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Stromatoporoid growth orientation as a tool in palaeotopography: a case study from the Kadzielnia Quarry, Holy Cross Mountains, central Poland

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ABSTRACT:

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Growth orientation of stromatoporoids has allowed reconstruction of the palaeotopographic position of a large Frasnian organic buildup exposed in the Kadzielnia Quarry in the Holy Cross Mountains, central Poland. Two main, mature stage, stromatoporoid growth modes have been discerned: erect and semi-buried. The growth orientations of the stromatoporoids were studied in 17 sections that expose four different facies in the quarry. The inclinations of the basal surfaces of specimens and direction of the growth axes were measured and compared in terms of different growth modes, facies and positions in the organic buildup. The results support the earlier opinions that the inclined contact between the Kadzielnia stromatoporoid-coral limestones and the detrital limestones is depositional and represents an inclined depositional surface, and that the Kadzielnia buildup developed in a calm water setting below the storm wave base on a slope or at its foot. General conclusions emerging from the studies are: 1) stromatoporoid growth directions hold a key to reconstructing ancient topography; 2) erect stromatoporoids that grew on inclined surfaces changed the growth axes to the vertical direction during their growth; and 3) stromatoporoid growth directions and particularly the changing mode of growth of erect forms support the view that Palaeozoic stromatoporoids acted photosensitively.

Key words: Stromatoporoidea; Growth direction; Orientation; Palaeotopography; Devonian; Kadzielnia organic buildup; Holy Cross Mountains.

INTRODUCTION

Stromatoporoid morphological features provide much useful information on the sedimentary environment in which the stromatoporoid organism grew (e.g., Meyer 1981; Kershaw 1984, 1990, 1998; Kano 1990; Königshof *et al.* 1991; Sandström 1998; Kershaw and Brunton 1999; Sandström and Kershaw 2002, 2008; Łuczyński 2003, 2006; Kershaw *et al.* 2006; Königshof and Kershaw 2006). Attributes such as shape profile, arrangement of latilaminae (major growth bands within the skeleton), surface character, symmetry versus asymmetry, and type of initial growth surface can be used to interpret issues such as depositional rates, substrate consistencies and patterns of water turbulence. Stromatoporoid morphometry is potentially helpful in cases of recrystallized and/or dolomitized limestones, where the primary sedimentary structures and microfacies have been obliterated in the alteration processes.

In the present paper, stromatoporoid morphometry was studied to determine the environmental development of a large Frasnian organic buildup exposed in the Kadzielnia Quarry in the Holy Cross Mountains (HCM) in central Poland. The so-called Kadzielnia Limestone (Member) of Kadzielnia Quarry are a unique facies in the Holy Cross Devonian, and the quarry is the only certain place in the western part of the HCM where a large (more than 50 m thick) massive organic buildup composed of stromatoporoid-coral limestones is exposed (e.g., Szulczewski and Racki 1981, Hoffman and Paszkowski 1992). The closest possible equivalent in the HCM is exposed in the Karwów Quarry in the easternmost part of the region (Samsonowicz 1934, Łuczyński 1998) where, however, the rocks were subjected to intensive dolomitization obscuring the original sedimentary facies. Smaller bioherms and "biohermal-type limestones" (*sensu* Szulczewski and Racki 1981) of various compositions, and no more than a few metres high, have also been described from localities including the Kowala railway cutting, Wietrznia Quarry, Jaźwica Quarry-Łgawa Hill, Wola Quarry and Cmentarna Hill (Racki 1981, Szulczewski and Racki 1981, Racki *et al.* 1993). Most of them were, however, only temporarily visible in active quarries and are now definitely destroyed.

The massive limestones exposed in the Kadzielnia Quarry have been a subject of numerous descriptions (e.g., Szulczewski 1971, 1979, 1981, 1995a; Szulczewski and Racki 1981; Narkiewicz 1988; Racki 1993), but several questions concerning the nature of the buildup, its palaeogeographic and palaeotopographic position and relationship to neighbouring Frasnian deposits remain unresolved (cf. Szulczewski 1981, Narkiewicz 1988, Racki 1993). This paper is an attempt to present additional arguments relating to these questions based on the stromatoporoid studies.

The morphometrical features of stromatoporoids from the Kadzielnia buildup were first studied by Kaźmierczak (1971). Łuczyński (1998) has presented results of morphometrical measurements of the stromatoporoid assemblage from the Kadzielnia Limestone that were made according to the parameterization method introduced by Kershaw and Riding (1978). Generally these results point to an environment with a high but variable rate of sediment supply.

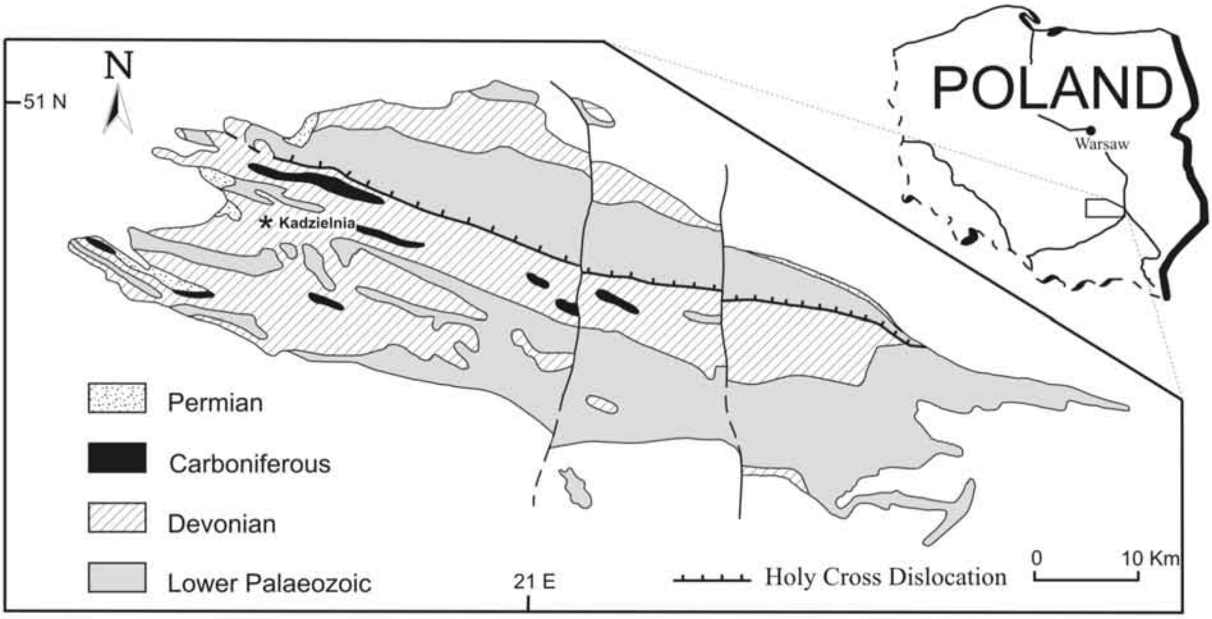
The author's previous studies (Łuczyński 1998) revealed that the Kadzielnia Limestone abounds in stromatoporoid specimens with a great variety of basic morphometrical parameters, such as shape profiles and arrangement of latilaminae. Different growth forms show various responses to changing environmental conditions. In the present paper special interest is paid to differences in distribution patterns of the various morphotypes within the organic buildup. Since that work, the parameterization method has been improved by adding new attributes (such as the types of initial surfaces) and by redefining the old parameters (Łuczyński 2003, 2005, 2006). Here the analysis concentrates, however, on the stromatoporoid growth direction of *in situ* specimens, as this is the main key to deciphering the position of the organic buildup.

Three main aspects of stromatoporoid growth orientation studies proved to be particularly useful: (1) comparison of growth orientation of stromatoporoids in bedded and unbedded Frasnian facies within the quarry; (2) distinguishing the erect forms from the semi-buried forms and comparing their growth directions; and (3) analysing the variability patterns of stromatoporoid growth directions in different parts of the buildup. Detailed analyses of these features enabled conclusions on the palaeotopographic position and orientation of the Kadzielnia buildup to be drawn. The Kadzielnia studies also allowed the formulation of some general principles governing the orientation of stromatoporoids colonizing an inclined sea bottom, which may be useful when applied to other stromatoporoid-bearing facies.

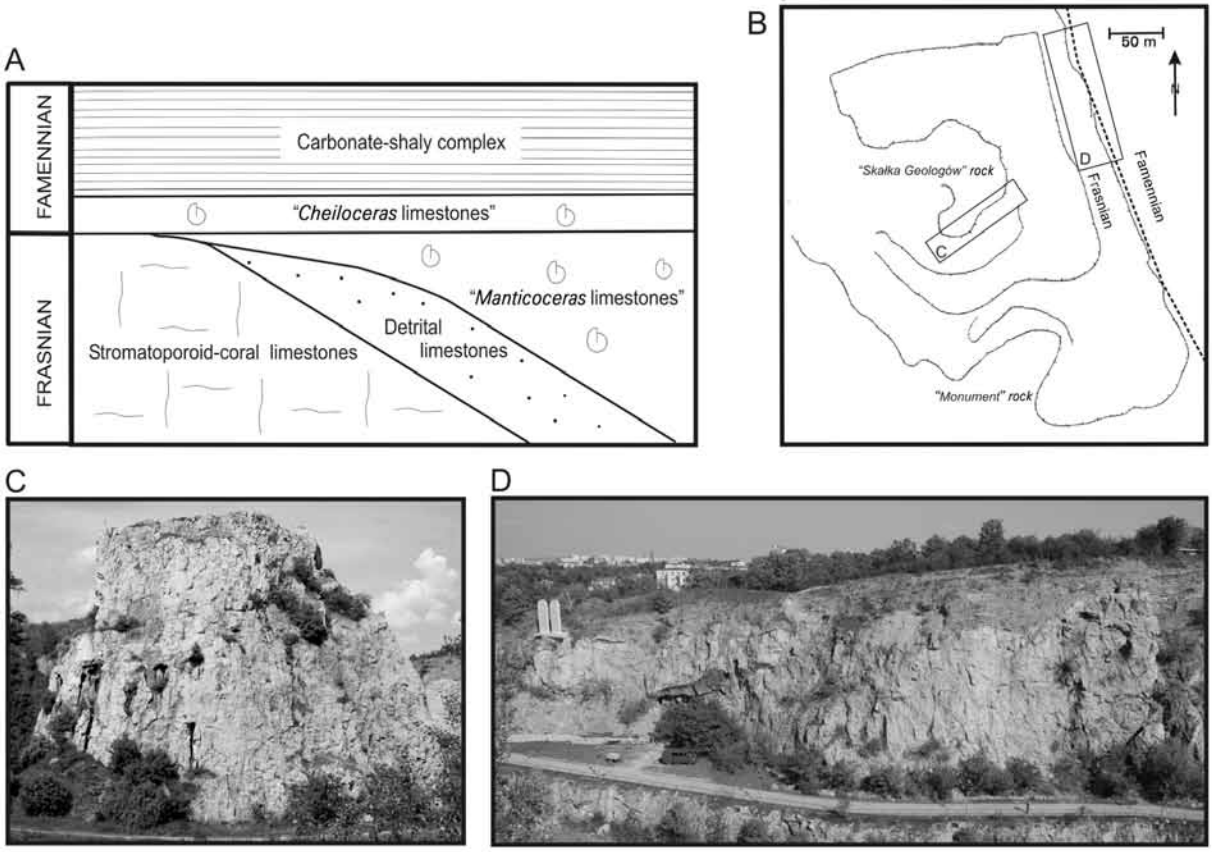
GEOLOGICAL SETTING

The abandoned Kadzielnia Quarry is a natural reserve located in the town of Kielce in the Holy Cross Mountains in central Poland (Text-fig. 1). The quarry is one of the best known exposures of the Holy Cross Upper Devonian with outcropping Frasnian and Famennian deposits (Text-fig. 2A and B). The large Frasnian organic buildup (over 50 m thick) is exposed in the quarry and is unique for the region. The locality belongs to the so-called Kadzielnia Range, which forms an approximately east-west alignment of Devonian outcrops.

The Palaeozoic of the HCM consists of two main tectonic units: the southern Kielce unit and the northern Łysogóry unit. The two regions are separated by the Holy Cross Dislocation (Text-fig. 1) and differ distinctly in facies development, thicknesses of particular stratigraphic units and the completeness of the stratigraphic record. In terms of facies, the Holy Cross Devonian is subdivided into three zones (Szulczewski 1977): northern (Łysogóry), central (Kielce) and



Text-fig. 1. Location of the Kadzielnia Quarry on a sketch geological map of the Holy Cross Mountains. Insert map shows the position of the Holy Cross Mountains in Poland



Text-fig. 2. Kadzielnia Quarry. A – General pattern of facies exposed on the eastern wall of the quarry (after Szulczewski 1981; simplified); B – Plan view of the quarry; the dotted line marks the boundary between the Frasnian and the Famennian sediments; C – "Skałka Geologów" rock (rectangle C on Fig. B); D – View of the eastern wall of the quarry seen from the "Skałka Geologów" rock (rectangle D on Fig. B) southern (Chęciny-Zbrza). The Kadzielnia Quarry belongs to the Kielce zone in both tectonic and facies senses. During the Frasnian the area was located near the northern edge of a shallow-water carbonate platform surrounded by deeper inner-shelf basins (Szulczewski 1995b). In the Famennian the platform became drowned and pelagic facies began to dominate.

