis forms are often dish-shaped or inclined in vertical section (C), and the large specimens are typically jointed to form thick, laterally-expanding, and upward-climbing structures (D). Polished surfaces of garden marble balls, Rosenborg Castle, Copenhagen, imported from Senzeille area of Belgium in 1674; with tabulate corals *Alveolites elongatus*, *A. complanatus*, etc. E – an example of stromatactis structures of the Middle Silurian (Wenlock) age, Porsgrunn, SW Oslo, Norway. The stromatactis fenestrae are very low, like the vertical interconnecting branches collapsed together with the shortening of the entire sediment column (?). Details: several thousands of square metres of these coral limestones were used for cladding the walls of the Danish National Bank, Copenhagen, in the 1970s. F – thrombolite stromatactis-like fabric of the Neoproterozoic age, adapted from material by Grotzinger et al. (2000), Huns Platform, Witputs, S Namibia. This example, however, bears a remarkable similarity to the Late Devonian specimens (in C, left). G – many structures were possibly once stromatactis, but were changed substantially due to the circulation of corrosive fluids. This can be exemplified by Middle Triassic (Lower Anisian) dolomitized limestone from Mahmudia Quarry, N Dobrogea, Romania. Details: described by Baud et al. (1997), material by C. Panaiotu. Remarkable stromatactis floors are marked by arrows, non-stromatactis objects are crossed.
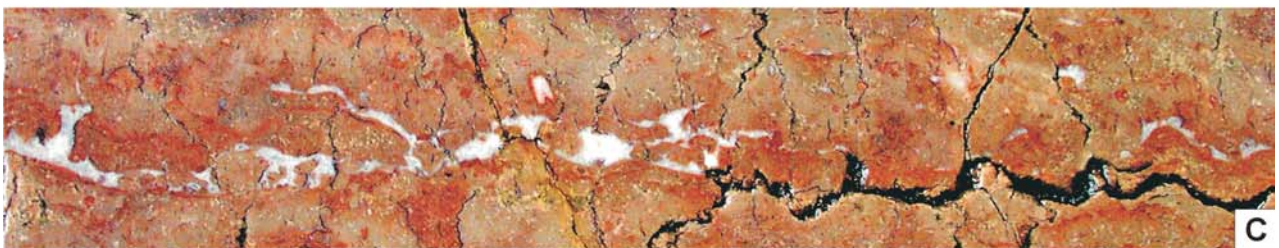
Stromatactis related sediment compositions

Beds containing stromatactis are usually described as carbonate muds, polymuds, or in other terms with similar meaning. However, a number of authors describe how plentiful and diversified the fine and coarse sand-size carbonate grains (or even fine gravel-size clasts) are. An interesting confirmation of this point comes from the common linkage of stromatactis to crinoidal debris that is made mainly in recent papers (Hilali et al. 1999, Krause 2001, Aubrecht et al. 2002b, Berkowski 2004, or da Silva and Boulvain 2004). The present author has found that only in a few thin sections from typical and well-preserved stromatactis beds can the grain sizes be called "carbonate mud". It can thus be hypothesized that this general characterization of the rock composition in which stromatactis occur is problematic.

Many thin section micrographs of rocks with stromatactis show sedimentary particles of unusual shapes (including sponge spicules, a variety of angular or porous clasts, skeletal chips, blackish or translucent lumps, clumps and floccules) regardless of the mean particle size, i.e. even if the material has the average appearance of mud/calcilutite or calcarenite/calcirudite. Although the very fine-grained varieties of stromatactis-containing sediments were traditionally believed to be the predominant type of host rock, a more realistic assessment of the proportions of fine to coarse varieties would be 2 : 1, or even higher. This conclusion could be reached even on the basis of previously published photographs (e.g., Elrick and Snider 2002, Fig. 7, Bourque et al. 2004, Fig. 20), though the study of thin-sections further encouraged the development of this hypothesis (especially using ultra-thin sections in combination with high-resolution imaging).

These sections, studied since the 1980's, provide evidence about the very specific grain compositions of the stromatactis-containing limestones. The particulate sedimentary materials are typically polydisperse (with polymodal frequency distributions), and their shapes are very complex: the grains are mostly angular, irregularly indented, and porous. Spatially inhomogeneous sedimentary fabrics suggest that many grains were friable, and that small particles could form unstable assemblages or even lumps. The widely varying ultrastructures and colour-hues of both the finest (micrite, silt) and medium-sized grains are indicative of the heterogeneity of this particulate material. Many of these rock fabrics resemble a mixture of black and white semolina. Although there is much very fine-grained material, the average grain-size values are regularly so high that they can be compared with calci-siltite/grainstone categories. The typical peaks in grain-size (mass) histograms are characterised by peak values at

~ 20, 60 and 120 μm for the finest varieties, and ~ 40, 200 and 600 μm for the coarsest. Naturally, the polymodal frequency distributions have varying characteristics, but always with rugged (never smooth) shapes of grains.

This implies that the traditional meanings of terms like "mud" or "micrite" in this usage seem to be somewhat exaggerated, whilst the examples of stromatactis-containing rocks with a real predominance of original sedimentary grains smaller than 4 μm (or 20 μm) are extremely rare. The false "micrite" appearances may be due to the failure to distinguish aggregated micritized particles and clots, or secondary micrite precipitates.

The facies frameworks of stromatactis beds

The present knowledge of related facies structures (e.g., Bourque et al. 2004) seems to be particularly focused on classic Niagaran, Frasnian, and Waulsortian (Silurian, Devonian and Carboniferous) examples, in which the more-or-less domed stromatactis beds underlie reef structures. However, the domed and flat bodies of these limestones are often found in clinoform sediments occurring along with reefs worldwide. The cryptic, subhorizontal, and undulated bedding has a reduced number of very sharp and smooth bedding planes, and interbedded shales are practically absent.

A noteworthy feature that can be seen on many outcrops is how these stromatactis-containing (and relatively flat) beds alternate with zones of other sediments. Typical stromatactis beds are arranged in tabular bed sets a few decimetres thick, where the beds have contacts that are mostly planar but not sharp. These beds are well cemented, with considerably small numbers of the stylolites and pressure solution features of microscopic dimensions which can develop in this material. The thin-bedded, laminated, or nodular limestones are not capable of generating stromatactis swarms. And the coarse grained sediments, particularly those with non-porous and sorted sand and gravel fractions, evince the same degree of incapability for producing stromatactis. The stromatactis beds usually occur as strata between the lime mud to fine-grained carbonate slope deposits (e.g., the Lower Devonian Řeporyje Limestone, Trněný Újezd WSW of Prague, or the Middle/Upper Jurassic limestones of Priboržavskoje and Bolšoj Kamenec sections in Transcarpathian Ukraine – Aubrecht et al. 2002a, J. Matyszkiewicz and R. Aubrecht, personal communication). Furthermore, in contrast to these relatively deep sedimentary environments, the stromatactis beds can occur also together with the peri-reef skeletal debris (e.g., together with the alveolitid corals, stromatoporoids and algae in classical Frasnian sections – Boulvain et al. 2004, or

