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Growth forms and distribution patterns of stromatoporoids exposed on Devonian palaeobottom surfaces; Holy Cross Mountains, central Poland

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ABSTRACT:

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Well preserved palaeobottom surfaces with stromatoporoids are exposed in two Devonian localities in the Holy Cross Mountains in central Poland: Skały and Bolechowice-Panek quarries. The stromatoporoids were subjected to morphometric analysis and distribution studies. Stromatoporoids were studied hitherto only in vertical cross sections; the study of three-dimensional stromatoporoid domes has created a need to introduce a new set of parameters describing their shapes, which includes: horizontal length and width, vertical height, elongation ratio and elongation azimuth. In order to make the measurements made by various methods comparable, and thus to allow comparable interpretations, recalculation formulas have been presented. Comparison of the results obtained by the two methods indicates that the measurements made in vertical cross sections substantially bias the dimensions and shapes of the stromatoporoids, which may influence stromatoporoid-based palaeoenvironmental reconstructions. The results of the measurements were interpreted in terms of palaeonvironmental conditions. In Bolechowice-Panek the stromatoporoids lived in a quiet shallow water setting with a low and stable sedimentation rate. In Skały the stromatoporoids grew in a shallow subtidal setting and located themselves on parallel ripples, most probably to escape being buried by deposits accumulating in inter-ripple depressions.

Key words: Stromatoporoids, Morphometry, Parameterization, Palaeobottom surfaces, Palaeoenvironments, Devonian, Holy Cross Mountains.

INTRODUCTION

Palaeozoic stromatoporoids occur in facies ranging from deeper shelf to intertidal, and may form reefs, bioherms and biostromes. Although some of the stromatoporoid species are predisposed to specific growth forms (e.g. STEARN 1982, KERSHAW & KEELING 1994, STEARN & *al.* 1999), only general growth tendencies are determined by taxonomy, while the external shapes and sizes are thought to be governed mainly by various environmental factors.

Stromatoporoids adopted a range of shapes, which are interpreted in terms of their growth environment (e.g. BROADHURST 1966; KAŹMIERCZAK 1971; ABBOTT 1973, 1976; KAPP 1974; KOBLUK 1978; MEYER 1981; HARRINGTON 1987; KANO 1990; KÖNIGSHOF & *al.* 1991; JAMES & BOURQUE 1992; SWAN & KERSHAW 1994; MACHEL & HUNTER 1994; ŁUCZYŃSKI 1998; SANDSTRÖM 1998; KERSHAW & BRUNTON 1999; SANDSTRÖM & KERSHAW 2002; YOUNG & KERSHAW 2005; KÖNIGSHOF & KERSHAW 2006). The palaeoenvironmental analyses take into account their overall shape, the arrangement of growth bands within the skeleton (the latilaminae), and the character and type of initial surface from which the stromatoporoid began to grow (e.g., Kershaw 1998; Łuczyński 2003). The factors most commonly regarded to have governed stromatoporoid shapes are deposition rate and sedimentation dynamics (e.g. Broadhurst 1966; Kershaw 1981, 1984, 1998; Braun & *al.* 1994; Łuczyński 1998, 2003, 2005), substrate consistency (e.g. Kaźmierczak 1971; Kershaw 1980, 1990; Łuczyński 2003; Kershaw & *al.* 2006), water turbulence (e.g. Abbott 1973; Kershaw 1981, Königshof & *al*. 1991; Königshof & Kershaw 2006), and existence of bottom currents (e.g. Broadhurst 1966, Kapp 1974, Kershaw 1998). In general, the same factors are also thought to have influenced the morphologies of Jurassic stromatoporoids (Leinfelder & *al.* 2005), chaetetids (Kershaw & West 1991; Miller & West 1996) and sclerosponges (Stearn 1984).

Stromatoporoid shapes are categorized by the relationships between their basic dimensions, as proposed by Kershaw & Riding (1978). The original parameterization method has subsequently been markedly improved, by adding new parameters or by redefining the old ones (Kershaw 1984, 1998; Łuczyński 2003, 2005, 2006). However, analyses of stromatoporoid shapes were made hitherto only in the plane of a vertical cross section through a skeleton preserved in the rock. In the present paper, the parameterization method is adapted to three-dimensional specimens that are exposed on palaeobottom surfaces. The three main advantages of this approach as compared with the studies performed so far are: (a) a possibility to observe actual growth forms of stromatoporoids protruding from a palaeobottom surface instead of relying only on random vertical cross sections; (b) an insight into the spatial distribution of stromatoporoids on the sea floor; and (c) a certainty that all the specimens studied constituted an *in situ* assemblage representing the same palaeoenvironmental conditions.

GEOLOGICAL SETTING

Well preserved palaeobottom surfaces with stromatoporoids are exposed in two Devonian localities in the Holy Cross Mountains (HCM) in central Poland: the Skały Quarry and the Bolechowice-Panek Quarry (referred to herein as Panek) (Text-fig. 1). Both quarries expose rocks of a vast Devonian carbonate platform.

The abandoned Skały Quarry is situated in the northern part of the HCM about 10 km north-east of the town of Nowa Słupia (Text-fig. 1). The area belongs to the northern Łysogóry Region of the HCM in both tectonic and palaeofacies (*sensu* Szulczewski 1977) senses. The exposed succession represents the upper Crystalline Dolostone Member of the Eifelian Wojciechowice Formation (Text-fig. 2A; Kłossowski 1985). Its Eifelian age is indicated by brachiopods (Biernat 1964) and ostracods (Malec 1984). The formation represents a unique episode of shallow-water carbonate sedimentation within the generally shaly and siliciclastic facies deposition that prevailed during the Middle Devonian in the northern part of the HCM. The

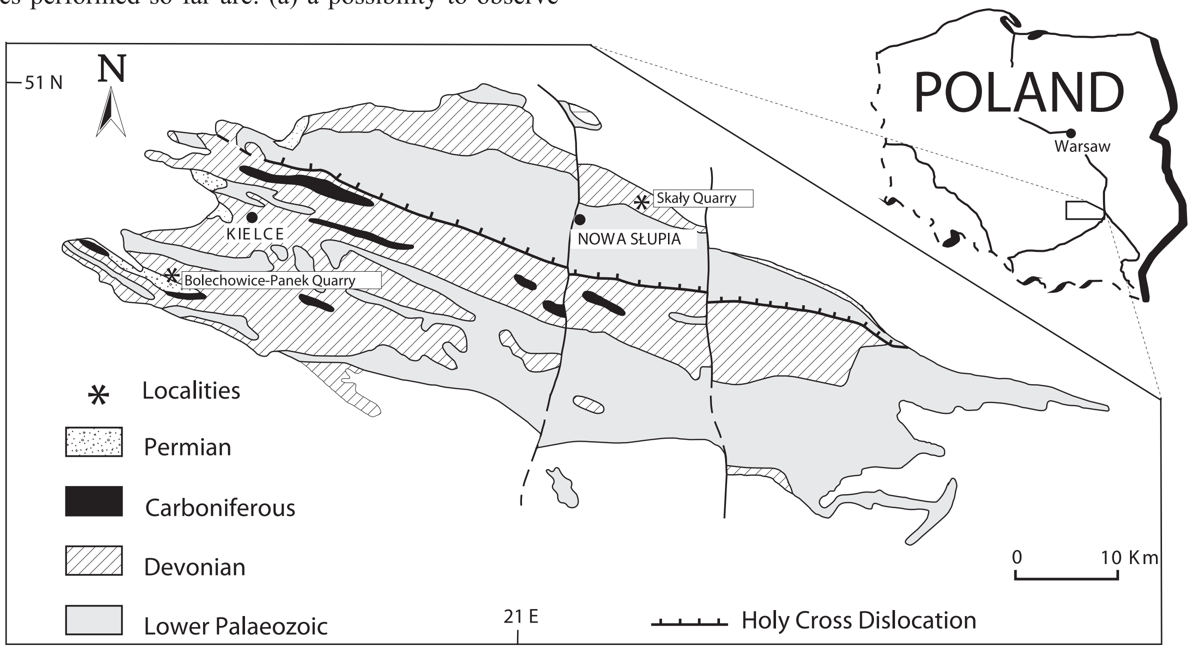

Fig. 1. Location of the Skały and Bolechowice-Panek quarries on a geological sketch map of the Holy Cross Mountains

