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# STROMATACTIS CAVITIES AND STROMATACTIS-LIKE CAVITIES IN THE UPPER JURASSIC CARBONATE BUILDUPS AT MŁYNKA AND ZABIERZÓW (OXFORDIAN, SOUTHERN POLAND)

**Jacek MATYSZKIEWICZ**

*University of Mining and Metallurgy, Faculty of Geology, Geophysics and Environmental Protection; al. Mickiewicza 30, 30-059 Kraków, Poland. Fax: 0048 12 332936, e-mail: jamat@geol.agh.edu.pl*

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**Abstract:** Stromatactis cavities (SCs) and stromatactis-like cavities (SlCs) occur in Upper Jurassic carbonate buildups of southern Poland. The carbonate buildups vary in the development of their rigid framework. Internal erosion, resulting from various agents, is the process leading to the formation of the SCs and SlCs.

In carbonate buildups of the cyanobacterial-sponge mud-mound type with weakly developed rigid framework, formation of the SCs occurred in the subtidal zone, on the slope of a buildup, and was caused by partial winnowing of unlithified sediment. This winnowing took place during early diagenesis and rapid tectonic uplifting movements, when water within large pore spaces and growth cavities was strongly turbulent due to submarine mass flows which resulted in the formation of a network of cavities.

In reef-like carbonate buildups of the *Tubiphytes*-reef type with well developed rigid framework the internal erosion was caused by cavitation linked to intensive wave action in the intertidal zone. The rigid framework, where it was well developed, prevented the formation of networked cavities permitting the development of a single SlCs only. Such process of stromatactis formation occurred with a break after the growth of the *Tubiphytes*-reef.

Precipitation of sparry calcite cement took place at various stages of the diagenesis. In the SCs formed in the subtidal zone, on the slope of a cyanobacterial-sponge mud mound, the formation of the cements began under marine phreatic conditions and continued during late diagenesis in various environments. In the SlCs originated in the intertidal zone in *Tubiphytes*-reef the early diagenetic cementation usually did not take place because the stromatactis were subaerially exposed soon after their formation. Some of them were slightly restructured and got filled with cement as a result of hydrothermal processes in Tertiary time.

**Abstrakt:** W górnojurajskich budowlach węglanowych południowej Polski występują kawerny stromatactis (SCs) i kawerny stromatactis *sensu lato* (SlCs). Budowle te charakteryzują się zróżnicowanym rozwojem sztywnego szkieletu. Procesem odpowiedzialnym za tworzenie się SCs i SlCs jest erozja wewnętrzna osadu wywołana różnymi czynnikami.

W budowlach węglanowych typu cyjanobakteryjno-gąbkowych kopców mułowych o słabo rozwiniętym szkielecie wewnętrznym tworzenie się SCs zachodziło na stoku budowli, w strefie sublitoralnej i było spowodowane wymywaniem części niezlityfikowanego osadu. Wymywanie to miało miejsce we wczesnej diagenezie, podczas gwałtownych, tektonicznych ruchów wznoszących, kiedy woda wypełniająca przestrzenie międzyporowe i kawerny wzrostowe ulegała silnej turbulencji w wyniku oddziaływania spływu podmorskiego powodując powstanie systemu połączonych kawern.

W rafopodobnych budowlach węglanowych typu rafy tubiphytesowej o dobrze rozwiniętym szkielecie wewnętrznym erozja wewnętrzna była spowodowana przez erozję kawitacyjną wywołaną oddziaływaniem intensywnego ruchu falowego w strefie międzypływowej. Dobrze rozwinięty sztywny szkielet zahamował rozwój sytemu połączanych kawern, co doprowadziło do utworzenia jedynie pojedyńczych SlCs. Tworzenie się SlCs zachodziło w tym wypadku z hiatusem czasowym względem wzrostu rafy tubiphytesowej.

Wytrącanie cementu węglanowego miało miejsce w różnych stadiach diagenezy. W SCs powstałych w sublitorale, na stoku cyjanobakteryjno-gąbkowego kopca mułowego tworzenie się cementów rozpoczęło się w morskich warunkach freatycznych i było kontynuowane podczas późnej diagenezy w różnych środowiskach. W SlCs powstających w strefie międzypływowej, w rafie tubiphytesowej wczesnodiagenetyczna cementacja nie miała zwykle miejsca na skutek ich wynurzenia niedługo po utworzeniu. Część SlCs została przemodelowana i wypełniona cementami krystalizującymi z roztworów hydrotermalnych w trzeciorzędzie.

**Key words:** stromatactis, carbonate buildup, Upper Jurassic, Kraków region, Southern Poland.

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## INTRODUCTION AND GEOLOGICAL SETTING

The term stromatactis denotes "a spar network, whose elements have flat to undulose smooth lower surfaces and digitate upper surfaces, made up principally of isopachous crusts of centripetal cement and embedded in finely crystalline limestone" (Bourque & Boulvain, 1993, p. 608). These sparry masses are mostly cement-filled upper parts of cavities, usually about 1 to 3 cm thick (Bathurst, 1959; 1982). The smooth base of the stromatactis is mostly developed on internal sediment.

Cementation and filling with internal sediment occur usually with a time hiatus after the formation of the cavities, and in some cases may not occur at all. The cement and internal sediment filling the cavities may also be leached or washed out. Taking this into account, two new terms are proposed (Tab. 1): 'stromatactis cavities' (SCs) and 'stromatactis-like cavities' (SlCs).

Stromatactis are observed mainly in carbonate buildups of the mud-mound type or on their flanks (Pratt, 1995). The stromatactis occur mostly in deep-water carbonate buildups, but they are also known from shallow-water deposits (MacDonald *et al.*, 1994; Stenzel & James, 1995). It seems that one term 'stromatactis' denotes structures with different origins. The hitherto existing opinions on the origin of stromatactis may be divided in two major groups. The first one includes those which link stromatactis with organic structures or their diagenesis (Dupont, 1881, 1882; Lowenstam, 1950; Bathurst, 1959; Philcox, 1963; Textoris & Carozzi, 1964; Shinn, 1968; Bechstädt, 1974; Coron & Textoris, 1974; Bourque & Gignac, 1983; Tsien, 1985; Beauchamp, 1989; Bourque & Boulvain, 1993; Flajs & Hüssner, 1993, Hüssner *et al.*, 1995). The second group are those which ascribe various physical processes as fundamental in the formation of stromatactis (Schwarzacher, 1961; Lees, 1964; Kukal, 1971; Heckel, 1972; Ross *et al.*, 1975; Logan & Semeniuk, 1976; Bathurst, 1982; Pratt, 1982, 1995; Wallace, 1987; Matyszkiewicz, 1993; MacDonald *et al.*, 1994).