The stratigraphic and facies framework of the rocks cropping out in the Kadzielnia Quarry has been presented in detail by Szulczewski (1971, 1979, 1981, 1995b). The Frasnian and the Famennian are separated by a stratigraphic gap and distinct unconformity (Text-fig. 2A). The Frasnian of the quarry consists of three units: massive (and partly faintly bedded) stromatoporoid-coral limestones (Kadzielnia Limestone Member of Narkiewicz *et al*. 1990), detrital limestones and the so-called "*Manticoceras* limestones" (Text-fig. 2A). The boundaries between the units are not horizontal but inclined to the south (Text-figs 2A, D and 15). The average apparent inclination of the boundary between the stromatoporoid-coral limestones and the detrital limestones as seen on the western wall of the quarry is 11ºS.

The Kadzielnia Member is represented by a large organic buildup composed of bindstones *sensu* Embry and Klovan (1971). Stromatoporoids and corals, although present in abundance, occur scattered in the matrix and did not construct a rigid framework (e.g., Szulczewski and Racki 1981). The matrix deposit is mainly micritic (mudstones and wackestones) with microbial clotted and spongiostromid fabrics (Bednarczyk *et al.* 1997a, Hoffman and Paszkowski 1992), although in some parts grainstones are also present. Apart from massive stromatoporoids and corals, the facies contains a diverse fauna, including: brachiopods, which often occur in nests (Racki *et al.* 1993), rich debris of echinoid fragments (in grainstones), amphiporoids, abundant and diverse foraminifers, ostracods and various microproblematica (Szulczewski and Racki 1981, Racki 1993, Bednarczyk *et al.* 1997a). Laterally, in the eastern part of the quarry ("Skałka Geologów" rock; Text-fig. 2B and C), the massive limestones pass into faintly bedded stromatoporoid-bearing facies.

The Kadzielnia Limestone is generally interpreted as a mud mound (or reef mound). Bednarczyk *et al.* (1997a) have described the buildup as a cryptomicrobial mud mound. To some extent the facies resembles those from the Frasnian mounds of the Ardennes in Belgium (comp. Da Silva and Boulvain 2004, Boulvain 2007, Boulvain and Da Silva 2008). In palaeogeographic interpretations the Kadzielnia mound is located on a gentle slope of the Dyminy reef, or at its foot, and is thought to have formed in a relatively calm setting, away from the zone of active wave action (Kaźmierczak 1971, Szulczewski 1971, Szulczewski and Racki 1981, Narkiewicz 1988). Racki (1993), applying the bathymetrical model of Embry and Klovan (1972), has considered the Kadzielnia buildup to have occupied a midslope subturbulent zone at depths of 10–20 metres.

The detrital limestones that are in contact with the Kadzielnia Member on the western wall of the quarry are developed as thick-bedded calcarenites and calcirudites, with abundant detritus of crinoids and brachiopods accompanied by intraclasts and pellets, but with only scarce stromatoporoids and corals (Szulczewski 1971). Bednarczyk *et al.* (1997b) have described this facies as a debris reef with microbial patch reefs. According to Szulczewski (1981) such a composition of the detrital material indicates that these limestones did not form from the destruction of the stromatoporoid-coral limestones. The "*Manticoceras* limestones" are developed as faintly bedded micritic limestones with internal breccias, devoid of stromatoporoids and corals, but containing a pelagic fauna including goniatites.

The above-described pattern of Frasnian facies exposed in the main (eastern) wall of the quarry (Text-fig. 2A) is interpreted (Szulczewski 1981, 1995a) as a progradational sequence, which is represented by an organic buildup (Kadzielnia Limestone), by detrital deposits accumulating on its slope (detrital limestones), and by pelagic limestones forming offshore ("*Manticoceras* limestones"). The inclined boundaries between particular Frasnian lithosomes are thus depositional, and the angular disconformity between the Frasnian and the Famennian is only apparent. Block tectonic movements displacing the Frasnian/Famennian boundary are, however, clearly visible in the quarry. Tectonic movements associated with the Frasnian-Famennian boundary were common in the Holy Cross area (Szulczewski 1971, Racki 1998, Lamarche *et al.* 2003, Narkiewicz 2007). The weak discordance separating the Frasnian and the Famennian was connected with partitioning and drowning of a carbonate platform, and has been described in detail from the Ostrówka Quarry in the south-western part of the HCM by Szulczewski *et al.* (1996). Tectonic instability in the Kadzielnia area during the Frasnian and the Famennian is indicated by the occurrence of a number of generations of neptunian dykes, filled by deposits ranging in age from Frasnian to Carboniferous (Szulczewski 1971, 1979; Łuczyński and Szulczewski 2003).

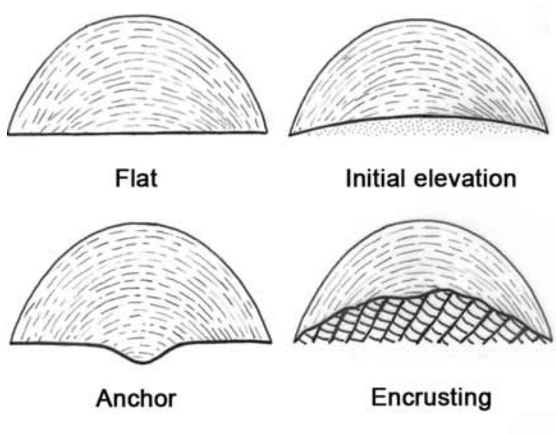
APPLICATION OF STROMATOPOROID GROWTH DIRECTION STUDIES TO RECONSTRUCTING THE TOPOGRAPHIC POSITION OF THE ORGANIC BUILDUP – CONCEPTUAL FRAMEWORK

The palaeotopographic position and orientation (dip) of the Kadzielnia Limestone can be determined in various ways. The problem can be approached using both stratigraphic and tectonic methods.

Stromatoporoids may serve to determine the orientation of rocks in various ways. Together with other sessile benthic organisms, e.g. tabulate and rugose corals, the synsedimentary orientation of the deposits may be determined on the basis of the growth direction of *in situ* specimens (e.g., Hodges and Roth 1986). In the case of stromatoporoids several problems arise, because the stromatoporoids often change growth direction during their development, which on the one hand makes the determination more complicated, but on the other, opens up the opportunity for proposing a wider range of alternative suggestions.

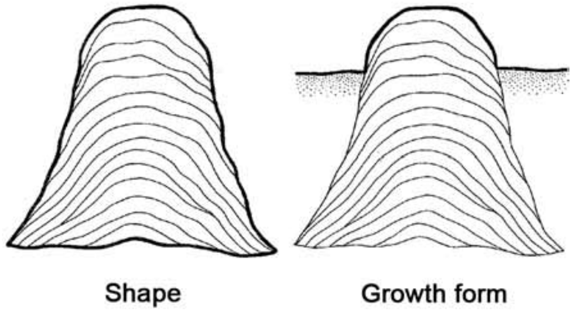
The systematic position of the Stromatoporoidea is still a subject of controversy (cf. Stearn *et al.* 1999; Kaźmierczak 2003). Regardless of the interpretation, as has been several times indicated in numerous papers (e.g., Stearn 1993; Wood 1990, 1991; Stearn and Picket 1994; Swan and Kershaw 1994; Kaźmierczak 1976, 1980; Kaźmierczak and Kempe 1990), stromatoporoids had flexible growth habits and were capable of developing a wide variety of growth forms that seem to be largely dependent on the range of differing sedimentary conditions. Stromatoporoid morphometric features are therefore interpreted in terms of various palaeonvironmental factors. One of the stromatoporoid features that can be interpreted in such terms is the growth orientation – the direction of consecutive growth stages in relation to the basal surface. Among the factors determining stromatoporoid growth direction are: directional water flow (see below), competition, directional light and nutrient supply, as well as the inclination of the substrate on which the specimens grew. The last one is the most important factor in the context of this paper.

The type of initial surface of stromatoporoids is dependent mainly on the substrate consistency. Stromatoporoid preferences for substrate type have been discussed by Kano (1990); however, his terminology and approach has been criticised by Kershaw (cf. Kershaw 1991, Kano 1991). Generally it may be assumed that the basal surface of the stromatoporoid coincided with the sea bottom, although examples of cavities beneath stromatoporoid skeletons occupied by cryptic fauna are known (Kershaw 1980, Kershaw *et al.* 2006). The basal (or initial) surfaces adopt various outlines that Łuczyński (2003) has distinguished into three main types – flat, initial elevation and anchor (Text-fig. 3). Encrusting specimens are treated as a separate group, in which the outline of the basal surface drapes directly over the top of the foreign body (Text-fig. 3). Only in the case of a flat base can the initial surface of a stromatoporoid be assumed to be parallel to the sea-bottom surface. In the cases of an initial elevation or an anchor, the discrimination between the basal surface and the sides of the skeleton can be made based on the arrangement of the latilaminae. In these cases, a straight line between the two extreme limits of the basal surface as seen in cross section represents the basal dimension (*D*) and can be treated as an approximation to the average surface of the sea bottom (see Łuczyński 2005).

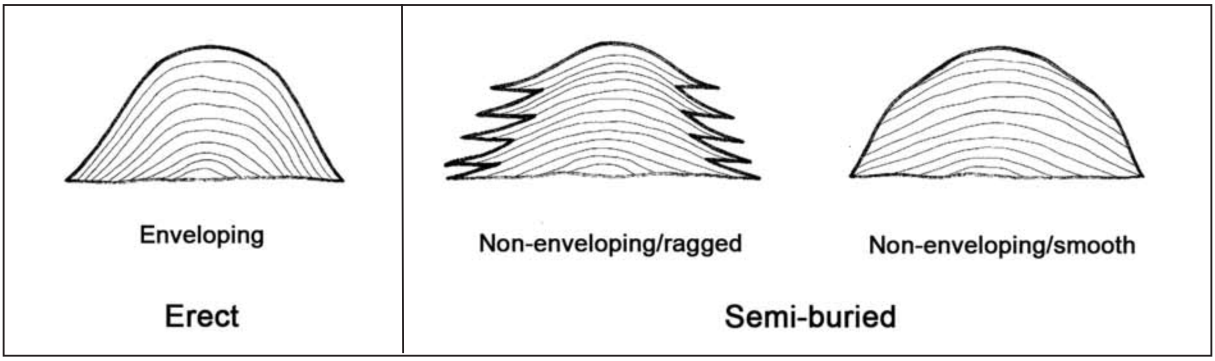


Text-fig. 3. Stromatoporoid initial surfaces

Among stromatoporoid attributes considered to have environmental significance are: the shape profile of the whole skeleton and the profile of the living surface above the sea bottom (Text-fig. 4). The latter is defined as the growth form. These two attributes differ distinctly in those specimens that are characterized by a high burial ratio (*BR*), describing how large a part of the skele-



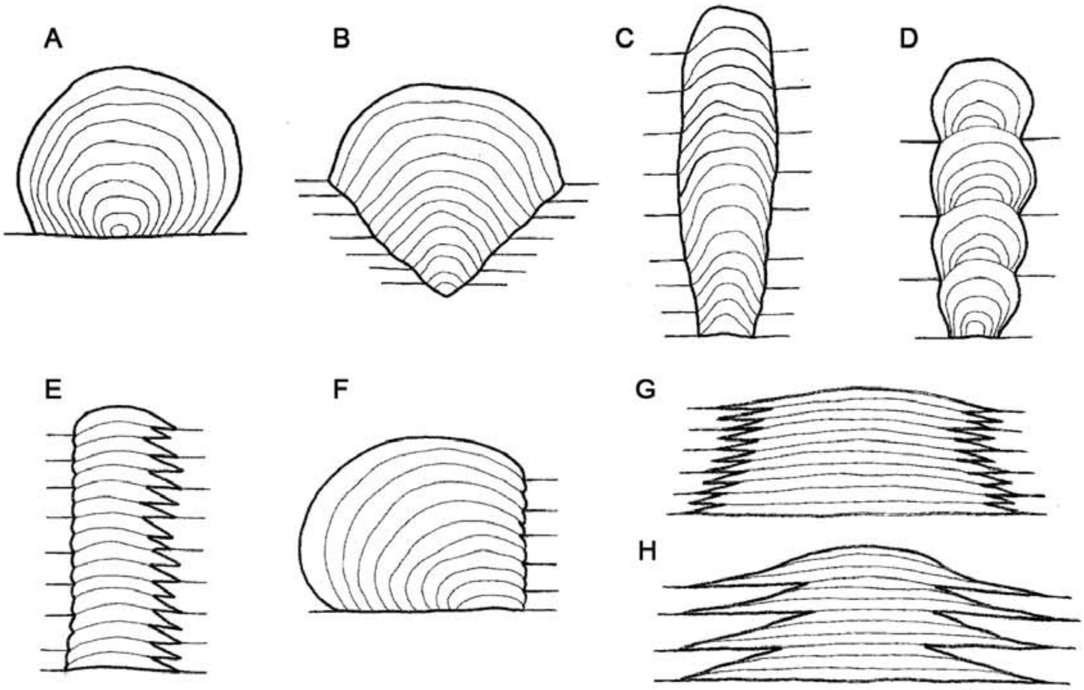
Text-fig. 4. Shape of the skeleton and growth form (living surface profile) of a stromatoporoid specimen



Text-fig. 5. Erect and semi-buried stromatoporoids. The ascription of a stromatoporoid to one of these categories is based on the arrangement of the latilaminae – enveloping and non-enveloping. Semi-buried stromatoporoids display two characters of the upper surface – ragged and smooth

ton was hidden beneath the sediment during consecutive growth stages (see Łuczyński 2006). The relationship of a growing stromatoporoid to the sediment that accumulated around it can be reconstructed by tracing the arrangement of the latilaminae and the character of the upper surface of the skeleton (Text-fig. 5). An enveloping arrangement is where each successive latilamina covers (or envelops) the preceding latilamina of the skeleton, as opposed to the non-enveloping arrangement, where the marginal part of the preceding latilamina is uncovered by the succeeding latilamina There are two basic types of a non-enveloping arrangement. The first occurs where successive latilaminae extend over the sediment, giving the skeleton a ragged appearance (non-enveloping/ragged). The second type occurs where the consecutive latilaminae extend to the lateral margins of the skeleton but only partially overlap each preceding latilaminae (non-enveloping/smooth).

