Stromatoporoid morphology in the Devonian of the Holy Cross Mountains, Poland

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Stromatoporoids have been measured in three Upper Devonian localities in the Holy Cross Mountains: Karwów, Kadzielnia and Sitkówka–Kowala quarries. Quantitative analysis of the measurements demonstrated several differences, that have been interpreted in terms of ecological variations between the localities. Rate of deposition is proposed to be of special importance in controlling the stromatoporoid morphology. Deposits exposed in Kadzielnia and Karwów quarries represent an environment with periodically accelerating deposition and water turbidity, where low domical individuals with a ragged surface and non-enveloping arrangement of latilaminae constitute the most numerous group of stromatoporoids. The deposits outcropping in Sitkówka–Kowala quarry, formed in a calm setting with low deposition rate, are characterized by following stromatoporoid features: usually extended domical or bulbous shape, smooth surface and an enveloping arrangement of latilaminae. The similarity of stromatoporoid assemblages from Karwów and Kadzielnia confirmed, that dolomites exposed in the Karwów quarry represent Kadzielnia-type reef-mound deposits.

Key words: Stromatoporoids, morphometric features, depositional environment, Devonian, Holy Cross Mountains.

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Introduction

There has been a long-lasting controversy on the relative importance of environmental factors on the stromatoporoid shape (Fischbuch 1968; Meyer 1981; Stearn 1982; Kershaw 1990). Most of the authors agree, however, that several features of stromatoporoid morphology can be regarded as powerful indicators of certain environmental agents (Broadhurst 1966; Abbott 1973, 1976; Kapp 1974; Kobluk 1975; Kershaw & Riding 1978; Kaźmierczak 1980; Kershaw 1981, 1984, 1990; Königshof *et al.* 1991; Swan & Kershaw 1994) and may be used as tools of all scales of palaeoenvironmental analysis (Kershaw 1998). Moreover, stromatoporoids, being most commonly regarded as a taxonomic unit within the Porifera (Stearn 1975, 1980, 1993; Stearn & Picket 1994), according to the most recent views (Wood 1990; Swan & Kershaw 1994), represent skeleton organisation in which several features of the individuals' external morphology are to a great extent unrelated to taxonomy. They were highly integrated organisms, where coloniality existed on cellular rather than on individual level. Even greater effect of environmental factors on both stromatoporoid internal structure and external morphology is suggested by advocates of cyanobacterial nature of stromatoporoids (Kaźmierczak 1976, 1980; Kaźmierczak & Kempe 1990). Coccoid cyanobacteria cell aggregates display various growth patterns that reflect palaeoecological conditions (Kaźmierczak 1980). The most commonly listed environmental factors influencing stromatoporoid shapes are: rate of deposition, paleocurrents, water turbidity and consistence of the sea bottom (Kaźmierczak 1971; Meyer 1981; Stearn 1982; Kershaw 1984, 1987, 1990, 1998; James & Macintyre 1985; Königshof *et al.* 1991; James & Bourque 1992; Machel & Hunter 1994; Łuczyński 1998).

Stromatoporoids occurred in a continuous range of shapes. Several classifications of morphologies have been proposed (e.g., Nicholson 1892 *fide* Kershaw & Riding 1978; Kaźmierczak 1971; Abbott 1973; Kobluk 1978). Most recently Kershaw (1998) has developeped a hierarchical growth form classification comprising of three levels. The present paper is an attempt to apply a parameterization scheme proposed by Kershaw & Riding (1978) to stromatoporoid assemblages of some localities from the Upper Devonian of the Holy Cross Mountains, in order to assist the environmental analysis.

Localities

Stromatoporoid assemblages have been studied in three Upper Devonian localities in the Holy Cross Mountains (Fig. 1).

Kadzielnia Quarry. — Kielce, Frasnian, Kadzielnia Limestone Member of the Kowala Formation (Szulczewski 1971; Szulczewski & Racki 1981).