**Table 1**

Proposed terminology

| | |
|---|---|
| **Stromatactis** | "a spar network, whose elements have flat to undulose smooth lower surfaces and digitate upper surfaces, made up principally of isopachous crusts and centripetal cement and embebdded in finely crystalline limestone" (after Bourque & Boulvain, 1993) |
| **Stromatactis cavities (SCs)** | a cavity network, whose surfaces are digitate, as a whole or partly filled with spar cements and/or internal sediment, embedded in finely crystalline limestone |
| **Stromatactis-like cavities (SlCs)** | isolated cavities, whose upper surfaces are digitate, as a whole or partly filled with spar cements and/or internal sediments, embedded in finely crystalline limestone |

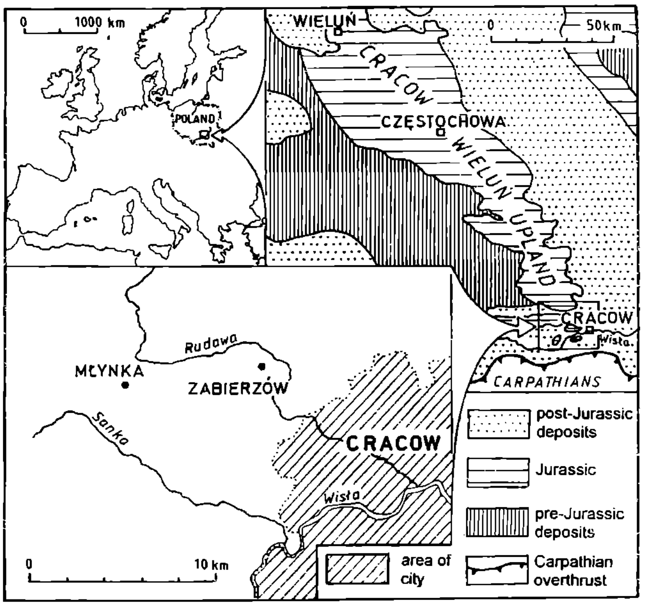


**Fig. 1.** Location of the Mlynka and Zabierzów quarries in the Cracow region

The Upper Jurassic (Oxfordian–?Kimmeridgian) deposits in the vicinity of Cracow represent probably two indistinct shallowing sequences (Matyszkiewicz, 1994, 1996). Each of them begins with condensed deposits and platy limestones, which locally contain marly intercalations and isolated small bioherms. Above, in both sequences, dominate strongly differentiated carbonate buildups with their flank beds and bedded facies. Each sequence is topped with submarine mass flow deposits, which also may be locally observed in the whole profile.

In the cyanobacterial-sponge buildup at Młynka quarry near Cracow (Fig. 1) stromatactis (more precisely: stromatactis cavities – SCs) were observed and interpreted as a constructional growth-framework cavity system modified by winnowing of lime mud by turbulent water (Matyszkiewicz, 1993). A proposed model of SCs development refers to cyanobacterial-sponge mud mounds with incipient but differentiated rigid framework (reticulate and laminar framework; *sensu* Pratt, 1982). The buildups of this type, visible at Młynka, developed mainly in the middle and late Middle Oxfordian below wave base at a moderate depth. Even if this process could operate during early diagenesis in weakly or moderately lithified sediment, its role in the formation of SCs in strongly lithified sediments is rather doubtful. Observations of sedimentary structures occurring in another exposure, at Zabierzów (Fig. 1), in a carbonate buildup of the *Tubiphytes*-reef type with a well developed rigid framework, have lead to expansion of the proposed model and its linking with that particular type of carbonate buildup.

### Methods

The main research methods included field observations and microfacies analysis and were supported by the following techniques. Polished thin section were studied using a

Cambridge Image Technology Ltd. Cold Cathode Luminoscope MK-III-8300 operating under 15-18 kV beam energy, 400 mA beam current, with a variable beam diameter. Trace elements analyses were conducted using electron microprobe ARL SEQM at 15 nA beam energy and at 20 kV, with the beam diameter of about 1 mm. Detection limits are for Mn 140 ppm, for Mg 360 ppm, for Fe 190 ppm, and for S 160 ppm. Analyses of carbon and oxygen stable isotopes were carried out at Institut für Mineralogie der Universität Erlangen-Nürnberg by Dr. M. Joachimski.

## MEZOSCOPIC OBSERVATIONS

Stromatactis cavities (SCs) at Młynka (Tab. 2) are no longer visible because of the progress in quarrying. At the end of 1980s the SCs occurred within the flank beds of a large cyanobacterial-sponge mud mound (Hoffmann & Matyszkiewicz, 1989; Matyszkiewicz, 1993), intersected by a vertical neptunian dykes. The SCs at the Młynka quarry were visible in a 1.5 m thick zone in the uppermost part of slope sediments of the cyanobacterial-sponge mud mound. The preserved part of this carbonate buildup, determined previously as the lower-middle Middle Oxfordian (*Plicatilis–Transversarium* Zones; Hoffmann & Matyszkiewicz, 1989), may be slightly younger, representing the upper Middle Oxfordian (*Bifurcatus* Zone) also (B. A. Matyja; pers. comm., 1995).

Calcified siliceous sponges together with cyanobacterial crusts build initial rigid-framework of the mud mound (cf. Matyszkiewicz, 1994; Matyszkiewicz & Krajewski, 1996). Incipient fragments of laminar framework occur at the slope of the carbonate buildup whereas the centre of the buildup consists of a reticulate framework (Matyszkiewicz, 1993; cf. Pratt, 1982). The SCs were observed in light, massive limestone. They are up to one cm high, some centimetres width, and filled in their upper parts with cement and in the lower parts with internal sediment.