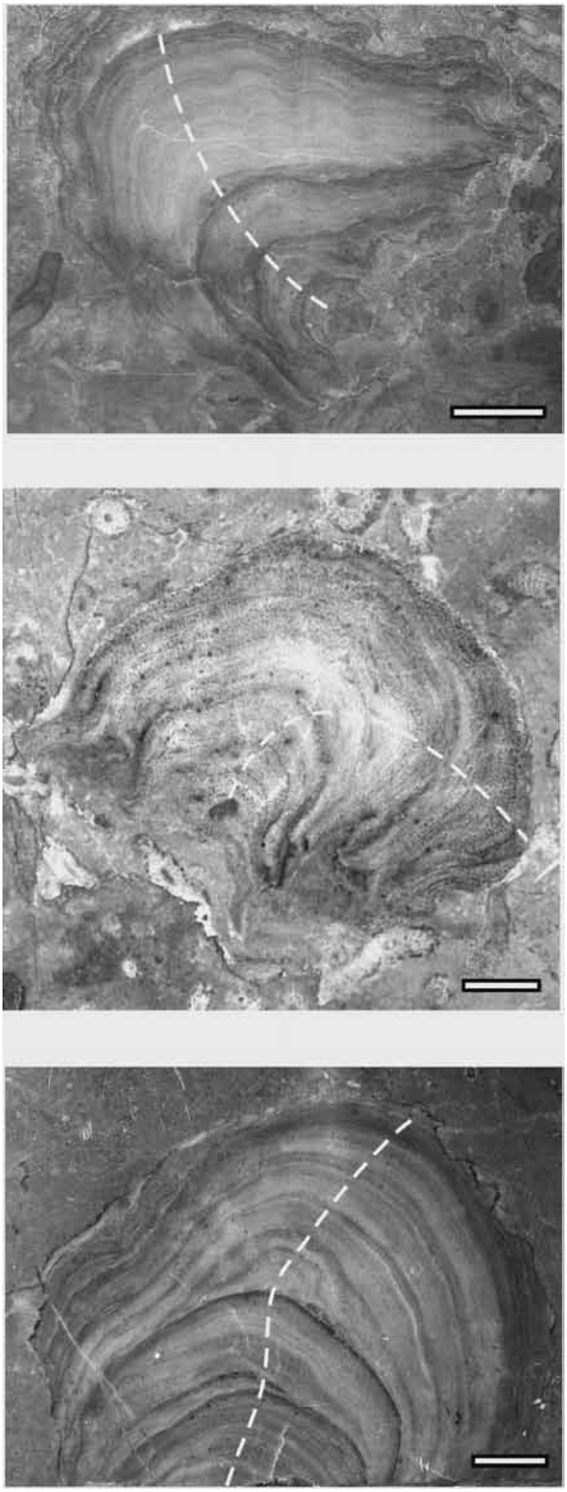
In the first two cases (enveloping and non-enveloping/ragged) the external limits of a selected latil-



Text-fig. 6. Schematic drawings of selected types of stromatoporoid growth depending on the growth mode and dynamics of sediment accumulation; A, B – erect specimens with enveloping arrangements of latilaminae that grew during suspended (A), or limited and stable sediment supply (B), C – a semi-buried specimen with a smooth upper surface that grew during fast, but stable sediment supply, D – a semi-buried specimen with mixed arrangement of latilaminae that grew during punctuated sediment supply, E, F – asymmetric semi-buried specimens that grew during sediment supply from one direction, G, H – semi-buried specimens with a ragged upper surface that grew in conditions of unstable rates of sediment supply amina mark the position of the sediment surface at the moment of its formation. The enveloping varieties could develop only with very limited sediment supply. The non-enveloping/ragged forms suffered repeated partial burial of the marginal parts of their upper surfaces. Such specimens, although their skeletons could adopt various shapes, including high profile varieties, usually had a low profile of growth form at every latilamina stage of its growth. In the case of the non-enveloping/smooth forms, the exact relationship between the arrangement of the latilaminae and the surrounding sediment remains uncertain – whether they grew as sediment gradually accumulated, or whether they grew up as erect columns that were subsequently buried by sediment. Łuczyński (2003) has presented specimens with overall smooth upper surfaces, which include minor raggedness, and small sediment increments between the latilaminae. Young and Kershaw (2005) noticed that most latilaminae visible within stromatoporoid skeletons pass laterally into sediment incisions at ragged margins, and concluded that latilaminae are not real density growth bands, but instead represent growth-interruption banding. This indicates that the mode of life of non-enveloping stromatoporoids with both ragged and smooth surfaces were rather similar in terms of gradual sediment coverage during their skeletal growth.

Stromatoporoids could adopt various arrangements of the latilaminae according to the sedimentary conditions, showing different growth phases, or even different arrangements on either sides of the same latilamina (see Łuczyński 2006, text-figs 9–11 therein). Some different styles of growth depending on the growth mode and the dynamics of sediment accumulation are presented in Text-fig. 6. Similar shapes were obtained by computer modelling of stromatoporoid skeletal growth (Swan and Kershaw 1994).

For the purposes of this paper two basic growth modes are recognized. The **erect forms** are here considered to be those specimens that show an enveloping arrangement of the latilaminae and thus are characterised by a low burial ratio (*BR*). Such forms grew as erect columns on the sea bottom (Text-fig. 5). The **semi-buried forms** are here regarded as those specimens that show a non-enveloping arrangement of the latilaminae (Text-fig. 5). They are characterised by a high burial ratio, which indicates that a substantial part of the skeleton was buried under the sediment surface during its consecutive growth stages. There is a whole range of intermediate varieties between these two modes, and an ideal example of the enveloping arrangement of latilaminae throughout the whole skeleton is rare. The ascription of a particular speci-

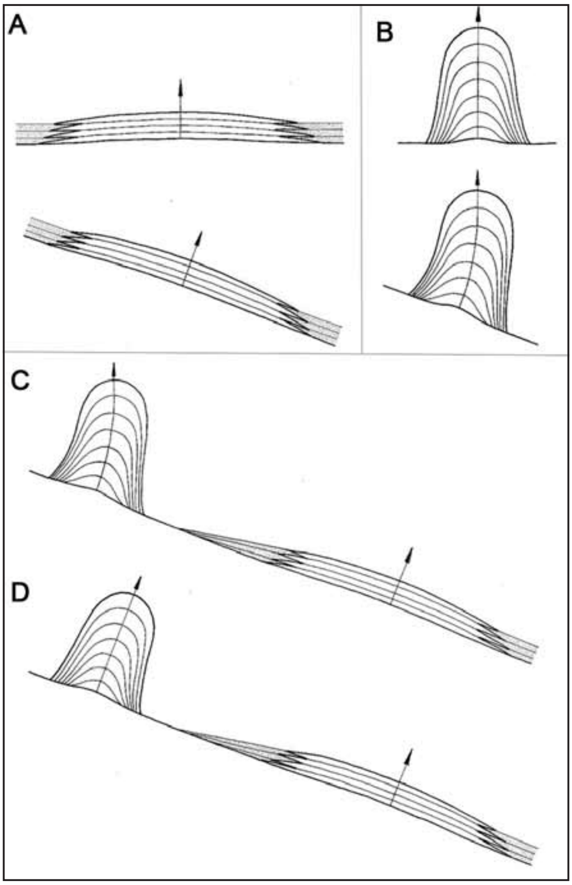


Text-fig. 7. Stromatoporoids with curving growth directions. Dashed lines (in white) mark the main growth directions of the three specimens. White scale bars are 2 cm long. Photographs of polished cross sections of specimens collected from the debris lying on the lowermost level of the Kadzielnia quarry men to an erect form had therefore to be made by means of the prevailing enveloping arrangement.

Generally, the growth axes of the stromatoporoids that mark the direction of the maximum growth (see Łuczyński 2005) are perpendicular to the skeletal bases. The growth axis, however, is not always straight (Text-fig. 7; see also examples in Łuczyński 2006). In the case of asymmetrical shapes the growth axis changes its direction. Previously this asymmetry was interpreted mainly as a result of directional water flow, e.g. bottom currents (Broadhurst 1966, Kapp 1974). Contradictory interpretations have been presented; one assuming that the curvature of the specimen is towards the direction of water flow from which the nutrients were derived (Broadhurst 1966), and the other assuming that the "windward" side of the skeleton tends to be buried by sediments brought with the current, which results in growth mainly towards the "leeward" side, and in curvature of the growth axis away from the direction of current flow (Kapp 1974). Most probably under different sedimentary conditions, and particularly where the supply of loose material is varied on the sea bottom, both interpretations may be correct. Such asymmetry, when observed in numerous simultaneously living, neighbouring specimens, may help in determining the dominant directions of water flow.

Directional water flow was, however, not the only cause of asymmetrical stromatoporoid growth. Another important factor was the inclination of the substrate on which the specimens grew. The stromatoporoids representing the two growth modes responded differently to this factor, as a consequence of different intensity of the sediment coverage. Semi-buried specimens grew in direct contact with the sediment surface, and therefore every latilamina (set of latilaminae) followed the outline of the sea bottom. The basal surface of the skeleton, as well as every other latilamina, remained therefore roughly parallel to the sediment surface, and the main growth axis remained perpendicular to it, even on slopes (Text-fig. 8A). Erect specimens, after the initial stage, in which they may resemble their semi-buried counterparts, tended to change their growth axis to the vertical direction. In the case of stromatoporoids growing on inclined surfaces this resulted in gradual change in the direction of the main growth axis, leading to the development of asymmetrical shapes (Text-fig. 8B). The curvature of the skeleton depended on the inclination of the slope.

The differences in growth directions between the erect and semi-buried specimens on inclined surfaces allow reconstruction of the inclination of palaeoslopes



Text-fig. 8. Erect and semi-buried stromatoporoids growing on flat and inclined surfaces. A – semi-buried specimen. B – erect specimen. C – erect and semi-buried specimens growing on an inclined depositional surface. D – erect and semi-buried specimens in tectonically inclined strata

and, more generally, offer the possibility of deciphering the palaeotopography of the basin. The proposed method, as with all morphometrical approaches to stromatoporoids, has to be based on a statistical study of large numbers of specimens, as drawing conclusions based on single specimens may be misleading. Several methods of approach were applied here:

- Different growth directions (directions of main growth axes) in the terminal growth phases of erect and semi-buried specimens indicate inclination of the surface on which the stromatoporoids grew. The angular difference between the two growth directions may be treated as an approximation to the slope inclination (Text-fig. 8C);
- Asymmetric erect specimens inclined in the same direction point to the inclination of the slope on which the stromatoporoids grew;
- The same growth direction of erect and semi-buried specimens indicates that the stromatoporoids grew

on a horizontal area of the sea floor. If in the outcrop the specimens are uniformly inclined, this indicates post-sedimentary tilting of the deposits (Text-fig. 8D);
– In the case of large bodies of massive limestones, such as an unbedded organic buildup, variations in the orientation of semi-buried specimens and variations in the asymmetry of erect forms in various parts of the buildup can help in reconstructing the outline of such a body;
– Variations in the relative abundance of erect and semi-buried forms in the different facies zones reflect the existing differences in sedimentary conditions.

MATERIALS AND METHODS

The basic morphometric features of the stromatoporoids from Kadzielnia were earlier described by the author (Łuczyński 1998) and compared with those from other selected localities in the HCM (Karwów and Sitkówka-Kowala quarries). The features then taken into account were: shape, dimensions and surface character. The assemblage studied consisted of low and high domical specimens with smooth and ragged surfaces. All the specimens occupied *in situ* positions and show no evidence of redeposition (overturning, breakage etc).