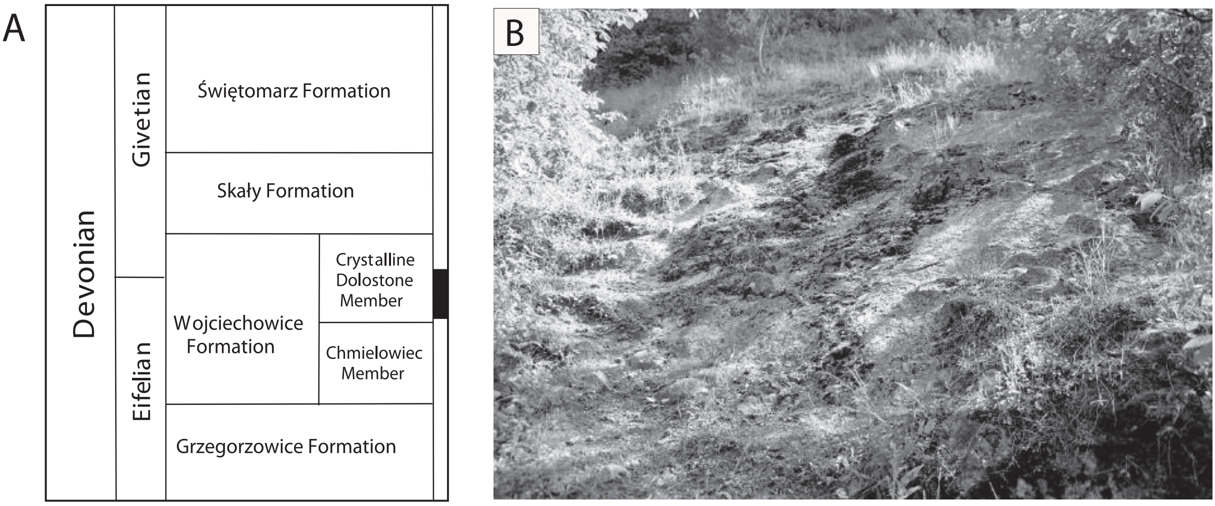

Fig. 2. Palaeobottom surface with stromatoporoids exposed in the Skały Quarry. A) Stratigraphic position (black vertical strip). B) General view of the exposure in a small river ravine south of the Skały quarry

exposed sequence is partly dolomitized and is characterized by shallowing-upward cyclothems. It was deposited in a tide-dominated low-energy environment intermittently affected by high-energy events (SKOMPSKI & SZULCZEWSKI 1994). The Wojciechowice Formation marks an episode when an extensive carbonate platform that developed in the central and southern parts of the HCM also extended onto the northern region. The palaeobottom surface with stromatoporoids investigated in this paper is exposed in a small river ravine south of the main quarry (Text-fig. 2B).

The working Panek Quarry is located in the south-western part of the HCM (Text-fig. 1), in the southern, Kielce Region, and in the central Kielce palaeofacies zone (*sensu* SZULCZEWSKI 1977). The succession represents the topmost part of the Upper Sitkówka Beds and the Detrital-Stromatoporoid Beds, both representing the Middle-Late Frasnian Kowala Formation (Text-fig. 3A; NARKIEWICZ & *al.* 1990). The age determinations are based on conodonts (SZULCZEWSKI 1981, RACKI 1993). The exposed sequence is developed mainly as biostromal stromatoporoid limestones interlayered by laminites, amphiporid limestones and by limestones with fenestral structures (birdseyes). It represents the shoal domain neighbouring the Dyminy reef and was deposited in shallow waters (KAŹMIERCZAK 1971; RACKI 1993). The stromatoporoids from the Sitkówka Beds were studied by KAŹMIERCZAK (1971, 2003) and ŁUCZYŃSKI (1998, 2003). The palaeobottom surface with stromatoporoids investigated in this paper is exposed on the lower level of the quarry (Text-fig. 3B).

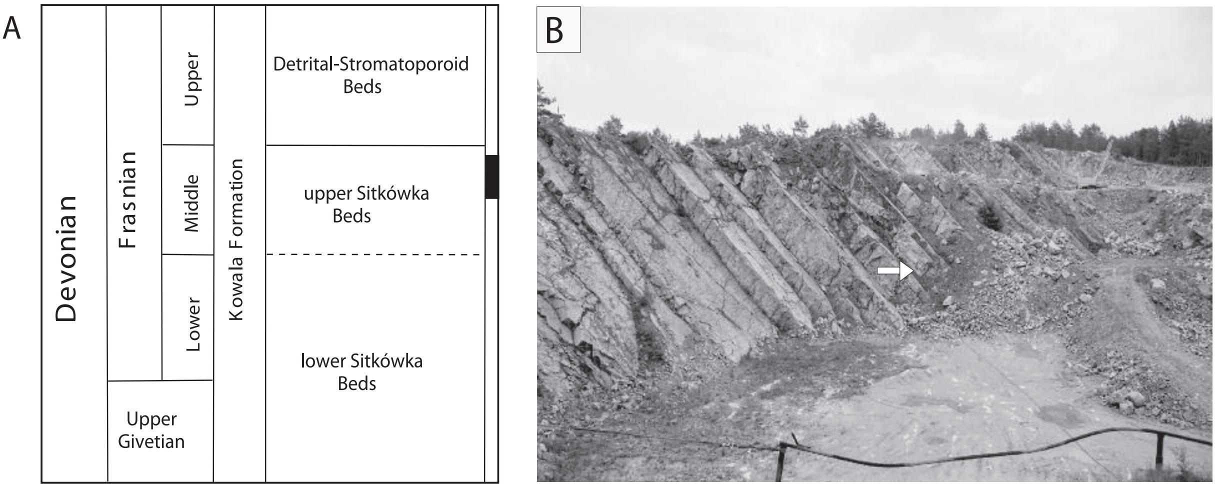

Fig. 3. Palaeobottom surface with stromatoporoids exposed in the Bolechowice-Panek Quarry. A) Stratigraphic position (black vertical strip). B) Main wall of the quarry; the arrow points to the palaeobottom surface

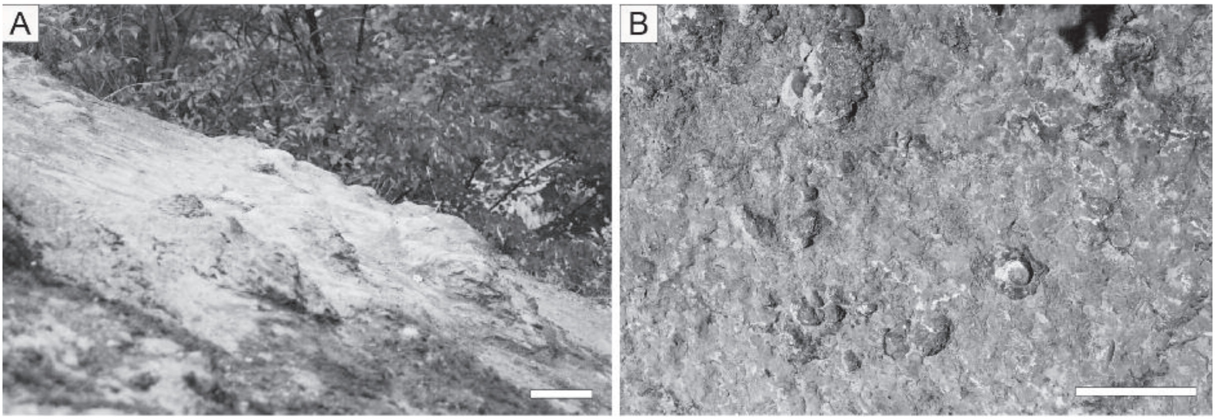

Fig. 4. Palaeobottom surfaces with stromatoporoids. A) Fragment of a surface exposed in a river ravine south of the Skały Quarry. B) Fragment of a surface exposed in the Bolechowice-Panek Quarry. The white scale bars are 10 cm long

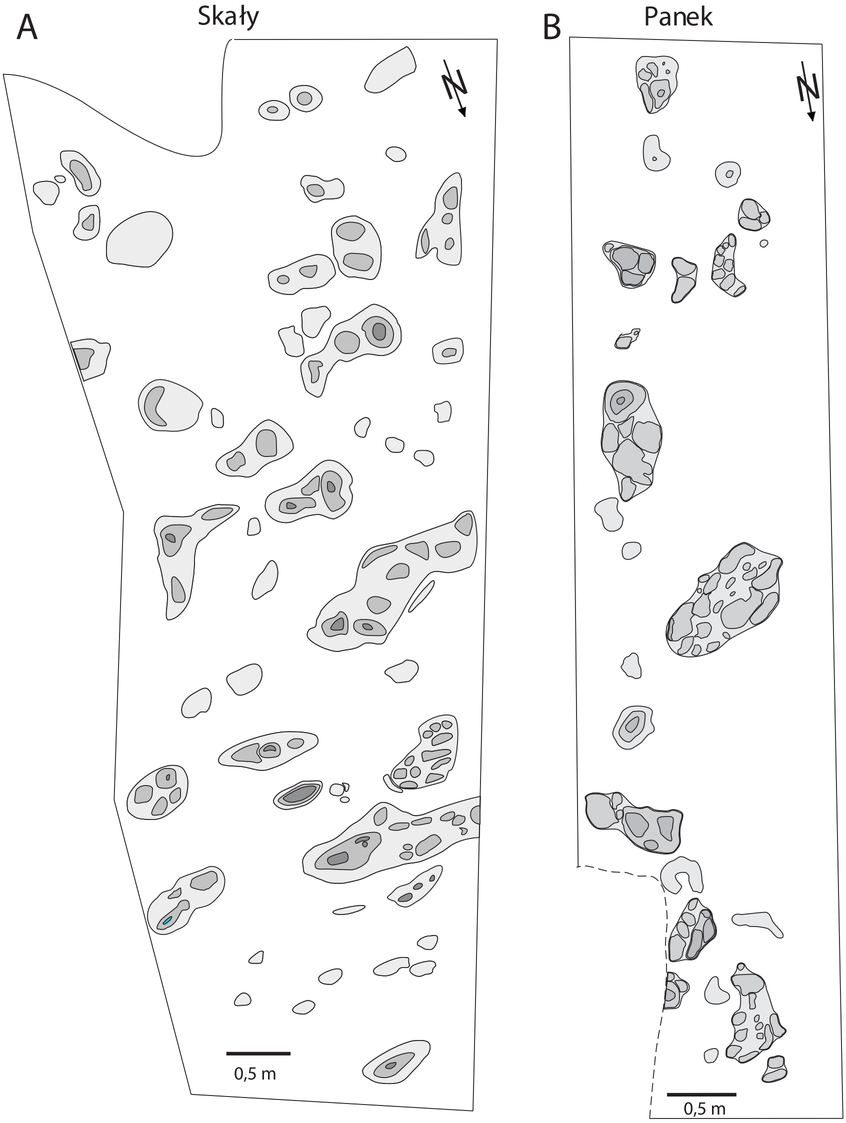

Fig. 5. Plans of excavated palaeobottom surfaces with stromatoporoids. A) Skały Quarry; contour lines represent heights of 5 and 10 cm above the surface; B) Bolechowice-Panek Quarry; contour lines represent heights of 2, 4 and 6 cm above the surface

MATERIALS AND METHODS

The preservation of the stromatoporoids exposed in Skały and Panek is similar. In both cases, the domes protrude from the exposed upper surface of a calcareous layer (Text-fig. 4A, B). The layers yielding the stromatoporoids were capped by relatively softer shaly facies, which have been removed by the weathering that exhumed the domes. In Skały, the palaeobottom surface is well exposed over an area of around 50 m^2, whereas in Panek the area of the surface exposed is only around 10 m^2. In Panek, in addition to those on the main palaeobottom surface, the stromatoporoids can also be observed in the quarry walls.