**Table 2**

Mezoscopic comparison of stromatactis cavities from cyanobacterial-sponge buildup and stromatactis-like cavities within *Tubiphytes*-reef

| | Stromatactis cavities | Stromatactis-like cavities |
|---|---|---|
| Type of carbonate buildup | Cyanobacterial-sponge mud mound | *Tubiphytes* reef |
| Locality | Młynka quarry | Zabierzów quarry |
| Rigid framework | incipient laminar and reticulate | well-grown |
| Stratigraphic position | Middle Oxfordian | Upper Oxfordian |
| Colour of the limestone | light | light, locally dark |
| Filling | cement and internal sediment | usually internal sediment (light limestone); cement and internal sediment (dark limestone) |

**Fig. 2.** The SlCs in the light variety of the *Tubiphytes*-reef at Zabierzów

The Oxfordian strata exposed at Zabierzów represent the uppermost part of the Jurassic deposits in the Cracow area, and belong probably to the Upper Oxfordian (*Bimmamatum/Planula* Zones). At Zabierzów quarry the SlCs occur on the uppermost bench, in massive, light but sporadically dark, highly porous limestone (Tab. 2; Fig. 2). The organic forms recognizable macroscopically include mostly *Tubiphytes* and stromatolites, accompanied by brachiopods (mainly *Terebratulina substriata* Schlotheim and *Sellithyris engeli* (Rollier) – pers. comm. M. Krobicki, 1995), crabs, fragments of bivalves, small gastropods, siliceous and calcareous sponges, juvenile ammonites and polychaetes. The dominant role of *Tubiphytes* and the presence of numerous growth cavities allow to classify this limestone as a so-called *Tubiphytes*-reef (cf. Pomoni-Papaioannou *et al.*, 1989; Matyszkiewicz & Felisiak, 1992) with well-grown rigid framework.

The SlCs observed in the light limestone at Zabierzów are usually not filled with cement. Only on the walls of larger cavities thin cement rims are occasionally present. The SlCs are spread some centimeters apart. They are on average about 2 cm high and some centimetre wide. Typical features of these cavities include uneven, digitate roof and smooth bottom. Macroscopically distinguishable components of the internal sediment include *Tubiphytes* and fragmented polychaetes cf. *Terebella* sp. Some of the cavities are filled with soft, light-greenish or yellowish clay which does not contain microfauna and probably represents Tertiary karst deposits (Felisiak, 1992).

The SlCs may also be observed in the dark limestone which occurs now only in the rubble. The limestone was observed in situ in the 1950s by Dżułyński & Żabiński (1954). The biota which may be macroscopically discernible are the same as in the light limestone. The dark colour grades locally, on the distance of 1–2 mm, into the typical creamy one. The forms and sizes of SlCs are similar as in those in the light limestone. The essential difference consists in the filling of cavities above the internal sediment with dark-grey cement.

## MICROSCOPE OBSERVATIONS

The SCs from cyanobacterial-sponge mud mound at Młynka occur in the cyanobacterial-sponge crust, stromatolite/thrombolite boundstone and in tuberolitic/peloid wackestone (Fig. 3; Matyszkiewicz, 1993). The upper parts of SCs are filled with several types of cement (Tab. 3). The walls are lined by thin granular isopachous or radiaxial (fibrous and bladed) cements (Fig. 4). The fibrous and bladed radiaxial cements occur in optical continuity. The pore space are filled with blocky granular cement, but the centres of largest cavities are filled with poikilotopic cement. The radiaxial and blocky cements are generally inclusion-rich. Only large crystals of the poikilotopic cement do not contain inclusions. Internal sediment within the SCs is composed of peloid wackestone, but the uppermost parts of the internal sediment consist locally of peloidal packstone with blocky cement.

The *Tubiphytes*-reef with SICs at Zabierzów is developed as boundstone or locally as nest-filling grainstone. Its main components are mostly irregular *Tubiphytes* with thick outer crust, single-envelope oncoids and peloids, which may also be observed in laminated stromatolites. Fauna is abundant and represented by fragments of bivalves, echinoids, brachiopods, calcified fragments of siliceous sponges, calcareous sponges, bryozoans, foraminifers, polychaetes, fine gastropods and juvenile ammonites. Most grains are covered with rims of isopachous granular cement or radiaxial fibrous and radiaxial bladed cement. The centres of small cavities (up to 5 mm) in boundstone and voids in grainstone are filled with blocky granular and poikilotopic cement. The radiaxial and blocky cements are inclusion-rich.

In the light limestone at Zabierzów the SICs are usually not filled with cement. Only sporadically a thin (up to 0.2 mm) rim of the isopachous granular cement lines the walls of cavities (Fig. 5). This rim is sometimes thicker at the roof of a SICs and reaches 0.4 mm in width. Small SICs, some millimeters across, are occasionally completely filled with blocky granular and poikilotopic cements without inclusions. Internal sediment filling the lower parts of large cavities is represented by grainstone with collapse features or by packstone-wackestone.

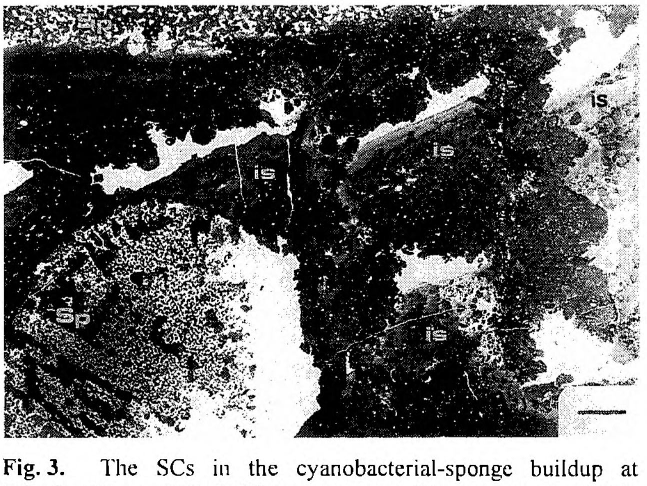


**Fig. 3.** The SCs in the cyanobacterial-sponge buildup at Młynka. Sp – calcified siliceous sponges. The upper parts of SCs are filled with cements. The internal sediment (is), filling the lower parts of the SCs, is clearly seen. Thin section, nicols parallel, scale bar 4 mm