The assemblage of massive (non-dendroid) stromatoporoids described from the Kadzielnia Limestone Member is very rich and comprises the following species after Kaźmierczak (1971, 2003): *Actinostroma crassepilatum* (Lecompte), *Anostylostroma ponderosum* (Nicholson), *Pseudostromatoporella damnoniensis* (Nicholson), *Pseudostromatoporella huronensis* (Parks), *Stictostroma sociale* (Nicholson), *Stictostroma kolymense* (Yavorsky), *Stromatopora cooperi* (Lecompte), *Stromatopora undata* (Riabinin) and *Stromatoporella mudlakensis* (Galloway). *Actinostroma* is by far the most common. Similarly as with most other species, its skeletons display a wide range of shapes, termed by Kaźmierczak (2003) lamellar (tabular), bell-shaped and bulbous, which correspond respectively to laminar, domical and bulbous of Kershaw and Riding (1978) and Łuczyński (2005), and which fall into both the erect and semi-buried growth modes.

The present study focuses on stromatoporoid growth orientation and draws less attention to their exact shapes, discriminating only the erect and semi-buried forms. Therefore, the analysis could include many specimens that were previously (Łuczyński 1998) considered as not fulfilling all the required measurement preconditions. All specimens that show readable orientation on a roughly vertical section were taken into consideration. Because the abandoned Kadzielnia Quarry is now a natural reserve the investigation could only be made on already existing vertical (or close to vertical) rock walls. A total number of 317 stromatoporoids has been investigated, consisting of 196 semi-buried forms and 121 erect forms.

The stromatoporoids occur in the following four areas representing various parts of the Kadzielnia Limestone and its bedded stromatoporoid-bearing equivalents cropping out within the quarry (Text-fig. 9):

A) bedded facies on the slopes of the “Monument” rock and at the foot of the “Skałka Geologów” rock;
B) faintly bedded and unbedded facies of the “Skałka Geologów” rock;
C) massive Kadzielnia Limestone close to the northern entrance to the quarry (central part of the Kadzielnia buildup);
D) massive Kadzielnia Limestone in the central part of the quarry, close to the boundary with detrital limestones (peripheral parts of the Kadzielnia buildup).

The stromatoporoid assemblages from the four areas have been compared in terms of growth mode and orientation.

The stromatoporoid growth orientations have been studied on rock walls of 17 selected sections (Text-fig. 9). The general azimuths of these study sections have been measured and categorized into four groups:

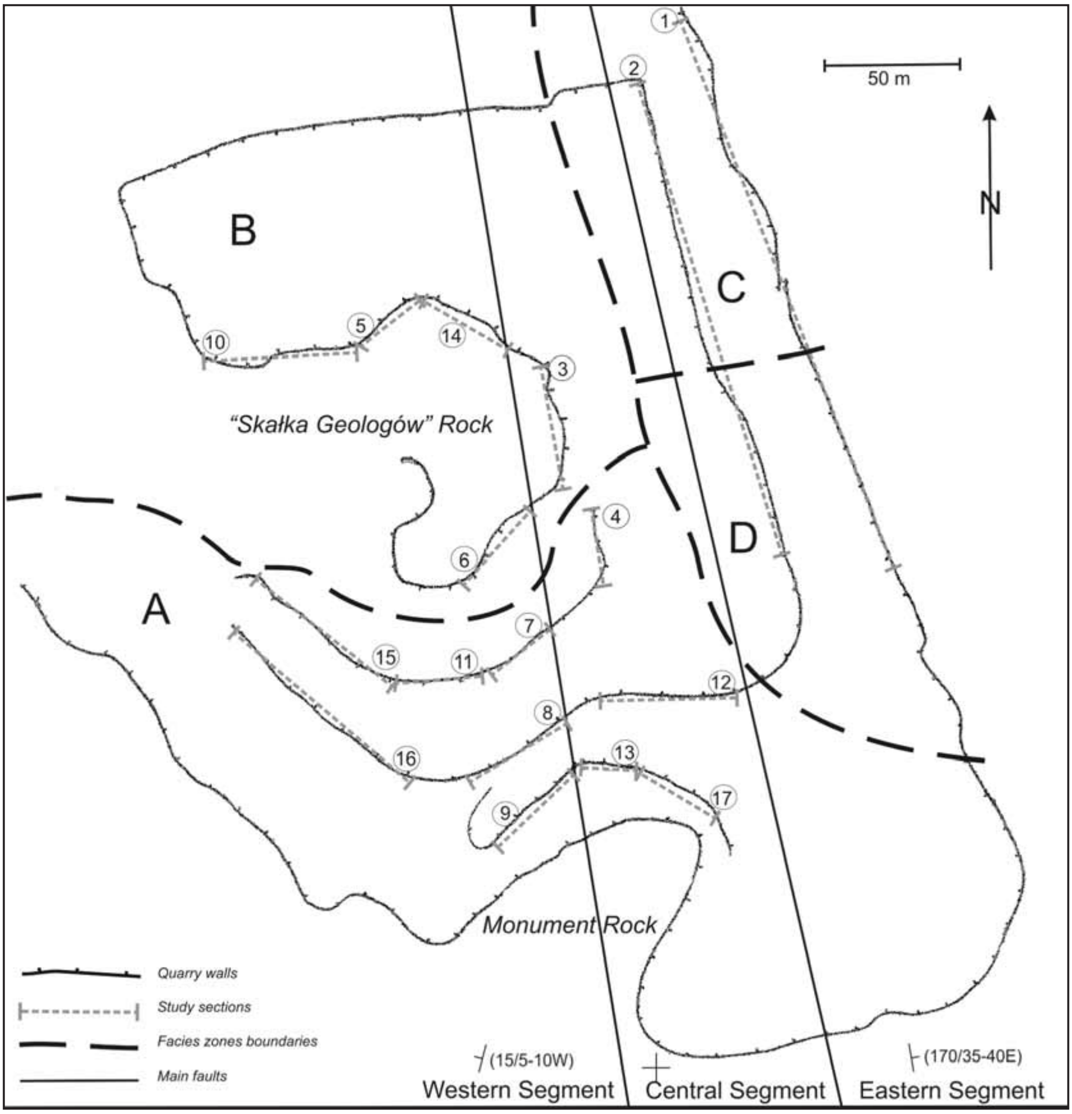
I. Sections 1–4 – azimuth 158–176,
II. Sections 5–9 – azimuth 45–64,
III. Sections 10–13 – azimuth 83–93,
IV. Sections 14–17 – azimuth 120–141.

The stromatoporoids exposed on rock walls with various azimuths present different cross-sections related to the tectonic orientation of the rocks and to their facies boundaries. Sections belonging to group I are particularly useful, as their azimuth is roughly perpendicular to the boundaries between the main Frasnian facies units cropping out in the quarry. Other section groups provide cross sections that are more or less perpendicular to the strike of the rocks in various parts of the quarry. Sections 1 and 2, which belong to group I, extend between two facies areas (C and D). All the other sections are restricted to just one facies area (Text-fig. 9).

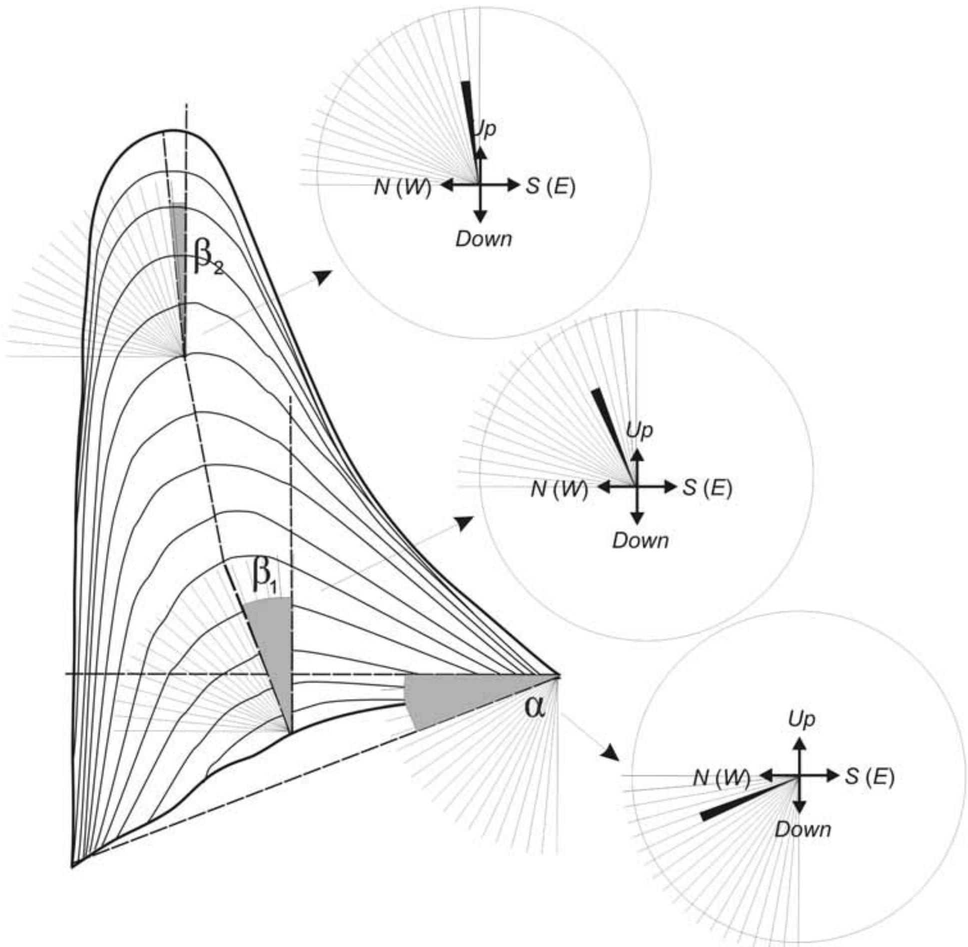
The strike and dip of the stromatoporoid-bearing Frasnian facies vary greatly within the quarry, but the values are relatively uniform in each of the three segments (blocks) shown in Text-fig. 9: the eastern segment, in which the strata dip at an angle of 35–40° along strike ca. 170°; the central segment, in which the strata lie roughly horizontally, and the western segment, with strata dipping at a low angle (5–10°) westwards along strike ca. 15°. Within particular segments the tectonic orientation of the Frasnian varies only in limited ranges and can be treated as uniform. The segments are separated by roughly meridional fault zones (Czarnocki 1958, pl 8). The sections studied (1–17) were selected so as not to cross the fault zones separating the segments.

Stromatoporoid growth orientation is described by the inclination of its basal surface seen in cross-section and by the orientation of its main growth axis. Because of the irregularity of the rock walls, and the difficulties in finding ideal vertical cross sections, all angles were measured to an accuracy of 5° and expressed in 5° classes.

Commonly the basal surface of a stromatoporoid is not flat (Text-fig. 4). In such cases it is approximated by a straight line joining the two limits of the basal surface along which the basal dimension (*B*) is measured. The α angle reflects the inclination of the basal surface from horizontal (Text-figs 10, 11). The growth axis of the stromatoporoid is also not always a straight line (*see* Text-fig. 7). Each stromatoporoid skeleton has therefore been divided into three growth stages, roughly equal in terms of height, and the orientation of the growth axis has been measured separately for the initial and the terminal one-third. The β_1 and β_2 angles de-



Text-fig. 9. Frasnian stromatoporoid-bearing facies zones in the Kadzielnia Quarry and location of sections (1–17), along which the stromatoporoid measurements have been made



Text-fig. 10. Growth orientation measurements made on a vertical cross-section of an erect curving stromatoporoid and the way of presentation of the results on rose diagrams. α – inclination of the averaged basal surface from the horizontal, β_1 and β_2 – inclination of the initial and final one-third of the growth axis of the specimen from the vertical respectively. All measurements are made to an accuracy of 5°

scribe the inclinations from the vertical of the initial and the terminal one-third of the growth axis respectively (Text-figs 10, 11). If β_1 and β_2 fell into different 5° classes, both results were presented, and if into the same class, the inclination was given by the mean value (and referred to as β). The difference between β_1 and β_2 reflects the curvature of the growth axis. The curvature directions are termed "towards the vertical" (when $\beta_2<\beta_1$) and "away from the vertical" (when $\beta_2>\beta_1$).

