

Stromatoporoid beds and flat-pebble conglomerates interpreted as tsunami deposits in the Upper Silurian of Podolia, Ukraine

PIOTR ŁUCZYŃSKI, STANISŁAW SKOMPSKI AND WOJCIECH KOZŁOWSKI

*Faculty of Geology, Warsaw University, Al. Żwirki i Wigury 93, 02-089 Warsaw, Poland.
E-mails: piotr.luczynski@uw.edu.pl; Skompski@uw.edu.pl; Wojciech.Kozlowski@uw.edu.pl*

ABSTRACT:

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Tsunami deposits are currently a subject of intensive studies. Tsunamis must have occurred in the geological past in the same frequency as nowadays, yet their identified depositional record is surprisingly scarce. Here we describe a hitherto unrecognized example of probable palaeotsunamites.

The Upper Silurian (Pridoli) carbonate succession of Podolia (southwestern Ukraine) contains variously developed event beds forming intercalations within peritidal deposits (shallow water limestones, nodular marls and dolomites). The event beds are represented by stromatoporoid and fine-grained bioclastic limestones, in some places accompanied by flat-pebble conglomerates. The interval with event beds can be traced along the Zbruch River in separate outcrops over a distance of more than 20 km along a transect oblique to the palaeoshoreline. The stromatoporoid beds have erosional bottom surfaces and are composed of overturned and often fragmented massive skeletons. The material has been transported landward from their offshore habitats and deposited in lagoonal settings. The flat-pebble conglomerates are composed of sub-angular micritic clasts that are lithologically identical to the sediments forming the underlying beds.

Large-scale landward transport of the biogenic material has to be attributed to phenomena with very high energy levels, such as tropical hurricanes or tsunamis. This paper presents a tsunamigenic interpretation. Morphometric features of redeposited stromatoporoids point to a calm original growth environment at depths well below storm wave base. Tsunami waves are the most probable factor that could cause their redeposition from such a setting. The vastness of the area covered by parabiostromal stromatoporoid beds resembles the distribution of modern tsunami deposits in offshore settings. The stromatoporoid beds with unsorted stromatoporoids of various dimensions evenly distributed throughout the thickness of the beds and with clast-supported textures most probably represent deposition by traction. In some sections, the stromatoporoids are restricted to the lowermost parts of the beds, which pass upwards into bioclastic limestones. In this case, the finer material was deposited from suspension. The coexistence of stromatoporoid beds and flat-pebble conglomerates also allows presenting a tsunami interpretation of the latter. The propagating tsunami waves, led to erosion of partly lithified thin-layered mudstones, their fragmentation into flat clasts and redeposition as flat-pebble conglomerates.

Key words: Palaeotsunami; Silurian; Podolia; Stromatoporoid beds; Flat-pebble conglomerates.

INTRODUCTION – PALAEO-TSUNAMI STUDIES

Tsunamis have lately attracted much attention. The last two great catastrophic events (the 2004 Sumatra tsunami and the 2011 Japanese tsunami) stimulated the study of tsunamis and modern tsunami deposits (e.g. Morton *et al.* 2007; Bourgeois 2009; Goff *et al.* 2012). Sedimentary effects of recent tsunamis have been described from various locations (e.g. Szczuciński *et al.* 2006; Goto *et al.* 2007, 2009, 2011; Paris *et al.* 2009; Matsumoto *et al.* 2010; Yawsangratt *et al.* 2009, 2012).

