

Possible origin of stromatactis-like cavities in Upper Jurassic sediments from the Wielkanoc quarry near Gołcza (Kraków–Częstochowa Upland, southern Poland)—experimental studies

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Abstract Isolated stromatactis-like cavities were found in a microbial-sponge buildup exposed in the Wielkanoc quarry (eastern part of the Kraków–Częstochowa Upland). The cavities are filled with several generations of carbonate cements and with internal sediments. The top surfaces of internal sediments are flat or wavy, whereas the roofs of cavities are arcuate. The origin of cavities from the Kraków–Częstochowa Upland is difficult to constrain. It seems that the stromatactis-like cavities from the Wielkanoc quarry resulted, at least partly, from remodeling of open spaces left after dissolution of corals in incompletely lithified sediment. Dissolution of corals disturbed the primary stress field within the carbonate buildup and generated the secondary stress characterized by the appearance of compressional forces in the walls of cavities and tensional forces in their roofs. Thus, the lack of support of sediments over roofs of cavities after dissolution of corals resulted in their instability and collapse triggered by vibrations caused by various factors. One of such triggers might have been the rejuvenation of the Kraków–Lubliniec Fault Zone in the Late Jurassic or the collapse of reticular framework within the buildup. The material falling down from the roofs was deposited at the bottoms of cavities as an internal sediment. Results of experimental studies demonstrate that the arcuate shapes of the roof surfaces of cavities are related to compressional stress in the walls and tensional stress in their roofs.

Keywords Stromatactis-like cavities · Dissolution · Stress field · Experimental studies · Wielkanoc quarry · Southern Poland

Introduction

Stromatactis are accumulations of spar with some addition of internal sediment. Such accumulations show smooth bases, digitate roofs, and occur in swarms with reticulate distribution (Bathurst 1982). Stromatactis reach vertical dimensions even over decimeter and lateral extension of swarms up to tens of meters (Flajs and Hüssner 1993).

The origin of stromatactis is still controversial, despite numerous studies. The review of hypotheses can be found, e.g., in Monty (1995), Aubrecht et al. (2002), and Hladil (2005, 2007). Two groups of hypotheses exist. The first group assumes purely biological origin of stromatactis (cf. Tsien 1985; Flajs and Hüssner 1993). According to Bourque and Gignac (1983), the formation of stromatactis is related to decomposition and collapse of uncemented bodies of sponges. Delecat and Reitner (2005) explain stromatactis as an effect of syndiagenetic shrinkage of sponge bodies. Moreover, these authors found that some stromatactis were formed immediately after deposition in the subsurface part of sediments. This produced a system of cavities remaining in hydraulic contact with the basinal bottom waters. The coexistence of stromatactis in sediments with bioclastic sand, large oncoids, and calcareous algae (*Girvanella*) indicate shallow-marine environment of their formation (Stenzel and James 1995).

The second group of hypotheses presumes purely physical origin of stromatactis. Bathurst (1980) suggests that stromatactis may develop as a result of filling of a system of cavities within submarine-cemented crusts with

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cement and sediment. According to Wallace (1987), internal erosion and redeposition of sediment caused upward migration of cavities within the sediment. The range of migration was controlled by lithification or by the presence of larger skeletal fragments, which hampered this process.

Kukal (1971) noticed that stromatactis may develop at various depths. The presence of stromatactis in mud mounds formed beneath the storm-wave base, as described by Matyszkiewicz (1993), Krause (2001), and Boulvain et al. (2004), suggests that internal erosion of sediments caused by migrating waters is not a decisive factor in the formation of stromatactis. Recently a new sedimentary hypothesis of stromatactis origin has been presented by Hladil (2005, 2007) and Hladil et al. (2006) who suggested that these structures originated during turbulent deposition and separation of highly unsorted clastic material from strongly dispersed suspension cloud.

In the Kraków region, the stromatactis were described by Matyszkiewicz (1993, 1997) and Matyszkiewicz et al. (2004, 2007) from microbial-sponge-*Crescentiella* (Senowbari-Daryan et al. 2008) carbonate buildups, in which single specimens of hermatypic corals *Stylosmilia* were locally observed. These buildups formed both beneath (Matyszkiewicz 1993) and above (Matyszkiewicz 1997) the storm-wave base. This author related the origin of stromatactis to the internal erosion of sediment. The factor responsible for internal erosion could have been a gravity flow resulting in high turbulence of waters (Matyszkiewicz 1993) or intensive wave action in the intertidal zone, which gave rise to cavitation erosion (Matyszkiewicz 1997).

The terminology applied in this paper was proposed by Matyszkiewicz (1997) who defined stromatactis-like cavities as isolated cavities with digitated upper surfaces, which are entirely or partly filled with spar cements and/or internal sediments, and are embedded within finely crystalline limestone. Stromatactis-like cavities differ from stromatactis in size and the way of occurrence. Stromatactis are usually larger than those described in this paper and they occur in swarms with reticulate distribution (Bathurst 1982; Neuweiler et al. 2001).

The formation model of stromatactis-like cavities proposed in this paper assumes the presence of secondary porosity within the sediment. According to Wallace (1987), the appearance of precursor cavities is a *sine qua non* condition in stromatactis development. The principal question, however, is how such precursor cavities might have formed.

Here, I focus on explanation of the origin of stromatactis-like cavities about 1 cm wide. In their lower parts, such structures are filled with internal sediment, whereas in the upper parts, several generations of carbonate cements

occur. It is demonstrated that the stress field within the sediment having secondary porosity influences the shape of roof surfaces of stromatactis-like cavities. This hypothesis was confirmed by modeling. The process that was verified by modeling might not be responsible for the creation of stromatactis.

Geological setting

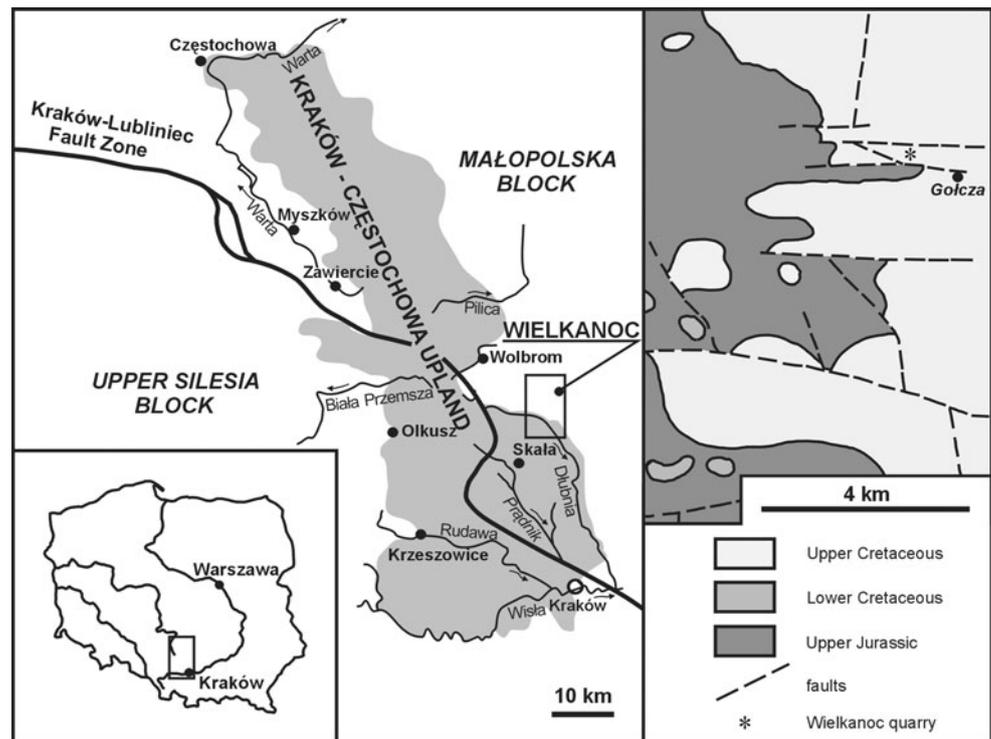
The Wielkanoc quarry is located in the eastern part of the Kraków-Częstochowa Upland, in the Wielkanoc village near Gołcza, some 35 km north of Kraków (Fig. 1). In this area, Upper Jurassic sediments are underlain by Middle Jurassic and Triassic strata of combined thickness up to about 60 m (Bukowy 1963) and are overlain by Cretaceous formations. All sediments dip gently to the northeast, towards the Miechów Trough.