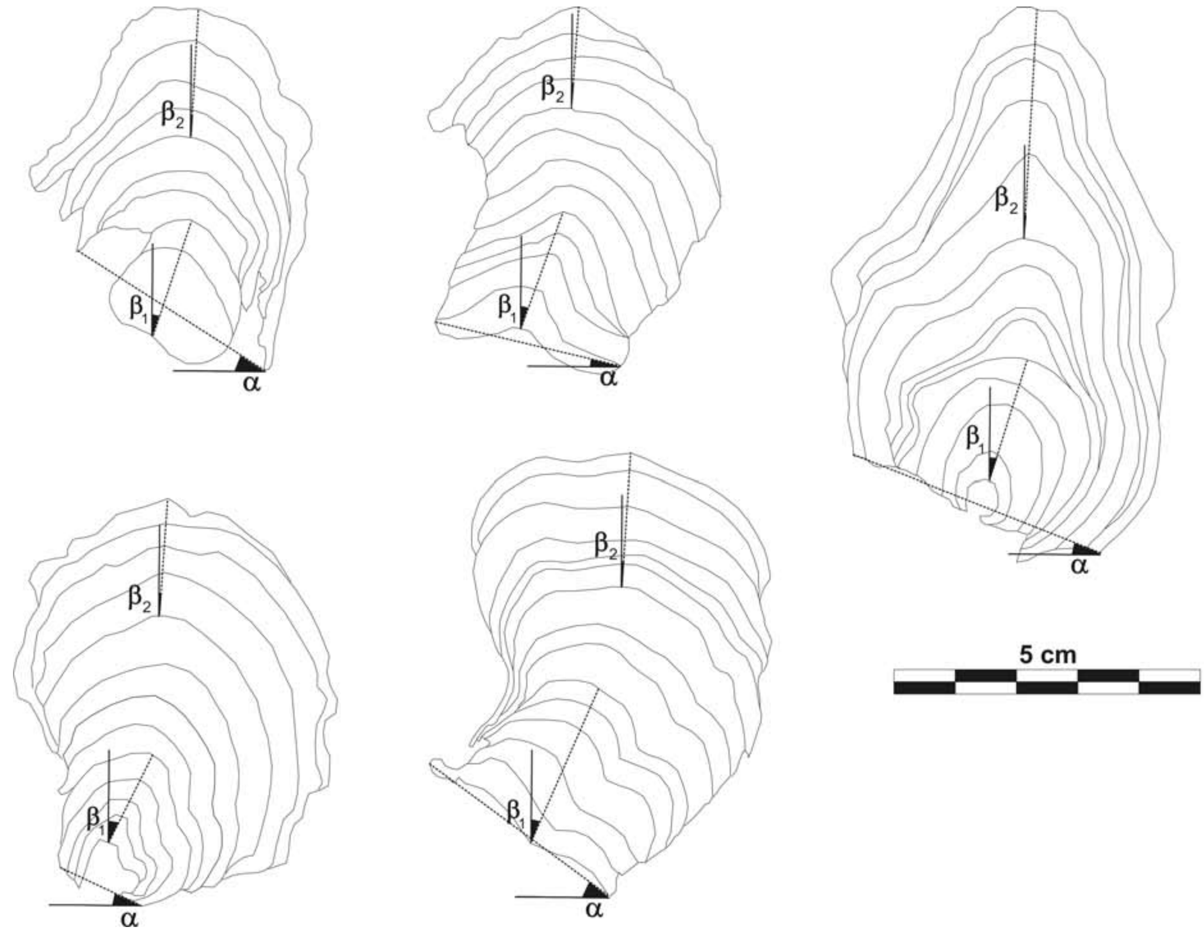
Stromatoporoids on rock walls are seen in cross-sections, and so the strike of their basal surfaces could not be determined. Therefore, the cross-section of the basal surface represented by a straight section (*B* parameter of Kershaw and Riding (1978)) was treated as a linear feature, similarly as were the sections approximating growth directions in various growth stages. In such cases the apparent leftward/rightward inclination of particular lines seen in a vertical cross section of the rock wall was measured. However, to avoid confusion, as the walls representing the same azimuth group are exposed on opposite sides of the quarry (e.g. section 5 and 6; see Text-fig. 9), the inclinations are expressed in terms of four basic geographical directions. Collective data are presented on rose diagrams (Text-figs 12–15).

Apart from the growth orientation studies new observations are presented on the distribution of various stromatoporoid growth forms within the organic buildup and in the bedded stromatoporoid-bearing facies.

RESULTS OF MEASUREMENTS

Growth orientation

Measured growth orientations are presented separately for each azimuth group (I–IV). Exact numbers of analyzed specimens in particular azimuth groups



Text-fig. 11. Examples of curving stromatoporoids from area D (sections 1 and 2). Orientation as seen on rock walls. α – inclination of the surface from horizontal, β_1 and β_2 – inclination of particular segments of the growth axis from the vertical.

and facies areas (A-D) are presented in rose diagrams (Text-figs 12–15).

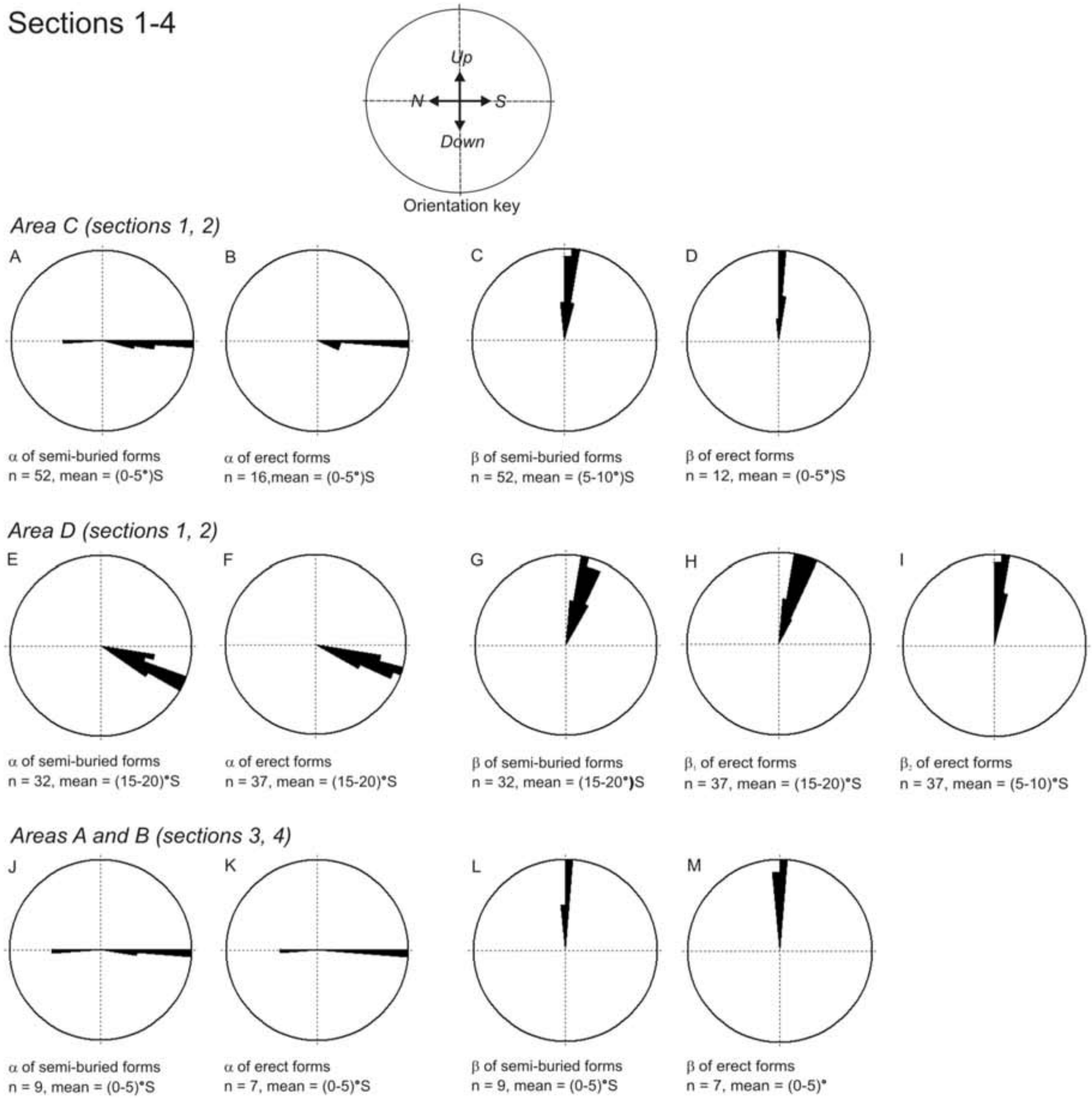
Group I. Sections 1 to 4 of this group cover all the facies areas (A–D) and are located within the eastern and central segments of the quarry (Text-fig. 9). Results from sections 1 and 2 are particularly important as they reveal the different patterns of stromatoporoid growth orientation in various parts of an organic buildup.

In area C (sections 1 and 2), which represents the central part of the organic buildup, the apparent orientation of the basal surfaces (α) of the stromatoporoids is roughly horizontal, with a slight (0–5°) mean inclination to the south for both the erect and the semi-buried forms (Text-fig. 12A, B). The average stromatoporoid growth direction is roughly vertical (mean inclination 0–5°S), and no distinct difference can be seen between the erect and semi-buried forms (Text-fig. 12C, D). Most erect forms show no curving. The few (four) erect stromatoporoids that revealed changes of growth orientation are curved towards the vertical. Comparison of data from sections 1 and 2, which are located on different levels of the quarry, show that the stromatoporoids from the lower level (section 2) show slightly more uniform growth directions, whereas more common curving is observed on the upper level (section 1), which yields all four erect specimens in this area with a distinct curvature (>5º) of the growth axis.

Distinctly different results were obtained from area D (sections 1 and 2), which represents the peripheral parts of the buildup. The basal surfaces of the stromatoporoids are distinctly inclined to the south. The α parameter ranges between 10° and 35ºS, and is generally slightly higher for the semi-buried forms than for the erect counterparts (Text-fig. 12E, F). The growth orientation (β) of semi-buried forms falls between 5° and 30ºS (Text-fig. 12G). All but one erect specimens show evident curving towards the vertical. The β_1 parameter, which reveals the growth direction in the initial growth phase, ranges between 5° and 30ºS (Text-fig. 12H), which is the same as the range for the semi-buried forms (Text-fig. 11G). In contrast, the β_2 parameter, which describes the growth direction of erect forms in the terminal growth stage, falls between 0° and 15ºS (Text-fig. 12I). The change of growth direction of individual specimens varies between 5° and 25º.

Sections 3 and 4, both located in the central section of the quarry, but representing respectively areas B and A, offered only a small number of measurable stromatoporoids, and were therefore shown together in spite of the fact that they belong to different facies areas. The basal surface of both erect and semi-buried forms is mostly horizontal (Text-fig. 12J, K) or inclined slightly south. The growth direction of the two growth types is close to vertical (Text-fig. 12L, M). Erect forms show no distinct changes in growth direction.

Group II. Sections 5–9 of this group cover areas A and B and are all located in the western segment of the quarry. The cross-section is oblique to the strike of the strata (Text-fig. 9).

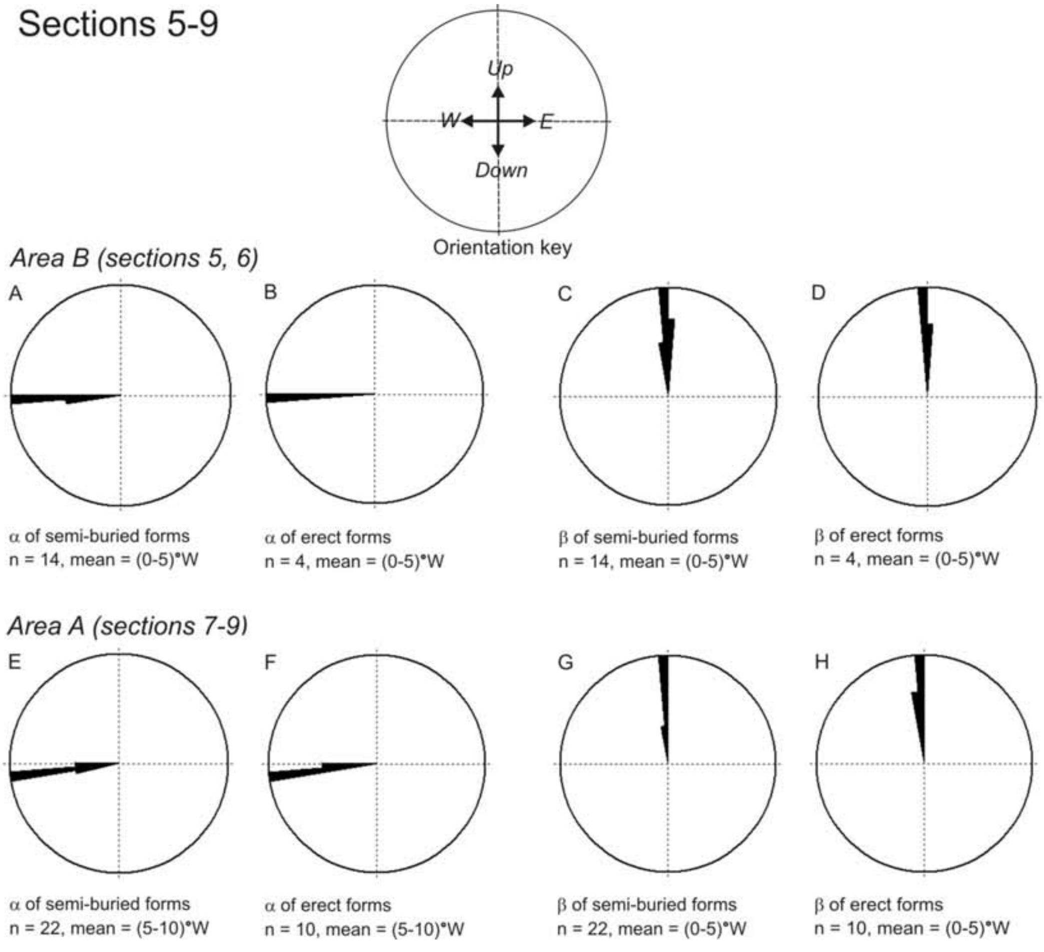


Text-fig. 12. Results of stromatoporoid growth orientation measurements. Sections 1–4 (Group I). α – basal surface inclination from the horizontal; β (β_1, β_2) – growth axis inclination from the vertical. Apparent leftward and rightward inclinations on rock-walls are expressed in terms of basic geographical directions (N-S)

The orientation of the basal surface (α), is uniform for erect and semi-buried specimens and in both facies areas (A and B). In area B (section lines 5 and 6), representing mostly the unbedded facies, the α parameter of the semi-buried forms ranges between 0° and 10ºW (Text-fig. 13A), and the β parameter falls between 10°W and 5°E (Text-fig. 13C). Only four erect specimens were found in this area to lack any distinct curving of the growth direction, with growth axes remaining roughly perpendicular to the bases. The α parameter of these forms falls between 0° and 5°E (Text-fig. 13B) and β ranges between 5°W and 5ºE (Text-fig. 13D). A similar pattern occurs in area A, represented mostly by faintly bedded facies (sections 7–9), where the α parameter falls between 0° and 15ºW for the semi-buried forms (Text-fig. 13E), and between 0° and 10°W for the erect forms (Text-fig. 13F). In this area the erect specimens show no changes in growth directions, and their growth, similarly as in the case of their semi-buried counterparts, remained roughly perpendicular to the basal surface, with β ranging between 0º (vertical) and 10ºW (Text-fig. 13G, H).