Measurements were made from unbedded stromatoporoid-coral limestones of the Kadzielnia Limestone Member. A section 15 meters thick outcropping in the lowermost part of the quarry, where the individuals are best preserved (see next chapter), has been selected for the studies. Apart from variously shaped stromatoporoids the complex abounds in numerous and diversified tabulates, rugose corals, brachiopods, crinoid debris, and numerous stromatactoid structures (Szulczewski 1971). Laterally it is gradually replaced by detrital limestones with sporadical enclaves of oolitic limestones. The Kadzielnia Limestone is interpreted as reef-mound facies that were deposited in quiet waters on a deep part of a slope (Szulczewski 1981; Szulczewski & Racki 1981; Narkiewicz 1988), or in subturbulent zone in depths of 10–20 m (Racki 1992). Stromatoporoids and corals, although richly represented, did not construct a rigid framework, and instead the mound was build by microbial organisms (Hoffman & Paszkowski 1992). Morphological features of stromatoporoids from Kadzielnia have been studied by Kaźmierczak (1971), who, among other forms, described colonies with central parts plunged

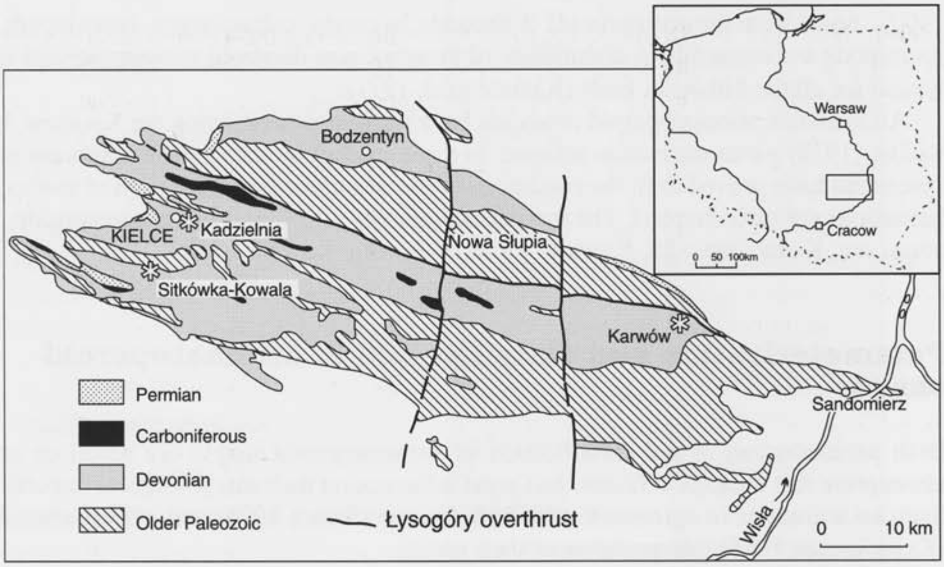

Fig. 1. Localization of the studied stromatoporoid-bearing outcrops on a sketch geological map of the Holy Cross Mountains.

in the sediment, a very rare feature amoung stromatoporoids, which he interpreted as an effect of growth on a soft seabottom.

Karwów Quarry. — Easternmost part of the Holy Cross Mountains, Frasnian (Samsonowicz 1934; Godefroid & Racki 1990).

A complex about 20 meters thick of unbedded dolomites outcrops in the quarry. Due to intensive dolomitization and recrystallization big stromatoporoid specimens occurring as limestone relicts are the only commonly observed macrofossils (Łuczyński 1995), which however did not construct a rigid framework. Stromatactoid structures are common. The unbedded complex locally contains enclaves of detrital and oolitic limestones, with stromatoporoid, coral and crinoid debris (Łuczyński 1995).

Basing on their lithological resemblance and stratigraphic position the Frasnian rocks exposed in Karwów have been compared with Kadzielnia Limestones (Samsonowicz 1934) and ascribed to Kadzielnia Limestone Member of the Kowala Formation (Narkiewicz *et al.* 1990). Most probably they represent a Kadzielnia-type reef-mound grown in subturbulent zone, with fairly agitated waters.