The sub-Mesozoic basement of the Silesian-Kraków Monocline includes folded Paleozoic formations divided by the Kraków-Lubliniec Fault Zone into the two tectonic blocks: the Małopolska and the Upper Silesian ones (Żaba 1995, 1999; Buła et al. 1997) (Fig. 1). The fault zone is accompanied by Paleozoic intrusions clustered mostly along the margin of the Małopolska Block (Buła et al. 1997; Żaba 1999).

In the Kraków region, the Upper Jurassic sediments belong to the Oxfordian and the Kimmeridgian (Krajewski 2001). Their thickness reaches up to 250 m in the eastern part of the region and decreases westward (Siewniak 1967; Matyszkiewicz 2001) due to erosion of the monocline. The Upper Jurassic bedded facies are represented by two facial varieties: platy limestones interlayered by marls and bedded limestones with early diagenetic siliceous concretions (cherts), both interpreted as products of deposition on the slopes of carbonate buildups. The carbonate Upper Jurassic massive facies include microbial-sponge and microbial buildups (Matyszkiewicz 2001). It is commonly accepted that spatial distribution of buildups over the Kraków-Częstochowa Upland was controlled by the structure of sub-Mesozoic basement (see Jędrys et al. 2004; Matyszkiewicz et al. 2006).

The lowermost Upper Jurassic sediments in the Kraków region are Oxfordian marls and platy limestones with small sponge bioherms (Trammer 1985; Matyszkiewicz 1997) (Fig. 2). Up the sequence, bioherms grade into vast carbonate buildups with well-developed rigid frameworks (Matyszkiewicz 2001). Simultaneously, other varieties appear: thick-bedded limestones with flints, clotted limestones and rarely exposed chalky limestones (Krajewski 2001). Moreover, in the whole Oxfordian sequence (particularly in its upper part) gravity-flow sediments occur (Matyszkiewicz 1997, 2001). The uppermost part of Upper

Fig. 1 Location of the Wielkanoc quarry in the Kraków area. Geological map after Kaziuk (1978), simplified. Kraków-Lubliniec Fault Zone after Buła (1994), modified by Żaba (1999)



Jurassic sequence comprises Lower Kimmeridgian marls (Bukowy 1963; Krajewski 2001).

The Wielkanoc quarry is located in a 0.3-km-wide, NNW-SSE-trending graben. Average throw of marginal faults is about 40 m (Bukowy 1968). In the quarry, a 10-m-thick sequence of Upper Jurassic massive limestones is observed together with about 5-m-thick succession of Upper Cretaceous sediments (Fig. 3a,b).

Lithology of Upper Jurassic sequence is dominated by massive limestones, which represent the Uppermost Oxfordian, presumably the *Planula* ammonite zone (Matyszkiewicz, pers. comm.) (Fig. 2). Towards the northwest, in the vicinity of Gołcza village, massive limestones are replaced by marls and marly limestone facies (Bukowy 1968). Upper Jurassic strata are overlain by Upper Cretaceous glauconitic sandstones, conglomerates, and glauconitic limestones, about 5 m thick (see Bromowicz 2001) and dated at the Cenomanian/Turonian boundary (Bukowy 1968; Marcinowski and Szulczewski 1972). The Upper Cretaceous strata form a continuous cover in the area.

Lithology of limestones from the Wielkanoc quarry

The oldest member of the sequence is the massive limestone in which calcitized siliceous sponges, fine serpulid worm tubes, bivalve shells, and numerous stromatolite-like cavities are observed (Fig. 3b). Some siliceous sponges are

partly pyritized, which results in their color being distinctly darker than the enclosing rock. Under the microscope, thrombolite-sponge associations and wackestones are evident. In wackestones, fine peloids, numerous *Crescentiella* specimens up to 2 mm across, tuberooids, serpulid worm tubes, sponge spicules, and single echinoderm plates can be identified together with syntaxial cement and echinoid spines. Common are geopetal fillings of serpulid worm tubes. Locally, in the lower part of the sequence, detrital limestone (grainstone) occurs as lenses, some tens of centimeters long and a dozen of centimeters thick, embedded within the massive limestones. Among irregular grains (up to 3 mm across) one can identify *Crescentiella*, fragments of siliceous sponges rimmed by microbial crusts up to 0.2 mm thick, serpulid worm tubes, bivalve shells, and echinoderm plates. Most of the grains are rimmed by isopachous cement, up to 0.4 mm thick, whereas the remaining intergranular spaces are filled with blocky cement.

In the middle part of the massive limestone sequence, siliceous sponges (up to 1.5 cm thick) are visible along with serpulid worm tubes (up to 0.5 cm across), tuberooids (up to 1 cm across), bivalves, and single ammonites. Some siliceous sponges are fractured and their fragments are displaced by 0.5 cm. Above the sponge specimens, wackestones are commonly present, whereas beneath the specimens, grainstones occur, which grade down the sequence along a distance of some 2 cm into packstones

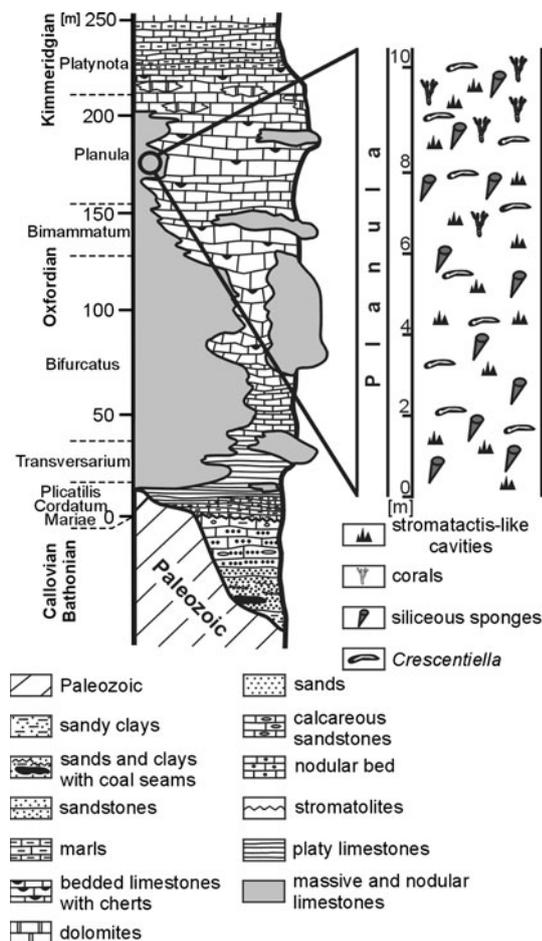


Fig. 2 Lithostratigraphic column of Upper Jurassic sediments in the Kraków area (after Krajewski and Matyszkiewicz 2004, modified) and schematic diagram with approximate stratigraphic position of the Upper Jurassic sediments from the Wielkanoc quarry with stromatactis-like cavities and dominant components