The palaeobottom surface exposed in Skały reveals 114 stromatoporoid domes; 36 of which grew as single domes, and 77 of which are concentrated in 18 aggregates containing two or more summits (subsequently referred as "multidome aggregates"). This gives 54 independent stromatoporoid bodies. Its counterpart in Panek reveals 92 stromatoporoid domes; 11 single domes and 81 in 13 multidome aggregates, which gives 24 independent stromatoporoid bodies. All the stromatoporoids visible on the two excavated surfaces were mapped, including contour lines indicating elevation above the base surface (Text-fig. 5A, B). In Skały the contour lines represent heights of 5 and 10 cm above the surface, whereas in Panek they represent heights above the surface of 2, 4, and 6 cm.

The exposed stromatoporoids were subjected to morphometric studies. Because the stromatoporoid domes could be accessed directly, the original parameterization method by means of vertical cross section (Kershaw & Riding 1978) could not be used. Therefore, a new set of parameters has been established to describe the dimensions of the preserved stromatoporoid growth forms.

Both single stromatoporoid domes and multidome aggregates were measured. The internal structure of each aggregate could only be determined by studying the arrangements of the latilaminae by means of several vertical cross sections, but these aggregates are most probably clusters composed of several coalescent specimens growing close to each other. Coalescence of neighbouring stromatoporoids is a feature that has been observed by Kershaw (1990). The type of preservation hindered both tracing the internal arrangement of the latilaminae and determining the type of initial surface (Łuczyński 2003). The only specimens offering insight into these features are those exposed on the edges of the surfaces studied (Text-fig. 6).

Also studied was the distribution of the stromatoporoids on the exposed palaeobottom surfaces. The orientation of distinct lineaments was measured (after correction of the tectonically inclined strata to their original horizontal position). The distribution has been interpreted in terms of palaeoenvironmental conditions and factors controlling particular features. Specimens preserved only partially at the edges of the surfaces were mapped, but their dimensions and shapes could not be taken into considerations together with the other data.

PARAMETERIZATION OF STROMATOPOROID DOMES EXPOSED ON PALAEOBOTTOM SURFACES

The parameterization of stromatoporoid shapes was introduced by Kershaw & Riding (1978). A massive (non-dendroid) stromatoporoid skeleton seen in a vertical cross section is measured in three directions. The obtained dimensions: *B* – basal length, *V* – vertical height and *D* – diagonal distance, describe the

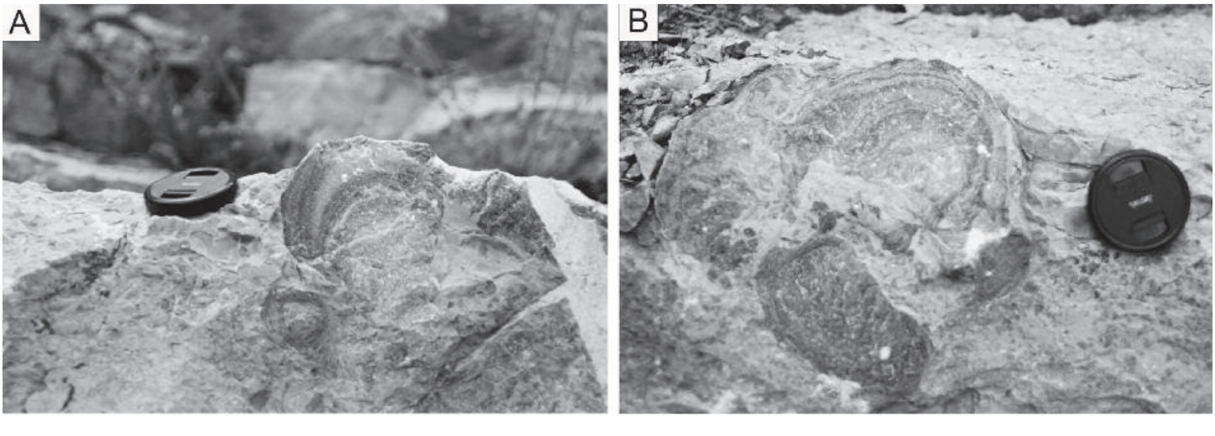

Fig. 6. Stromatoporoids located on the edge of the palaeobottom surface in Panek, deeply rooted into the calcareous layer with an enveloping arrangement of latilaminae

Fig. 8. A stromatoporoid dome and a multidome aggregate with outlines approximated by ellipses; Skały; x = summits of individual domes

stromatoporoid shape (Text-fig. 7A, B). The relationships between the three measurements determine the assignment of the stromatoporoid to a particular shape category (Text-fig. 7C). In field conditions, the *D* parameter is commonly skipped (e.g. KERSHAW 1990; SANDSTRÖM 1998) and the stromatoporoid shape is determined by the *V/B* ratio. Apart from the shape of the whole skeleton, the shape of the growth form above the sea floor (living surface profile) is also studied (e.g. KERSHAW 1998; ŁUCZYŃSKI 2003).

The original parameterization method has been improved several times. KERSHAW (1984) supplemented it by a method of measuring the zones of vertical and horizontal raggedness, and proposed a new parameter; *W* – the maximum width of the specimen measured parallel to *B* (KERSHAW 1998). ŁUCZYŃSKI (2003) introduced a classification of initial surfaces, and a new parameter of burial ratio – *BR* (ŁUCZYŃSKI 2005), which

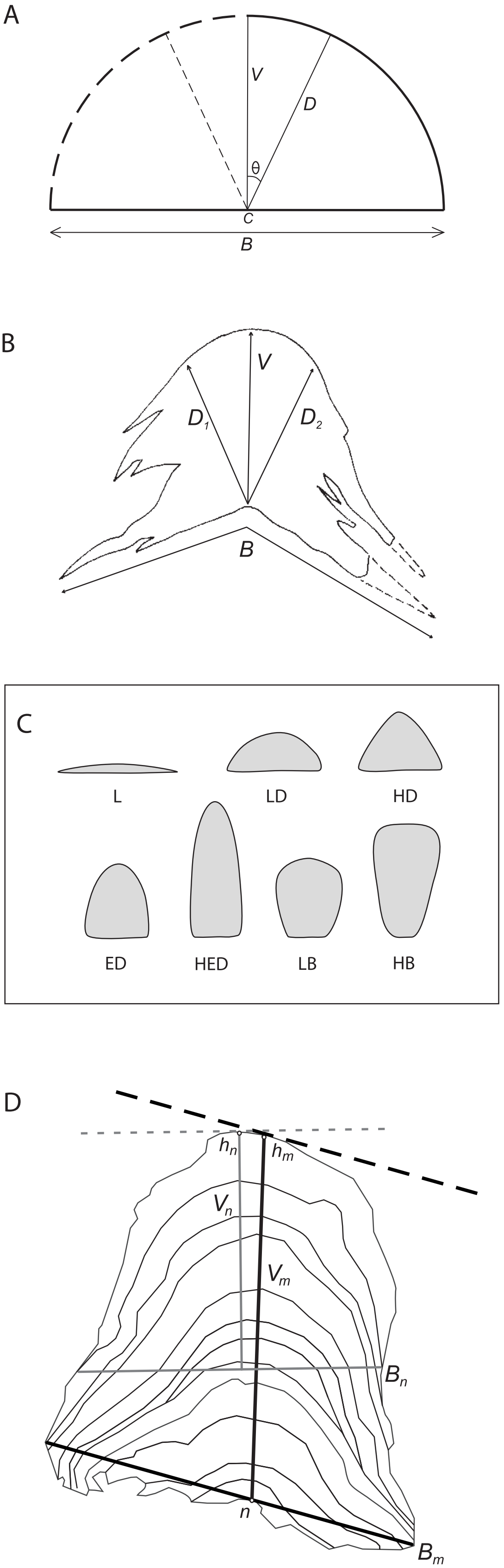

Fig. 7. Stromatoporoid measurements made in a vertical cross section. **A** − Measurements of an idealized cross section cut through a stromatoporoid introduced by KERSHAW & RIDING (1978; text-fig. 6); *B* = basal length, *V* = vertical height, *D* = diagonal distance. *V* and *D* are plotted from a central point (c) on *B*. **B** − Measurements of an incomplete ragged specimen by KERSHAW & RIDING (1978; text-fig. 14); *B* = basal length, *V* = vertical height, D_1, D_2 = diagonal distances. **C** − Basic stromatoporoid morphotypes: laminar (L), low domical (LD), high domical (HD), extended domical (ED), highly extended domical (HED), low bulbous (LB) and high bulbous (HB). **D** − Measurements introduced by ŁUCZYŃSKI (2005; text-fig. 8, simplified); B_m = basal length of the skeleton, B_n = basal length of the growth form above the sea floor, V_m = vertical height of the skeleton, V_n = vertical height of the growth form above the sea floor, *n* = initial growth nucleus, h_m = highest point on the surface above the B_m line, h_n = highest point on the surface above the B_n line. Dashed lines are parallel to B_m and B_n respectively and serve to localize the h_m and h_n points