Sitkówka–Kowala Quarry (northernmost part). — Sitkówka; south of Kielce, Frasnian, set A (*sensu* Racki 1992) of the Upper Sitkówka Beds of the Kowala Formation (Racki 1992).

Varied facies outcropping in the quarry represent a wave resistant accretion rim of the Dyminy reef and shoal domain with fairly agitated waters (Kaźmierczak 1971; Racki 1992). Measurements were made from a 10 m thick sequence exposed in the northernmost part of the quarry, which is particularly rich in stromatoporoids. It consists of micritic fossiliferous biostromal limestones, representing a quiet-water setting from the shoal domain variety, located at most 10 m below the sea level (Racki

1992). Apart from stromatoporoids it abounds in corals, calcisponges, brachiopods, gastropods and ostracods. A community of massive, non-dendroid stromatoporoids is typical for all the Sitkówka Beds (Kaźmierczak 1971).

All available stromatoporoid crosscuts have been measured, using the Kershaw & Riding (1978) parameterization scheme. In three studied localities varied amounts of specimens have proved to fit the conditions of measurement (for discussion of method limitations see next chapter). The respective numbers of colonies taken into considerations are: Kadzielnia – 25, Karwów – 150, Sitkówka–Kowala – 88.

Parameterization and classification of stromatoporoid shapes

Both parameterization and classification of stromatoporoid shapes are based on an assumption that ecological factors had great influence on their morphological features. Such an attitude is in agreement with both sponge (Stearn 1975) and cyanobacterial (Kaźmierczak 1976) interpretation of their nature.

The author has used parameterization scheme of stromatoporoid shapes proposed by Kershaw & Riding (1978). Stromatoporoid skeleton is commonly characterized by a convex upward upper surface and a flat or undulating base. Each specimen has been measured in three dimensions (Fig. 2): B – basal length, V – vertical height, D – diagonal distance (at an angle of 25° from the vertical).

In the case of asymmetry, two diagonal measurements have been made (D_1 and D_2) and for further analysis their average has been taken.

The results are presented on a triangular array (Fig. 3). Each triangle summit represents one of three measurements (B, V, D), where $B + V + D = 100\%$. This determines the position of a point representing the stromatoporoid shape within the triangle, where particular areas are ascribed to certain morphologies.

A feature especially useful for ecological analysis is the relative height of the specimen, represented by the V/B ratio (Kershaw 1984, 1990). Its value is used to distinguish a range of morphotypes.

I use the following terms describing stromatoporoid shapes (Fig. 2):
laminar – low forms with convex or undulating upper surface ($V/B < 0.1$),
domical – forms with convex upper surface and a broad base,
bulbous – forms with convex upper surface and a narrow base,
dendroid – branching forms.

All non-dendroid forms are refered to as *massive*. Domical colonies are separated into low- ($0.1 < V/B < 0.5$), high- ($0.5 < V/B < 1$) and extended ($V/B > 1$) varieties.

The external surface is described as *smooth* or *ragged* (Fig. 2). Two arrangements of latilaminae – thin bands within the skeleton representing its growth increments – are distinguished (Fig. 2). *Enveloping* arrangement takes place, when the following latilaminae entirely covers the preceding and reaches the base of the skeleton. *Non-enveloping* arrangement occurs, when the following latilaminae doesn't cover the preceding, being separated from it by sediment, or restricted to only the uppermost parts of the colony. Smooth varieties usually have enveloping latilaminae, whereas ragged, by definition, are characterized by a non-enveloping arrangement.