and peloid wackestones. Occasionally, the space between the bottom surface of a sponge and the bioclastic grainstone is filled with carbonate cements. In wackestones regular, oval pores can be observed, up to 4 mm in diameter. Common are stromatactis-like cavities, up to 1.5 cm wide. Under the microscope dominating components are microbialites (laminated thrombolites) and *Crescentiella*. Moreover, fragments of siliceous sponges and echinoderms, bivalves are observed together with serpulid worm tubes. Interiors of serpulid worm tubes and bivalve shells are commonly geopetally filled. Top surfaces of geopetal fillings dip at angles up to 25°. In wackestones, frequent are calcified spicules of siliceous sponges. In this part of the sequence, single hermatypic corals of Cladophyllidae were found.

In the upper part of the sequence, massive limestones have developed as thrombolite-sponge biolithites. Apart from microbialites and calcified siliceous sponges, also

Crescentiella, tuberoids, serpulid worm tubes, echinoderms plates, single echinoids spicules, and *Terebella lapilloides* are observed. Locally, elongated and oval pores occur, up to 2 cm long and about 4 mm across. In some pores, partly dissolved cladophyllid corals are preserved (Fig. 4a,b). Beneath the siliceous sponges bioclastic grainstones of graded particle size, from silt up to 3 mm in diameter are common. Down the sequence, grainstones grade into peloidal wackestones/packstones in which calcified spicules of siliceous sponges are observed. In this sediment, stromatactis-like cavities up to 5 mm wide were found. Tilting of the top surfaces of internal sediments filling the lower parts of cavities reaches 25°. Commonly, in vertical sections through the contact of the host-rock (wackestone) with the lower surface of internal sediment (wackestone/packstone) it is evident that the bottoms of cavities are convex.

In the whole sequence of massive limestones, yellowish laminated internal sediments are observed. Laminae of thickness up to 1 mm (usually from 0.1 to 0.4 mm) are sometimes disturbed. Internal sediments often occur under siliceous sponges and fill completely or partly the interiors of karst cavities or gastropods shells. Sometimes the internal surfaces of gastropod shells are filled with dog-tooth calcite cement, up to 1 mm in size, covered by laminated sediment. Such filling suggests post-Late Jurassic (Cretaceous?) age of laminated sediments. Thickness of laminated sediments rarely reaches 5 cm in the middle part of the sequence. Dominating are sediments up to several centimeters wide and about 1.5 cm thick.

Description of stromatactis-like cavities

The stromatactis-like cavities are observed in the complete sequence of massive limestones. At the weathered rock surface, such structures appear as single cavities, about 4 cm wide and 2 cm high, of irregular, rounded roofs (Fig. 3b). Occasionally, roof surfaces are smooth and arcuate. In the upper parts of cavities, their walls are covered with dog-tooth calcite cement up to 2 mm in size. The lower parts of cavities are filled with internal sediments. Their top surfaces are planar, whereas the contacts of lower surfaces with the host-rocks are difficult to identify macroscopically as the internal sediments grade into the host-rocks.

Under the microscope, the stromatactis-like cavities occur within thrombolite-sponge and *Crescentiella*-peloid wackestones. The roofs of cavities are usually irregular (Fig. 5a–c), locally reflecting the shapes of *Crescentiella* (Fig. 5d). Sometimes beneath skeletal components shelter cavities appear. In some cavities, roofs have smooth, arcuated surfaces. In their upper parts, the stromatactis-like

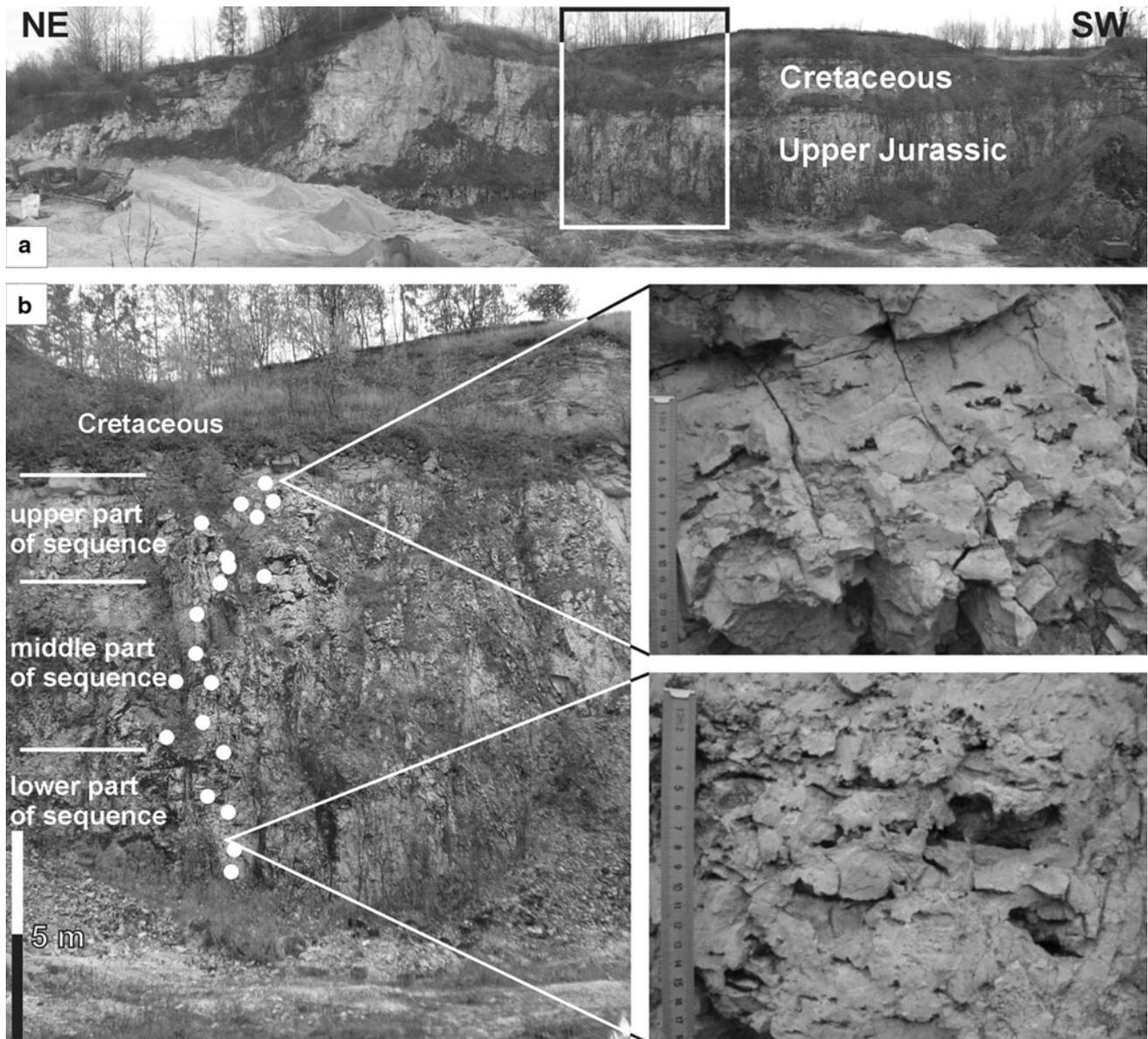


Fig. 3 General view of SE wall of the Wielkanoc quarry with sampling site. **a** SE wall of the Wielkanoc quarry. **b** Sampling site (white dots) with stromatactis-like cavities observed at the weathered rock surface. Close-up of box marked in (a)