Figure 6. Examples of complex stromatactis swarms in layers with abruptly (but repeatedly, and with high recurrence rates) resuspended/deposited portions of carbonate sedimentary material. The beds have no clearly distinguishable boundaries, and the irregularities of their interfaces combine truncation with possible particle ejection (elutriation) mechanisms due to microbubble/bubble flow, as well as the sinking of the sediment load above the dewatering dish-like structures. A, B – polished vertical sections of the lowermost Eifelian Acanthopyge Limestone (with cystimorph rugose corals), from the Červený lom (Red) Quarry near Suchomasty. C – thin layer with stromatactis fenestrae, Pragian Slivenec Limestone (fine variety) from the Na Cikánce Quarry near Radotín. Width of imaged areas is 50 cm. The marble cladding of the Mlýnská (Mill) Colonnade in Karlovy Vary (Carlsbad) Spa.
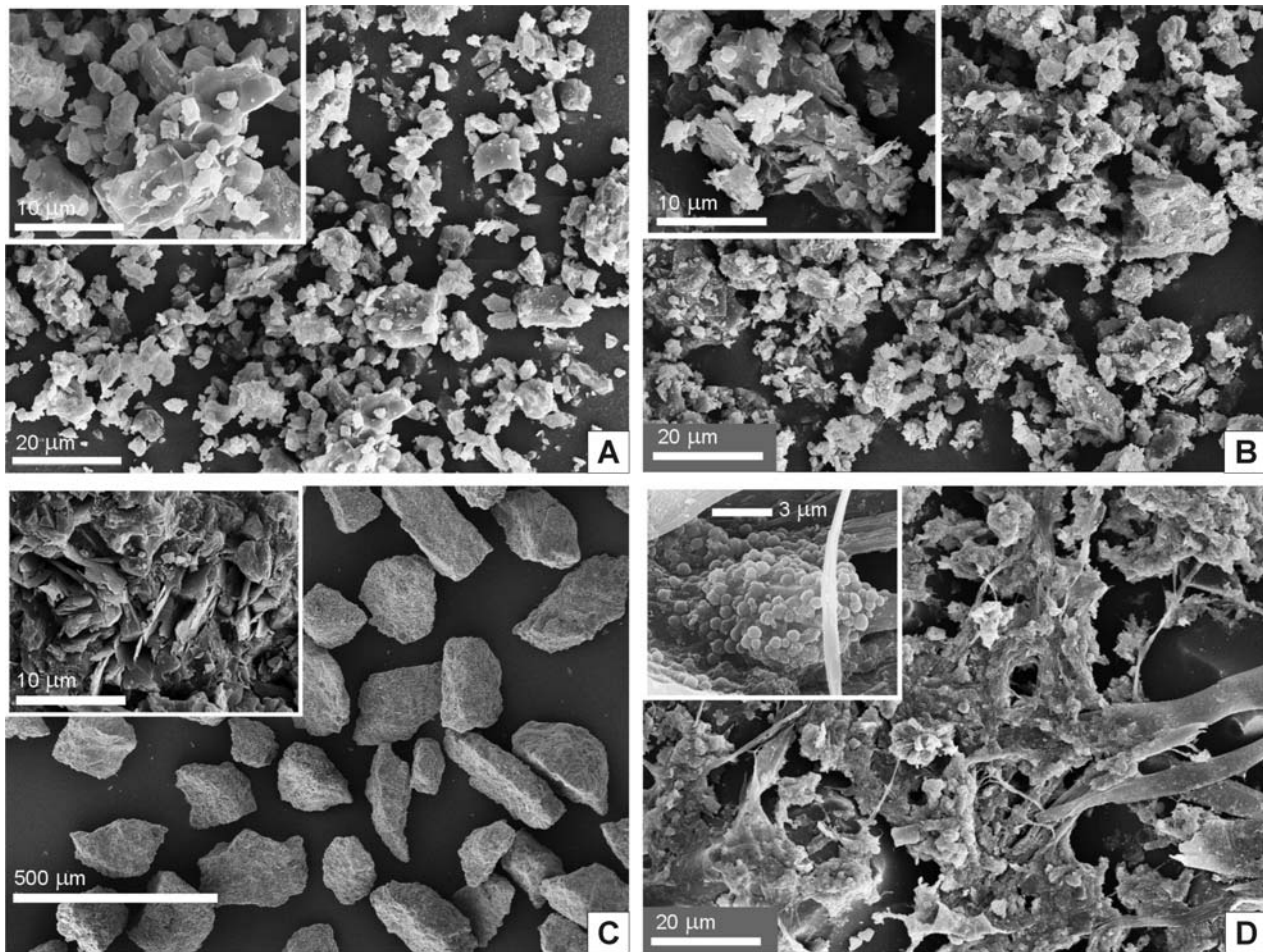
Figure 7. Four components used in the mixing of experimental slurries (fine-grained particulate matter, artificial; secondary scanning electron images, with selected details in upper left corners). A – limestone detritus/powder No. 1, the basic material for sedimentation experiments. B – limestone detritus/powder No. 2, the first additive. C – detritus/powder No. 3, the second additive (concentrated from the previous material). D – active organic mud, separated from sewage sludge, Prague Water Purification Plants; typical examples of filamentous and variously shaped particles, mostly decomposed organic materials and bacterial clusters. The scales are different for each micrograph (as indicated in the picture frames).

with first favositid corals and stromatoporids on SW periphery of the Lower Devonian Koněprusy reef in the Barrandian area).

The stromatactis beds embedded in lime-mud slope sediments are indicative of their moderately coarser texture. These beds are mainly "cementite", and not "compactite" rock types. The latter occurrences exemplify specific, occasionally sedimented debris with a "wild" microclastic admixture that originated before or in between the reef episodes. It can be reasonably speculated that stromatactis formation most significantly corresponds to the areal extent of firm sedimentary surfaces (neither soft nor very hard substrates), and these conditions seem to be preferentially associated with the transition levels between the low stand and transgressive system tracks.

In spite of the fact that many of documented stromatactis formed more-or-less domed structures, there are many examples of stromatactis beds lacking any significant syndepositional relief (e.g., Neuweiler and Bernoulli 2005). Because of the fact that the stromatactis beds themselves are typically without any in situ reef framework (all larger clasts, if present, were redeposited, crushed, or

mixed from different sources), it is possible to speculate that these beds are event sediments. Moreover, it makes a difference whether the material was deposited all at once, without repeated baffling and binding into clotted thrombolite or laminated stromatolitic fabrics.