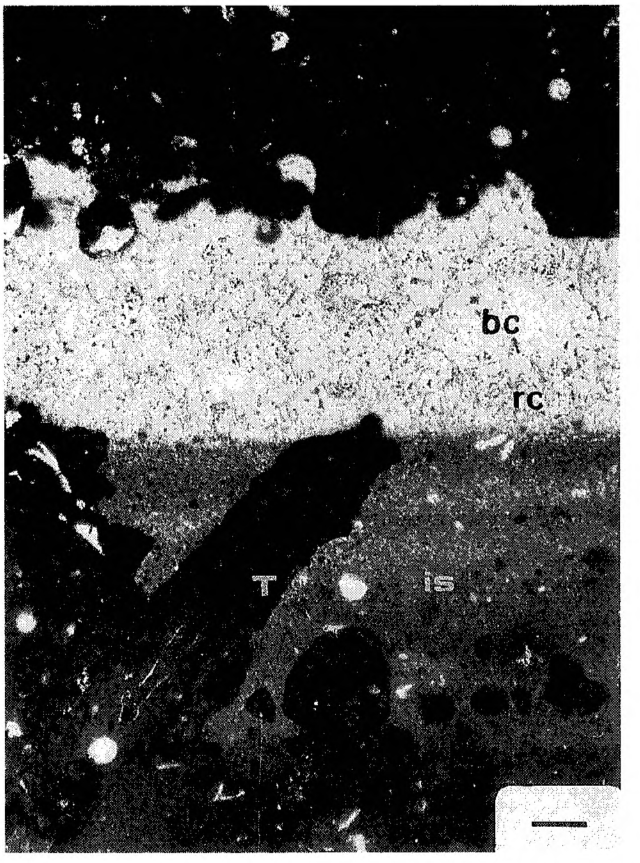


**Fig. 4.** The SCs in the cyanobacterial-sponge mud-mound at Młynka. The roof part of the SCs is filled with radiaxial (rc) and blocky calcite (bc) cements. The internal sediment (peloidal wackestone (is) is distinctly lighter than the surrounding host-rock. *Tubiphytes* (T), which are rare at Młynka, together with other cyanobacterial structures locally form fragments of the rigid framework resistant to internal erosion. Thin section, nicols parallel, scale bar 0.2 mm

The dark limestone at Zabierzów is similarly developed. The differences are related to the cement within the SICs. It is composed of crystals approx. 0.3 to 0.4 mm across, which are inclusion-rich and contain dark intercrystalline insertions. In polarized light these crystals form a mosaic. Within this cement there are embedded single, angular rock fragments (Fig. 6), derived from the limestone adjacent to the cavities. The cement locally disturbs the flat surface of the internal sediment (Fig. 6). The roofs of SICs are more smooth than in the light limestone. The described cement may be observed only in large cavities, but smaller (up to 1 mm wide) fractures branching from the SICs are sometimes filled with blocky granular and poikilotopic cements without inclusions (Fig. 7).

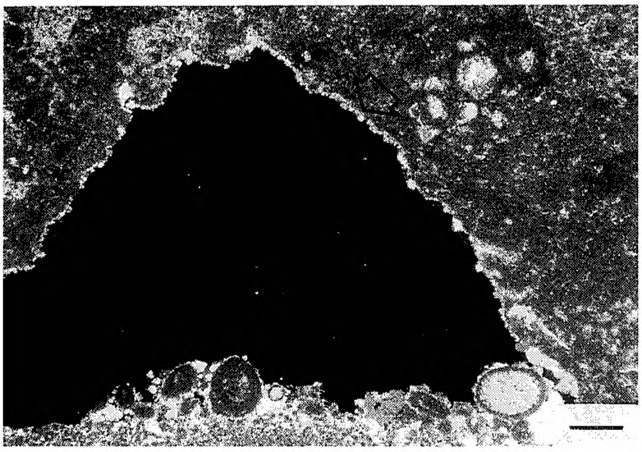

**Fig. 5.** The SIC in the *Tubiphytes*-reef at Zabierzów (the light limestone). Only the walls of the SIC are lined with a thin rim of the isopachous granular cement (*arrow*). Thin section, nicols crossed, scale bar 2 mm

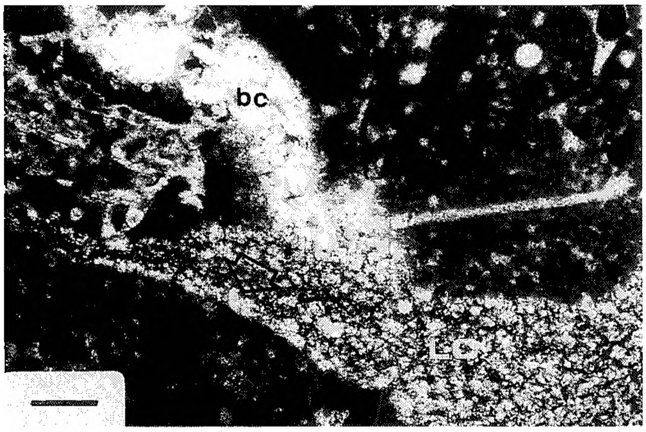


**Fig. 7.** The SIC in the *Tubiphytes*-reef at Zabierzów (the dark limestone). In the part of the SIC close to the roof, thin fractures branching from the cavity are filled with the transparent blocky cement (bc). The major part of the SIC is filled with the late cement (lc) containing numerous intercrystalline insertions. On the walls of the SIC are locally preserved relicts of the isopachous granular cement (arrow). Thin section, nicols parallel, scale bar 1 mm

### Cathodoluminescence

The cements filling SCs in cyanobacterial-sponge buildup show differentiated luminescence (Tab. 3): radiaxial cement is non-luminescent, and the remaining ones show luminescence from dull- to medium orange. The most contrasting luminescence effects are those between the blocky granular cement and the poikilotopic without inclusion one.

All the observed cements within the SICs from *Tubiphytes*-reef at Zabierzów show liminescence (Tab. 4). The internal texture of the clasts is better visible under the luminoscope. The clasts of sediment embedded in the cement filling the SICs in the dark limestone were subject to more detailed analyses. They reveal distinct traces of dissolution along their edges. The traves of dissolution also occur along the borders of cavities filled with a late cement.