cavities are filled with carbonate cements, whereas their lower parts are occupied by internal sediments. Types of cements are similar in the whole sequence. The walls of cavities are covered with isopachous cement, which grades towards the center of cavities into the radial cement, whereas the inner parts of cavities are filled with blocky cement (Fig. 5d). Locally, both the isopachous and the blocky cements are present or cavities are filled only with the blocky cement (Fig. 5e) of crystal size up to 1.5 mm.

In their lower parts, the stromatactis-like cavities are filled with the internal sediments composed of the same constituents as the host-rocks (Fig. 5e, f). The internal sediments are wackestones with fine *Crescentiella*, peloids,

and sponge spicules. Occasionally, packstones with *Crescentiella* are present or the internal sediments are packstones in the upper parts and grade into peloid wackestones in the lower ones (Fig. 6a, b).

The boundary between the internal sediment and the host-rock can be identified with variable accuracy. In some cavities, the internal sediments become darker towards the bottom of the cavities (Fig. 5d), which hampers the localization of initial bottom surface. In other structures, boundaries between the internal sediments developed as packstones and host-rocks developed as wackestones are sharp. Such boundaries are arcuated and are typical of the middle and upper parts of the sequence (Figs. 5e, f, 6c, d).

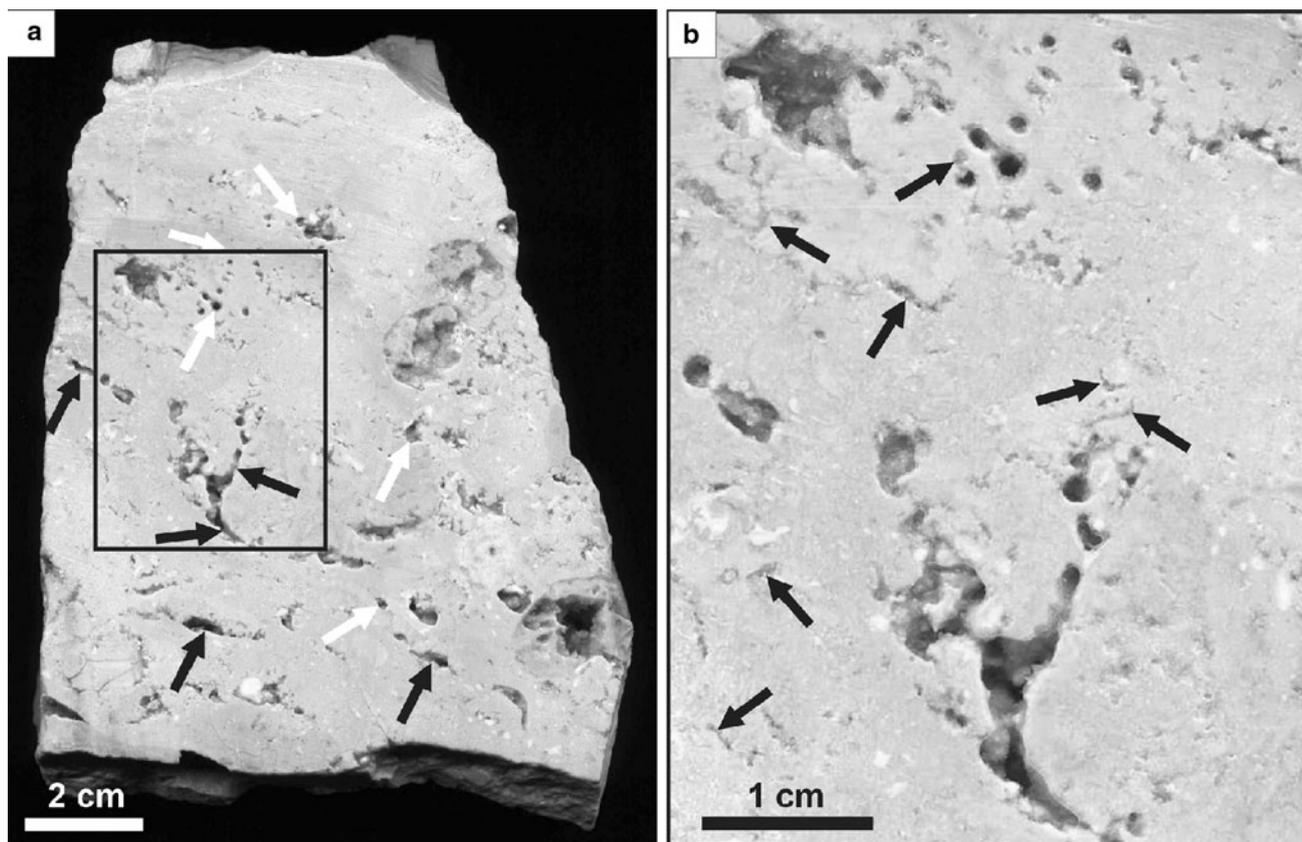


Fig. 4 Biomoldic porosity developed after aragonitic *Stylosmilia* coral dissolution. **a** Oval shape of voids (*white arrows*) correspond to the shape of a coral with bifurcating morphology observed in transverse section. Locally, pores are elongated and correspond to

vertical section of coral branches (*black arrows*). Upper part of the sequence. **b** Close-up of box marked in **a**. Preserved coral branches (*black arrows*)