Synopsis of the possible conditions of origin

If we consider all of the above mentioned constraints suggesting that common carbonate deposition mechanisms do not support the creation of stromatactis (i.e. mainly the typical settings of tempestites, turbidites, or drift sediments), it can be further hypothesized that the stromatactis limestones are unusual deposits from slow, sideways moving turbid flows or eddies that were loaded with a heterogeneous mixture of relatively thick and viscous suspensions of low mass density.

These suspensions must have contained polydisperse, polymodal mixtures consisting of ultra-fine to coarse, often angular to irregularly-shaped, porous grains. These grains would alternatively clump together and break apart, in combination with various lumps, clots, or needle- and

lath-shaped particles. Of equal importance would be the role of microbubbles, as well as bacterial filaments together with particulate organic matter and detritus. Active (living) natural biomud material could also be involved, as may be indicated by the observation that the stromatactis levels are frequently associated with thrombolites, mud mounds, and all varieties of firm sediment surfaces that occurred in situ or, and mostly, had at least a chance of developing in adjacent areas.

Defining this problem from the other side, we can say that the main difference consists in very low proportions of rounded, uniformly shaped, or well-sorted grains. Extrapolating further brings us to the idea that any large amounts of these well-sorted and/or round-grain sedimentary materials may directly inhibit the formation of stromatactis cavities. This idea is distinct from the first "sedimentary" approach to the stromatactis problem by Heckel (1972), who concentrated on non-uniform post-sedimentary compaction and dewatering, whereas the requirements on suspensions, sedimentary material, and the sedimentation mechanisms were considered to be secondary.

Hence, the simplest formulation of this working hypothesis leads to the assertion that the swarms of stromatactis fenestrae could be caused by the very specific compositional and hydrodynamic conditions of sedimenting particulate materials (as defined above – polydisperse, polymodal, etc.), and the origin of these structures is deeply rooted in the sedimentation process itself. This hypothesis is amenable to confirmation or refutation by physical experiments.

Sedimentation experiments

Basic requirements of the particulate materials

The image analysis counts of sedimentary particles in limestones thin-sectioned closely around the typical stromatactis cavities and fenestrae suggest that applicable material must consist of a polydisperse mixture of unsorted particles (more than 90–95 wt.%; parameter $\sigma\phi > 4$). These grains must be angular (or subangular to irregularly-shaped), some of them also friable or porous, with size ranges of ϕ (0, 10), i.e. approximately between 1 millimetre a 1 micrometre. The size frequency must be polymodal with 3 (2–4) maxima, and also sufficient amounts of ϕ (5, 8) and ϕ (2, 4) particulate material, i.e. wild silt and fine sand.

Artificial particulate materials – finely crushed limestones

A readily obtainable material of roughly similar attributes was found in the fine detritus and powder produced from solid natural limestones using jaw- and roll-crushing. Because many natural carbonate sediments (fine-grained, soft) are well sorted, the particles have relatively narrow size distributions, with only slight bimodality or polymo-

dality, and the majority of grains are also rounded or at least isometric, having also inner compositions and structures that are basically uniform across their populations. The artificially produced material (jaw- and roll-crushed limestone) also contains friable and porous grains with cracks, small lumps, and chips of carbonate, and also rare platelets of carbonate and mica/illite impurities. It is much easier to prepare this material than to collect the appropriate components separately, although the latter method would also be possible.

In the first set of experiments a three-component artificial material was used (Figs 7A to C), in which the main component was finely-crushed unexceptional Devonian limestone rock (~ 97 % calcite, early Givetian limestone from Moravian Karst, 21 m into the Josefov-Barova Section), detritus-1. This material, if crushed/powdered in the most common way, meets the above mentioned requirements for shapes and size distributions of particles [grain size category (μm), on sieves; total mass (%): < 63, 17.32; 63–125, 9.25; 125–250, 28.36; 250–500, 17.89; 500–1000, 22.18; > 1000, 5.01]. The Mokrá Frasnian limestone was used as the first supplementary component (Mokrá Quarry West, point –20.0 m). These limestones have little admixture of clay and iron-oxides, a slightly higher density, and some variability of grain surfaces (rugged, spiny, or bladed), detritus-2. The third accessory of this three-component artificial mixture was the first moderately heavy Wilfley-table concentrate that was produced from the latter supplementary component (~ 85 % calcitic grains, size ϕ ~ 2–3, $\sigma\phi > 0.35$), detritus-3.

Several other characteristics of the one main and two accessory materials are as follows (values ordered from detritus-1 to -3): ρ_s (average density of particles, solid mineral material only, kg . m^{-3}) = 2730, 2770, 2950; ρ_d (density of free dump detritus, in its entirety, kg . m^{-3}) = 1610, 1710, 1830, n_d (porosity of dry detritus, vol%) = 41, 38, 38, ω_d (angle of repose, on dry detritus, in degrees) = 40, 39, 32, μ_d (coefficient of internal friction, dry detritus) = 0.839, 0.810, 0.625. From these additional characteristics it can be seen that these polydisperse (polymodal) materials with subangular, angular, or rugged surfaces, platelet-like or acicular shapes, and partly also cracked and friable grains have unusually high values of internal friction. Their angle of repose is greater than can be measured by normal gap-graded mixtures of angular sand/silt grains (e.g., Hecht 2004), but, in contrast, the packing is less dense. This feature (high internal friction but low density) of these extremely heterogeneous particulate mixtures is significant and, in modified form, may also be effective in dense particulate suspensions where the anomalous characteristics correspond mainly to increased dynamic viscosity in contrast to relatively low density.

Biologically active, organic, detrital and filamentous material

The carbonate and other mineral constituents, which ought to have primary importance, are not necessarily the only

ones that contribute to sedimentary stromatactis-forming processes. The hypothesis described in this paper also postulates the presence of microbial particulate and colloid matter. The next step was to find an available material resembling the natural substance.

This was found in active organic mud that was concentrated from municipal sewage sludge (compare Fig. 7D; provided by the Prague Water Purification Plants, Prague-Podbaba). This matter consists of sufficient amounts of bacterial and decayed organic filaments, small organic detrital particles, clots and floccules, living, dead and mineralized bacterial clumps, organic colloids, and also various inorganic, fine detrital and unstable amorphous impurities. The mixture of this composition contains (and can produce) numerous microbubbles, so that it, at least roughly, simulates the natural material from dissected (and suspended) thrombolite/bacterial mat layers. Although the most prevalent organic particles in this material were shreds and clumps of decayed organic matter and bacteria, longer filaments were also abundant (some in tens of millimetres, other in millimetres). The *Melosira-* and *Asterionella*-like diatoms are rare, but their effects can be compared to sponge spicules in natural materials. Large particles around 0.2 mm were rare, and any that were larger were separated. The composition and soft fabrics of this organic material were documented, but they do not change rapidly enough to affect reproducibility.

A thick (i.e. 50 vol% of organic particles) active aqueous organic mud concentrate was used as an additive, which was mixed and dispersed in the slurry. This additive was used in various amounts according to the working hypothesis that an uncertain amount of these biogenic particulate/colloidal materials would be involved in the natural suspensions that settled as stromatactis beds.