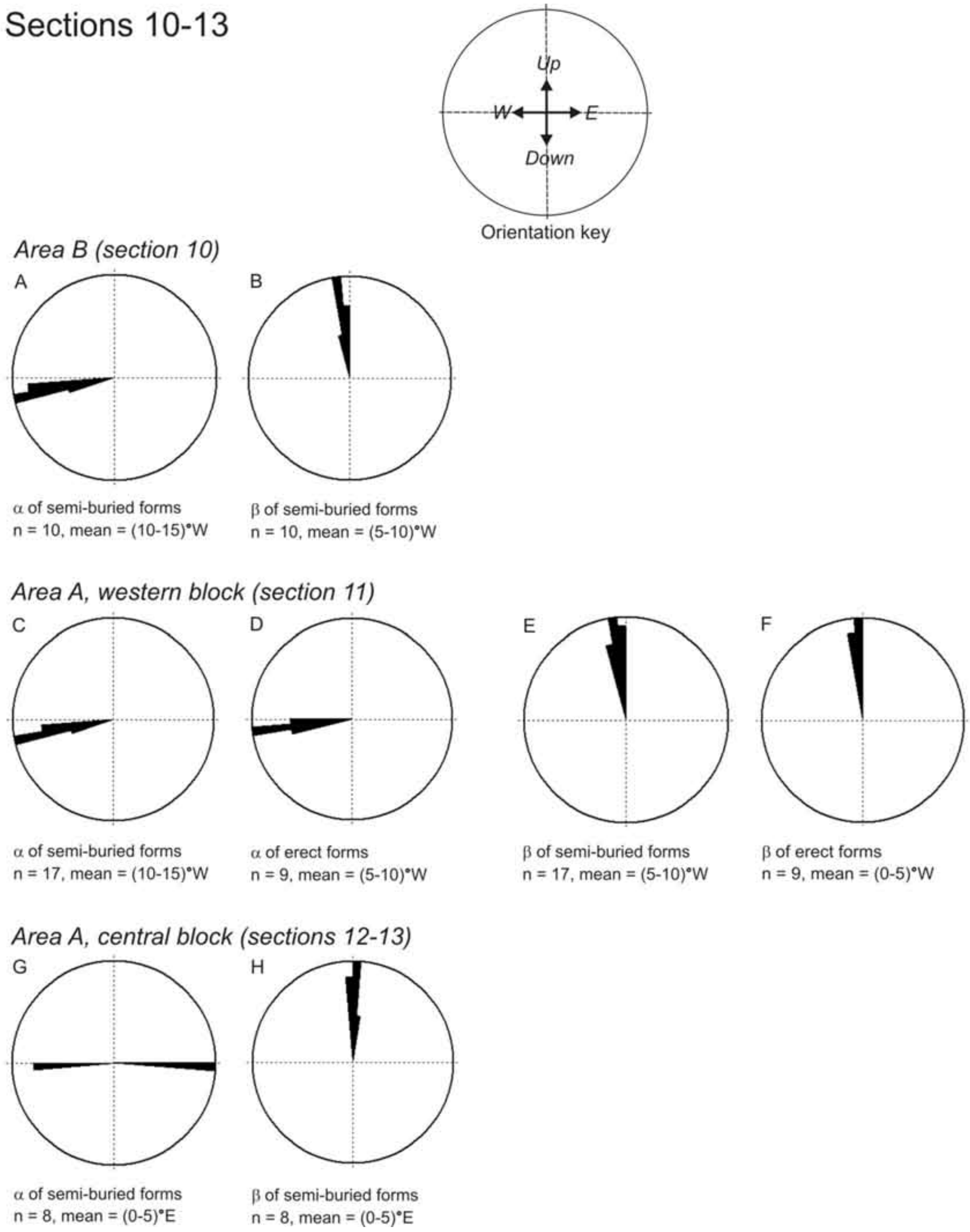
Group III. Sections 10–13 of this group are within areas A and B and located in the western and central segments of the quarry (Text-fig. 9). In the western segment (sections 10 and 11) the cross-section is close to perpendicular to the average strike of the bedded strata.

Area B (mainly unbedded facies) is represented by only one section (section 10) located within the western segment of the quarry (Text-fig. 9), which yielded only ten semi-buried stromatoporoids. The basal surfaces of the specimens are generally inclined to the west with α values ranging between 5° and 20º (Text-fig. 14A). The β parameter falls between 0° and 15ºW (Text-fig. 14B).



Text-fig. 13. Results of stromatoporoid growth orientation measurements. Sections 5–9 (Group II). α – basal surface inclination from the horizontal; β (β_1, β_2) – growth axis inclination from the vertical. Apparent leftward and rightward inclinations on rock-walls are expressed in terms of basic geographical directions (W-E)

Sections 11–13 in area A (bedded facies) yielded both erect and semi-buried forms that exhibit approximately similar patterns. Section 11 covers the western segment (Text-fig. 9). The basal surfaces are slightly inclined to the west, with the α parameter ranging between 5° and 20º for the semi-buried forms, and between 0° and 15º for the erect forms (Text-fig. 14C, D). The semi-buried specimens grew perpendicularly to their basal surfaces with β values falling between 0° and 15ºW. Seven of the nine erect specimens grew in a constant direction, with β values between 0° and 10º to the west. The other two stro-



Text-fig. 14. Results of stromatoporoid growth orientation measurements. Sections 10–13 (Group III). α – basal surface inclination from the horizontal; β (β_1, β_2) – growth axis inclination from the vertical. Apparent leftward and rightward inclinations on rock-walls are expressed in terms of basic geographical directions (W-E) matoporoids revealed curving of the growth direction towards the vertical. Sections 12–13 intersect the central segment of the quarry. These cross-sections yielded only eight semi-buried specimens with horizontal basal surfaces and vertical growth axes (Text-fig. 14G-H).

Group IV. Sections 14–17 of this group cover areas A and B in the western and central segments of the quarry (Text-fig. 9). In the western segment the cross-section is close to perpendicular to the mean strike of the strata.

Section 14, intersecting the unbedded facies (area B), yielded only seven erect and eleven semi-buried forms. The basal surfaces of the stromatoporoids belonging to both groups are uniformly inclined to the west, respectively at angles 0–20º for the semi-buried and 0–15º for the erect varieties (Text-fig. 15A, B). The erect specimens are slightly curved towards the vertical, with their β_1 values ranging between 5° and 15ºW (which is comparable with the values of their semi-buried counterparts (0–15º)), and β_2 falling between 0° and 10ºW (Text-fig. 15C, D, E).

Sections 15–16 expose the bedded facies (area A) in the western segment of the quarry. Both the erect and semi-buried forms show a similar westward inclination of their basal surfaces – 0–15º (Text-fig. 15F, G). The erect forms show no distinct curving of their growth directions. The main growth axes remain roughly perpendicular to the basal surfaces, ranging between 0° and 10°W for both erect and semi-buried forms (Text-fig. 15H, I).

Section 17, located in the central segment, yielded only four semi-buried stromatoporoids with roughly horizontal basal surfaces and vertical growth directions (Text-fig. 15 J, K).

Distribution patterns

The erect and semi-buried specimens reveal different distribution patterns throughout the various subfacies of the Kadzielnia Limestone cropping out in the quarry. The semi-buried forms are generally abundant in all the facies areas (A–D). In contrast, the erect forms seem to occur mainly in the unbedded biohermal facies (B–D). Particularly rich in erect forms is area D, representing the peripheral parts of the Kadzielnia buildup close to its boundary with the detrital limestones. In this area most of the erect specimens show distinct curving of their growth direction. The bedded facies yielded relatively few erect stromatoporoids.

INTERPRETATION OF THE MEASUREMENTS AND DISCUSSION

Variability of stromatoporoid growth directions in different parts of the organic buildup (sections 1–2, areas C and D).

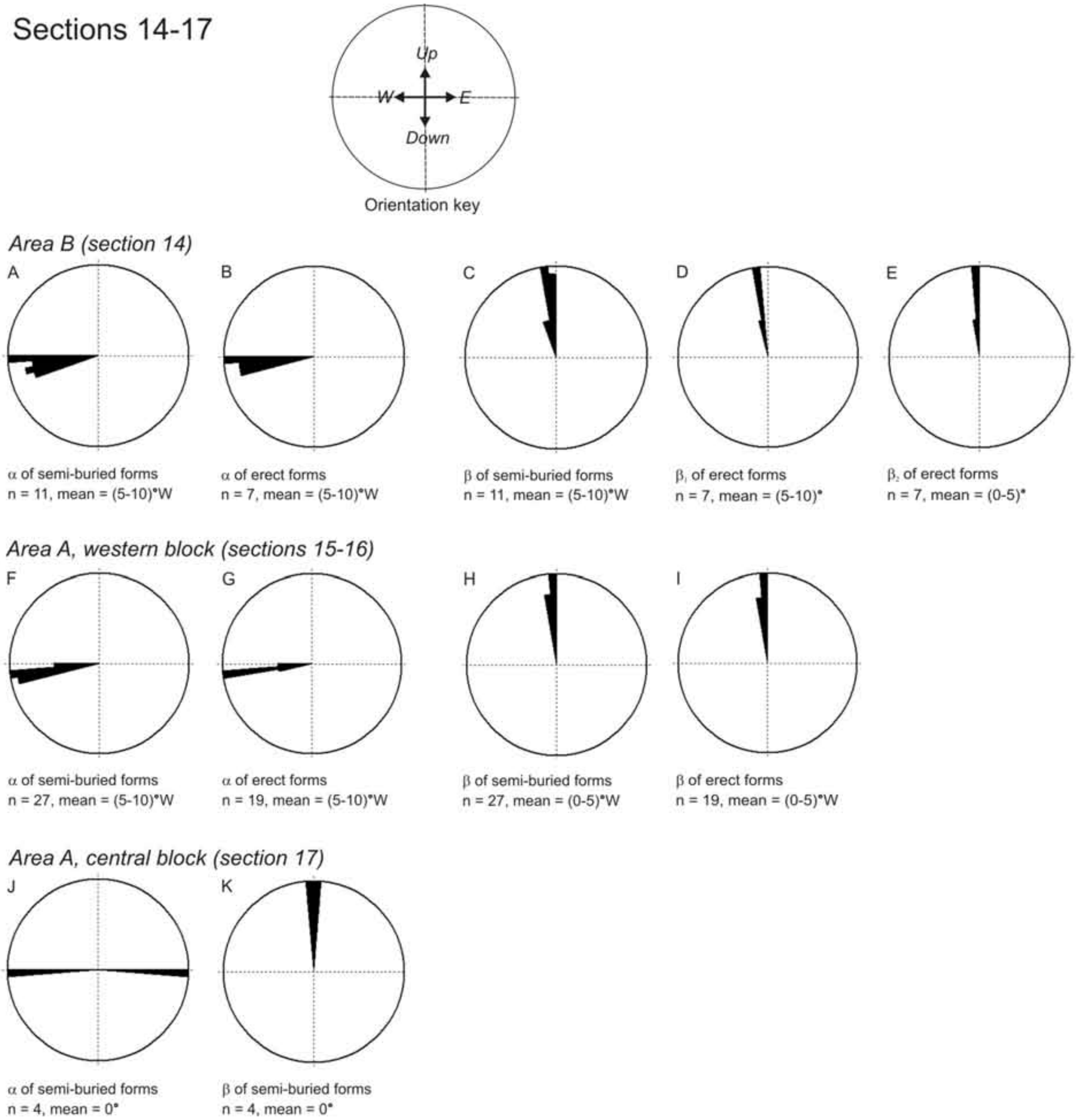
The most interesting results are those obtained from sections 1 and 2 intersecting the massive stromatoporoid-coral limestones forming the Kadzielnia buildup (Text-figs 9, 16). The sections run through two facies areas – C and D, which represent different parts of the buildup – the central zone and the flank respectively. Comparison of the results from sections 1 and 2, which are located close to each other and parallel, and on two levels of the quarry (Text-fig. 16), also allows observation of the differences in distribution patterns and growth directions in a vertical profile.