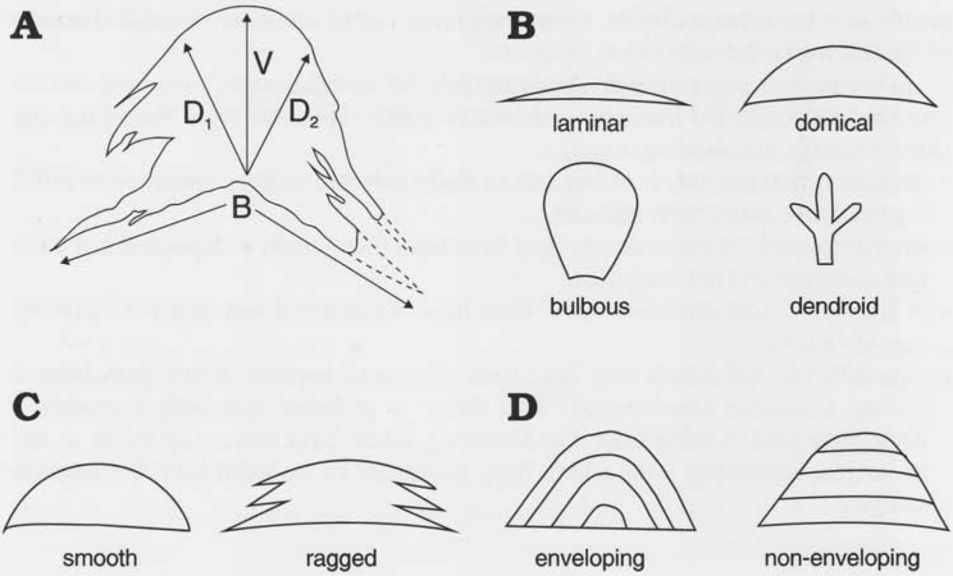

Fig. 2. Stromatoporoid shapes (after Kershaw & Riding 1978). **A**. Measurements of the stromatoporoid shape; B – basal length, V – vertical height, D_1, D_2 – diagonal distance (at an angle of $\theta = 25°$ from the vertical). **B**. Stromatoporoid shapes. **C**. Surfaces. **D**. Arrangements of latilaminae.

The parameterization scheme proposed by Kershaw & Riding (1978) can only deal with massive morphologies, with dendroid being too complex. During the measurements several preconditions need to be met (Kershaw & Riding 1978; Kershaw 1984):

- the stromatoporoid specimen is complete,
- studied individual is in growth position,
- skeletons are measured in a vertical section (perpendicular to the base),
- the studied section contains the specimen's main axis,
- B value is constant in a given individual – the skeleton is perfectly symmetrical.

In field it can be difficult to determine whether all the preconditions have been fulfilled (Kershaw 1981). Among the studied localities, stromatoporoids in the Sitkówka–Kowala quarry are best preserved. The clearly visible arrangement of latilaminae, especially on weathered surfaces, enables easy estimation of the specimen's positioning, even when it is equidimentional. On the other hand, the stromatoporoids found here are very densely packed, probably partly due to redeposition processes. Especially careful examination of each skeleton is therefore necessary to determine its orientation and completeness. Overturned individuals, when undamaged and with clear orientation, have been included into considerations.

In the Karwów quarry internal structure of the skeleton is not visible due to extensive recrystallization. Stromatoporoids are preserved here as limestone relicts in a dolomitic background. They are therefore very easily recognizable. Fortunately, most of the specimens belong to a relatively low-shaped, ragged variety, what makes their orientation easy to be determined.

The lowest number of measured specimens in the Kadzielnia quarry is caused by difficulties in finding suitable cross-sections. The stromatoporoids are not so clearly visible as in two other localities, where their limits can be accurately identified because of weathering or dolomitization processes.

In the present paper all individuals suitable for measurements have been studied, (not randomly selected like e.g., in Kershaw 1990). This may have biased the considered sample in following ways:

- some morphotypes may have been more easily detected and/or considered as fulfilling the above listed preconditions,
- stromatoporoids of some shapes may have been more easily redeposited and therefore damaged and not measured,
- in Karwów, small skeletons could have been dolomitized and thus not taken into considerations.
- especially big individuals may have been eliminated because of low probability of finding a suitable cross-section. This factor is probably especially important in Kadzielnia (and to some extend in Karwów), where large stromatoporoids, as well as laminar specimens with a long base, could not be included into the measured sample.