Description of experiments

The limestone detritus/powder was mixed with a small amount of active organic component in 37 ‰ pure sea water, which was slightly acidified using formic acid (0.01 mol). Proportions: detritus-1, 70 g, detritus-2, 10 g, detritus-3, 5 g, organic component, 15 g, sea water, 500 ml. A slurry of this composition was gently stirred and mixed until pH values stabilized at ~ 7.5; the sludge in suspension expanded and became diluted, with a minimum of bubbles (~ 2 hours). This turbid slurry was transferred into a sedimentation vessel (flattened, transparent plastic cylinder, 1500 ml, partly filled with 500 ml of 37 ‰ normal marine water; subsequently other shapes and sizes of sedimentation vessels and troughs were used).

Although the active organic-mud suspension in water takes several days to settle (buoyant floccules, reticulation of fibres, microscopic bubbles), the complex slurry (with carbonate detrital components and this organic matter) sedimented very quickly. The sedimentation process was documented using a high-speed digital camera (Institute of Chemical Process Fundamentals, Academy of Sciences CR). This high-speed recording increased the precision of the observations of the sedimentary processes (examples of these records in electronic form are included as supplementary material to this paper – ESM 1). The sedimentation can be subdivided into three stages.

During the first stage, the largest and most bulky, isometric, and relatively dense grains settled out first. The undifferentiated suspensions of the beginning stages correspond to a chaotic, turbulent slurry, including the development of eddies. As the chaotic state first began to settle (in what was still a relatively homogeneous particulate suspension), the formation of unstable to sub-stable, isometric domains began to form in sizes ranging from several millimetres to centimetres. These domains were filled by opalescent, very fine particle mixtures and separated by narrow zones of relatively clear water containing larger particles. The shape of these fluctuating domains gradually changed from the former sub-spherical, oval, kidney-shaped or polyhedral cells to shapes with nearly rhombic vertical cross sections. The arrangement of slowly settling and vertically flattening cells resulted in the formation of thin boundary layers. These thin zones also contained relatively clear water with larger particles, and formed diagonally dipping planes. The entire middle part of the suspension thickened and further settled toward the basal layer built up by the imperfect upward fining earliest sediment.

The second stage was characterized by the formation of a vertical, two directional flow pattern, in which the finer particles, water, microbubbles, and the finest bacterial particles vigorously escaped upward in numerous parallel but fluctuating, turbulent strings, whereas the heavier particles settled, forming counter-directional, transient strings. The downward movement of these moderately larger or more bulky particles was accompanied by much microturbulence and disturbance along their sub-vertical trajectories. They thus formed imperfect strings in the moderate turbulence caused by the very strong upward flow of water and small particles. Concurrently, the underlying layer with imperfectly shaped, nearly rhombic cells became thicker and started its transformation into sediment. The contact between the grains became more permanent, and the grains settling from above filled the interstices, forming a vaulted or saddle-shaped roof. This process determined the outlines of typical stromatactis fenestrae in their earliest stages. From all of these early stromatactis cavities a jet of water with fine particulate, opalescent material continued to escape. These cavities, which formed side by side or stacked in a diagonal reticulate network, were successively closed and covered by further layers of sediment, which formed subsequent but usually smaller fenestrae.

In the third stage of sedimentation, the fenestrae in the middle part of the sedimentary bed were practically closed. Occasionally a grain fell from their roof, or a cusp was formed by water escaping from this cavity together with very small light particles and microbubbles. These cuspate protrusions from the roof end in strings that became thinner and thinner and are connected to normal pores among the grains of the overlying sediment. The stromatactis cavities became enclosed spaces with very calm microenviron-

ments, in which the finest residual suspensions began to deposit the first internal sediment. The flocculation and very quiet and calm sedimentation of these ultra-fine particles in stromatactis cavities are metaphorically referred to as "snowing". This sediment filled the pores in the floor of the cavity, fining upward until the finest particles produced a sharp bottom to these fenestrae. In this fairly advanced stage of their formation, these stromatactis-like fenestrae are wider than they are high, having smoothed, flat, or slightly undulated floors, but with vaulted, cuspate, and rugged sub-spherical roofs. The above mentioned escaping of water with very fine and light microparticles and microbubbles (from cusps in the roof to small pores) initiates a process of washing and filling in the surrounding sediment. This resulted in the formation of a characteristically mottled pattern.

Although the shapes of the fenestrae seemed to be considerably stable (see illustrations in Figs 8–12) and the sediment structures were remarkably firm, additional changes of the cavity shapes slowly continued for about two hours, until they were stopped (or reduced to almost invisible degree). These changes consisted of the deformation of some stromatactis into flattened and bent shapes, occasionally with the build-up of oblique, upwardly-directed channels and small daughter stromatactis cavities along these water-escape channels. During this time interval, the uppermost layer of the sediment bed became considerably condensed and formed a relatively homogeneous, fine-grained to muddy cover over the stromatactis-bearing horizons. This layer was locally pierced by vertical bundles of thin and collapsing (refilled) water-escape channels. The final stromatactis bed, consisting of the lowermost graded layer, the lower/middle parts with horizons or reticulated meshworks of stromatactis fenestrae, and a cover of silt/mud, was a remarkably cohesive and deformation-resistant structure. After one day, it could even be rotated into a vertical position for several minutes without any sliding or collapse.

It was evident that the increased amounts of active organic mud (with bacterial filaments and accompanying light particles with microbubbles) resulted in larger forms of stromatactis cavities. The most successful experiments were made with 30 wt.% of this additional component, half of which was comprised of organic particles and the other half of water. The development of the largest artificial stromatactis fenestrae also required a large proportion of organic filaments and microbubbles. According to the presence of this diluted network of filaments (with adhesive microbubbles), one might reasonably infer that the early-stage liquid fills in the largest stromatactis cavities are relatively viscous but also very light (having smaller mass density).

Additional changes in the stromatactis shape developed several days after the sedimentation itself. The stromatactis fenestrae preserved their shapes, but the decomposition of buried organic components produced bubbles of millimetre to centimetre dimensions, which deformed small structures or pushed and formed various digitate cavities in the roofs of the larger stromatactis. The further stages of sediment evolution, after several months, were characterized by stiffening and volume shrinkage that lead to the formation of singular planar fissures that obliquely crossed the sediment upward. The finest, uppermost layer of the sediment can be locally rugged due to micro-horst/graben systems and contraction of the material (i.e. with the consequent lateral extension of the bed). Concurrently, or later on, the surface of the bed is covered by rubbery bacterial mats with lumpy surfaces. However, their influence on the sedimentation of a subsequent layer, or the resedimentation of the whole layer, is not a cause of stromatactis formation. This corresponds to other structures that are spread along the contacts of beds.