On a human timescale, a tsunami is a relatively rare phenomenon. The need for establishing tsunami frequencies has created a necessity to study tsunamis from the past – from times without reliable historical sources. There is no reason to assume that any of the phenomena inducing tsunamis (e.g. submarine earthquakes, mass movements, volcanic eruptions, and bolide impacts) is any more frequent today than in the past. Bearing in mind the geological time scale, in an appropriate geotectonic location a tsunami eventually becomes inevitable. However, tsunami deposits are relatively rarely identified in fossil sedimentary successions (Łuczyński 2012; Goff *et al.* 2014). This is mainly due to the vulnerability of tsunami deposits (especially those deposited onshore) to erosion (e.g. Dawson and Stewart 2007) and their susceptibility to early diagenetic changes obscuring original sedimentary features (Szczuciński 2012a, b). Another factor is the different approach to identifying modern and fossil tsunami deposits. In modern examples, the deposits are identified as tsunami-induced by linking their formation with a particular event, according to eyewitnesses, historical data etc. In the case of their fossil counterparts, a sedimentological approach is needed. In many cases the identified modern tsunami deposits, particularly those deposited offshore, contained no set of unique criteria and therefore, if not attributed to a known tsunami event, could easily be overlooked (comp. Sakuna *et al.* 2012; Ikehara *et al.* 2014).

Another problem is the exact definition of tsunamites – tsunami-induced deposits. According to Shiki and Yamazaki (1996), the term ‘tsunamite’ should be used broadly, not only for the deposits laid down by the oncoming tsunami wave itself, but also for all of the other sediments connected with the resulting backwash flow, currents, mass gravity movements etc. This leads to a “*Nomenclature overlap*” (Shanmugam 2006) – a situation, in which the same deposit can be properly named in different ways, as various genetic definitions refer to different moments of the sedi-

mentary process. Goff *et al.* (2014) have recently proposed a new definition of a “mega-tsunami” that is based solely on initial wave height/amplitude at source exceeding 100 m/50 m respectively, which, however, is difficult to be applied in the fossil record.

Some authors (e.g. Dawson and Stewart 2007; Sakuna *et al.* 2012) have presented catalogues of features that are characteristic of interpreted tsunami deposits in marine successions; however, none of them can be treated as a single, independent indicator of a tsunami. In spite of several attempts at identifying sedimentary features that would enable the tsunami deposits to be distinguished from those connected with other high-energy phenomena (e.g. Fujiwara and Kamataki 2007; Kortekaas and Dawson 2007; Morton *et al.* 2007; Bourgeois 2009; Chagué-Goff *et al.* 2011, Goff *et al.* 2012; Phantuwongraj and Choowong 2012), the task proved to be extremely difficult. In many cases, tsunami deposits showed no distinct sedimentary features (Shanmugam 2006), or show a tendency to mimic other abrupt and high-energy marine processes (Shiki 1996; Shiki *et al.* 2000; Matsumoto *et al.* 2010; Goto *et al.* 2011).

Among the most important factors indicating a tsunami origin is the depth at which the erosion took place, exceeding that of even extremely fierce tropical storms (Bourrouilh-Le Jan *et al.* 2007; Ikehara *et al.* 2014). This often results in an admixture of open shelf faunal elements in shallow-water deposits or in mixing of marine and terrestrial elements (Kaźmierczak and Goldring 1978; Bussert and Aberham 2004; Cantalamessa and Di Celma 2005; Paris *et al.* 2009). Another feature is the common incorporation of ripped-up mud clasts within fine-grained deposits (Yawsangratt *et al.* 2012) or, more generally, a bimodal character of the deposited material, with large clasts embedded within finer sediments (Cantalamessa and Di Celma 2005; Yawsangratt *et al.* 2009). Some authors point to the association of tsunami deposits with other structures that can be attributed to seismic shocks, such as neptunic dykes or synsedimentary faults (Spaletta and Vai 1984; Pratt 2002), or with plastic deformations of the underlying sediments (Michalik 1997). By far the most conspicuous effect of tsunamis are great boulders deposited in moats and on the beaches, called *tsunami-ishi* in Japanese, most commonly composed of light porous reef limestones (e.g. Goto *et al.* 2007, 2010a, 2010b) or, more generally, the occurrence of anomalously coarse sediment layers within fine grained deposits (e.g. Albertão and Martins 1996).

The Upper Silurian (Pridoli) carbonate succession exposed along the Zbruch River (Podolia, southwestern Ukraine) is represented by inner shelf la-

goonal facies dominated by fine-grained peritidal deposits (shallow-water laminated limestones and dolomites). A common feature of the lagoonal successions is the occurrence of beds with redeposited stromatoporoids, in some sections accompanied by flat-pebble conglomerates.