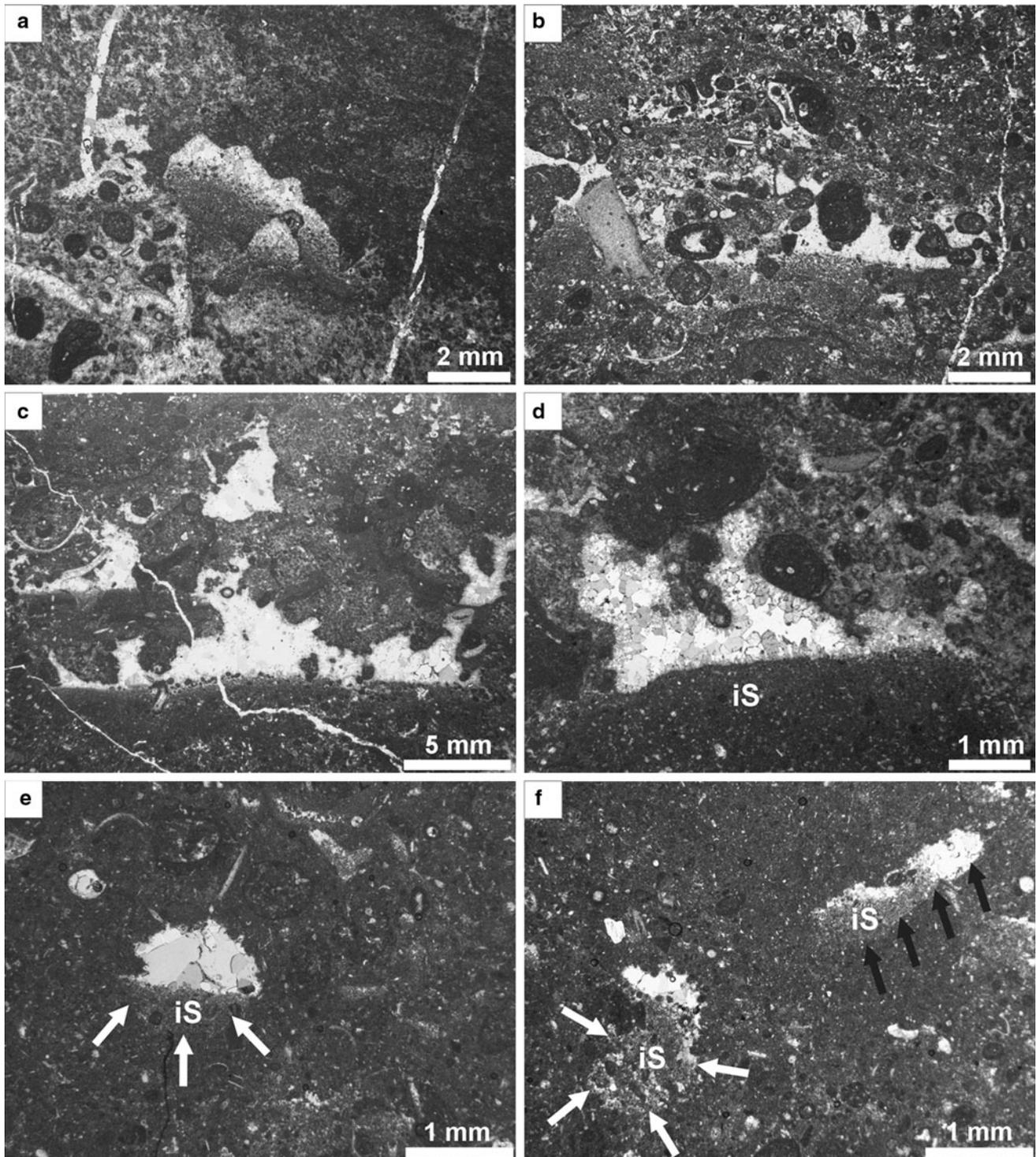
Materials and methods

Experimental studies were run in a water tank of dimensions $22 \times 14.5 \times 16.5$ cm. Limestone powder used in the experiment was collected from a dump at the Wielkanoc quarry. Grain-size distribution of limestone powder was determined with the sieve analysis. The following grain size distribution of powder was measured: $\text{Ø} < 0.10$ mm (29.6%); 0.10–0.16 mm (11.4%); 0.16–0.20 mm (8.9%); 0.20–0.32 mm (16%); 0.32–0.40 mm (7.6%); 0.40–0.63 mm (15.1%); 0.63–0.80 mm (6.5%); > 0.80 mm (4.9%). Before the experiment, the moisture of powder was increased from 1.3 to 22.1%, which resulted in the appearance of capillary water in the fabric. Negative pressure of capillary water caused additional compressional stress in the fabric and enabled the author to form blocks of limestone powder, 14.5 cm wide, 14 cm high, and 6 cm thick. The experiment was run with two blocks, in which the cavities were made of dimensions 36×12 mm, oriented horizontally (Fig. 7) and vertically (Fig. 8), respectively.

The experiment has commenced with the formation of a 4-cm-thick layer of limestone powder, which was

subsequently compacted to 3-cm thickness using the vertical load. On the layer, a wooden brick was placed, which side walls fitted close to the wall of the tank. Then, the second, 4-cm-thick powder layer was placed atop the first

Fig. 5 Stromatactis-like cavities from the lower (**a–b**) and middle (**c–f**) part of the sequence of the Upper Jurassic carbonate buildup in the Wielkanoc quarry. **a** Stromatactis-like cavity in thrombolite-peloidal wackestone. **b** Stromatactis-like cavity in thrombolite wackestone/packstone with bioclasts and *Crescentiella*. **c** Stromatactis-like cavities with irregular roofs in microbial-peloidal wackestone. **d** Stromatactis-like cavity in wackestone. Color of the internal sediment (*iS*) becomes darker towards the bottom of the cavity, which hampers the localization of initial bottom surface. **e** Stromatactis-like cavity developed after the dissolution of an aragonitic coral. The boundary between the internal sediment (*iS*) (lighter wackestone) and the host-rock (darker wackestone) is oval (*white arrows*) and corresponds to the cross section through the branch of coral. **f** Stromatactis-like cavities developed after the dissolution of branched aragonitic corals. The boundary between internal sediment (*iS*) and the host-rock in the left part of the photo is oval and corresponds to the cross section through the coral branch (*white arrows*). The internal sediment (*iS*) in the right part of photo infilled partly an open space in sediment which shape corresponds to the vertical section through the coral branch (*black arrows*)



one and again compacted to thickness of 3 cm. Afterwards, two subsequent, 4-cm-thick layers were formed and also compacted to thickness of 3 cm each. Finally, the last, 2.5-cm-thick layer was placed atop the formers and compacted to thickness of 2 cm. As a result, 14-cm-thick blocks of limestone powder were obtained. The wooden brick was

then first lowered by 2 mm in order to separate its upper surface from the powder and then raised by 1 mm, and removed from the tank. This produced a rectangular cavity in the powder block (Figs. 7a, 8a). Dynamic loads of the block were generated by hitting the basement of the tank with the frequency 1 hit per 2 s.