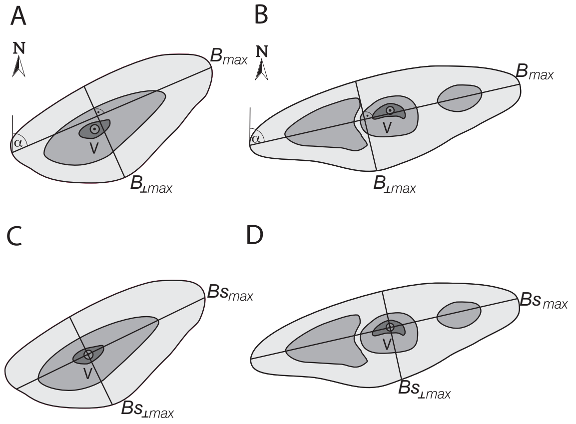

Fig. 9. Measurements of stromatoporoids exposed on a paleobottom surface. **A** – Single stromatoporoid dome; B_{max} = maximum basal dimension (horizontal length), $B_{\perp max}$ = maximum basal dimension measured perpendicular to the B_{max} (horizontal width), V = vertical height (the black dot points to the summit of the specimen), α = azimuth of the B_{max}. **B** – Multidome aggregate; symbols as in A. **C** – Single stromatoporoid dome; Bs_{max} = maximum basal dimension measured along a vertical plane running through the summit of the stromatoporoid (horizontal length “S”), $Bs_{\perp max}$ = basal dimension measured perpendicular to the Bs_{max} along a vertical plane running through the summit (horizontal width “S”), V = vertical height (the black dot points to the summit). **D** – Multidome aggregate; symbols as in C

describes what proportion of the skeleton remains buried under the sediment, and has proposed (Łuczyński 2005) new and stricter definitions of particular parameters (Text-fig. 7D). Finally, Łuczyński (2006) has proposed a more detailed approach to parameterization by means of measuring consecutive growth stages marked by the arrangement of the latilaminae, thereby enabling the tracing of changes in shape of the stromatoporoid during growth.

In both quarries, the specimens exposed on the edges of the palaeobottom surfaces studied have their lowermost parts located below the top of the carbonate layer from which they protrude (Text-fig. 6). It may therefore be assumed that all the other domes studied also do not reflect the dimensions of the whole skeletons, but only of their growth forms above the sea floor at a given time (Text-fig. 7D). Growth forms are considered even more informative than the whole shapes, as they reflect the part of the skeleton that protruded above the sediment and interplayed with the changing environmental conditions (e.g. Kershaw 1998, Łuczyński 2005, 2006).

Basal length – *B*. In both the settings studied most of the stromatoporoid domes and multidome aggregates are distinctly elongated (Text-figs 5A, B; 8). The projection of the domes onto a horizontal plane (top of the calcareous layer from which they protrude) can be approximated by an ellipse. In vertical view, the B measurement is made along a random cross section through such an ellipse. In the case of domes seen from above, such random measurements can be replaced by the actual dimensions of their elliptical projection onto a horizontal plane. New parameters are therefore introduced here. The horizontal length – B_{max} (the maximum basal dimension), is defined as the longest axis of the ellipse (Text-fig. 9A, B). The horizontal width – $B_{\perp max}$ is defined as the maximum basal dimension measured perpendicular to the B_{max} (Text-fig. 9A, B).

The lines along which the B_{max} and the $B_{\perp max}$ are measured do not always run through the summit of the dome (Text-fig. 9A). Therefore, for the convenience of recalculation (see “Recalculation…”), two more parameters are introduced. The Bs_{max} is thus defined as the maximum horizontal dimension of a stromatoporoid dome measured along a vertical plane running through its summit – horizontal length “S”, and the $Bs_{\perp max}$ is defined as the horizontal dimension measured along a plane that runs through the summit perpendicular to the plane along which the Bs_{max} is measured – horizontal width “S” (Text-fig. 9C, D). In the case of multidome aggregates, the “S” parameters are measured along lines cutting the highest dome within the aggregate.

Vertical height – *V*. The lowermost parts of the stromatoporoids remain hidden within the calcareous layer, and therefore the only vertical dimension that can be measured is the vertical height of the growth form above the sea bottom. In the case of the domes studied, it is most convenient to measure the height above the averaged top of the calcareous layer (Text-fig. 10A, B). In this case, all the heights of the individual domes are measured in the same direction and are directly comparable.

Diagonal distance – *D*. The diagonal distance parameter is the least important and is often skipped in morphometric analyses. The aim of incorporating the value of D into the analysis is to discriminate the bulbous forms (with $D>V$) from the domical forms (with $D\leq V$). Introducing two diagonal measurements – D_1 and D_2, serves also to underline the asymmetry of specimens seen in a vertical cross section (Kershaw 1984). In the case of the domes studied, an easier way of expressing eventual stromatoporoid asymmetry is to present the Bs_{max1}/Bs_{max2} relationship, where the Bs_{max1} and Bs_{max2} are the parts of the Bs_{max} dimension on both sides of the point from which the vertical height has been measured (Text-fig. 10B).