The present paper describes the sedimentary features of the stromatoporoid beds and flat-pebble conglomerates, and proposes a tsunami interpretation of their origin. The aim of this paper is to present a new type of palaeotsunami deposit and to add new arguments to the discussion on sedimentological features of ancient tsunamis. The argumentation presented below is based mainly on the analysis of:

(1) the supposed depth, at which the erosion of the redeposited material took place, inferred from stromatoporoid morphometric features indicating a calm original growth environment located below storm wave base,

(2) the lateral distribution and internal structure of the stromatoporoid beds, indicating their deposition from both traction and suspension,

(3) the character and composition of the flat-pebble conglomerates, which can be identified as accumulations of rip-up clasts.

SEDIMENTARY AND STRATIGRAPHICAL SETTING

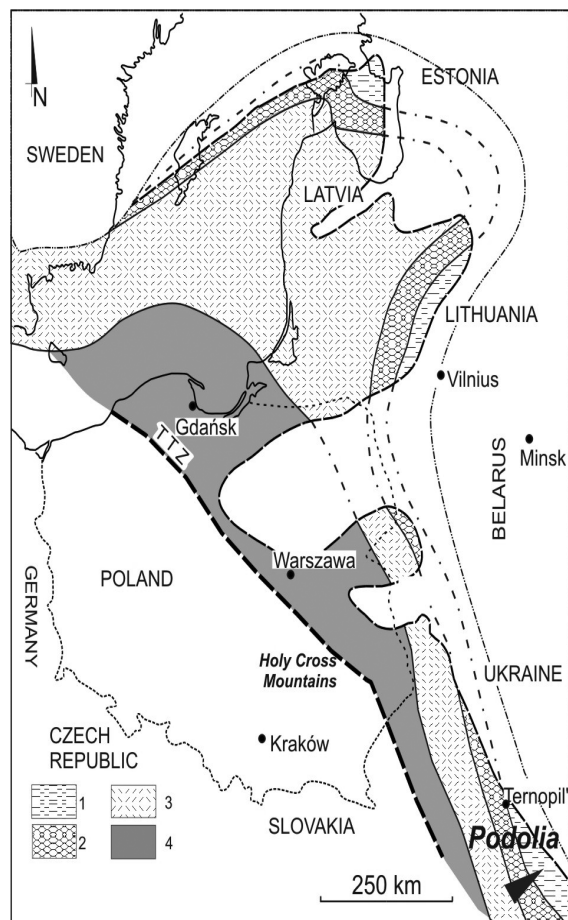
In the Middle and Late Silurian the region of present-day Podolia was part of a vast carbonate shelf belonging to a marginal sea that rimmed Baltica from the south (Silurian orientation), stretching from modern western Ukraine, through Belarus and north-eastern Poland to the Baltic States and the island of Gotland in the Baltic Sea (Calner 2005). Over its whole length, the shelf maintained a constant width of about 150–200 km and a constant facies pattern (Text-fig. 1). Today the Podolia region offers the best exposures of a widespread facies belt. A central position on the shelf was occupied by a zone of stromatoporoid-coral shoals and barriers, which separated the inner shelf lagoonal environments from the outer shelf and slope facies that pass into basinal graptolitic shales (Kaljo *et al.* 1983; Einasto *et al.* 1986). During sea-level fluctuations, the position of particular facies belts shifted, but the general pattern remained unchanged (Predtechensky *et al.* 1983). The outer shelf and slope facies are dominated by limestones and marls with stromatoporoids, tabulate and rugose corals, brachiopods and other

abundant and diverse open-marine benthic faunas (Racki *et al.* 2012). The inner shelf facies are mainly developed as laminites and dolomicrites with eurypterids and ostracods, with intercalated thick stromatoporoid-rich beds (Skompski *et al.* 2008).