The experiments of this first series were meant to simulate stromatactis-related sedimentation in a complex way. They clarify the timing involved in stromatactis formation (Fig. 13). The structures produced during these experiments accurately reproduce the natural structures of stromatactis beds, and explain the observable details of these processes (as described in the above paragraphs). It was then questioned whether stromatactis structures could be obtained even under simplified conditions. Such a simplification is of importance in discovering the essentials of the processes and accurately modelling them.

The second set of experiments was therefore run under very simplified conditions, in which only detritus-1 and tap water were used in the preparation of the slurry. The sedimentation of these very simplified slurries also resulted in the formation of fenestrae in the middle parts of the deposited beds. The stromatactis cavities were smaller than in the previous trial, having horizontal dimensions of 3–12 mm. Otherwise, the cavities had the same shape variations and arrangements, and the characteristic "snowing" of the finest particles also occurred inside them (Figs 9D and 10G). It seems that the most basic requirements in forming the sedimentary stromatactis structures consist of the polydisperse and polymodal content of a moderately dense particulate suspension, together with a diversity of angular, irregularly shaped, and friable grains. The composition of the sedimentary material and the conditions within the suspension prior to sedimentation are, therefore, the crucial factors in the origin of stromatactis structures. The presence of dispersed bacterial filaments and other decomposed bioparticles is an important circumstance which is, however, complementary and does not necessarily need to be involved in the process. Although the major part of stromatactis populations must originate with this significant catalyzing material, situations in which stromatactis structures originate during sedimentation process without this component were also demonstrated by the experiments.

Discussion

The occurrence of stromatactis structures is perhaps not so strictly limited to a few time spans in Earth's history, though the opposite conclusion has been inferred from the
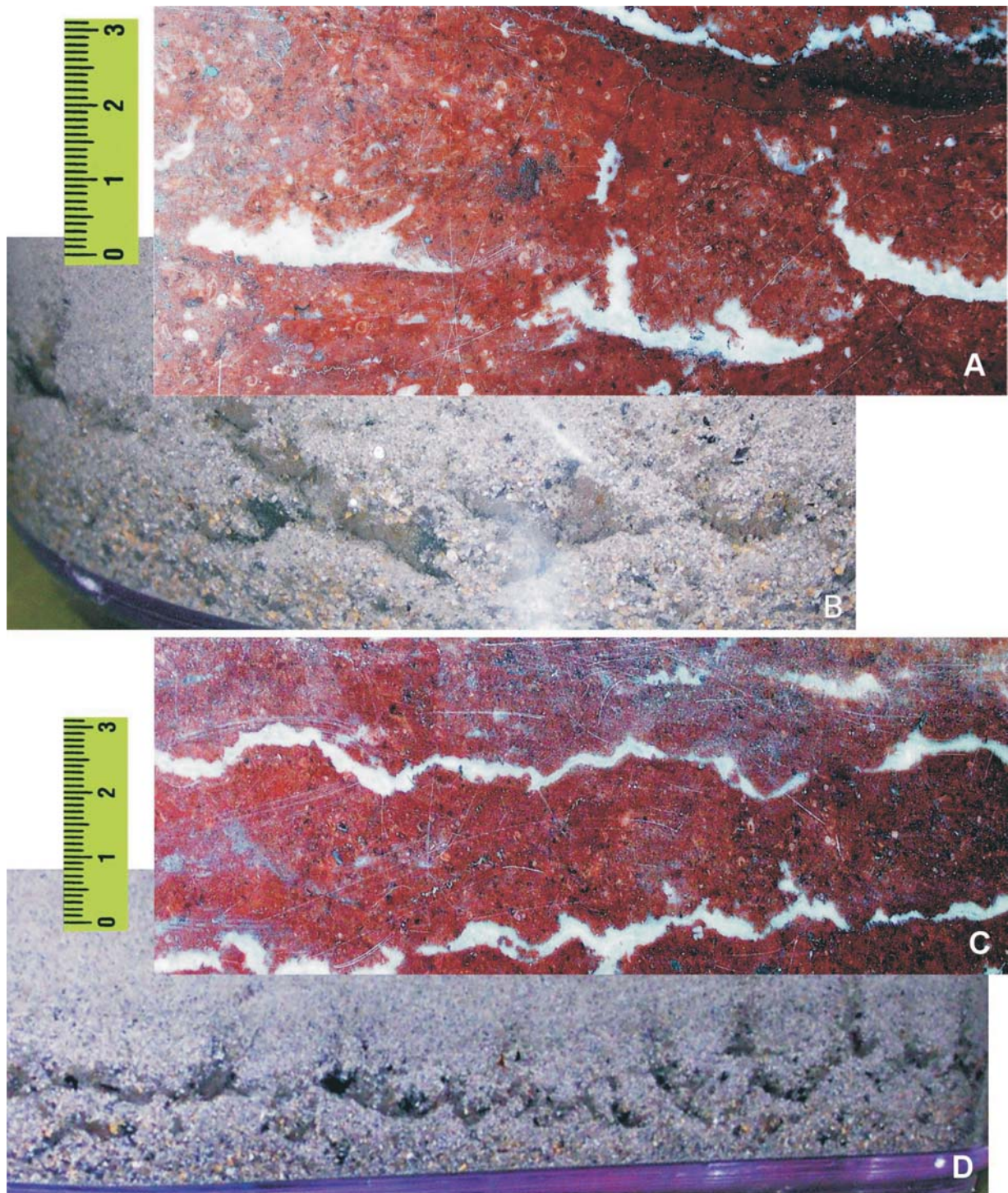
Figure 8. Direct comparison of natural and experimentally formed stromatactis cavities. A, C – Lower Devonian, Slivenec Limestone, cavities filled by concentric layers of fibrous milky calcite cement. B, D – counterparts to natural structures as obtained during experimental simulation of sedimentation process in laboratory.

abundance of these structures in domed carbonate bodies that are standardly described as stromatactis mud mounds. They are certainly less common in the carbonate formations prior to Ordovician and after the Carboniferous, but the mounting evidence of relatively rare stromatactis structures in non-traditional places and in new stratigraphical levels is beginning to fill these lacunae (e.g., Aguayo 1978 or Neuweiler et al. 2001), especially with the

future prospect of more detailed investigations of various stromatactis sediments.