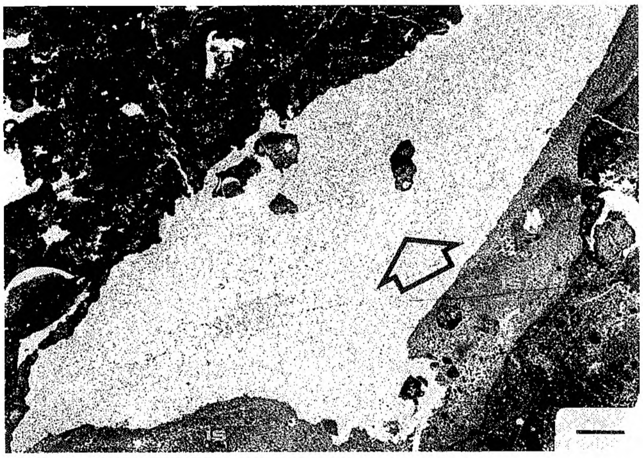

**Fig. 6.** The SIC in the *Tubiphytes*-reef at Zabierzów (the dark limestone). The arrow shows the direction of the roof. The top of the SIC is locally oval. One generation of the cement with numerous intercrystalline insertions is visible. The cement encloses clasts derived from the adjacent host-rock. The internal sediment (is) is distinctly disturbed by the cement. Thin section, nicols parallel, scale bar 3 mm

## ISOTOPE AND OTHER GEOCHEMICAL DATA

Isotope and geochemical investigations of cements filling SCs within cyanobacterial-sponge buildup at Młynka were carried out on the bulk sample because of problems with cement separation. As the cements were taken from the central parts of a large SCs it is assumed that they represent mostly the blocky granular and poikilotopic cements. Iso-

**Table 3**

A summary of cements in the stromatactis cavities from cyanobacterial-sponge mud mound at Młynka

| Cement | Habits | Size | Inclusions | Luminescence | Remarks |
|---|---|---|---|---|---|
| isopachous granular | crusts on wall | up to 0.1 mm | absent | medium orange | |
| radiaxial fibrous | radial, fibrous crusts | up to 0.8 mm | dusty | absent | |
| radiaxial bladed | radial, bladed crusts | up to 0.8 mm | dusty | absent | in optical continuity with the radiaxial fibrous cement |
| blocky granular | equant to inequant | up to 1 mm | dusty | dull orange | |
| poikilotopic | equant to inequant | up to 1.2 mm | rare or absent | medium ornage | |
| blocky within internal sediment | equant to inequant | up to 0.3 mm | absent | medium orange | |

**Table 4**

A summary of cements in the stromatactis-like cavities from *Tubiphytes*-reef at Zabierzów

| Cement | Habits | Size | Inclusions | Luminescence | Remarks |
|---|---|---|---|---|---|
| isopachous granular | crusts on wall | up to 0.4 mm | absent | medium orange | |
| blocky granular | equant | up to 0.5 mm | rare to absent | medium orange | |
| poikilotopic | equant to inequant | up to 2.5 mm | absent | medium orange | |
| late cement | equant | 0.4-0.5 mm | dusty | yellow-orange | |
| poikilotopic | equant to inequant | up to 1.2 mm | rare or absent | medium ornage | only in dark limestone |
| blocky within internal sediment | equant to inequant | up to 0.2 mm | absent | medium orange | |

**Table 5**

Results of trace element analysis and isotopic composition of cements in stromatactis cavities from cyanobacterial-sponge mud mound at Młynka and stromatactis-like cavities within *Tubiphytes*-reef (dark limestone) at Zabierzów

| | Stromatactis cavities | | Stromatactis-like cavities | |
|---|---|---|---|---|
| Type of carbonate buildup and locality | Cyanobacterial-sponge mud mound Młynka | | Tubiphytes-reef (dark limestone) Zabierzów | |
| Type of cement | Radiaxial (fibrous and bladed), blocky and poikilotopic cements n=6 | Matrix n=12 | Late cement n=6 | Matrix n=8 |
| Mn | 280±140 (110-560) | 280±30 (130-400) | 506±380 (230-680) | 240±160 (10-430) |
| Mg | 1170±490 (550-2120) | 1615±270 (950-2240) | 921±740 (10-1500) | 1677±40 (1470-2460) |
| Fe | 3850±4730 (10-12790) | 3940±340 (330-13430) | 5335±6250 (450-13040) | 66±95 (10-190) |
| S | 140±90 (10-290) | 269±210 (40-1340) | 3908±6020 (60-11390) | 630±230 (310-1960) |
| $\delta^{18}O_{PDB}$ | −3.79‰ n=2 | −1.42‰ n=1 | −6.85‰ n=2 | −2.08‰ n=1 |
| $\delta^{13}C_{PDB}$ | 2.36‰ n=2 | 2.12‰ n=1 | 1.34‰ n=2 | 2.66‰ n=1 |

topic investigations of cement within the SlCs from *Tubiphytes*-reef at Zabierzów were carried out on the late cement from the dark limestone. The remaining isotope determinations were carried out on the matrix of the cyanobacterial-sponge buildup from Młynka and the dark limestone from *Tubiphytes*-reef at Zabierzów (Tab. 5).

The results are presented in Figure 8 against the curve designating average $\delta^{13}C$ and $\delta^{18}O$ values for brachiopods from central Poland (Hoffman et al, 1992; Pisera *et al.*, 1992). The stratigraphic position of the studied samples are approximate. The $\delta^{18}O$ values in the cements from cyanobacterial-sponge buildup at Młynka and *Tubiphytes*-reef at Zabierzów are significantly lower than respective values for the matrix, and are particularly low in the cements from Zabierzów. The $\delta^{13}C$ values for the matrix from both localities and for the cements from the SCs at Młynka are comparable, and they are slightly higher than those for the cements within the SlCs from dark type of limestones at Zabierzów.

Trace element analyses show that the Mn content of the late cement in *Tubiphytes*-reef from Zabierzów averages 506 ppm, whereas in the cements from cyanobacterial-

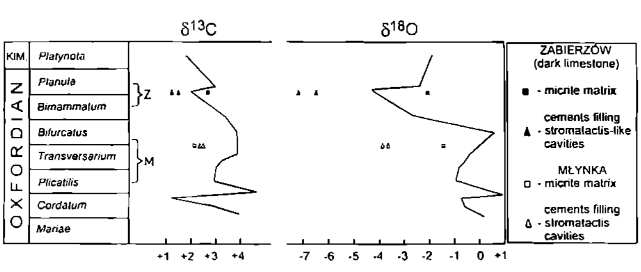


**Fig. 8.** $\delta^{13}C$ and $\delta^{18}O$ data measured in cements of the SCs, SlCs and matrix of limestones at Młynka and Zabierzów. The curve illustrating the variability of $\delta^{13}C$ and $\delta^{18}O$ during the Oxfordian and Early Kimmeridgian contains data obtained for brachiopod shells from central Poland (Hoffman *et al.*, 1992). Z – approx. stratigraphic position of Zabierzów-quarry, M – stratigraphic position of Młynka-quarry

sponge buildup from Młynka it is distinctly lower, with an average of 280 ppm. The Mg content of the cement is definitely lower than that of the matrix, both in the cyanobacterial-sponge buildup and the *Tubiphytes*-reef. Within the late cement from *Tubiphytes*-reef there are places distinctly enriched with S and Fe in comparison to the matrix.