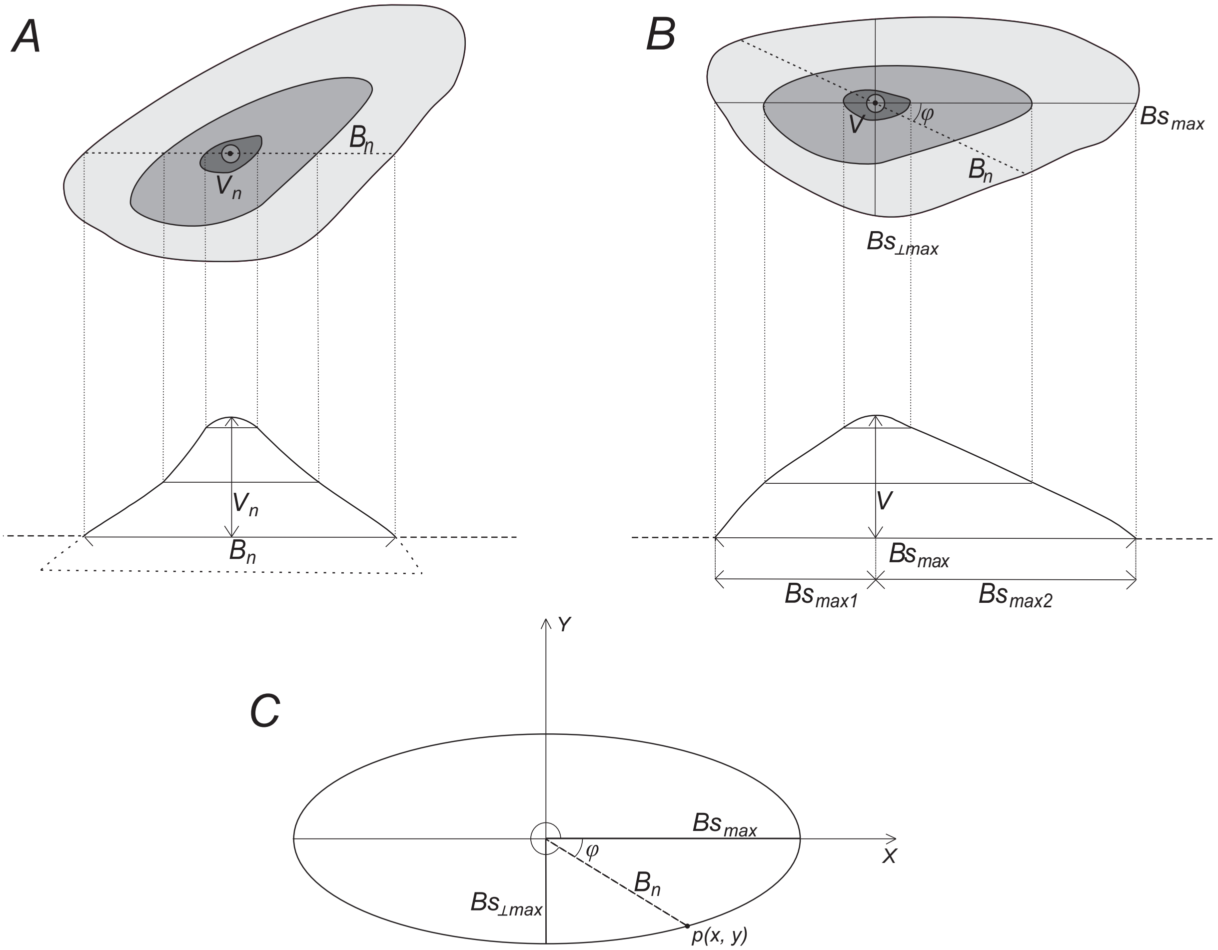

Fig. 10. Comparison of measurements of stromatoporoid domes exposed on a palaeobottom surface with measurements of stromatoporoids seen in a vertical cross section. **A** – Measurements made in a random vertical cross section; V_n = vertical height of the growth form above the sediment surface, B_n = basal length of the growth form above the sediment surface measured along the plane of a random vertical cross section running through the summit of the stromatoporoid. **B** – Measurements of a stromatoporoid dome exposed on a palaeobottom surface; V = vertical height (measured perpendicular to the average sediment surface), Bs_{max} = maximum basal dimension measured along a vertical plane running through the summit of the stromatoporoid (horizontal length "S"), $Bs_{\perp max}$ = basal dimension measured perpendicular to the Bs_{max} along a vertical plane running through the summit of the stromatoporoid (horizontal width "S"), φ = angle between the plane of a vertical cross section along which the B_n is measured, and the Bs_{max}, Bs_{max1} and Bs_{max2} = two sections of the Bs_{max} dimension situated on the two sides of the summit of the skeleton. **C** – Relationships between the measurements obtained by the two methods in an idealized stromatoporoid dome approximated by an ellipse; symbols as in A and B

Additional parameters. Two new parameters are introduced.

Elongation Ratio (Eccentricity). A new parameter reflecting the horizontal elongation of stromatoporoid domes is introduced. It is defined as the relationship between the horizontal length and the horizontal width – $ER = B_{max}/B_{\perp max}$. The *ER* is 1 in the case of a specimen with a circular base, and increases with elongation of the base. The proposed *ER* categories are as follows:

- round – $ER<1.25$,
- moderately elongated – $1.25\leq ER<1.5$,
- distinctly elongated – $1.5\leq ER<2$,
- very distinctly elongated – $ER\geq 2$.

The elongation ratio may also be calculated from measurements running through the summit of the specimen: $ER_s = Bs_{max}/Bs_{\perp max}$.

Elongation azimuth. Another feature that is useful in palaeogeographic interpretations, but not determinable from vertical cross sections, is the direction in which the stromatoporoids are elongated. The new parameter is expressed by the azimuth (α) of B_{max} (Text-fig. 9A, B). A consistent elongation azimuth of a group of simultaneously growing stromatoporoids can be interpreted in terms of water flow directions and basin topography.

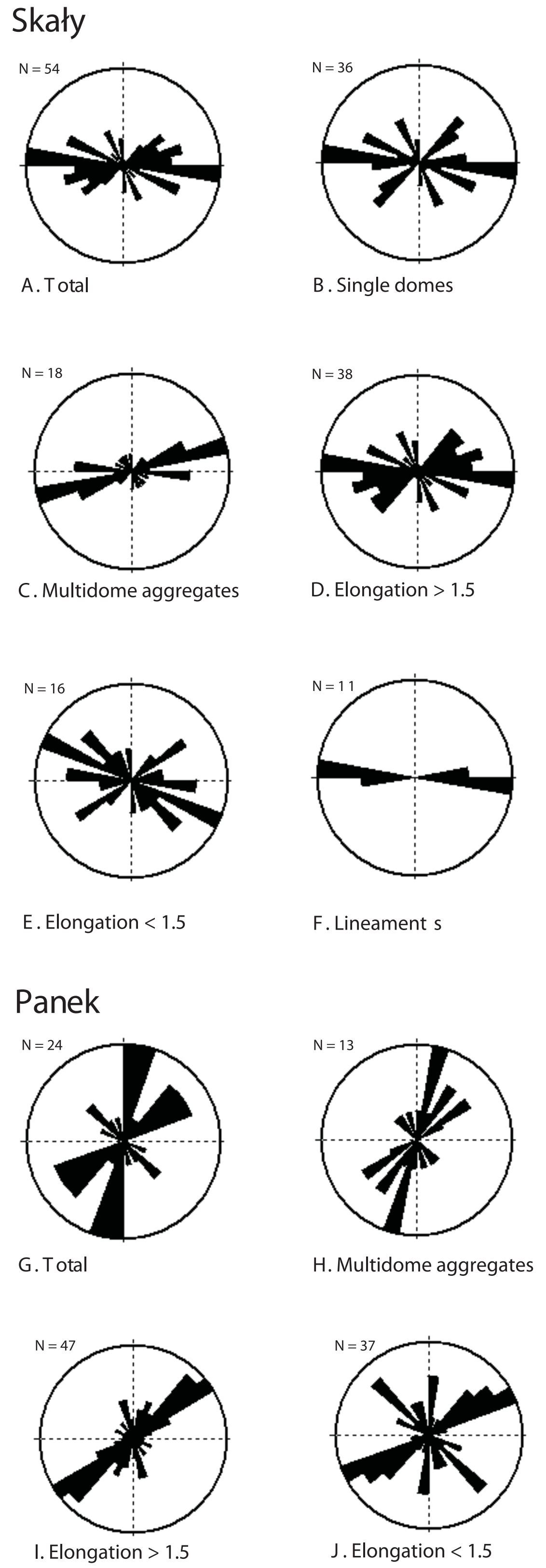

Fig. 11. Rose diagrams illustrating elongation azimuths of stromatoporoids exposed on the palaeobottom surfaces studied

MEASUREMENTS RESULTS

The following parameters and ratios were measured and calculated respectively (Tables 1, 2):

- B_{max} – horizontal length and $B_{\perp max}$ – horizontal width,
- Bs_{max} – horizontal length "S" and $Bs_{\perp max}$ – horizontal width "S",
- V – vertical height,
- ER – elongation ratio and $ER(s)$ – elongation ratio "S",

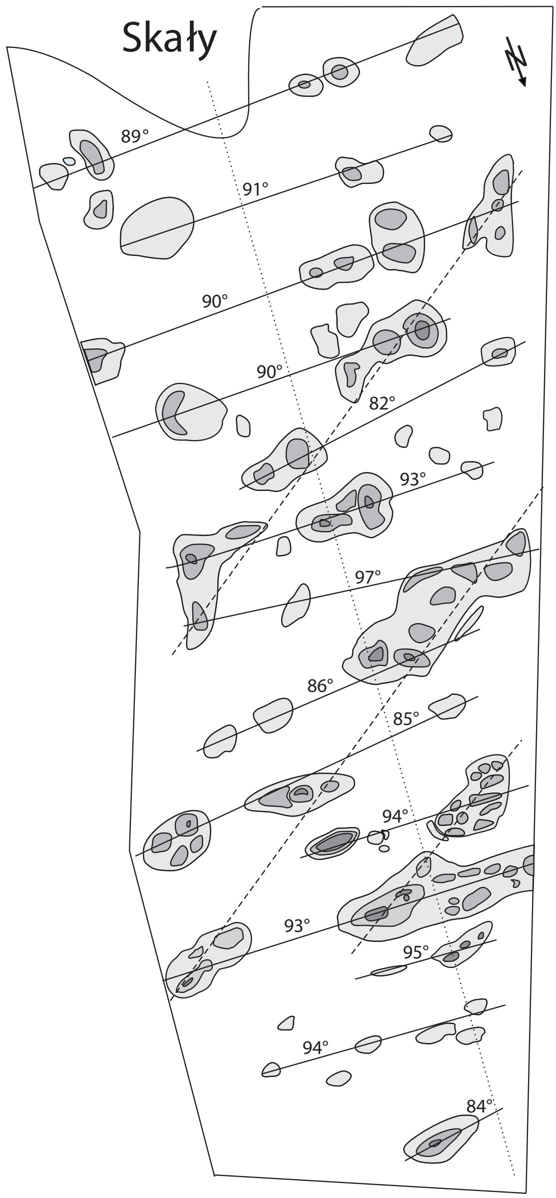

Fig. 12. Distribution of stromatoporoid domes exposed in the Skały Quarry along lineaments (continuous lines). The distances between the lineaments were measured along the dotted line. Less evident lineaments can also be drawn along azimuth c. 60° (dashed lines)

	Skały Quarry				Bolechowice-Panek Quarry			
	Single domes		Aggregates		Single domes		Aggregates	
	mean (range)	median	mean (range)	median	mean (range)	median	mean (range)	median
A. *Dimensions*								
B_{max} (cm)	24.8 (8-62)	23	80.4 (38-174)	71	21.0 (6-36)	19	45.9 (20-96)	40
$B_{\perp max}$ (cm)	14.4 (3-29)	12	37.5 (19-56)	39	14.8 (5-24)	16	26.0 (10-49)	26
V (cm)	4.7 (1-20)	4	9.8 (4-18)	9	2.1 (1-5)	2	4.7 (2-7)	4.5
Bs_{max} (cm)	23.7 (7-59)	21	76.3 (34-172)	70	19.4 (5-31)	18	43.8 (18-90)	39
$Bs_{\perp max}$ (cm)	12.7 (4-28)	12	34 (18-47)	36	14.5 (4-24)	15	19.5 (10-29)	19
B. *Shapes*								
V/B_{max}	0.19 (0.09-0.46)	0.17	0.13 (0.07-0.21)	0.12	0.10 (0.05-0.17)	0.11	0.12 (0.03-0.18)	0.13
$V/B_{\perp max}$	0.32 (0.18-0.78)	0.31	0.26 (0.09-0.42)	0.26	0.15 (0.06-0.21)	0.14	0.21 (0.06-0.39)	0.20
C. *Elongation*								
ER	1.90 (1.03-5.67)	1.60	2.15 (1.22-3.12)	2.02	1.48 (1.07-3.54)	1.30	1.75 (1.11-2.46)	1.78
ER(s)	1.99 (1.17-6.60)	1.70	2.15 (1.04-3.86)	2.12	1.38 (1.06-2.67)	1.28	2.19 (1.35-3.56)	2.00
D. *Recalculated values*								
B_n (cm)	20.3	–	64.7	–	18.4	–	36.9	–
V/B_n	0.23	–	0.15	–	0.11	–	0.13	–

Tab. 1. Mean and median values of measurements of single domes and multidome aggregates analyzed on the exposed palaeobottom surfaces. See text for explanation of particular parameters

- V/B_{max}, $V/B_{\perp max}$ – shape ratios based on various B measures,
- α – elongation azimuth.