Due to the focus on the possible direct sedimentary origin of stromatactis, the stratigraphical constraints on the conditions of their formation are not addressed in this paper. Therefore, the influence of such factors as the availability of polydisperse and polymodal sedimentary material, the proportions of particular grain shapes, the compo-
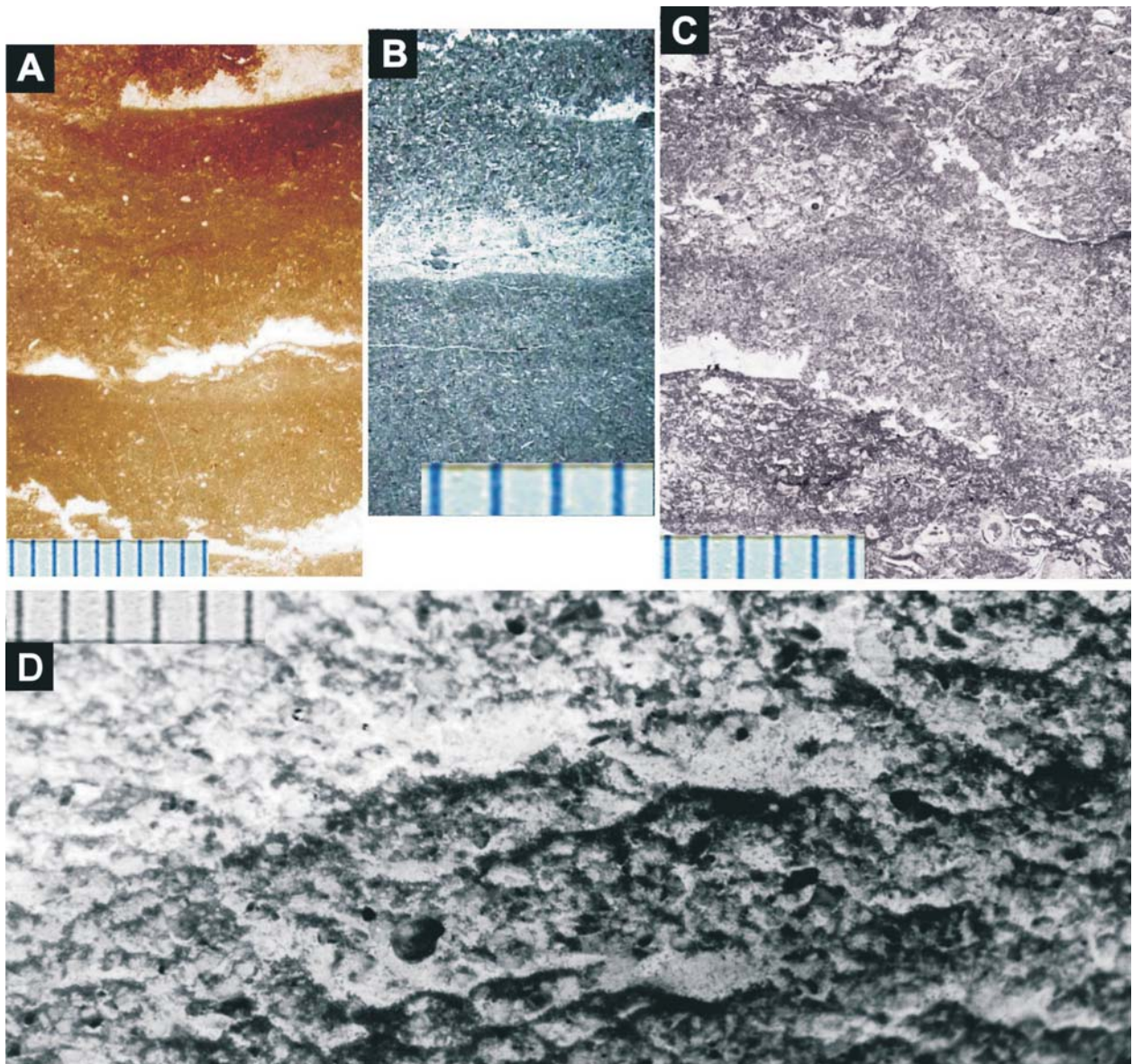
Figure 9. Small stromatactis (or stromatactis-like) fenestrae. A–C – from left to right, three examples of thin-sectioned limestones, two of the Pragian age (Čertovy schody Quarry East, Voskop Hill near Koněprusy, and the Cannibal Cave on Bacín Hill near Vinařice, respectively) and one younger, of the Eifelian age (Zadní Kobyla Hill near Suchomasty). D – fenestrae obtained during the most simplified experiments have shapes that are very similar to their natural counterparts. These experiments were conducted using the simplest turbulent suspension of limestone detritus/powder-1 in normal tap water. The tone inversion (cavities are whitish) has been used for easy comparison with natural cavities that are filled by bright calcite cements. The scales are in millimetres.

sitions of bacterial and organic muds, and the hydrodynamic or other conditions on the natural places of stromatactis-related sedimentation remain open to research.

In spite of this uncertainty, it is of interest to make a preliminary attempt to address the most controversial issues:

a) Practically no stromatactis sediments are known from Cenozoic (and present) seas. This scarcity or absence might correspond to a lack of environments in which bacterial mats cover the carbonate ramps from shallow subtidal to mid-slope bathymetric zones.