Results

Detailed results of the stromatoporoid measurements are given in Table 1. Stromatoporoid shape assemblages from the studied localities are shown in the form of triangular arrays on Fig. 3.

Table 1. Morphometric features of the measured stromatoporoids from Karwów, Kadzielnia and Sitkówka–Kowala quarries.

Locality		Karwów	Kadzielnia	Sitkówka–Kowala
Skeletons measured		150	25	87
Composition of shapes	laminar	2.7%	–	–
	low domical	56.7%	60%	3.4%
	high domical	39.3%	40%	33.3%
	extended domical	1.3%	–	42.5%
	bulbous	–	–	20.7%
Mean measures	B (cm)	24.2	29.1	8.6
	V (cm)	11.8	11.7	10.9
	D (cm)	11.0	10.9	8.8
Mean V/B value		0.49	0.43	1.49
V/B range		0.05–1.14	0.11–0.89	0.33–6
Surface	smooth	30.7%	32.0%	97.7%
	ragged	69.3%	68.0%	2.3%
Arrangement of latilaminae	enveloping	undetectable	undetectable	71.1%
	non-enveloping			29.9%

Two most striking features emerging from the performed analysis are: great similarity of the measured assemblages in Karwów and Kadzielnia on one hand, and a

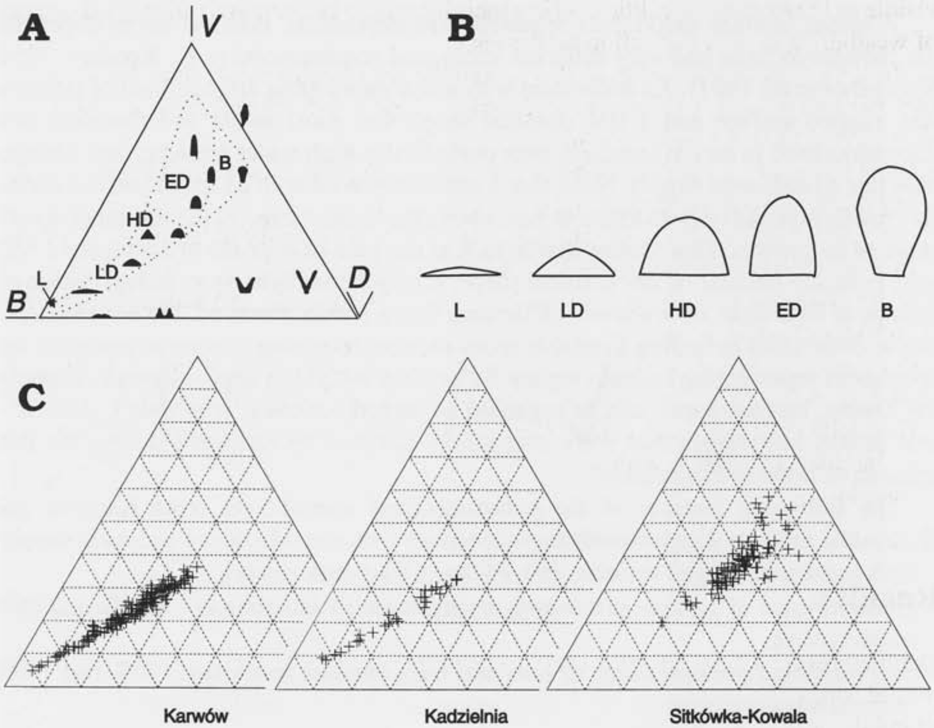

Fig. 3. Display of stromatoporoid morphology on traingular arrays. **A**. Triangular array (after Kershaw & Riding 1978); *B* – basal length, *V* – vertical height, *D* – diagonal distance (at an angle of $\theta = 25^{\circ}$ from the vertical). Various fields are occupied by basic stromatoporoid morphotypes: laminar (L), low domical (LD), high domical (HD), extended domical (ED), and bulbous (B). **B**. Basic stromatoporoid morphologies distinguished in the analysis. Symbols as in **A**. **C**. Triangular displays of stromatoporoid morphology from three studied localities in the Holy Cross Mountains, Poland.

totally different array of shapes obtained from the Sitkówka–Kowala quarry, on the other. These observations can be interpreted in terms of ecological variation between the studied localities.