All of the parameters describing the dimensions of the stromatoporoids were measured to an accuracy of 1 cm. The shape and elongation ratios (*V/B* and *ER*) were calculated to an accuracy of 0.01. The B_{max} *azimuth* (α) was determined to an accuracy of 1° and presented on rose diagrams in 10° classes (Text-fig. 11).

Dimensions. The stromatoporoid dimensions are described by B_{max}, $B_{\perp max}$ and V (Table 1A) and, for the purpose of recalculation, also by Bs_{max} and $Bs_{\perp max}$.

Single domes. In Skały, the range of dimensions of the stromatoporoids is much greater than in Panek, and the specimens are generally larger. The most distinct difference is in the vertical height – V, ranging between 1 and 20 cm in Skały (mean 4.7 cm) and not exceeding 5 cm in Panek (mean 2.1 cm). The differences are smaller when comparing the basal dimensions – B, but again with higher values attained by the domes measured in Skały.

Multidome aggregates. In both localities most of the stromatoporoid domes occur in aggregates. The number of individual domes constituting an aggregate reaches 13 in Skały and 20 in Panek (Text-fig. 5). The dimensions of the aggregates vary greatly and depend on the number of individual domes that build them, but generally they are larger in Skały, with their horizontal length – B_{max} reaching over 1.5 m, than in Panek, where they do not exceed 1 m (Table 1, Text-fig. 5). The ranges of the horizontal widths of the aggregates from the two quarries are comparable. As with the single domes, the aggregates are also distinctly higher in Skały, where V ranges between 4 and 18 cm (mean 9.8 cm), while in Panek it does not exceed 7 cm (mean 4.7 cm). It is worth noting that, while the horizontal dimensions of multidome clusters are significantly larger than those of single domes, the range of their vertical heights remains of the same order.

The difference between the two localities is much more distinct when comparing aggregates than single domes, which results from two main factors. First, the distribution, spacing and orientation patterns of individual domes building an aggregate (see “Elonga-

	Skały Quarry			Bolechowice-Panek Quarry		
	Mean azimuth	Dominant class	Consistency ratio	Mean azimuth	Dominant class	Consistency ratio
Total	94°	90-100°	0.80	48°	0-20°	0.70
Single domes	97°	90-100°	0.80	–	–	–
Aggregates	86°	70-80°	0.84	59°	10-20°	0.55
Elongation > 1.5	89°	90-100°	0.82	68°	50-60°	0.69
Elongation < 1.5	108°	110-120°	0.69	82°	60-70°	0.65
Lineaments	90°	90-100°	0.997	–	–	–

Tab. 2. Elongation azimuths of stromatoporoids exposed on the palaeobottom surfaces studied

tion" and "Distribution"). Second, their dimensions; in Skały, the domes constituting the aggregates are of the same order of dimensions as the individually growing stromatoporoids, whereas in Panek many of them are distinctly smaller.

Shapes. The shapes of the stromatoporoids are described by V/B_{max} and $V/B_{\perp max}$ ratios (Table 1A). The range of values for the V/B_{max} ratio of both individual domes and of multidome aggregates in the two quarries is relatively narrow (Table 1A). The widest range of values is that of single domes in Skały – 0.09-0.46. In both localities, the domes adopt laminar ($V/B \leq 0.1$) and low domical shapes ($0.1 < V/B \leq 0.5$), with the mean values corresponding to a low domical shape close to the lower limit of this category. The aggregates in both quarries also adopt laminar and low domical shapes, with the mean values close to the limit between the two categories.

The situation is different when the calculation of shape ratios is based on the horizontal width parameter – $B_{\perp max}$. The V/B ratios in this case are significantly higher, even reaching 0.78 for single domes in Skały. The mean shape ratios calculated in this way for single domes correspond to a low domical shape, with the range of shapes embracing laminar ($V/B \leq 0.1$), low domical ($0.1 < V/B \leq 0.5$) and high domical ($0.5 < V/B \leq 1$) forms. In the case of aggregates, the respective ranges correspond to laminar and low domical shapes (Table 1B).

Surface character. Of the macroscopic features other than shapes that are taken into account in stromatoporoid morphometric analyses, only the upper surface character could be studied here, as the other features (arrangement of latilaminae; type of initial surface) can only be observed in cross sections. In both localities the surfaces of both single domes and aggregates are smooth. The stromatoporoids exposed on the edges of the palaeobottom surfaces (Text-fig. 6) show minor initial elevations (see ŁUCZYŃSKI 2005) and a generally non-enveloping arrangement of the latilaminae; however, these are too few specimens to make more general conclusions.

Elongation. The elongation ratio of both single domes and of multidome aggregates is very variable in both quarries, and therefore the mean values by no means reflect any typical elongation of the group studied. In both localities, the calculated *ER* falls into the entire range of the proposed categories (Table 1C). The range of values is somewhat narrower for aggregates than for single domes, with mean elongations higher for aggregates, which indicates that clustering of specimens growing close to each other enhanced elongation.

Distribution. In Skały, the elongation azimuth (α) rose diagrams obtained for the various categories show consistent results (Text-fig. 11A-E; Table 2). Both the dominant classes and the mean vectors remain roughly the same, irrespective of the category analyzed (mean azimuth 85-97°, dominant class 70-100°). The results show a high consistency ratio, ranging between 0.80 and 0.84. Only the specimens with $ER < 1.5$ (round and moderately elongated) show a different array of elongation azimuths, albeit with a significantly lower consistency ratio (0.69).

A stromatoporoid distribution feature evident in Skały is their arrangement along distinct lineaments (Text-fig. 12). The 14 lineaments that run through almost all of the exposed specimens are almost parallel, with their azimuths ranging between 82° and 97° (Text-fig. 11F), which coincides with the elongation azimuths measured for domes and aggregates. The lineaments are roughly evenly spaced (Text-fig. 12), with the approximate distances between adjacent lines, measured along a selected section perpendicular to their average azimuth (dotted line on Text-fig. 12), ranging between 47 and 77 cm (mean 61 cm). Much less distinct, but also evident are lineaments that can be drawn along an azimuth of c. 60° (dashed lines on Text-fig. 12).

In Panek, most of the stromatoporoids are incorporated into aggregates (Text-fig. 5B) and therefore no separate rose diagram has been created for single domes (Text-fig. 11). The consistency ratios of the obtained results are much worse than in Skały (Table 2) and do not exceed 0.70, being the lowest for multidome aggregates (0.55). Also the consistency between the results calculated for particular categories is poor – both the mean azimuths and dominant classes differ greatly (Text-fig. 11G-J; Table 2). A characteristic feature is that the dominant classes do not coincide with the mean azimuth, indicating that the latter by no means represents the most common elongation direction, but is merely an average of widely spread, inconsistent values.

RECALCULATION OF THE MEASUREMENTS MADE BY VARIOUS METHODS

Different stromatoporoid measurement and parameterization methods can and should be used according to the actual exposure conditions, but, as the stromatoporoid shapes are used in palaeoenvironmental reconstructions, it is crucial that the various results be comparable and allow comparable interpretations. Therefore, there is a need to evaluate the differences and to develop recalculation formulas that would allow comparison of the results.

Basal dimensions – *B* values. Stromatoporoids adopt variable shapes, which do not follow simple geometrical figures, and it is thus impossible to introduce one simple recalculation formula. Some approximations can, however, be presented. Approximating the horizontal projection of the stromatoporoids as ellipses is a simplification but, to judge from the material studied, a justified one. The specimens show distinct elongation and rarely display embayments (Text-fig. 5).

The B_n measured in a vertical cross section can be directly compared only with the *Bs* values measured in planes running through the summit of the specimen. The B_n value, which is measured at a random φ angle between the plane of the cross section and the longer axis of an ellipse, is the mean of the ellipse diameter and ranges between the Bs_{max} and the $Bs_{\perp max}$ values, being respectively its longest and shortest axes (Text-fig. 10C). In order to find its value, the (x, y) coordinates of the *p* point (Text-fig. 10C) need to be calculated.