## DISCUSSION

The results obtained here suggest that the SCs in the cyanobacterial-sponge mud mound at Młynka and the SlCs in the *Tubiphytes*-reef at Zabierzów differ in origin. This is due to differences in the development of these two types of carbonate buildups.

The carbonate buildup at Młynka, of the mud mound type, was developed in the subtidal zone, at a moderate depth below the wave base. During formation of the SCs a significant role was played by internal erosion resulting in winnowing of the unlithified parts of the sediment (cf. Pratt, 1982, 1995; Wallace, 1987; Matyszkiewicz, 1993; MacDonald *et al.*, 1994). The winnowing occurred on slopes of the cyanobacterial-sponge buildup where its rigid framework was only partly developed and some fragments of sediment were still unlithified (cf. Pratt, 1982; Matyszkiewicz, 1993). The turbulence was probably induced by submarine mass flows (Fig. 9; Matyszkiewicz, 1993). The SCs were next filled by cements in early and late stages of diagenesis.

The $\delta^{18}O$ values for the matrix and cements filling stromatactis in cyanobacterial-sponge buildup from Młynka are situated left of the reference curve obtained for brachiopods (Hoffman *et al.*, 1992; Pisera *et al.*, 1992), as the former are more prone to diagenetic alterations in comparison with the brachiopod shell materials (Hudson, 1977). It seems that the significantly lower $\delta^{18}O$ values, relatively unchanged $\delta^{13}C$ values in comparison with the brachiopod shells, and the generally ferroan composition suggest a burial or a meteoric origin of the cements (cf. Lohmann, 1988; Bourque & Raymond, 1994; Reinhold, 1996) within the SCs from cyanobacterial-sponge mud mound at Młynka.

The succesion of filling the SCs in cyanobacterial-sponge buildup at Młynka with cements has been established on the basis of cathodoluminescence analysis. At first, the inclusion-rich, non-luminescent radiaxial fibrous and bladded cements were precipitated. The lack of luminescence in the radiaxial cements indicates that they were formed during early diagenesis under active marine phreatic conditions (cf. Machel, 1985; Bourque & Raymond, 1994). The blocky granular cement that fills the central parts of cavities and shows weak luminescence was probably formed slightly later under mixed, freshwater-marine phreatic conditions (cf. Longman, 1980). The poikilotopic cement with yellow-orange luminescence was formed in late diagenesis either in the vadose zone or during burial diagenesis (cf. Mohamad & Tucker, 1992). The genesis of the thin rims of isopachous granular cement with distinct, medium-orange luminescence is not clear. They represent probably a neomorphic cement, originating from replacement of the primary marine isopachous cement in stagnant fresh-water phreatic zone (cf. Amieux *et al.*, 1989).

In the carbonate buildup of *Tubiphytes*-reef type at Zabierzów a fully rigid framework was developed early, and complete early lithification took place. Thus, it is not probable that the SICs resulted from winnowing of the unlithified parts of sediment. The internal erosion of sediment may be, therefore, explained in terms of high-energy processes. It seems that cavitation may be seen as the process responsible for the formation and development of cavities in the early and completely lithified deposits.

Cavitation, understood in terms of the inability of a viscous liquid to transfer tensile strain under conditions of a rapidly lowered pressure, manifests itself as the loss of the liquid continuity and formation of cavities within the liquid. Cavitation followed by cavitational erosion stipulates the presence of undissolved gas bubbles, so-called cavitation nuclei, with diameters $10^{-5}$–$10^{-7}$ m (Terao & Ito, 1981). The gas dissolved in this liquid does not practically affect its proneness to cavitation (Knapp *et al.*, 1970).

The development of fine bubbles into big ones during cavitation proceeds under conditions of a suddenly decreased pressure. In turn, due to a sudden increase in pressure a bubble becomes strongly flattened and, then, a depression forms in it. This depression may be pierced by a high-energy microjet of the liquid which represents the