In area C (central part of the buildup) the orientations of the basal surfaces and the growth directions of the erect and semi-buried forms reveal a similar pattern. In both cases a slight southward inclination is observed (Text-fig. 16). Both the α and β parameters fall into relatively narrow ranges and the growth direction of most erect forms did not change significantly during their growth. All of these observations suggest that the stromatoporoids grew on a generally flat substrate. The observed slight southward inclination may either reveal a gentle slope or, more probably, incorporation of the specimens from an area close to the boundary with area D, where the slope of the buildup commences. This latter consideration is also supported by the four erect specimens in section 1 (upper level), which reveal distinct curving of the growth direction towards the vertical.

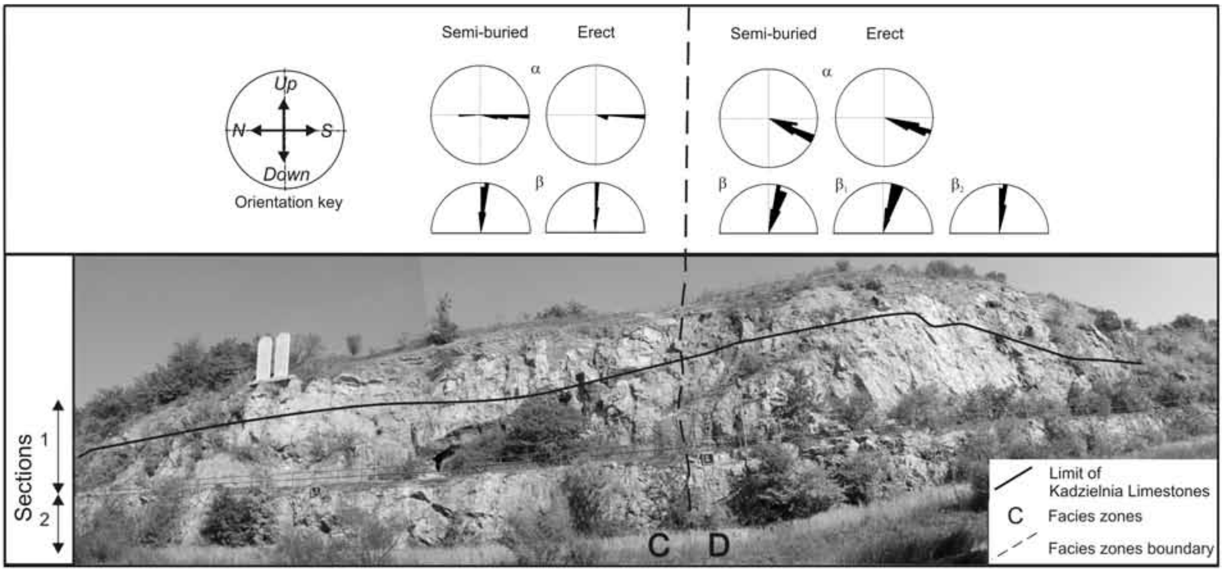
Although the two facies areas (C and D) reveal general similarity in facies of massive stromatoporoid-coral limestones, they differ in the relative abundances of the two growth forms and in their growth directions. In area D the basal surfaces of both the erect and semi-buried forms are steeply inclined to the south (Text-fig. 16). The Frasnian in the eastern segment of the quarry intersected by sections 1 and 2 is tilted at an angle of ca. 35–40°E, but this dip direction is perpendicular to the direction of the sections studied and therefore does not influence the northward/southward inclinations. The mean growth directions of stromatoporoids are not perpendicular to the bases, but reveal curving towards the vertical. The same is also indicated by comparison of the growth directions in particular growth stages of the erect forms – β_1 and β_2 (Text-fig. 12H, I). The mean change of growth directions between the initial and the terminal growth stages in this group is 10°. In their terminal stage the erect stromatoporoids grew almost vertically (Text-fig. 16). Furthermore, the ranges of both the α and β parameters are distinctly wider in area D than in area C.

The features described for area D correspond to what may be expected on a slope (Text-fig. 8C). The basal surfaces generally coincide with the slope inclination. The relatively wide range of the α parameter in this area for both the erect and semi-buried forms probably reflects the irregularity of the flanks of the buildup. Also the curving of the erect forms towards the vertical is indicative of the slope inclination – the greater the curving the steeper the slope. The same may be concluded from differential growth directions of the erect and semi-buried forms in their terminal growth stage. The suggestion that the stromatoporoids in Kadzielnia grew on a sloping bottom was also made by Kaźmierczak (1971), who considered tabular skeletons provided better stability in such a setting.

The differences between the data obtained from areas C and D result from the different positions of the



Text-fig. 15. Results of stromatoporoid growth orientation measurements. Sections 14–17 (Group IV). α – basal surface inclination from the horizontal; β (β_1, β_2) – growth axis inclination from the vertical. Apparent leftward and rightward inclinations on rock-walls are expressed in terms of basic geographical directions (W-E)



Text-fig. 16. Stromatoporoid growth directions in particular parts of the organic buildup. Limit of the Kadzielnia Limestone simplified, after Szulczewski (1971). α – basal surface inclination from the horizontal; β (β_1, β_2) – growth axis inclination from the vertical. Apparent leftward and rightward inclinations on rock-walls are expressed in terms of basic geographical directions (N-S)

two areas within the organic buildup. The curving of the erect specimens and the different growth directions relative to their semi-buried counterparts in area D suggests that the non-horizontal orientation of the basal surfaces of the stromatoporoids is an original growth feature, and is not the result of later tectonic or gravitational changes in the orientation of the strata. The stromatoporoid orientations in area D generally coincide with the inclination of the upper boundary of the Kadzielnia stromatoporoid-coral limestones at their contact with the detrital limestones as seen on the eastern wall of the quarry, which is 11° to the south. The mean palaeoslope inclination, as revealed by stromatoporoid orientation measurements, is even slightly greater (Text-fig. 16). It is possible that the flank of the buildup changed its inclination and became slightly steeper in the course of its growth.

The stromatoporoids lack direct evidences of photosensitivity (no photoresponsive tissue has yet been identified). Their internal banding patterns reveal attributes that differ from the density banding features (Young and Kershaw 2005). Some authors, however, have considered that stromatoporoids acted photosensitively or contained photosynthetic endosymbionts (Coates and Jackson 1987, Brunton and Dickson 1994, Wood 1999). Indirect arguments to support this thesis are: large dimensions of stromatoporoids in shallow water environments, reaching diameters of up to several metres (cf. Racki and Sobstel (2004), who described a specimen with a diameter of at least 8.5 metres from the Early Frasnian from the Śluchowice Quarry in the HCM), rapid growth enabling outgrowth of other metazoans, and growth forms resembling those of living zooxanthellate corals.

The above-described patterns of growth directions, and particularly the growth mode of asymmetrical erect specimens which curve the growth axis towards the vertical, support these suppositions. Phototrophy would also be in accordance with the cyanobacterial interpretation of stromatoporoids (Kaźmierczak 1976, 1980, Kaźmierczak and Kempe 1990).

Distribution of erect and semi-buried forms in various facies areas (all sections and areas)

Generally in the Kadzielnia buildup the semi-buried stromatoporoids are more abundant than the erect forms. The most common shape in the studied sample is low domical with a ragged surface, which is interpreted as characteristic of a setting with a high, but intermittent depositional rate on a rather soft substrate (Łuczyński 1998). The bottom surface was also postulated to be rather soft by Kaźmierczak (1971), with some specimens developing central under surface parts that apparently plunged downward under their weight into the unstable sediment.

The above description is correct for almost all the selected facies areas and sections studied, with one important exception – in area D (sections 1 and 2). In this zone the erect specimens are abundant and outnumber their semi-buried counterparts. The relative abundance of forms with enveloping latilaminae points to a limited sediment input, enabling development of the soft living tissue also on the lowermost located peripheral parts of the skeleton. Apparently such a situation occurred on a slope of the organic buildup that did not receive any sediment. In contrast, it is interesting that in area C, which represents the central part of the buildup, the erect specimens are relatively rare and the non-enveloping arrangement of the latilaminae predominates. Consequently, it seems likely that during the stromatoporoid growth area C was a place with a high deposition rate. The distribution of the two growth modes in area C does not follow any distinct tendencies, but shows a rather patchy pattern. This resembles the interpretation of Pajchlowa and Stasińska (1965), who treated the faintly bedded stromatoporoid-coral limestones exposed on the "Skałka Geologów" rock (area B herein) as a facies that contained numerous small bioherms scattered on a micritic surround rather than one large organic buildup.

The comparison of stromatoporoid growth modes and growth directions from areas C and D reveals that the massive stromatoporoid-coral limestones forming the Kadzielnia buildup that crop out in the quarry represent two distinct zones. Area D, inhabited by numerous erect stromatoporoids, represents a distinctly inclined slope, while area C, with predominantly semi-buried specimens, represents the inner part of the buildup, which was characterized by a patchy array of small internal bioherms scattered in a relatively soft, perhaps even muddy surrounding, on a flat bottom.

The present reconstruction and particularly the general lack of reworked and overturned stromatoporoids support the earlier interpretations of a relatively calm setting for the Kadzielnia limestones (e.g., Szulczewski 1971, Narkiewicz 1988). Both microfacies and stromatoporoid features indicate a location below the storm wave base. However, this setting, although calm in terms of water turbulence, was punctuated by periods of high sediment supply, as indicated by the abundance of semi-buried stromatoporoids with ragged margins. These episodes probably mark the input of storm-derived sediment from adjacent shallower areas, an interpretation which is in accordance with the proposed position of the buildup on the slope (Racki 1993) or at its foot (Narkiewicz 1988).

Stromatoporoid orientation in the central and western segments of the quarry (sections 5–17, areas A and B).

In the central segment of the quarry the stromatoporoid-bearing rocks maintain a horizontal orientation (Text-fig. 9). In all sections that intersect this segment of the quarry the basal surfaces of both erect and semi-buried forms are approximately horizontal (Text-figs 12J, K; 14G and 15J). The growth of all forms is close to perpendicular to their bases, and the erect specimens follow the same growth direction throughout their development (Text-figs 12L, M; 14H and 15K). All this indicates that the stromatoporoids grew on a near flat sedimentary surface. The only slight sloping of the sea bottom may perhaps be suggested in sections 2 and 3 (Text-fig. 12J, M), in which a minor mean southerly inclination of the stromatoporoids basal surfaces occurs. These two sections are parallel and proximal to sections 1 and 2, which cover area D, where a slope distinctly inclined to the south has been described (see above).

In the western segment of the quarry the sections belonging to groups II–IV intersect the rocks at various angles in relation to their dip and strike (Text-fig. 9). Closest to perpendicular to the strike are sections 14–16. The basal surfaces of the erect and semi-buried stromatoporoids in this section are distinctly inclined westwards. The inclination generally follows the dip (Text-fig. 15A, B). The mean growth direction of the semi-buried forms is perpendicular to their bases (Text-fig. 12C), whereas the erect specimens show curving towards the vertical during growth (Text-fig. 12D, E). This situation resembles that described in area D, and indicates growth of the stromatoporoids on a gentle slope. Section 14 runs through the faintly bedded facies of the "Skałka Geologów" rock (area B), which probably represent a flank of the buildup, where the massive Kadzielnia limestones pass laterally into bedded biostromal facies that are slightly bent upward in the immediate proximity of the buildup (cf. Szulczewski and Racki 1981).

Section 14 is the only section intersecting the western segment of the quarry where a distinct curving of the erect stromatoporoids is observed (plus 2 specimens in section 11). Regardless of their azimuth, and thus also regardless of their relation to the strike of the rocks, all other sections intersecting the western segment of the quarry (belonging to groups II, III, and IV) reveal distinct similarities in stromatoporoid growth. In all of these, a westerly inclination of the stromatoporoid basal surfaces is observed, generally following the dip of the rocks (Text-figs 13A, B, E, F; 14A, C, D and 15F, G), and in all cases where the erect and semi-buried forms are present, they adopted a similar growth direction (Text-figs 13C, D, G, H; 14 E, F and 15H, I). These features correspond to the situation sketched in Text-fig. 8D, indicating that the stromatoporoids originally grew on a flat substrate inclined by post-sedimentary tectonic processes.

CONCLUSIONS

Detailed studies of stromatoporoid growth modes and growth directions in the Kadzielnia Quarry allow the following conclusions to be drawn:

– stromatoporoid growth directions hold the key to reconstructing ancient topographical facies relationships;
– erect stromatoporoids that grew on inclined surfaces changed growth direction during their development;
– stromatoporoid growth directions and, particularly, the growth mode of erect specimens support the supposition that the Palaeozoic stromatoporoids grew photosensitively.

Moreover, the analysis of the stromatoporoid assemblage from the Kadzielnia Limestone provides the following observations about the character, orientation and palaeotopographic position of the organic buildup exposed in the Kadzielnia Quarry:

– the inclined contact between the Kadzielnia stromatoporoid-coral limestones and the detrital limestones exposed on the western wall of the quarry is depositional (as postulated by Szulczewski 1995b), and reflects the slope of an organic buildup,
– the Kadzielnia limestones cropping out in the quarry are not uniformly developed. Instead, they represent a sloping flank, and an internal zone with small bioherms scattered in a muddy surrounding,
– the Kadzielnia buildup developed in a calm water setting below the storm wave base on a slope or at its foot.