The stromatoporoid beds intercalating the shallow water inner shelf facies in the Upper Silurian of Podolia were traditionally interpreted as biostromes marking the deepest (or at least the most open-marine) environment in a peritidal cyclic sedimentary pattern (e.g. Predtechensky *et al.* 1983). However, recent studies (Skompski *et al.* 2008; Łuczyński *et al.* 2009) of the Ludlow and Pridoli strata cropping out in the vicinities of Skala Podil'ska and Kam'janec' Podil'skyj have revealed that the stromatoporoid beds are in fact developed as lenticular parabiosomes (*sensu* Kershaw 1994) composed of overturned and often fragmented massive skeletons, which is typical of most Silurian–Devonian stromatoporoid “reef” deposits. The biogenic material has been transported landward from their offshore habitats by high-energy sedimentary events punctuating the shallow-water shelf (Skompski *et al.* 2008) and deposited in shallow lagoonal or even near-shore settings. Such a dynamic interpretation of the stromatoporoid beds implies changes to the cyclicity curves of the Silurian succession in Podolia.

The investigated outcrops are located along the Zbruch River, south of the town of Skala Podil'ska (Text-fig. 2). These are natural exposures in a deeply incised, meandering river valley. The Zbruch River, being a northern tributary of the Dnister River, flows southwards through the study area. The beds are close to horizontal, which allows tracing particular horizons over long distances. No distinct tectonic disruptions are recognizable in the field.

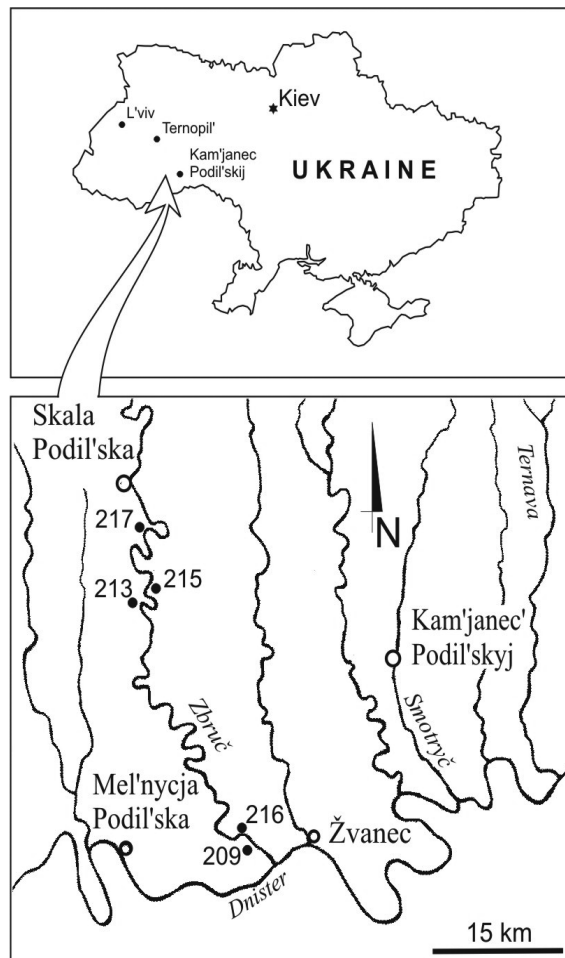
The research concentrated on an area between the villages of Berezhanka (no. 217 – numbering of sections after Abushik *et al.* 1985), Podpilip'e (no. 215-1 – northern periphery of the village and no. 215-2 – on the opposite river bank to the village) and Verbovka (no. 213) (Text-fig. 2). Additional investigations were carried out in two closely located outcrops, about 25 km down the Zbruch River, not far from its mouth to the Dnister River, close to the village of Baryshkovtsy (nos. 216 and 209). In terms of the palaeogeography, with the shore located somewhere in the north-east, this means a slightly more offshore setting of the southern exposures (Baryshkovtsy). The transect represented by the sections is probably oblique to the palaeoshoreline, with the northern group of exposures (Berezhanka, Podpilip'e and Verbovka) situated in a generally slightly shallower environment.