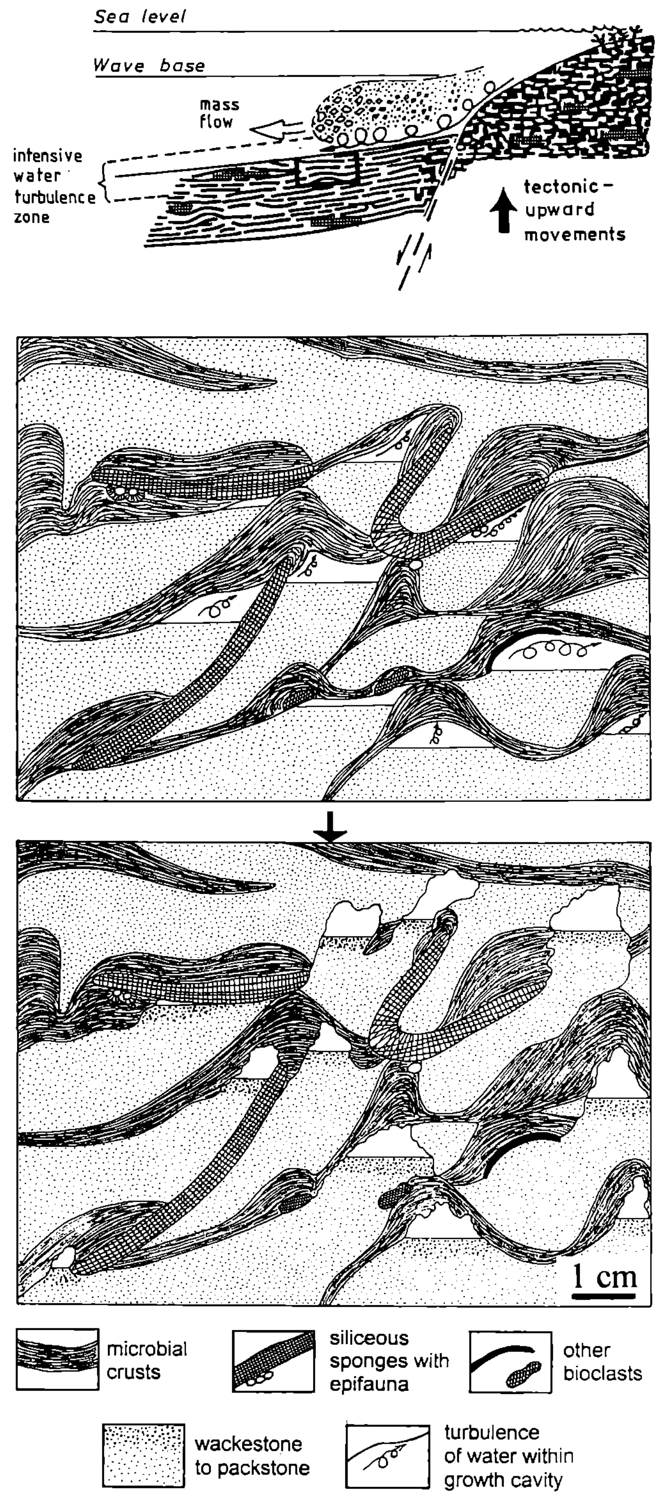


**Fig. 9.** Development of the SCs in a carbonate buildup with an initial stage of the rigid framework (partly after Matyszkiewicz, 1993). The cyanobacterial-sponge buildup developed at a moderate depth below wave base. The incipient laminar rigid framework was a delicate construction composed of cyanobacterial crusts and calcified siliceous sponges. Most of the spaces between the framework was filled with the soft carbonate mud, but part of the pore spaces and growth cavities was filled with sea water. Strong water turbulence, resulting from a mass flow induced by tectonic upward movements, caused washing out of the soft sediment around pore spaces and growth cavities and development a cavity network. This course of an internal erosion led to remodelling and the "upward migration" of cavities (cf. Wallace, 1987)

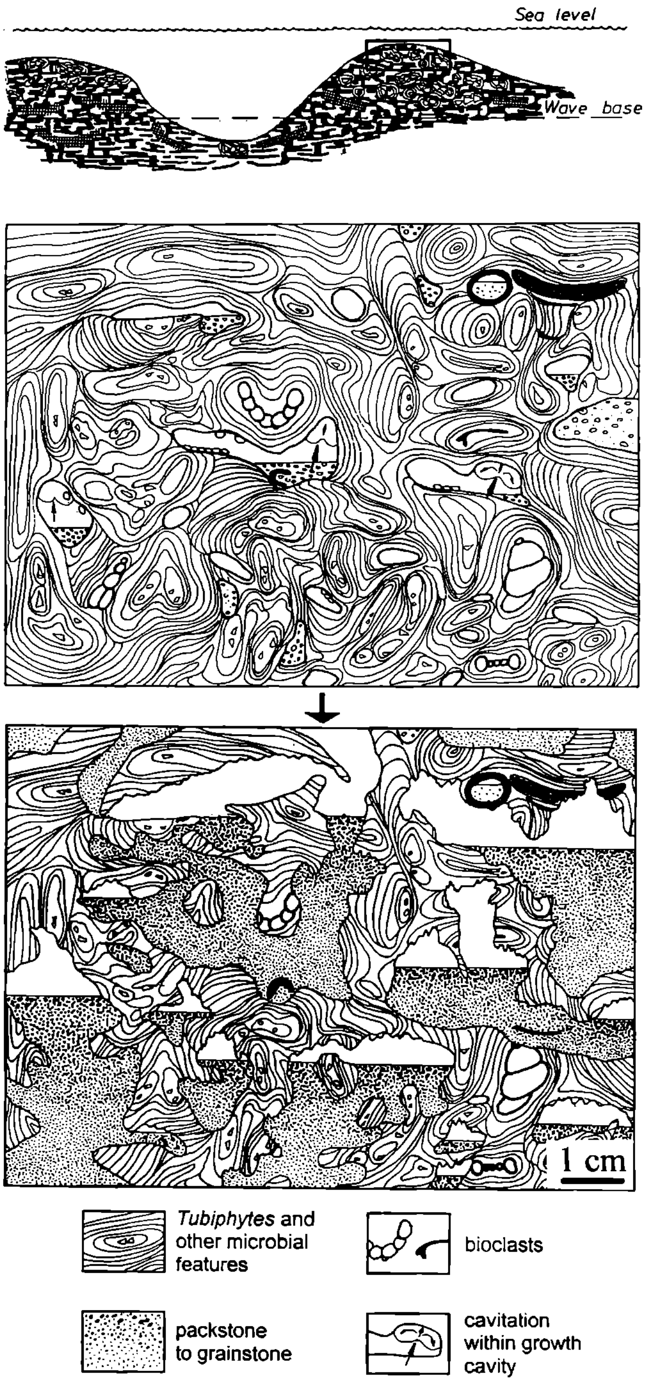


**Fig. 10.** Development of the SICs in a carbonate buildup with a well-grown rigid framework. The *Tubiphytes*-reef was primarily formed near wave base and have been subsequently shifted above the wave base. The rigid framework was a massive construction built of *Tubiphytes* and other cyanobacterial features. Within this framework there were numerous growth cavities, incrusted with fauna. The buildup was affected by waves when it was in the intertidal zone. Sudden and repeating many times changes of the pressure gradient resulted in cavitational erosion of primary growth cavities but the well-grown, strong lithified rigid framework stopped a formation of cavity network

proper factor of the cavitational erosion. Laboratory observations prove that such bubbles are numerous, and grow and implode close to each other or to surrounding surfaces (Knapp *et al.*, 1970). This observation corresponds well with the swarm occurrences of the SICs.

It may be accepted that cavitation explains well the internal erosion within strongly lithified limestones (Fig. 10). In carbonate buildups with rigid framework which were rich in growth cavities, the presence of cavitation nuclei in the form of bubbles of undissolved gas seems obvious. The intertidal zone is an environment in which cavitation plays an important role as changes of the pressure caused by the wave action are particularly strong and repeat many times (Fig. 10).

The *Tubiphytes*-reef at Zabierzów formed near the wave base in the period of distinct shallowing of the Jurassic basin in the vicinity of Cracow. However the SICs did not develop within it during early diagenesis but after a hiatus, and resulted from strong wave action. It was a process which began during the Late Jurassic regression and later recurred during numerous transgressions and regressions during the Cretaceous.