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REFERENCES

Bednarczyk, J., Hoffman M. and Paszkowski M. 1997a. The Upper Devonian cryptomicrobial-algal-stromatoporoid buildups from the Holy Cross Mountains, Poland. 3rd IFAA Regional Symposium and IGCP 380 International Meeting, Guidebook, 3–7.

Bednarczyk, J., Hoffman M. and Paszkowski M. 1997b. Kadzielnia, abandoned quarry, The Holy Cross Mts. Upper Devonian mud mound and debris reef (*Stachyodes, Renalcis, Girvanella*). 3rd IFAA Regional Symposium and IGCP 380 International Meeting, Guidebook, 47–48.

Boulvain F. 2007. Frasnian carbonate mounds from Belgium: Sedimentology and palaeoceanography. *Geological Society, London, Special Publication*, **275**, 125–142.

Boulvain F. and Da Silva A.-C. 2008. Frasnian reefs, mounds and atolls from Belgium: sedimentology and palaeogeography. 26th IAS Regional Meeting / SEPM-CES SEDIMENT 2008 – Bochum; Excursion Guidebook, 21–34.

Broadhurst, F.M. 1966. Growth forms of stromatoporoids in the Silurian of southern Norway. *Norsk Geologisk Tidsskrift*, **46**, 401–404.

Brunton, F.R. and Dickson O.A. 1994. Siliceous sponge-microbe biotic associations and their recurrence through the Phanerozoic as reef mound constructors, *Palaios*, **9**, 370–387.

Coates, A.G. and Jackson, J.B.C. 1987. Clonal growth, algal symbiosis, and reef formation by corals. *Paleobiology*, **13**, 363–378.

Czarnocki, J. 1958. Surowce mineralne w Górach Świętokrzyskich, zeszyt 3 – Surowce skalne. *Prace Instytutu Geologicznego*, **21**, 1–121.

Da Silva A.-C. and Boulvain F. 2004. From paleosols to carbonate mounds: facies and environments of the middle Frasnian platform in Belgium. *Geological Quarterly*, **48**, 253–266.

Embry A.F. and Klovan J.E. 1971. A late Devonian reef tract on northeastern Banks Island, N.W.T. *Bulletin of Canadian Petroleum Geology*, **19**, 730–781.

Embry A.F. and Klovan J.E. 1972. Absolute water depth limits of late Devonian palaeoecological zones. *Geologische Rundschau*, **61**, 672–686.

Hodges, L.T. and Roth, A.A. 1986. Orientation of corals and stromatoporoids in some Pleistocene, Devonian and Silurian reef facies. *Journal of Paleontology*, **60**, 1147–1158.

Hoffman, A. and Paszkowski, M. 1992. Mikrobialne budowle organiczne górnego dewonu w synklinie kieleckiej. *Przegląd Geologiczny*, **10**, 606–607.

Kano, A. 1990. Species, morphologies and environmental relationships of the Ludlovian (Upper Silurian) stromatoporoids on Gotland, Sweden. *Stockholm Contributions in Geology*, **42**, 85–121.

Kano, A. 1991. Stromatoporoid palaeoecology in the Ludlovian of Gotland; a reply. *GFF Volume,* **113**, 247–248.

Kapp, U.S. 1974. Mode of growth of middle Chazyan (Ordovician) stromatoporoids, Vermont. *Journal of Paleontology,* **4**, 1231–1240.

Kaźmierczak, J. 1971. Morphogenesis and systematics of the Devonian Stromatoporoidea from the Holy Cross Mountains, Poland. *Palaeontologia Polonica* **26**, 1–146.

Kaźmierczak, J. 1976. Cyanophycean nature of stromatoporoids. *Nature*, **264**, 49–51.

Kaźmierczak, J. 1980. Stromatoporoid stromatolites: new insight into evolution of cyanobacterial. *Acta Palaeontologica Polonica*, **25**, 243–251.

Kaźmierczak, J. 2003. Stromatolity stromatoporoidowe. In: Malinowska, L. (Ed.), Budowa Geologiczna Polski; Atlas skamieniałości przewodnich i charakterystycznych; T III, 1b, z1 – Dewon. Wydawnictwa Państwowego Instytutu Geologicznego, 690–707.

Kaźmierczak, J. and Kempe, S. 1990. Modern Cyanobacterial Analogues of Palaeozoic Stromatoporoids. *Science*, **250**, 1244–1248.

Kershaw, S. 1980. Cavities and cryptic faunas beneath nonreef stromatoporoids. *Lethaia*, **13**, 327–338.

Kershaw, S. 1984. Patterns of stromatoporoid growth in level – bottom environments. *Palaeontology*, **27**, 113–130.

Kershaw, S. 1990. Stromatoporoid palaeobiology and taphonomy in a Silurian biostrome on Gotland, Sweden. *Palaeontology*, **33**, 681–705.

Kershaw, S. 1991. Stromatoporoid palaeoecology in the Ludlovian of Gotland; a reply. *Geologiska Föreningens i Stockholm Förhandlingar* (*GFF*), **113**, 247–248.

Kershaw, S. 1998. The applications of stromatoporoid palaeobiology in palaeoenvironmental analysis. *Palaeontology*, **41**, 509–544.

Kershaw, S. and Brunton, F.R. 1999. Palaeozoic stromatoporoid taphonomy: ecologic and environmental significance. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **149**, 313–328.

Kershaw, S. and Riding, R. 1978. Parameterization of stromatoporoid shape. *Lethaia*, **11**, 233–242.

Kershaw, S. Wood, R. and Guo, L. 2006. Stromatoporoid response to muddy substrates in the Silurian. *Geologiska Föreningens i Stockholm Förhandlingar* (*GFF*), **129**, 131–138.

Königshof, P., Gewehr, B., Kordner, L., Wehrmann, A., Braun, R. and Zankl, H. 1991. Stromatoporen – Morphotypen aus einem zentralen Riffbereich (Mitteldevon) in der sdwestlichen Lahnmulde. *Geologica et Palaeontologica*, **25**, 19–35.

Königshof, P. and Kershaw S. 2006. Growth forms and palaeoenironmental interpretation of stromatoporoids in a Middle Devonian reef, southerm Marocco (west Sahara). *Facies*, **52**, 299–306.

Lamarche, J., Lewandowski, M., Mansy, J-L. and Szulczewski, M. 2003. Partitioning pre-, syn- and post-Variscan deformation in the Holy Cross Mountains, eastern Variscan foreland. *Geological Society London, Special Publications*, **208**, 159–184.

Łuczyński, P. 1998. Stromatoporoid morphology in the Devonian of the Holy Cross Mountains, Poland. *Acta Palaeontologica Polonica*, **43**, 653–663.

Łuczyński, P. 2003. Stromatoporoid morphology in the Devonian of the Holy Cross Mountains, Poland, and its palaeoenvironmental significance. *Acta Geologica Polonica*, **53**, 19–27.

Łuczyński, P. 2005. Improving the parameterization of stromatoporoid shapes – a detailed approach to stromatoporoid morphometry. *Lethaia*, **38**, 143–154.

Łuczyński, P. 2006. Stromatoporoid shape and burial ratio changes during growth history and their methodological consequences for morphometrical analyses. *Lethaia*, **39**, 339–358.

Łuczyński, P. and Szulczewski, M. 2003. Devonian-Carboniferous neptunian dykes in disintegrating carbonate platform of the Holy Cross Mountains, Poland. 22nd IAS Meeting in Sedimentology – Opatija 2003, Abstracts book, 109.

Meyer, F.O. 1981. Stromatoporoid growth rhythms and rates. *Science*, **213**, 894–895.

Narkiewicz, M. 1988. Turning points in sedimentary development in the Late Devonian in southern Poland. *Devonian of the World, Canadian Society of Petroleum Geologists Memoirs*, **14**, 619–635.

Narkiewicz, M. 2007. Development and inversion of Devonian and Carboniferous basins in the eastern part of the Variscan foreland (Poland). *Geological Quarterly*, **51**, 231–256.

Narkiewicz, M., Racki, G. and Wrzołek, T. 1990. Lithostratigraphy of the Devonian stromatoporoid-coral carbonate sequence in the Holy Cross Mountains. *Kwartalnik Geologiczny*, **34**, 433–456. [In Polish]

Pajchlowa, M. and Stasińska, A. 1965. Formation récifales Dévonien des Monts de Sainte-Croix (Pologne). *Acta Palaeontologica Polonica*, **10**, 249–260.

Racki, G. 1981. Stratygrafia i tektonika utworów dewonu środkowego i górnego w kamieniołomach Jaźwica. Przewodnik LIII Zjazdu Polskiego Towarzystwa Geologicznego, 171–179.

Racki, G. 1993. Evolution of the bank to reef complex in the Devonian of the Holy Cross Mountains. *Acta Palaeontologica Polonica*, **37**, 87–182.

Racki, G. 1998. Frasnian-Famennian biotic crisis: undervalued tectonic control? *Palaeogeography, Palaeoclimatology, Palaeoecology,* **141**, 177–198.

Racki, G., Makowski, I, Mikłas, J. and Gawlik, S. 1993. Brachiopod biofacies in the Frasnian reef complexes: An example from the Holy Cross Mts., Poland. *Prace Naukowe Uniwersytetu Śląskiego* **1331**, *Geologia* **12-13**, 64–109.

Racki, G. and Sobstel, M. 2004. Very large stromatoporoid indicating Early Frasnian reef core (Holy Cross Mts., Poland). *Geological Quarterly*, **48**, 83–88.

Samsonowicz, J. 1934. Objaśnienia arkusza Opatów ogólnej mapy geologicznej Polski w skali 1:100000. Państwowy Instytut Geologiczny; Warszawa

Sandström, O. 1998. Sediments and stromatoporoid morphotypes in Ludfordian (Upper Silurian) reefal sea stacks on Gotland, Sweden. *Geologisk Forum*, **120**, 365–371.

Sandström, O. and Kershaw, S. 2002. Ludlow (Silurian) stromatoporoid biostromes from Gotland, Sweden: facies, depositional models and modern analogues. *Sedimentology*, **49**, 379–395.

Sandström, O. and Kershaw 2008. Palaeobiology, ecology, and distribution of stromatoporoid faunas in biostromes of the mid-Ludlow of Gotland, Sweden. *Acta Palaeontologica Polonica*, **53**, 293–302.

Stearn, C.W. 1993. Revision of the Order Stromatoporida. *Palaeontology*, **36**, 1–21.

Stearn, C.W. and Pickett, J.W. 1994. The Stromatoporoid animal revisited: Building the skeleton. *Lethaia*, **27**, 1–10.

Stearn, C.W., Webby, B.D., Nestor, H. and Stock, C.W. 1999. Revised classification and terminology of Palaeozoic stromatoporoids. *Acta Palaeontologica Polonica*, **44**, 1–70.

Swan, A.R.H. and Kershaw, S. 1994. A computer model for skeletal growth of stromatoporoids. *Palaeontology*, **37**, 409–423.

Szulczewski, M. 1971. Upper Devonian conodonts, stratigraphy and facies development in the Holy Cross Mts. *Acta Geologica Polonica*, **21**, 1–129.

Szulczewski, M. 1977. Main facial regions in the Paleozoic of the Holy Cross Mountains. *Przegląd Geologiczny*, **8-9**, 428–432. [In Polish]

Szulczewski, M. 1979. Devonian carbonate platform of the Holy Cross Mountains. Devonian and Carboniferous coral-bearing sequence of the Holy Cross Mountains. Guidebook of the Third International Symposium on Fossil Cnidarians, 5–36.

Szulczewski, M. 1981. Dewon środkowy i górny zachodniej części Gór Świętokrzyskich. Przewodnik LIII Zjazdu Polskiego Towarzystwa Geologicznego, 68–81.

Szulczewski, M. 1995a. Evolution of the Polish-Moravian carbonate platform in the late Devonian and Early Carboniferous: Holy Cross Mts., Kraków Upland, Moravian Karst. Stop 2. Kadzielnia Quarry. XIII International Congress on Carboniferous-Permian, Guidebook, 16-19.

Szulczewski, M. 1995b. Depositional evolution of the Holy Cross Mts. (Poland) in the Devonian and Carboniferous – a review. *Geological Quarterly*, **39**, 471–488.

Szulczewski, M. and Racki, G. 1981. Early Frasnian bioherms in the Holy Cross Mts. *Acta Geologica Polonica,* **31**, 147–162.

Szulczewski, M., Bełka, Z. and Skompski, S. 1996. The drowning of a carbonate platform: an example from the Devonian-Carboniferous of the south-western Holy Cross Mountains, Poland. *Sedimentary Geology*, **106**, 21–49.

Wood, M.R. 1990. Reef-building sponges. *American Scientist*, **78**, 131–156.

Wood, M.R. 1991. Non spicular biomineralization in calcified demosponges. In: J. Reitner and H. Keupp (Eds), Fossil and recent sponges, 322–344. Springer Verlag.

Wood, M.R. 1999. Reef evolution, 414 pp. Oxford University Press; Oxford.

Young, G.A. and Kershaw, S. 2005. Classification and controls of internal banding in Palaeozoic stromatoporoids and colonial corals. *Palaeontology*, **48,** 623–651.

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