Text-fig. 1. Distribution of the Upper Silurian facies on the margin of the East European Platform (after Einasto *et al.* 1986, simplified). 1 – littoral and lagoonal deposits, 2 – stromatoporoid barriers and shoals, 3 – shallow external (carbonate) shelf, 4 – deep external (muddy) shelf. Black arrow indicates the study area

The lithological succession exposed in the sections is dominated by low-energy facies representing generally calm-water conditions, which are interbedded by a number of high-energy event beds. The low-energy facies are developed mainly as laminated limestones with desiccation cracks and fenestral structures, and as nodular marly limestones accompanied by some mudstones and clays. In one of the sections (215-2), beds with an exceptionally preserved assemblage of algae and terrestrial flora are exposed. The event beds are represented by stromatoporoid and bioclastic limestones and by flat-pebble conglomerates. The beds are laterally continuous, which differentiates them from the lenticular stromatoporoid bodies described from other Upper Silurian sections in Podolia (comp. Skompski *et al.* 2008; Łuczyński *et al.* 2009).

The Silurian succession of Podolia is divided into four informal units – so-called ‘formations’ or ‘hori-



Text-fig. 2. Positions of the studied sections; 217 – Berezhancka, 215 – Podpilip'e, 213 – Verbovka, 209 and 216 – Baryshkovtsy

zons’: Kitaigorod, Bagovytsya, Malynivtsy and Skala, which are divided into a number of ‘members’ (Text-fig. 3). The division is based on a mixture of lithostratigraphical and biostratigraphical criteria (Nikiforowa *et al.* 1972; Tsegelnjuk *et al.* 1983; Drygant 1984, Koren' *et al.* 1989; for more detailed description see Skompski *et al.* 2008; Racki *et al.* 2012). Alternatively, a traditional subdivision proposed by Abushik *et al.* (1985), which divides the succession into so-called ‘suites’, is used locally.

The studied sections are of Pridoli age (Abushik *et al.* 1985) and belong to the Varnytsya Member of the Skala Formation and to the upper subsuite of the Rashkov suite (Text-fig. 3). The bottom limit of the stromatoporoid interval is easily recognizable as a sharp boundary between yellowish dolomites and grey limestones, and can be identified in both the northern and southern groups of sections (Text-fig. 4). The boundary between the dolomite and limestone complexes proba-

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Period	Epoch	Lithostratigraphy 1		Lithostratigraphy 2		
		formation	member			
Silurian	Pridoli	Skala	Dzvenygorod	Dzwinogorod suite	Skala Horizon	
			Trubchyn	Rashkov suite		U
			Grey band			M
			Varnytsya			L
			Ludlow	Prygorodok		Isakovtsy suite
	Isakivtsi					
		Malynivtsy	Grinchuk	Grinchuk suite		

Text-fig. 3. Stratigraphic position of the studied sections within the lithostratigraphic subdivisions of the uppermost Silurian in Podolia; Lithostratigraphy 1 – compilation after Nikiforova *et al.* 1972, Tsegelnjuk *et al.* 1983, Drygant 1984, Koren' *et al.* 1989; Lithostratigraphy 2 – traditional subdivision used by Abushik *et al.* 1985. Grey band illustrates the stratigraphic position of the investigated sections

bly corresponds to the start of a transgressive interval terminating the Varnytsya Member (comp. fig. 2 in: Skompski *et al.* 2008), and is treated here as a correlation horizon.

FACIES DESCRIPTION

Low-energy facies

Laminated limestones

Laminated limestones are typical mainly of the lower parts of the sections (Text-fig. 4). They are developed as pale grey laminites (Text-fig. 5d) with flat or crinkled lamination and sporadically with desiccation cracks. Relatively rare are tens of centimetres-thick intercalations of mudstones with fenestral structures and with vertical, calcite-filled tubes and shrinkage pores. A common feature is the occurrence of cm-thick intercalations of coarse-grained material, which indicates that the generally calm sedimentary conditions were interrupted by some minor erosional events. Extremely rare fossils are represented mainly by leperditid ostracods and small gastropods.