The lack of cement above the internal sediment in most SICs in the *Tubiphytes*-reef results probably from subaerial exposure of the sediment soon after the formation of the SICs. The isopachous granular cement, lining sometimes the cavity walls, indicates probably a short marine episode, when the sea water filled the cavities. Burial diagenesis took place at the end of the Cretaceous and in the Tertiary, but the significant dimensions of the SICs caused that they could not be filled by capillary-drawn fluids, from which cements could have precipitated. Still later, under the continental conditions which prevailed in the vicinity of Cracow in Tertiary time, part of the SICs were filled with greenish clay of continental origin (Felisiak, 1992).

The cement filling the SICs in the dark limestone definitely differs in hand specimens from the other cements. This observation is confirmed by (i) the Mg content of this cement, distinctly lower in comparison with the matrix, (ii) the yellow-orange luminescence, definitely different than in other cements, and (iii) the $\delta^{18}O$ values, distinctly lower than the ones an the Młynka-quarry. All these data suggest that the cement in question was formed during epigenetic processes. The dissolution phenomena observed along the borders of cavities, filled with the late cement, indicate clearly the corrosive action of solutions, from which the cements precipitated. It seems that the late cement may be linked with low-temperature hydrothermal solutions (cf. Lohmann, 1988; Reinhold, 1996) reported from the Cracow area (Morozewicz, 1909; Dżułyński & Żabiński, 1954; Matyszkiewicz, 1987; Reinhold, 1996).

The results of microprobe investigations confirm that the substance which locally imparts the grey colour of limestone is finely dispersed pyrite (cf. Dżułyński & Żabiński, 1954). The total content of pyrite is very low and often the mineral is not identifiable by classical analytical methods. Pyritization took place probably in the Miocene, when the platform sediments were faulted. The fault zones were major conduits for solutions from which pyrite-rich cements precipitated in the dark limestone. The mineralization of the matrix with pyrite resulted from penetration of these solutions along stylolite seams (cf. Braithwaite, 1989). This low-temperature hydrothermal mineralization also caused a local infilling of the already existing SICs. As the temperatures of these solutions were low and the time of their action was short, the primary shape of the SICs has only been slightly modified through dissolution.

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## Streszczenie

### KAWERNY STROMATACTIS I STROMATACTIS *SENSU LATO* W GÓRNOJURAJSKICH BUDOWLACH WĘGLANOWYCH W MŁYNCE I ZABIERZOWIE (OKSORD, POŁUDNIOWA POLSKA)

*Jacek Matyszkiewicz*

Stosowanie terminu „stromatactis" jest zasadniczo ograniczone do cementu sparytowego stanowiącego wypełnienie górnej części systemu kawern (Bathurst, 1959; 1982; Bouque & Boulvain, 1993). W tym znaczeniu termin ten nie uwzględnia całości wypełnienia, które w dolnej części kawern tworzy zwykle sedyment wewnętrzny. Przy zachowaniu klasycznej definicji stromatactis proponuje się dwa nowe terminy (Tab. 1): „kawerny stromatactis" (SCs) i „kawerny stromatactis *sensu lato*" (SlCs).

Górnojurajskie budowle węglanowe okolicy Krakowa cechują się różnym stopniem rozwoju sztywnego szkieletu. W budowlach typu cyjanobakteryjno-gąbkowych kopców mułowych rozwijających się generalnie poniżej podstawy falowania szkielet ten jest rozwinięty słabo. W centralnych partiach budowli jest on wykształcony w postaci tzw. szkieletu siatkowatego (reticulate framework; *sensu* Pratt, 1982), natomiast na stokach budowli występuje inicjalny szkielet laminarny (laminar framework; *sensu* Pratt, 1982).

W regionie krakowskim budowle o tak wykształconym szkielecie występują w środkowo- i górnooksfordzkich osadach (Matyszkiewicz, 1994; Matyszkiewicz & Krajewski, 1996) i w latach osiemdziesiątych odsłaniały się w kamieniołomie w Młynce (Hoffmann & Matyszkiewicz, 1989). W cyjanobakteryjno-gąbkowych kopcach mułowych tworzyly sie SCs na skutek erozji wewnętrznej budowli węglanowej spowodowanej turbulencją wody wywołaną przez podmorski spływ masowy (Matyszkiewicz, 1993). Cementacja powstałych w ten sposób SCs zachodziła początkowo w morskiej strefie freatycznej i była kontynuowana w różnych stadiach diagenezy.

Sztywny szkielet w budowlach węglanowych jest dobrze wykształcony w rafach tubiphytesowych, które w regionie krakowskim rozwijały się w poblizu podstawy falowania, podczas spłycenia zbiornika w późnym oksfordzie. Typowa rafa tubiphytesowa z licznymi SlCs odsłania się obecnie w nieczynnym kamieniołomie w Zabierzowie. Rozwój SlCs w tak wykształconych budowlach zachodził na skutek erozji kawitacyjnej. Proces ten miał miejsce u schyłku jury, z hiatusem względem wzrostu budowli i mógł się kontynuować w kredzie podczas wielokrotnych transgresji i regresji. Erozja kawitacyjna związana z oddziaływaniem intensywnego ruchu falowego w strefie międzypływowej spowodowała erozję wewnętrzną silnie zlityfikowanej rafy przejawiającą się rozsadzaniem pierwotnych kawern wzrostowych. SlCs o takiej genezie nie zostały zwykle wypełnione przez cement. Na ściankach SlCs jest rozwinięta niekiedy powłoka izometrycznego cementu granularnego, wytrąconego prawdopodobnie bezpośrednio po powstaniu kawerny, podczas krótkiego okresu diagenezy w morskich warunkach freatycznych.

W kamieniołomie w Zabierzowie występuje ponadto ciemna odmiana wapienia z SlCs wypełnionymi ciemnym cementem. Ciemna barwa skały i cementów wypełniających SlCs jest efektem trzeciorzędowych procesów hydrotermalnych (cf. Morozewicz, 1909; Dżułyński & Żabiński, 1954; Matyszkiewicz, 1987; Reinhold, 1996), które objęły utwory mezozoiczne w rejonie Krakowa. Niskotemperaturowe, prowadzące piryt roztwory spowodowały także częściowe przemodelowanie istniejących SlCs.