b) Some stromatactis associations are concentrated in carbonate mounds with gently to steeply inclined slopes, whereas others occur in relatively flat beds. A speculative explanation of this phenomenon could be based on the sustainability of polydisperse and polymodal organic-mud suspensions. If they arise from vigorous eddies, storm conditions, or other circumstances of severe turbulence, they would have to evolve. With decreased turbulence in a cloud of such a suspension, without contact with the sea floor, the particles would undergo gravitational sorting, and the suspension would be diluted. This means that there exists a theoretical possibility that the sedimentation is limited to certain timing, depths, or places. Other possibilities can be derived from the organization of gravity flow surges in which the basal layers are fed by slope-derived material, and
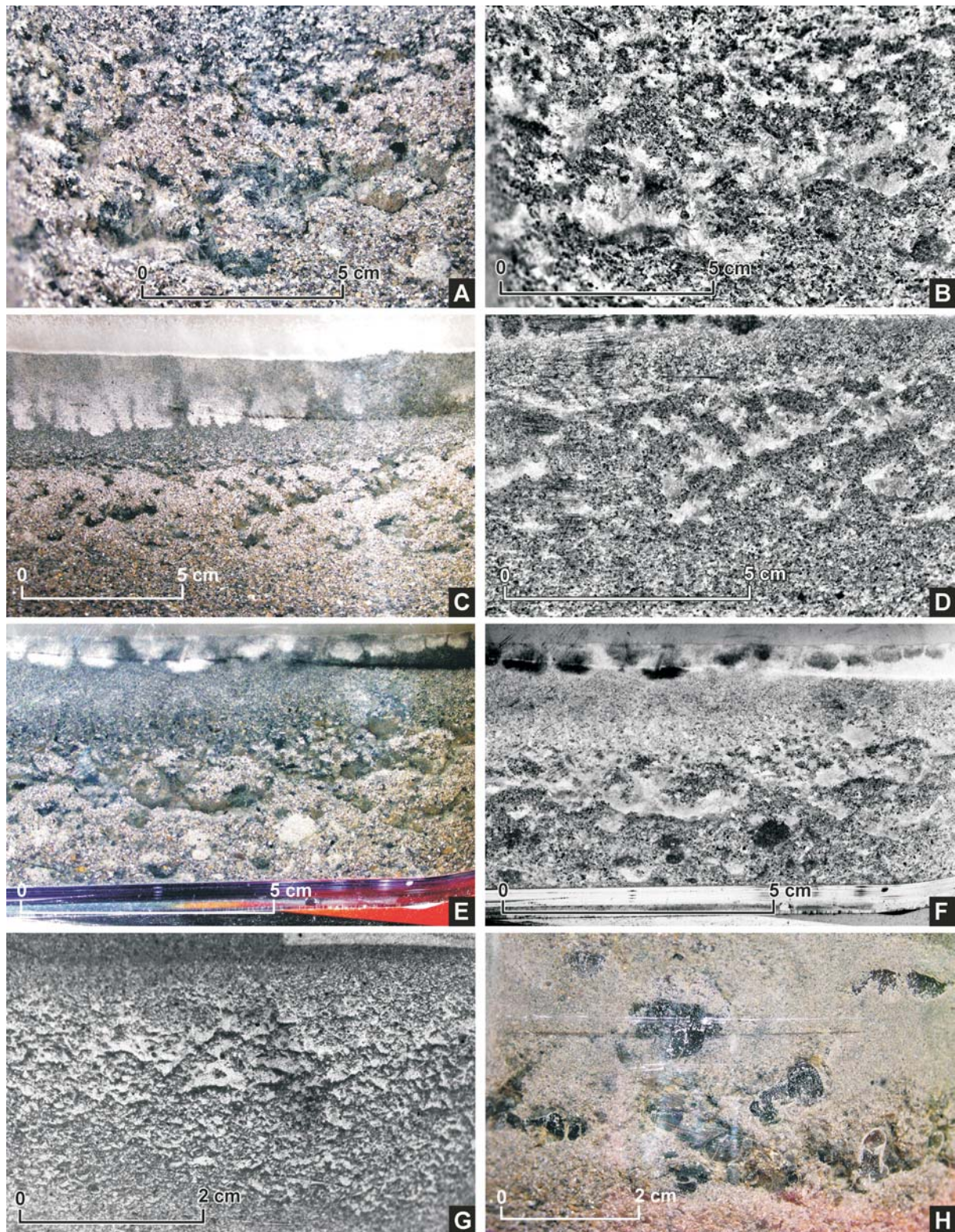
Figure 10. Further illustrations of fenestral structures obtained during the sedimentation experiments. Paired images A–B to E–F show these structures of sedimented beds in real colours (left) and in inverted grey tones (right). The minor amounts of detritus-2, 3, and organic matter, partly with filamentous particles, were used as additives in the artificial slurry. All components were mixed together in seawater (see the text for details). G – another example of artificially produced stromatactis-like fenestrae of the smallest size. Sedimentation of a very simple slurry without organic matter, and consisted exclusively of detritus-1 and tap water. H – bubbles from decomposed, buried organic matter formed several days after the sedimentation of the complex slurries.
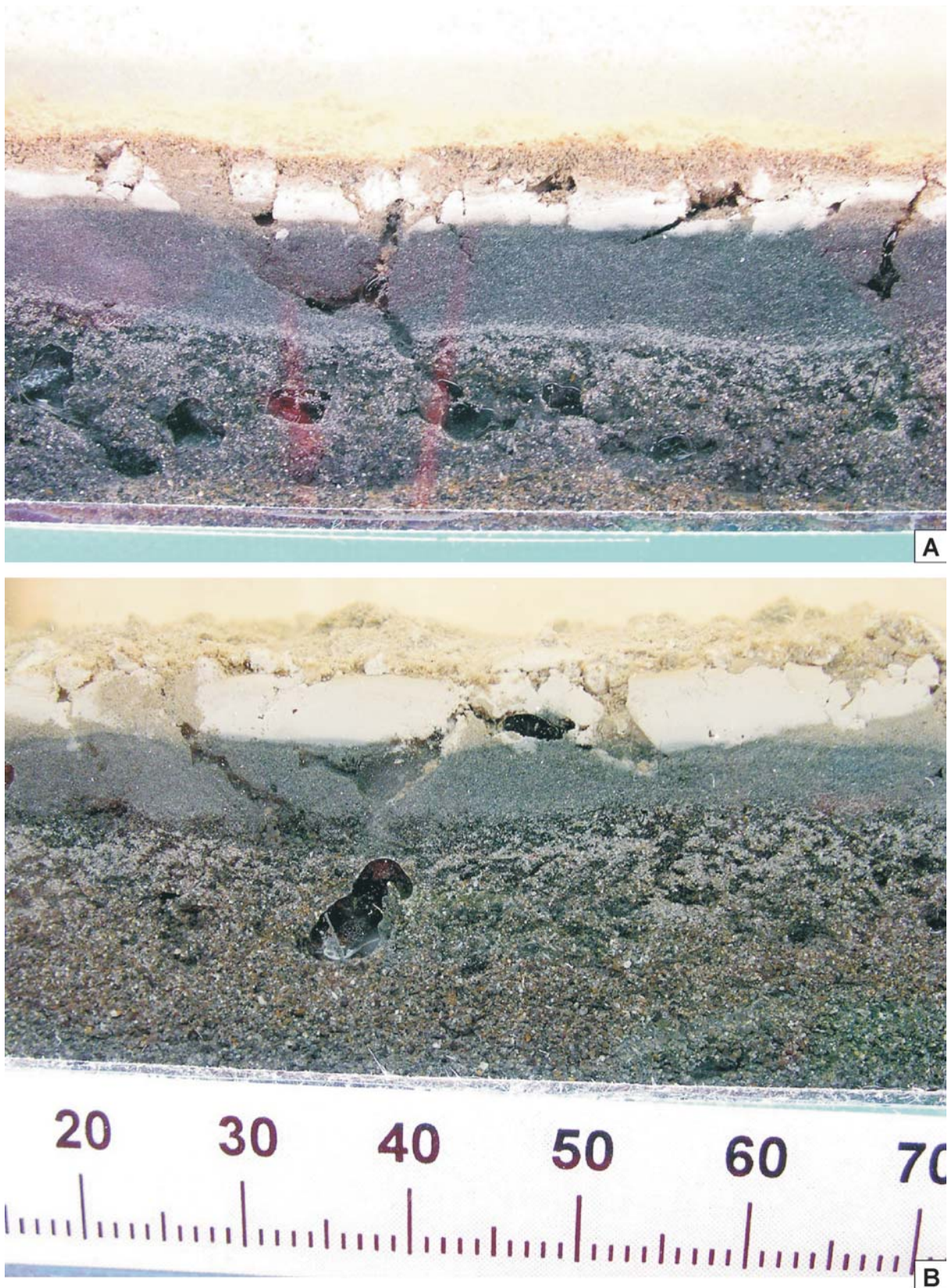
Figure 11. An example of occasionally-occurring strongest changes, six months after the experimental sedimentation in sea water. A – several fenestrae are swelling and vertically stretched by large bubbles, others are cut by oblique planar fissures. B – another example of the extreme changes. Note the connection by delicate channels, one cavity was selectively deformed by a large bubble. The uppermost mud layers, after stiffening, have been affected by microfaults and cracks that result in a horst/graben structure. A rubbery microbial mat developed on the upper surface of the sediment. Scale: millimetres.
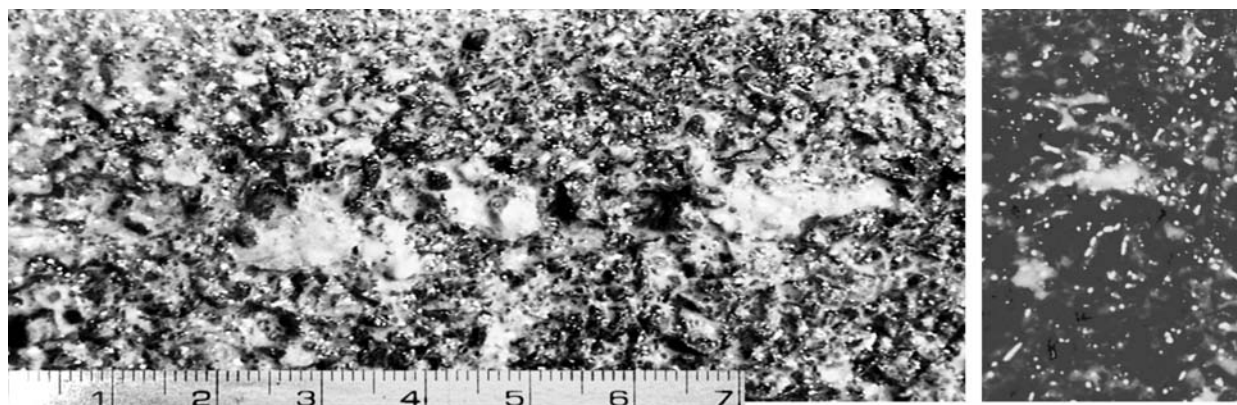
Figure 12. Sections with stromatactis fenestrae from sliced sediment (after deep freezing in liquid nitrogen). These structures are from one hour after the experimental sedimentation. They exemplifies that the same fenestrae as we can see at transparent walls of experimental vessels (or in troughs) are present everywhere inside the middle part of the sedimentary stromatactis bed.
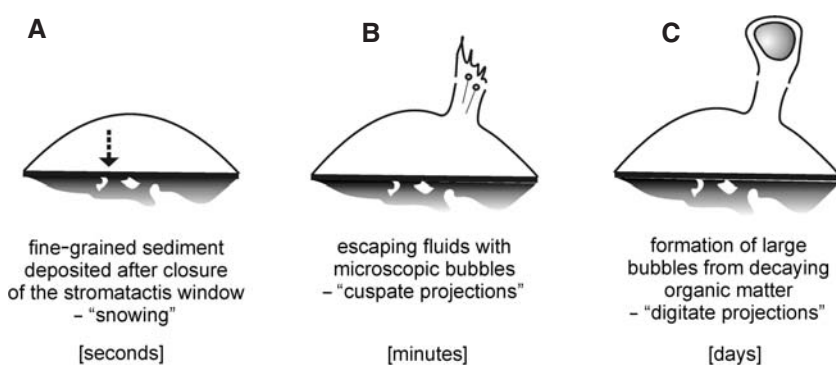