Nodular marly limestones

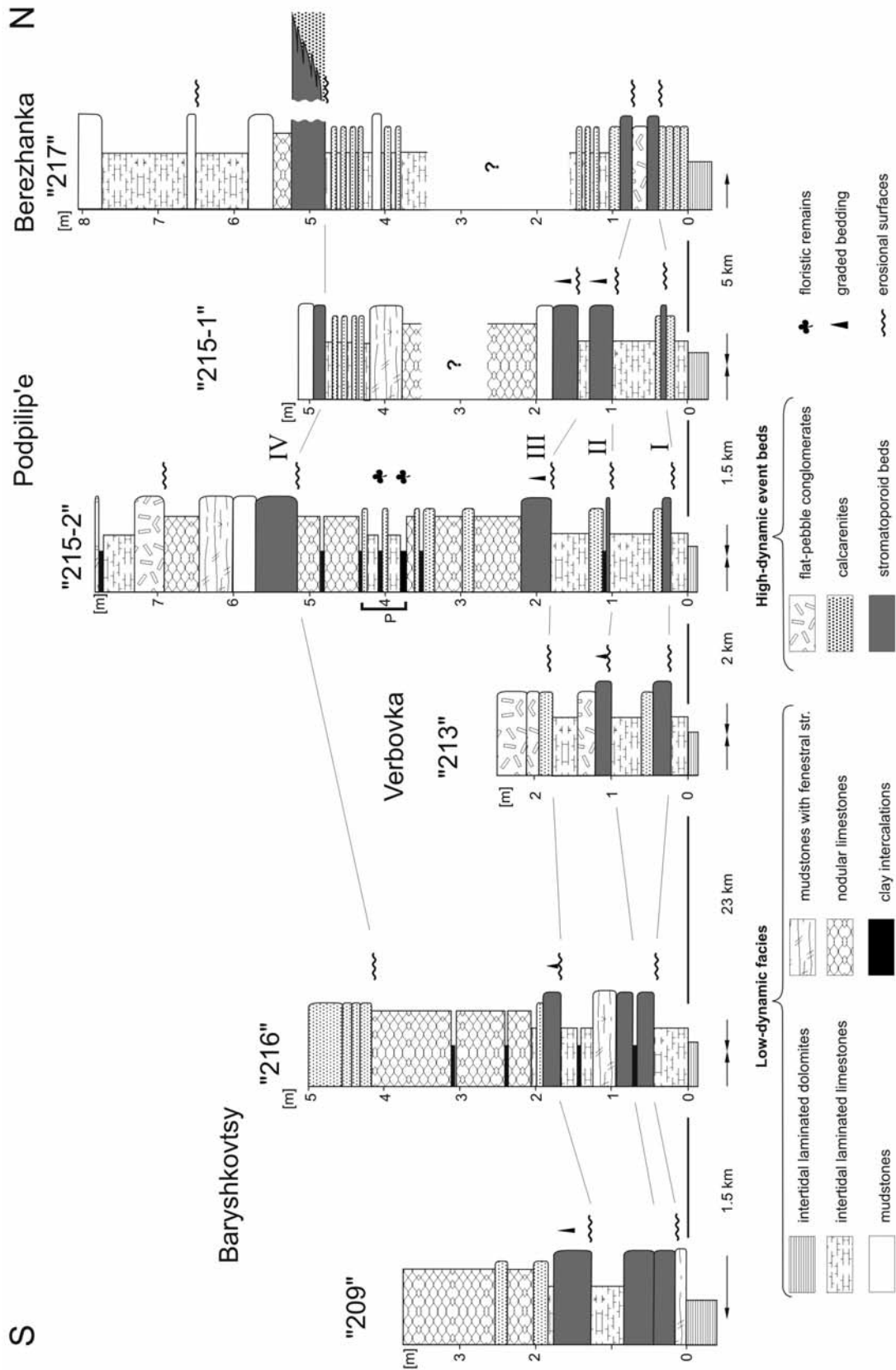
The marly facies, usually developed as nodular limestones, are devoid of lamination and form thick weathering-resistant complexes. Microfacially they are represented by mudstones or wackestones domi-

nated by gastropods, ostracods, bivalves, more or less disintegrated bryozoans and solenoporacean calcareous algae. Crinoid particles are present, but rare. Bioturbations and cm-thick intercalations of fine-grained bioclastic or peloidal material (peloidal packstones and grainstones) are a common feature. In the bioclastic intercalations, there are also sporadic gastropod-bivalve coquinas of complete shells, deposited in a convex-up position and with geopetal infillings (Text-fig. 8e).