Karwów and Kadzielnia quarries. — One of the most widely recognised ecological factors influencing the stromatoporoid shape is the rate of deposition (Broadhurst 1966; Kershaw 1981, 1984, 1987, 1990, 1998; Königshof *et al.* 1991; Kershaw & Swan 1994). Ragged varieties indicate a high overall rate of deposition with variable rate of sediment supply. During calm deposition intervals, an undisturbed individual expanded both horizontally and vertically. In the following episode of rapid sediment influx, possibly partly being a result of lateral redistribution of sediment during storms, the lowest parts of the stromatoporoid were buried and the growth continued only in the central, highest part of the skeleton. If such a sequence was repeated several times, it often resulted in a characteristic ragged stromatoporoid shape, resembling a Christmas-tree (Kershaw 1984). Quite similarly, a non-enveloping arrangement of latilaminae proves, that the individuals development was restricted only to its uppermost part, possibly due to greater environmental stress (e.g., caused by sedimentation) on the lower sections.

Whereas laminar individuals required slow deposition, domical stromatoporoids are thought to have had very different ecological requirements (e.g., Kershaw 1984; Königshof *et al.* 1991). An individual with a non-enveloping arrangement of latilaminae, ragged surface and a low domical shape was most stable and therefore best accommodated to an environment with periodically high water turbidity and changeable rate of sediment supply. Note, that a stromatoporoid with a ragged surface during its growth exposed only its topmost part, above the highest band of the sediment at each stage of its growth. This means, that in fact, at the time of deposition it adopted a very low, typically laminar or low domical shape. It may throw light on an interpretation of, strange at first sight, coocurrence of laminar forms (often observed, but not measured due to difficulties in finding a suitable cross-section) requiring a calm environment and specimens representing features typical for settings with high deposition rate. Namely, the lowest, laminar forms can be regarded as ragged varieties 'who didn't make it' – that means individuals that were completely covered by sediment during the first episode of rapid sedimentation.

The following features of the stromatoporoid assemblages from Karwów and Kadzielnia indicate a high overall deposition rate with variable rate of sediment supply:
- high content of ragged varieties (69.3% and 68% respectively),
- predominance of an non-enveloping arrangement of latilaminae (69.3% and 68% respectively),
- overwhelming predominance of low- and high domical specimens (96% and 100% respectively).

High deposition rate well corresponds with relatively big thickness of the Kadzielnia Limestones as compared with their stratigraphic equivalents. Softness of bottom sediments, postulated by Kaźmierczak (1971), may have also been a result of rapid sedimentation, when lithification could not keep pace with deposition. Postulated periodical high water turbidity seems to back the shallow water interpretation of the Kadzielnia Limestones (Racki 1992), where storm activity could influence the depositional environment.

Sitkówka–Kowala quarry. — The incidence of various morphologies within the measured population in the Sitkówka–Kowala quarry differs dramatically from that observed in Karwów and Kadzielnia. The biggest group (70.1%) of measured individuals have displayed an enveloping arrangement of latilaminae. The stromatoporoid's surface was typically smooth (97.7%). Most of the skeletons accommodated very high morphotypes, with V/B ratio exceeding 1 (63.2%).