$x = Bs_{max} cos\varphi$

$y = Bs_{\perp max} sin\varphi$

Let $Bs_{max} = a,$ and $Bs_{\perp max} = b$, then:

$$B_n = \sqrt{a^2\cos^2\varphi + b^2\sin^2\varphi}.$$

The mean diameter of the ellipse

$$<B_n> = \frac{1}{2\pi}\int_0^{2\pi}\sqrt{a^2\cos^2\varphi + b^2\sin^2\varphi}\,d\varphi.$$

$a > b$, and therefore

$$<B_n> = \frac{a}{2\pi}\int_0^{2\pi}\sqrt{1+\left[\left(\frac{b}{a}\right)^2-1\right]\sin^2\varphi}\,d\varphi.$$

Taking $k^2 = 1-\frac{b^2}{a^2} \geq 0$,

we obtain

$$<B_n> = \frac{a}{2\pi}\int_0^{2\pi}\sqrt{1-k^2\sin^2\varphi}\,d\varphi,$$

which is an elliptical integral, than cannot be expressed by elementary functions. It may however be approximated by the Taylor series, based on the formula:

$$\sqrt{1-x} = 1-\frac{1}{2}x-\frac{1}{2\times 4}x^2-\frac{1\times 3}{2\times 4\times 6}x^3 - \ldots\ldots\ldots,$$

where $|x| < 1$.

In this case $|x| = \left|1-\frac{b^2}{a^2}\right|\times\left|\sin^2\varphi\right|$, and is < 1,

and therefore

$$\sqrt{1-k^2\sin^2\varphi} = 1-\frac{1}{2}k^2\sin^2\varphi-\frac{1}{2\times 4}k^4\sin^4\varphi -$$

$$-\frac{1\times 3}{2\times 4\times 6}k^6\sin^6\varphi \ldots\ldots\ldots\,,$$

thus:

$$<B_n> = \frac{a}{2\pi}\int_0^{2\pi}\left[1-\frac{1}{2}k^2\sin^2\varphi-\frac{1}{2\times 4}k^4\sin^4\varphi -\right.$$

$$\left.-\frac{1\times 3}{2\times 4\times 6}k^6\sin^6\varphi - \ldots\ldots\right].$$

If $I_n = \int\sin^n x dx$,

then $I_n = -\frac{1}{n}\sin^{n-1}x\cos x+\frac{n-1}{n}I_{n-2}$, for $n \geq 2$,

and therefore

$$<B_n> = \frac{a}{2\pi}\left[\varphi-\frac{1}{2}k^2\left(-\frac{1}{2}\sin\varphi\cos\varphi+\frac{1}{2}\varphi\right)-\right.$$

$$-\frac{1}{2\times 4}k^4\left(-\frac{1}{4}\sin^3\varphi\cos\varphi+\frac{3}{4}\left(-\frac{1}{2}\sin\varphi\times\right.\right.$$

$$\left.\left.\left.\times\cos\varphi+\frac{3}{4}\times\frac{1}{2}\varphi\right)\right)-\ldots\ldots\right]$$

$$<B_n> = \frac{a}{2\pi}\left[2\pi-\frac{1}{4}2\pi\times k^2-\frac{1}{2\times 4}\times\frac{3}{4}\times\frac{1}{2}2\pi\times k^4 -\right.$$

$$\left.-\frac{1\times 3}{2\times 4\times 6}\times\frac{5}{6}\times\frac{3}{4}\times\frac{1}{2}2\pi\times k^6-\ldots\ldots\right]$$

$$<B_n> \approx a\left[1-\frac{1}{4}k^2-\frac{1}{2\times 4}\times\frac{3}{4}\times\frac{1}{2}k^4-\frac{1\times 3}{2\times 4\times 6}\times\right.$$

$$\left.\times\frac{5}{6}\times\frac{3}{4}\times\frac{1}{2}k^6\right]$$

The approximation accuracy of this formula increases with the number of elements calculated; however, for the purposes of stromatoporoid morphometry, where particular dimensions are measured to an accuracy of only 1cm, it may be accepted that

$$<B_n> \approx a\left[1-\frac{1}{4}k^2\right],$$

where $k^2 = 1-\frac{b^2}{a^2}$.

Vertical height – V values. The vertical height of an exposed stromatoporoid dome (V) can only be compared with V_n – the vertical height of the growth form above the sea bottom (*sensu* ŁUCZYŃSKI 2005). The vertical dimension in both methods is measured in a similar way – as the height of the highest point above the base (Text-fig. 10A, B). The base is, however, understood differently in the two methods: in the original method it is the B_n line, determined from the arrangement of the latilaminae, and in the newly presented method it is the averaged top of the layer from which the domes protrude. The values obtained according to the two definitions do not vary substantially and can be compared directly.

The diagonal dimension – D is skipped in the 3D method of measurements. Recalculated B_n and V/B_n are presented in Table 1D.

METHODOLOGICAL AND STATISTICAL CONSEQUENCES

Bias of the results obtained by measurements made in a vertical cross section. The relationship between the B_n and the Bs_{max} reveals the statistical error in the basal dimensions of stromatoporoids obtained by the traditional method. The relationship changes with the elongation ratio, but remains roughly of the same order of size: ($B_n \approx 0.8\ Bs_{max}$) regardless of the *ER(s)*. For example, for $<ER> = 1.5$ ($Bs_{max} = 1.5\ Bs_{\perp max}$) the $B_n \approx 0.86 Bs_{max}$, for $<ER> = 2$ the $B_n \approx 0.81 Bs_{max}$, for $<ER> = 3$ the $B_n \approx 0.78 Bs_{max}$. More pronounced are the differences between the B_n and the $Bs_{\perp max}$ (for $<ER> = 1.5$ the $B_n \approx 1.25 Bs_{\perp max}$, for $<ER> = 2$ the $B_n \approx 1.63 Bs_{\perp max}$, for $<ER> = 3$ the $B_n \approx 2.33 Bs_{\perp max}$). The difference between the B_n and the "actual" maximum basal dimension is even greater if we take into account that $B_{max} \geq Bs_{max}$. The danger of repeating the same error in each measurement increases when the stromatoporoid domes are elongated in the same direction. On the other hand, the vertical heights measured using the two methods are comparable. This means that the assignment of stromatoporoids to certain shape categories, based on the V_n/B_n parameter, with an underestimated B_n and a comparable V_n, is also biased.

To make a direct comparison between the measurements made by various methods, 20 vertical cross sections were measured through specimens with traceable arrangements of the latilaminae from layers adjacent to the palaeobottom surface in Panek. In this case, the final growth forms display apparently higher shape profiles (mean 0.16; range 0.11-0.20) than those of the domes exposed on the palaeosurface itself, albeit remaining of the same order of size (compare Table 1), which strongly suggests that the differences between the results obtained by the two methods may be attributed at least in part to the different measurement techniques.

Relationship between the B_{max} and $B_{\perp max}$ and the Bs_{max} and $Bs_{\perp max}$ parameters. In both quarries, the differences between the two horizontal length measurements (B_{max} and Bs_{max}) do not exceed a few percent (Table 1). The differences between the horizontal width measurements ($B_{\perp max}$ and $Bs_{\perp max}$) are greater, reaching even 33.3% for multidome aggregates in Panek (Table 1). This suggests that the B_{max} value might thus be treated as a fair approximation of the Bs_{max} parameter and could replace it in recalculation formulae. However, the substantially greater differences between the horizontal width values do not allow replacing the $Bs_{\perp max}$ by the $B_{\perp max}$, which means that both these measurements need to be obtained.

Representativeness of individual measurements. One of the advantages of studying stromatoporoids exposed on palaeobottom surfaces is the opportunity to test if, and to what extent, a single specimen can be treated in morphometric analyses as a representative of a greater group. All the stromatoporoids exposed on such a surface represent the same moment in the sedimentary development of the area.

The main morphometric features of the stromatoporoids proved to be rather uniform. The V/B ratios, irrespective of which B parameter is chosen, show a limited range of values, and this generally does not effect the environmental interpretations (Table 1). Similarly, the observed non-dimensional macroscopic features, such as the character of the upper surface, show no variation within the groups studied. It can thus be concluded that in the case of these parameters a few or even single specimens can be treated as representatives of the whole population.

The situation is different when the range in values of the elongation ratio (*ER*) is analyzed. In both settings, both for single domes and for multidome aggregates, the range in *ER* values is very wide, and round specimens ($ER < 1.25$) can occur close to those that are very distinctly elongated ($ER > 2$).

Distribution studies. The data obtained for specimens with elongation ratios exceeding 1.5 (distinctly elongated and very distinctly elongated) show a distinctly better consistency ratio than their counterparts with $ER < 1.5$ (Table 2). This indicates that the elongation azimuth studies should be limited to specimens with a distinct *ER*. The existence of clear lineaments with azimuths corresponding to the elongation directions of the stromatoporoids verifies their value in environmental interpretations.

DISCUSSION AND INTERPRETATION OF THE RESULTS

Panek

The stromatoporoids studied in Panek constitute a uniform group in terms of their growth forms (Table 1). Both single domes and multidome aggregates adopted mainly laminar and low domical shapes with smooth upper surfaces. Where visible, the latilaminae show an enveloping arrangement, and the initial surface is either flat or shows minor initial elevations. Individual specimens remain small and reached limited heights above the sediment surface. Most of the stromatoporoids occurred in aggregates composed of several coalesced domes that covered larger areas of the sea floor but remained low. Elongation of both individual domes and of aggregates is highly variable and ranges from round to very distinctly elongated. The elongation azimuths show poor consistency (Table 2), and no clear distribution patterns can be discerned (Text-fig. 5B).