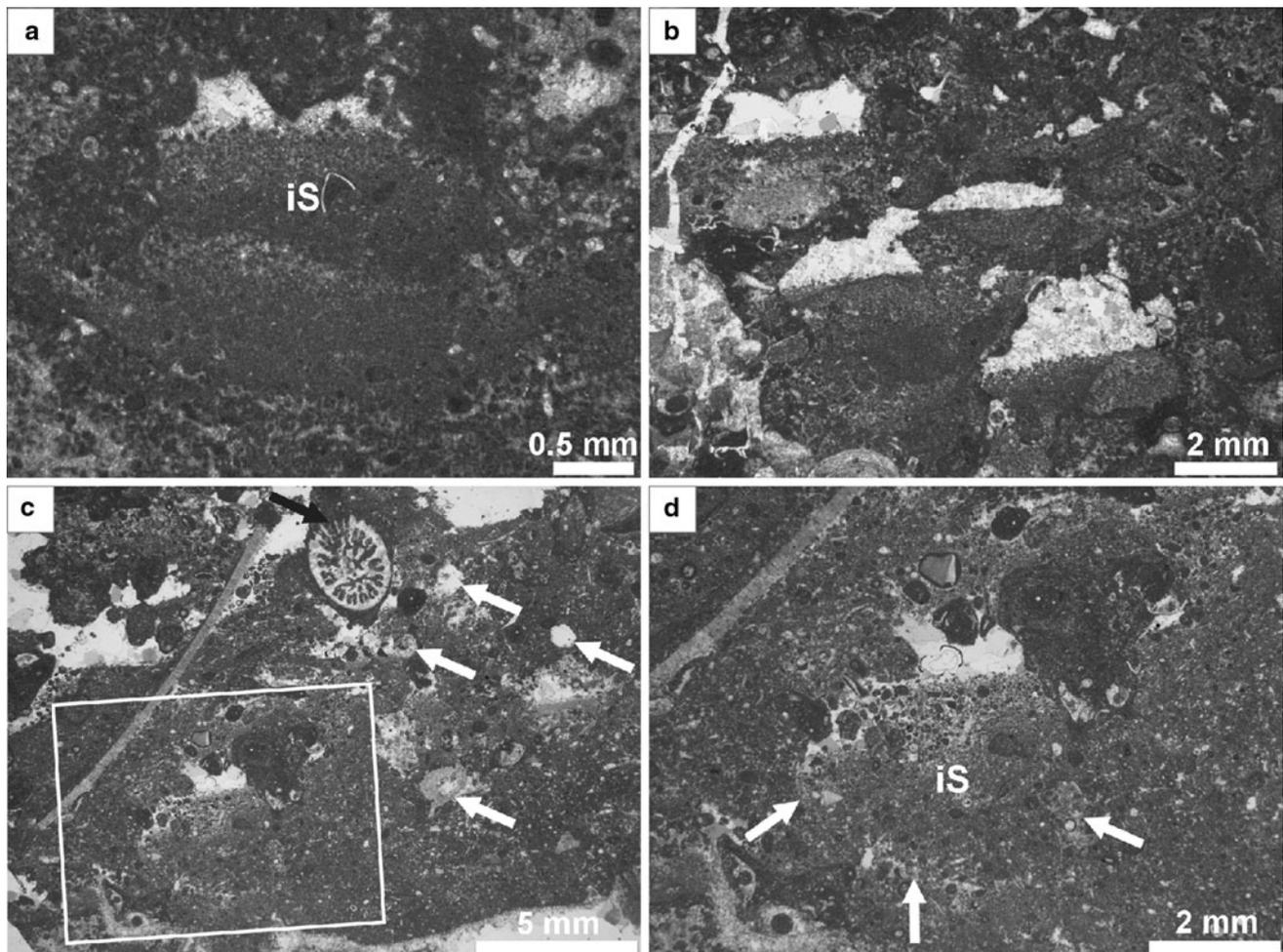


Fig. 6 Stromatactis-like cavities from the upper part of the sequence of the Upper Jurassic carbonate buildup in the Wielkanoc quarry. **a** Stromatactis-like cavity in peloidal wackestone. The top surface of internal sediment (*iS*) is packstone, which grades towards the bottom into a wackestone. **b** Stromatactis-like cavities in thrombolite wackestone. **c** Stromatactis-like cavities in microbial boundstone. In the upper part, a partly dissolved phaceloid *Stylosmilia* with microbial

coating (*black arrow*) is visible. Below the coral, numerous rounded voids occur (*white arrows*), which formed after the dissolution of coral branches. **d** Close-up of box marked in **c**. Stromatactis-like cavity in wackestone with *Crescentiella* and bioclasts. The boundary between the internal sediment (*iS*) and the host-rock is sharp (*white arrows*)

Experimental studies

The development of vertically and horizontally oriented cavities was different but the final shapes of both cavities were similar. In both cases, the repeating shocks produced arched fractures–cavities (Figs. 7a–c, 8a–c). Before the roof collapse of the cavities, distinct deflection of the roof of horizontal cavity was observed (Fig. 7b,c), whereas the roof of vertical cavity remained unaffected. After the collapse of the roofs, the domical vaults were produced (Figs. 7d, 8d). These vaults resembled tension domes observed during roof evolution of caves (see Ford and Williams 2007). Further shocks led to remodeling of cavity geometry. The modes of filling of horizontal and vertical cavities were different. The horizontal cavity was filled

mostly with the material falling from the roof, whereas the vertical cavity was filled with both the material falling from the roof and from the unstable walls (Fig. 8e–h). Material fallen from the roofs and walls was deposited at the bottoms of cavities (Figs. 7e–g, 8e–g) and, in this experiment, it corresponds to the internal sediment filling the natural stromatactis-like cavities. This internal sediment was compacted by the repeating shocks (Figs. 7g–k, 8g–k). However, the cavities were not entirely filled with the internal sediment because of this compaction and leveling of cavity floors. Final bottom surfaces of cavities were wavy or flat (Figs. 7 l, 8 l), whereas their roof surfaces were domed. In both samples, the final cavities were displaced in comparison to the initial position—their bottom surfaces raised by about 4 cm (compare Figs. 7a, l, 8a,

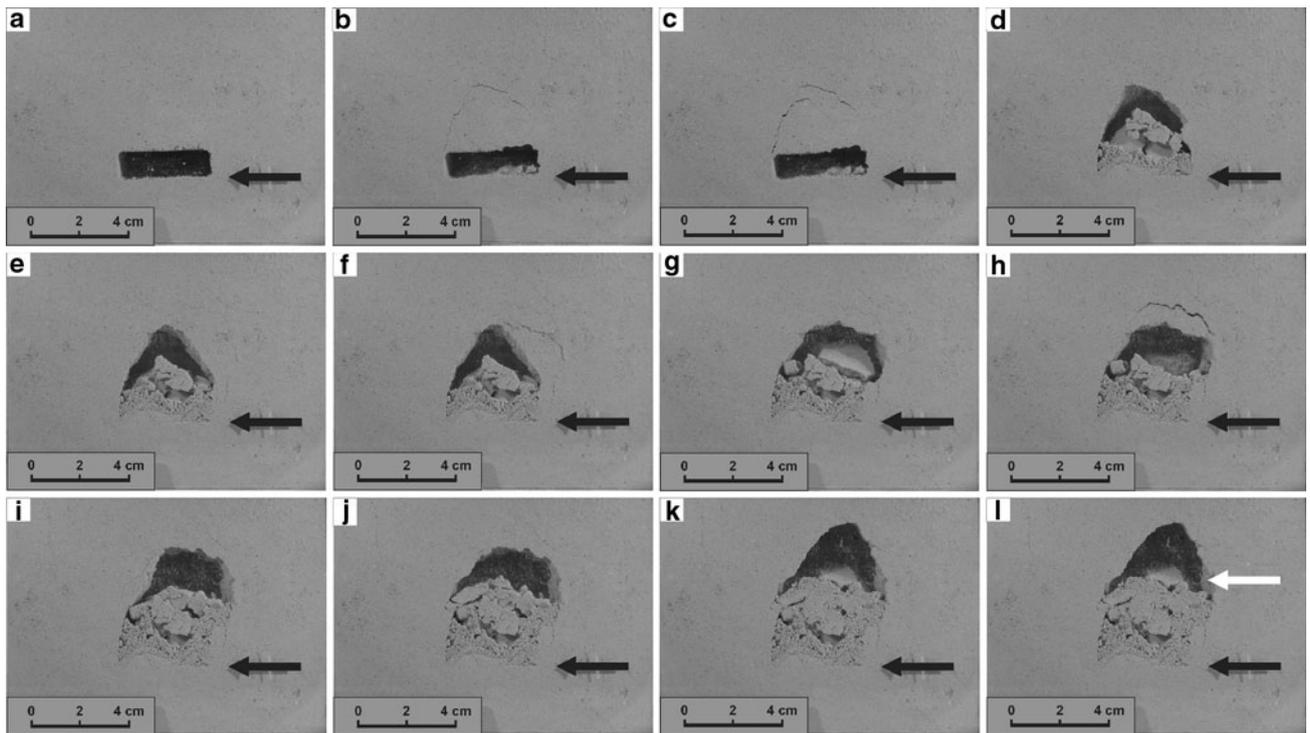


Fig. 7 a-l Experiment showing the behavior of a horizontally oriented rectangular cavity within limestone powder during the generation of a dynamic load. *Black arrows* indicate primary position

of the cavity bottom surface. *White arrow* indicates final position of the cavity bottom surface. For further explanation, see text