Typical settings for bulbous stromatoporoids with an enveloping arrangement of latilaminae and a smooth surface were calm waters with low rate of deposition (e.g., Kershaw 1990; Machel & Hunter 1994). As pointed out above, many individuals have been found overturned and/or transported. This could have been caused by turbulent episodes, probably storms. As noticed by Kershaw (1981), bulbous stromatoporoid colonies were especially susceptible to redeposition because of their narrow base, by which they were adjusted to the sea substrate. Skeletons adapted to a calm environment were thus easily redeposited during high energy intervals. Stromatoporoids redistributed from their growth localities were laid down in a more quiet setting. An extraordinarily abundant stromatoporoid assemblage in the northern part of the Sitkówka–Kowala quarry is interpreted as being partly deposited by a storm. Although the process of accumulation was turbulent, the observed stromatoporoid shapes are typical for a calm environment with a low deposition rate, where the specimens have grown, therefore this quiet setting was punctuated by high energy events.

Low deposition rate and water turbidity deduced from stromatoporoid morphological features are in agreement with the quiet water facies of the Upper Sitkówka Beds. Bulbous individuals with an enveloping arrangement of latilaminae have grown in calm shallow waters of shoal domain (Racki 1992), periodically interrupted by storms abrading the bottom sediments.

Conclusions

- Stromatoporoid assemblages measured in Karwów and Kadzielnia quarries suggest an environment with high deposition rate and periodically high water turbidity. The observed most numerous occurrence of low domical forms is typical for build-ups.
- Stromatoporoids studied in the Sitkówka–Kowala quarry have displayed several features indicative for a calm setting with low deposition rate. The observed dominance of high profile varietes, including extended domical and bulbous specimens, is a common characteristic of back-reef settings. An extraordinary abundant assemblage exposed in the northern part of the quarry is interpreted as being partly deposited by a storm.
- Deposition rates and water turbidity deduced from stromatoporoid shapes usually well correspond with data obtained from facial analyses.
- The similarity of stromatoporoid shapes from Karwów and Kadzielnia has confirmed that dolomites from the Karwów quarry represent Kadzielnia-type reef-mound deposits. Extensive dolomitization and/or recrystallisation of there exposed rocks has resulted in great difficulties in determining both their origin and age (Samsonowicz 1917, 1934; Narkiewicz & Olkowicz-Paprocka 1983; Narkiewicz *et al.* 1990; Racki 1992; Łuczyński 1995). This makes the importance of stromatoporoid shape analysis in this locality even greater.

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Morfologia stromatoporoidów z dewonu Gór Świętokrzyskich

PIOTR ŁUCZYŃSKI

Streszczenie

Wykonane zostały pomiary morfometrycznych cech stromatoporoidów w trzech odsłonięciach górnego dewonu w Górach Świętokrzyskich: w kamieniołomach w Karwowie, Kadzielni i Sitkówce–Kowali. Wykorzystano schemat parametryzacji, który zaproponowali Kershaw & Riding (1978). Przeprowadzona ilościowa analiza pomiarów wykazała wiele różnic pomiędzy poszczególnymi stanowiskami, które zostały zinterpretowane w świetle zmienności panujących warunków paleoekologicznych. Za czynniki szczególnie silnie wpływające na morfomeryczne cechy stromatoporoidów zostały uznane tempo depozycji i dynamika wód.

Nieuławicone wapienie stromatoporoidowo-koralowcowe odsłanianjące się w Karwowie i Kadzielni reprezentują fację kopców rafowych powstających w środowisku o okresowo wzrastających tempie depozycji i dynamice wód. Zespół stromatoporoidów jest tu zdominowany przez osobniki niskokopułowe o postrzępionej powierzchnii i nieoblekającym ułożeniu latylamin. Skały odsłaniające się w kamieniołomie Sitkówka–Kowala reprezentują płytkowodne facje powstające w środowisku ławicy. Tam, w spokojnych wodach i przy niskim tempie depozycji, charakterystycznymi cechami stromatoporoidów były: kształt bardzo wysokokopułowy bądź bulwiasty, gładka powierzchnia i oblekające ułożenie latylamin. Podobieństwo zespołów stromatoporoidów z Karwowa i z Kadzielni potwierdza tezę, że dolomity odsłaniające się w kamieniołomie w Karwowie reprezentują osady kopca mułowego typu kadzielniańskiego.