The above set of features points to a very calm setting with limited sediment input. Low growth forms with smooth upper surfaces and without visible sediment increments indicate that there was apparently no risk of burying by sediments (e.g. BRAUN & *al*. 1994; KERSHAW 1998; SANDSTRÖM & KERSHAW 2002; ŁUCZYŃSKI 2005). Both the growth forms and distribution patterns show no indications of water turbulence. A lack of overturned or redeposited specimens shows that the stromatoporoids grew under calm water conditions. Individual domes and aggregates show no pronounced asymmetry in any consistent direction, which would be interpreted as an effect of directional water flow (e.g. BROADHURST 1966). The same conclusion is supported by inconsistent elongation and elongation azimuth results, and by a lack of a clear distribution pattern. It may be speculated that the relatively small dimensions of the individual domes resulted from restricted circulation and an impoverished supply of nutrients. The very limited heights of both domes and aggregates may additionally indicate a very shallow water setting. The microfacies of the limestone layer capped by the palaeobottom surface consists of mudstones and wackestones with amphiporid and brachiopod debris (numerous *Emanuella* shells), which corresponds well with the above interpretation.

In Panek, in addition to the stromatoporoids exposed on the palaeobottom surface, massive stromatoporoids form numerous other accumulations of various types. The most common are parabiostromes (*sensu* KERSHAW 1994) up to more than two metres thick, composed of redeposited and/or overturned specimens. The matrix of these beds is bioclastic and composed mainly of amphiporid and crinoidal debris. The parabiostromes are commonly underlain by erosion surfaces. The exposed section also contains a number of autobiostromes (autoparabiostromes), consisting mainly of *in situ* massive and dendroid stromatoporoids accompanied by corals, brachiopods, large megalomid bivalves, gastropods and ostracods. The stromatoporoid-bearing facies interrupt the prevailing shallow-water deposition of laminites, micritic limestones with fenestral structures (birdseyes) and amphiporid limestones. Such a facies association is typical of a shallow-water setting with generally calm and quiet water conditions, but intermittently punctuated by high-energy episodes, such as storms or tsunami wave surges. The calm periods enabled the development of *Amphipora* meadows and stromatoporoid autobiostromes, and the deposition of laminites and limestones with fenestral structures, whereas the high-energy events resulted in the formation of erosional surfaces and the deposition of thick parabiostromal accumulations composed of exhumed and redeposited stromatoporoids.

Stromatoporoids from the Upper Sitkówka Beds were subjected to earlier morphometrical analyses. The results of the measurements performed in the nearby Sitkówka-Kowala Quarry (ŁUCZYŃSKI 1998), where there is a predominance of high profile forms (high domical, extended domical and bulbous), differ dramatically from the data obtained here. The same also applies to stromatoporoids from Panek that were studied on polished slabs used as decorative stones in public buildings in Poland (ŁUCZYŃSKI 2003, 2006). A large percentage of those specimens show high profiles, a non-enveloping arrangement of the latilaminae, anchors in initial surfaces and indications of redeposition. All this indicates an environment that was punctuated by high-energy episodes with rapid sediment input.

The difference between the morphometric features of the stromatoporoids from the palaeobottom surface and of those in other parts of the section reflects the variability in sedimentary environment of the deposits exposed in the quarry. The Upper Sitkówka Beds are interpreted as a shoal domain (KAŹMIERCZAK 1971; SZULCZEWSKI 1981; RACKI 1993) neighbouring the so-called Dyminy reef (RACKI 1993; RACKI & SOBSTEL

2004). Their depositional depth is estimated as no more than 10 m (Kaźmierczak 1971; Racki 1993). The environmental variability was connected with recurring storms or perhaps tsunami wave surges that invaded a generally calm and sheltered area, but may also be attributed to rapid oscillations in sea level (Kaźmierczak 1971). The stromatoporoid community on the palaeobottom surface grew during a particularly calm period, whereas most of the other accumulations formed under the influence of more turbulent water conditions. Moreover, the morphometric features of redeposited stromatoporoids reveal the sedimentary environment of their original growth settings rather than that of the places of their final accumulation (Skompski & *al*. 2008).

Skały

In terms of growth forms, the stromatoporoids exposed in Skały constitute a uniform group (Table 1). A large percentage of the specimens form multidome aggregates. Both single domes and aggregates show mainly low domical forms with smooth upper surfaces. Much less uniform are the actual dimensions of the stromatoporoids, with some specimens and aggregates attaining particularly large sizes. Both domes and clusters show variable elongation ratios, ranging from round to very distinctly elongated, with a predominance of distinctly elongated forms. The elongation azimuth is very consistent and, moreover, coincides with clear lineaments marked by stromatoporoid distribution along parallel, evenly spaced lines.

The above features are in many aspects similar to those in Panek. Low growth forms and a lack of evidence of redeposition indicate a calm setting. Smooth upper surfaces without sediment increments indicate a low and stable deposition rate. The two localities differ, however, in the dimensions of the stromatoporoids, and particularly in their elongation and distribution patterns.

The distinct elongation of the stromatoporoid domes and aggregates along a preferred azimuth indicates a consistent directional water flow. Interpretations of water flow were based hitherto mainly on symmetry versus asymmetry of the stromatoporoid skeletons (Broadhurst 1966, Kapp 1974, Kershaw 1998, Sandström 1998). The asymmetry was interpreted either as an effect of burying parts of the skeleton by sediments on their "windward" sides (Broadhurst 1966) or, in contrast, by leaning of the stromatoporoids towards the water flow bringing nutrients (Kapp 1974). No clear asymmetry pattern is, however, visible in the group studied. This leads to an assumption that the predominant elongation was perpendicular to the water flow rather than parallel to it. Such a conclusion is also supported by the roughly even spacing of the lineaments along which the stromatoporoids are distributed. The average distance of c. 60 cm between adjacent lines may correspond to big ripples on the sea bottom perpendicular to the water flow. Their elevation in relation to the intra-ripple depressions provided a better setting for the stromatoporoids as it prevented them from being buried by sediments, and possibly also provided a better nutrient supply. The limited width of the elevations enhanced the elongation of the stromatoporoids along their axes and also caused coalescence of closely growing specimens along the same direction, which further strengthened the elongation effect. The less clear lineaments oblique to the main elongation direction (Text-fig. 12) may represent interference ripples.

A continuation of the succession in the river ravine where the palaeobottom surface was studied is readily accessible in the nearby abandoned quarry. The pronouncedly cyclic succession of the Crystalline Dolostone Member of the Wojciechowice Formation exposed there is interpreted as representing shallow water, tide-dominated, low energy environments intermittently affected by high-energy events. An idealized shallowing-upward cyclothem is composed of three units representing environments ranging from deeper subtidal to supratidal (Skompski & Szulczewski 1994). Facies with massive, largely overturned and abraded stromatoporoids that reflect deeper subtidal settings recur several times throughout the succession exposed in the main quarry (mainly in its lower part). The accompanying fauna of brachiopods (*Bornhardtina* and *Emanuella*; Biernat 1953; Skompski & Szulczewski 1994) and scarce amphiporoids and gastropods is characteristic of restricted environments. The sequence is strongly dolomitized and composed mainly of crystalline dolostones, which suggests sabkha-type cyclicity.

The tidal context corresponds well with the stromatoporoid-based interpretation presented above. The palaeosurface represents calm sedimentation in a subtidal setting. A shallow-water subtidal environment is characterized by stabilized bimodal landward and seaward water flow. The bimodality of the flow was responsible for the lack of pronounced asymmetry of the stromatoporoid domes. Early dolomitization enhanced lithification and enabled stabilization of the ripples. Tidally induced water movements and currents brought rich nutrients, which enabled the growth of large stromatoporoid domes. The predominant lineation and elongation azimuth of c. 90-100° indicates that the water flow was meridional, according to present day orientations.

CONCLUSIONS AND SUMMARY

Detailed studies of stromatoporoids exposed on exhumed palaeobottom surfaces in the Skały and Bolechowice-Panek quarries allow for the following conclusions to be drawn:

1. Morphometric measurements of stromatoporoids based on vertical cross sections cannot reveal the whole complexity of their shapes. The obtained results may, moreover, be seriously biased, which may negatively influence the accuracy of stromatoporoid-based palaeoenvironmental reconstructions. Specimens exposed on exhumed paleobottom surfaces offer a better insight into their growth forms and distribution patterns, and are therefore particularly valuable for morphometric studies.
2. Direct access to three-dimensional stromatoporoid skeletons necessitates the use of new measurement methods and allows the introduction of new parameters: horizontal length – B_{max} and horizontal width – $B_{\perp max}$, elongation ratio – $ER = B_{max}/B_{\perp max}$ and elongation azimuth – α.
3. A formula $\langle B_n \rangle \approx Bs_{max}\left[1-\frac{1}{4}k^2\right]$,

   where $k^2 = 1 - \frac{Bs_{max}^2}{Bs_{\perp max}^2}$ allows recalculation of the basal stromatoporoid dimensions obtained by the two methods. The vertical heights obtained by the two methods can be compared directly.
4. In Panek, stromatoporoid shape and distribution analyses indicate a very quiet, shallow water setting with a low and stable sedimentation rate. The palaeobottom surface studied represents a particularly calm episode, whereas most of the other stromatoporoid accumulations exposed in the quarry formed under the influence of more turbulent water conditions.
5. In Skały, stromatoporoid shape and distribution analyses indicate a subtidal setting with bimodal water flow and a limited sediment supply. The stromatoporoid domes located themselves on parallel ripples, probably to escape burying by deposits accumulating in inter-ripple depressions.

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