Figure 13. A simplified evolution diagram of stromatactis cavities, derived according to experiments. Three stages are emphasized: A – fine-grained sediment deposited inside a closed stromatactis cavity (with "snowing" of the first geopetal internal sediment), duration of process in seconds. B – escaping of fluids together with microscopic bubbles (cuspate projections), in minutes. C – big bubbles from decomposing organic matter (digitate projections), after several days.

might rarely result in turbulent suspensions with the relevant features. The latter is of significance when considering the flat and deep-water stromatactis beds.

c) Examples of complex stromatactis swarms are known in both very fine and relatively coarse sediments. This disparity is explained by the basic requirements for stromatactis-producing suspensions that must contain a broad spectrum of irregularly shaped and porous particles within strongly polydisperse and polymodal systems, with the additive effect of bacterial filaments and organic detritus with microbubbles. The relative proportions and sizes of these components seem to be more significant for stromatactis formation than the variation in the grain size of the sediment.

d) The largest Paleozoic stromatactis structures commonly reach decimetre size, whereas the largest experimentally produced stromatactis-like cavities are smaller, 4–5 cm in maximum. The increased dimensions of stromatactis cavities do not correspond only to a graded amount of the organic component, but the present series of experiments in vessels and troughs of decimetre to metre size is also indicative of relationships between the size of the entire sedimentation system and size of proto-stromatactis domains in the set-

tling suspension. The initial results indicate that about 15–20 cm stromatactis cavities, such as the giant forms known from the Paleozoic, can be reached with an ideal composition of slurry in sedimentary systems of perhaps several metres in size or more. Naturally, it would be technically difficult to upscale the experiments to these large sizes, and thus the latter assertion has not yet been experimentally verified.

Conclusions

The detailed experimental analyses of the processes outlined above, including their modelling are currently in progress, however, they are laborious and can require several months or years of investigation. The most important current results are that the fenestrae, which are largely identical to the shapes of stromatactis, can originate directly from the sedimentation of polydisperse, polymodal, and irregularly-shaped particulate materials that fall from moderately dense, relatively viscous, and not very fast moving suspension clouds. The possible natural origin of stromatactis beds would, therefore, be compared with the sedimentation of viscous but relatively light turbid suspensions, comprised of a variety of clasts and fine particulate material in vigorously agitated water, on living and dead surfaces with bacterial mats, or elsewhere on firm or friable seafloors. It can also be compared, for example, with suspensions that were originally lifted by eddies. In the most simplified and thought-provoking form, we have demonstrated this sedimentation processes (and the consequent origin of stromatactis-like fenestrae), using limestone detritus/powder and tap water (in proportions ranging from about 1 : 3 to 1 : 5), and shaking this mixture in a wide, tightly closed glass vessel. The stromatactis-like fenestrae that form in the sediment are larger if a small amount (a few percent) of bacterial mud is used as an additive.

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ESM 1 – Electronic supplementary material: high-speed camera record, Video 1–3 is available in this work on-line on web page of this journal (www.geology.cz/app/bulletin.htm).

Video 1 – A part of high-speed record that exemplifies the earliest stage of sedimentation (with varying and still very unstable sub-spherical and rhombic domains).

Video 2 – A part of the record from the second stage (focused to formation of several small stromatactis cavities).

Video 3 – A part of the record from the late second stage (focused to vertical escape of water with small particles v. fall of bulky grains). This flow pattern develops above the middle stromatactis-rich part, and is effective during but also after the formation of these primitive stromatactis cavities.