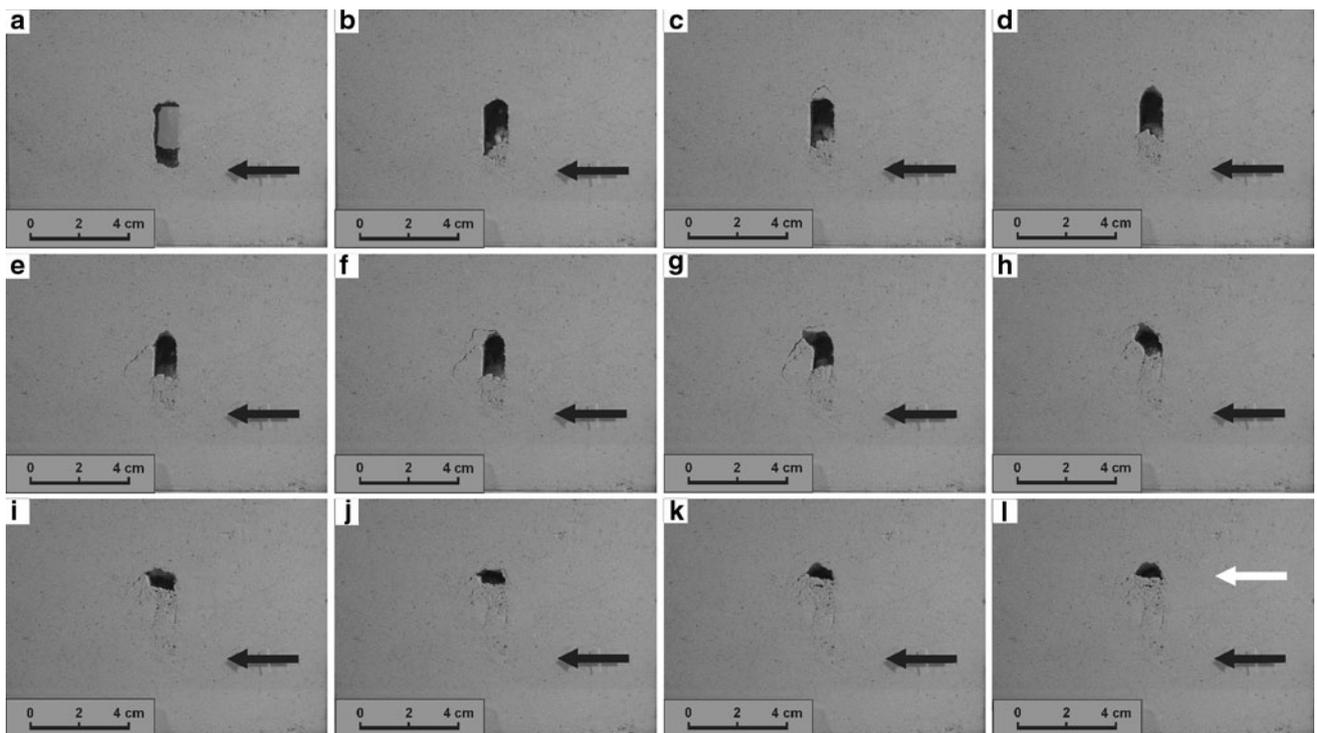


Fig. 8 a-l Experiment showing the behavior of a vertically oriented rectangular cavity within limestone powder during the generation of a dynamic load. *Black arrows* indicate primary position of the cavity

bottom surface. *White arrow* indicates final position of the cavity bottom surface. For further explanations, see text

l). However, the widths of the bottoms of both cavities remained identical before and after the experiment. Moreover, after remodeling the horizontally oriented cavity, the new cavity was larger in comparison to that obtained from remodeling of the vertical cavity (see Figs. 7l, 8l).

Interpretation of the results

The blocks of limestone powder with the wooden bricks placed inside have attained the primary stress field (Fig. 9). Vertical load originating from the weight of sediment layer above the brick generated insignificant horizontal stress in side walls of the brick as it could not be deformed in the horizontal plane.

The removal of wooden brick from the block led to the concentration of stress in the immediate vicinity of the cavity. Simultaneously, the primary stress field changed into the secondary one (Fig. 9). Horizontal stress in the side walls of cavity has ceased, whereas vertically directed

compressional stress has increased. This increase of compressional stress resulted from the new load distribution—the walls of cavities had to support the pressure from sediment over their roofs. Consequently, the increasing compression in the side walls caused tensional stress field directed vertically towards the roof of cavities (Fig. 9).

Generation of dynamic load in limestone powder disturbed stability of material over the roofs of cavities. The arcuated fractures over the roofs (Figs. 7b, 8c) resemble tension domes of which heights were determined by the widths of cavities (see Ford and Williams 2007). The tension domes reflected the tendency of material in cavity walls to gain the stability.

Possible origin of stromatactis-like cavities

The carbonate buildup is composed of overgrowing microbialites, siliceous sponges, and hermatypic cladophyllid corals. These organisms built the reticular framework in which intra-framework spaces are filled with calcareous mudstones, wackestones, or bioclastic grainstones (primary sediment, see Pratt 1982). In such sediments, numerous oval or elongated cavities are developed (Figs. 4a, b, 6c). It seems that cavities were formed by dissolution of corals during early diagenesis when sediment infilling the intra-framework spaces was incompletely lithified.

Aggradational growth of carbonate buildup was coeval with the building of primary stress field within the structure. The primary stress was a result of vertical load caused by the weight of overlying sediments. Vertical load exerted on a single component of a buildup (e.g., coral) led to the appearance of insignificant, lateral compressional stress affecting the vertical surfaces of such components.