Beds with flora

The beds with flora are developed as two units composed of black shales, laminites and thin layers of calcarenites (letter P on Text-fig. 4). All of the lithotypes contain numerous and taxonomically diverse ostracods. The shales contain characteristic coalified floristic fragments (Text-fig. 6c), but their poor state of preservation hinders a more precise classification. The bottom surfaces of the laminites reveal accumulations of calcareous tubes of the microproblematicum *Tuxekanella* (Text-figs 6a, b, d). Up to the present, this form has been known mostly from thin sections (Riding and Soja 1993; Skompski 2010). In Podpilip'e, three-dimensionally preserved specimens have been found for the first time. According to Skompski (2010), the most probable affinity of *Tuxekanella* is to the green algal Udoteaceae, formerly classified as Codiaceae or Siphonales (comp. Riding 1977).

Other enigmatic microfacies components of this subfacies are spherical, millimetre-size microforms



Text-fig. 4. Correlation of the stromatoporoid beds between the sections investigated

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Text-fig. 5. Details of the stromatoporoid beds in the Podpilip'e 215-1 section; **a** – intercalation of stromatoporoid beds (I-II-III) and low-dynamic peritidal deposits; **b** – erosional top of bed I; **c** – broken and overturned stromatoporoid from bed I; **d** – fragment of the peritidal succession between beds I and II; **e** – intercalation of intraformational breccia (enlarged from Fig. d)

composed of a weakly separated but regular internal part and of less regular coats (Text-fig. 7a–e). According to their general shape and dimensions, they correspond to the whorls of segmented dasycladacean algae, poorly known from the Silurian, but very well documented from the Devonian and Carboniferous carbonates (compare Mamet and Roux 1975 or Skompski 1984). On this basis, these forms have been provisionally determined as *Dasycladaceae* indet.