The formation of cavities after the dissolution of the aragonitic corals might have resulted in the disturbance of the primary stress field within the carbonate buildup, in the immediate neighborhood of the cavities. Precisely, the dissolution of corals might have caused the decline of lateral stress at the contacts between the sediments and the side walls of cavities. Simultaneously with the dissolution of corals, the secondary stress field has appeared in the side walls of cavities, which played the role of supports for roofs loaded with the overburden pressure. Hence, in the side walls of cavities the compressional stress might have increased, whereas in their roofs the vertical tensional stress field might have appeared due to the lack of support. Cavities left after the dissolution of phaceloidal clusters of coral colonies might have reached several centimeters in diameter (see Morycowa and Roniewicz 1990). Dissolution of single, bifurcating branches of corals embedded within the sediment that filled the intra-framework spaces led to the formation of elongated cavities, up to several

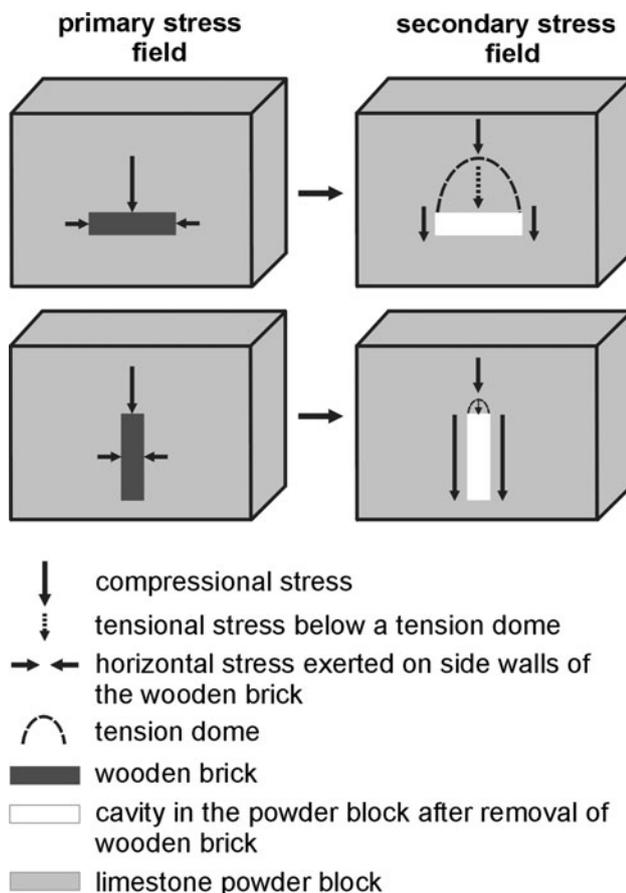


Fig. 9 Schematic diagram illustrating stress fields within the limestone powder block during the change of stress field from primary into secondary

millimeters in diameter (see Morycowa and Roniewicz 1990). Stability of the shapes of cavities in time was controlled by cementation of enclosing sediment. Shapes of cavities developed in strongly cemented sediment might have remained unaffected by later remodeling. However, if the cavities were embedded within poorly cemented sediment their roofs might have showed a tendency to collapse.

Partly lithified sediment revealed spatial diversity of cavities distribution controlled by random location of coral colonies. Thus, the stress field within a carbonate buildup was inhomogenous—the parts of sediment devoid of cavities might have preserved the primary stress, whereas the secondary stress might have appeared in those parts where cavities have formed. Around the cavities, the concentration of stress might have emerged. The presence of tensional stress in the roofs of cavities combined with the low strength of sediment might have caused separation of single grains from the roofs of cavities. Sometimes, the compact aggregates of grains might have been separated. The falling grains were then deposited at the bottoms of cavities producing the internal sediments. Falling down of sediment particles from the roofs caused upward migration of cavities.

Discussion

The experiments demonstrate how small cavities can be remodeled and how such forms may migrate upward within fine-grained limestone powder, which pore spaces are devoid of water. However, the environment generated during the experiments cannot be directly compared to the depositional environment of Late Jurassic carbonates. Under natural conditions, development of stromatactis-like cavities was much more complicated and controlled by both the lithification of sediments and the presence of larger grains or skeletal constituents. The presence of compressional stress in side walls of the cavities and tensional stress in their roofs might have determined their stable shapes. If the hosting sediment was well sorted and homogeneously lithified, the roofs of cavities were ellipsoidal, whereas cavities developed in random-grained and inhomogeneously lithified sediment would reveal irregular, jagged roofs. Aubrecht et al. (2009) found that some stromatactis have still preserved casts of sponges in their roofs. This suggests that internal sediment was not always formed by the sediment falling from the ceilings.

The formation model of stromatactis-like cavities presented in this paper assumes the presence of moldic porosity and dynamic loads within partly lithified sediment. According to Kukal (1971), Wallace (1987) and Neuweiler and Bernoulli (2005), the presence of precursor cavity

system is a necessary condition in the development of stromatactis. Such cavities might have formed during deposition (Pratt 1982) or after deposition, within a still uncomplete lithified sediment.

The stromatactis-like cavities from the Wielkanoc quarry might have formed, at least partly, as a result of remodeling of cavities formed after deposition within the intra-framework spaces of reticular framework (sensu Pratt 1982). Such cavities might have formed after dissolution of aragonitic skeletons of corals. It is possible that dissolution might have been caused by the action of aggressive solutions sourced in the Kraków-Lubliniec Fault Zone active in the Late Jurassic (Brochwicz-Lewiński et al. 1984; Matyszkiewicz et al. 2006) or from circulation of meteoric waters at the Late Jurassic/Early Cretaceous boundary. The sediment infilling the intra-framework spaces might have been still incompletely lithified during the early diagenesis, which gave rise to the roofs collapse and formation of stromatactis-like cavities. The emergence of sediments in question is documented by isopachous cement rimming most of grains in bioclastic grainstones.

The factor responsible for remodeling of cavities might have been the dynamic load periodically affecting the carbonate buildups with reticular framework. Such dynamic load might have originated for various reasons. The growth of the carbonate buildup from the Wielkanoc quarry proceeded in a marginal zone of the Małopolska Block, where tectonic disturbances were stronger than in the Upper Silesian Block (Żaba 1999). Tectonic activity of the Kraków-Lubliniec Fault Zone in the Late Jurassic (Matyszkiewicz et al. 2006) might have resulted in local movements (Olszewska-Nejbert and Świerczewska-Gładysz 2009) and the appearance of dynamic loads within the carbonate buildup. Such loads might have destabilized sediment above the roofs of cavities and, consequently, caused their collapse. However, at the Wielkanoc quarry, the undoubtful evidence of synsedimentary tectonics has not been found.

Vibrations in the sediments might have also been caused by other factors. The unlithified sediment filling in the intra-framework spaces exerted pressure, which generated the elastic deformations of reticular framework. Vertical load resulted from variable size of intra-framework spaces might have caused small, elastic strain in the framework. If the strength of reticular framework has been exceeded, local fractures might have appeared, followed by internal collapse. Such collapse might have generated elastic waves and vibrations, which propagated concentrically through the framework. The intensity of vibrations might have decreased with the distance from the collapse center and might have been controlled by development and rigidity of the internal framework of buildup.

Conclusions

The stromatactis-like cavities from the Wielkanoc quarry might have originated from internal erosion of partly lithified sediment having numerous empty voids. This sediment filled the intra-framework spaces within the reticular framework of carbonate buildup. The cavities were formed by dissolution of aragonitic skeletons of corals. Dissolution caused concentration of stress around cavities and simultaneous transition of stress field from primary to secondary in the immediate neighborhood of cavities. The secondary stress field included compressional stress in side walls of cavities and tensional stress in their roofs.

The internal erosion of sediment might have resulted from vibrations generated by local collapses of buildup frameworks and/or by periodical rejuvenation of movements along the Kraków-Lubliniec Fault Zone in the Late Jurassic. Vibrations generated dynamic loads that destabilized the sediment over the cavities and gave rise to their roofs collapse. The mode of filling the cavities with the internal sediments depended on the orientation of cavities within the sediment. In originally horizontal cavities, the internal sediments were formed mostly from material provided by the roof collapse, whereas in originally vertical cavities, it was supplied by the collapse of both the roofs and the walls. The geometry of cavities produced during experimental studies suggests the crucial role of compression in their side walls and tension in their roofs.

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