High-energy event beds

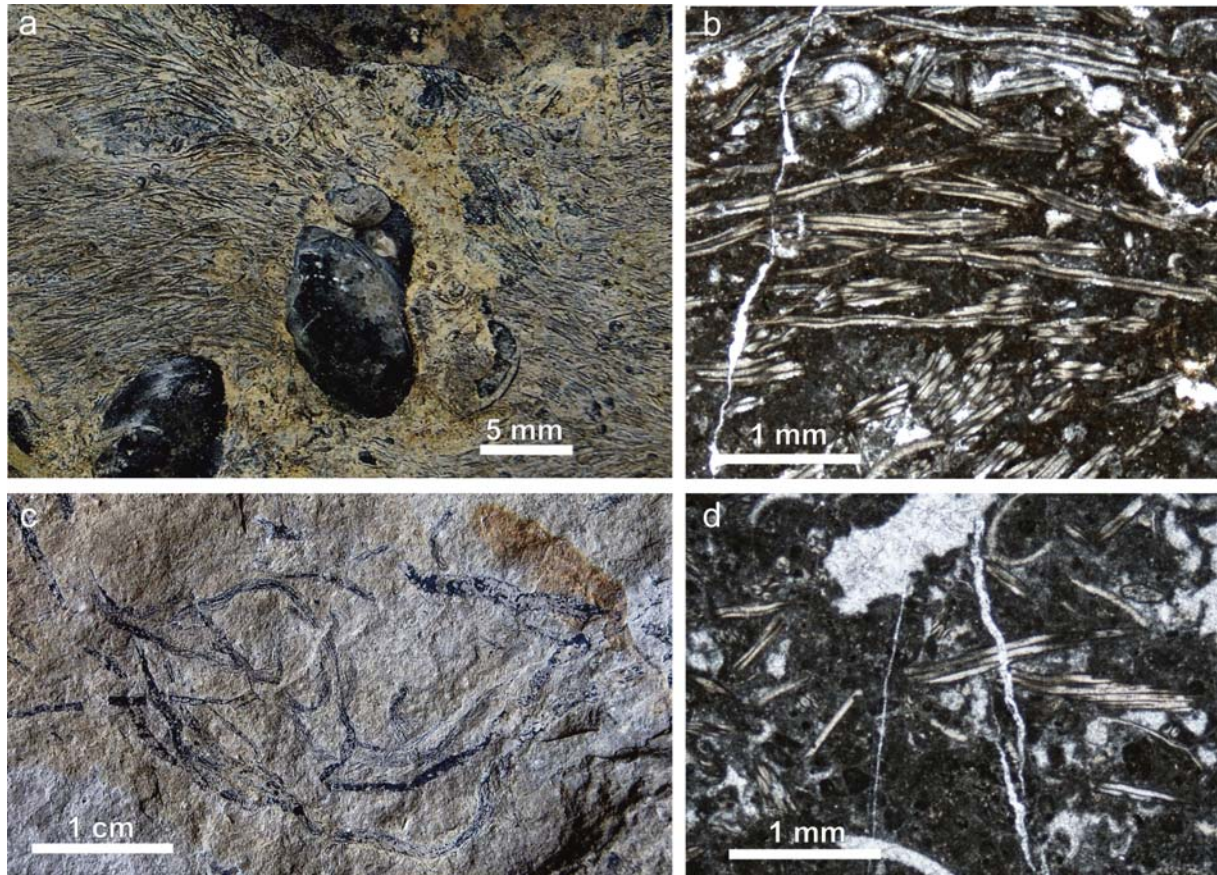
The lithotypes constituting the high-energy event beds are represented by stromatoporoid limestones, bioclastic limestones and flat-pebble conglomerates. The first two types pass into each other in a continuous spectrum, here referred to as stromatoporoid beds,

whereas the third type essentially occurs in distinct layers.

Stromatoporoid beds

Stromatoporoid and bioclastic limestones together form layers here referred to as stromatoporoid beds. Their thickness usually changes laterally between 15 and 25 cm, and only rarely reaches up to 50 cm. The bottom surfaces of the beds rest on low-energy facies and are always distinctly erosional. In some cases the top surfaces of the stromatoporoid beds also show an erosional character (Text-fig. 5b).

The main macrobiotic component of the stromatoporoid beds comprises massive stromatoporoids, usually with an enveloping latilaminae arrangement and with dimensions typically ranging between a few and



Text-fig. 6. Beds with floristic remains. All specimens taken from beds indicated as P-interval on Fig. 4; **a** – bottom surface of a layer covered by *Tuxekanella* thallus accompanied by ostracods; **b, d** – thin sections taken from the specimen illustrated on Fig. 4; **c** – floristic remains on the surface of shales

a dozen or so centimetres, sporadically up to 40 cm or more. The material is unsorted, and smaller and larger bioclasts are commonly mixed together. The orientation and fragmentation of the stromatoporoids unequivocally indicate redeposition. Fragments of tabulate and colonial rugose corals occur as accessory fauna, in some sections being more common. In most of the outcrops, the stromatoporoids form clast-supported textures, with only a small amount of matrix composed of scattered intraclasts, bryozoans, ostracods, gastropods and *Tuxekanella*. Laterally, in other parts of the same beds, the stromatoporoids are less common and are restricted to the lower part of the layer (Text-fig. 5c), and the whole bed, maintaining its thickness, is composed of bioclastic limestones (e.g. bed II on Text-fig. 5a). In such cases, the stromatoporoids occupy the lowermost part of the beds, and the whole layer shows graded bedding.

The bioclastic limestones are mostly represented by fine-grained wackestones, less commonly packstones, and sporadically by *Tuxekanella* grainstones. The main components of the wackestones are disintegrated bryozoans and gastropods, accompanied by ostracods, solenoporacean red algae and *Tuxekanella*. Irregular fenestral structures are also common.

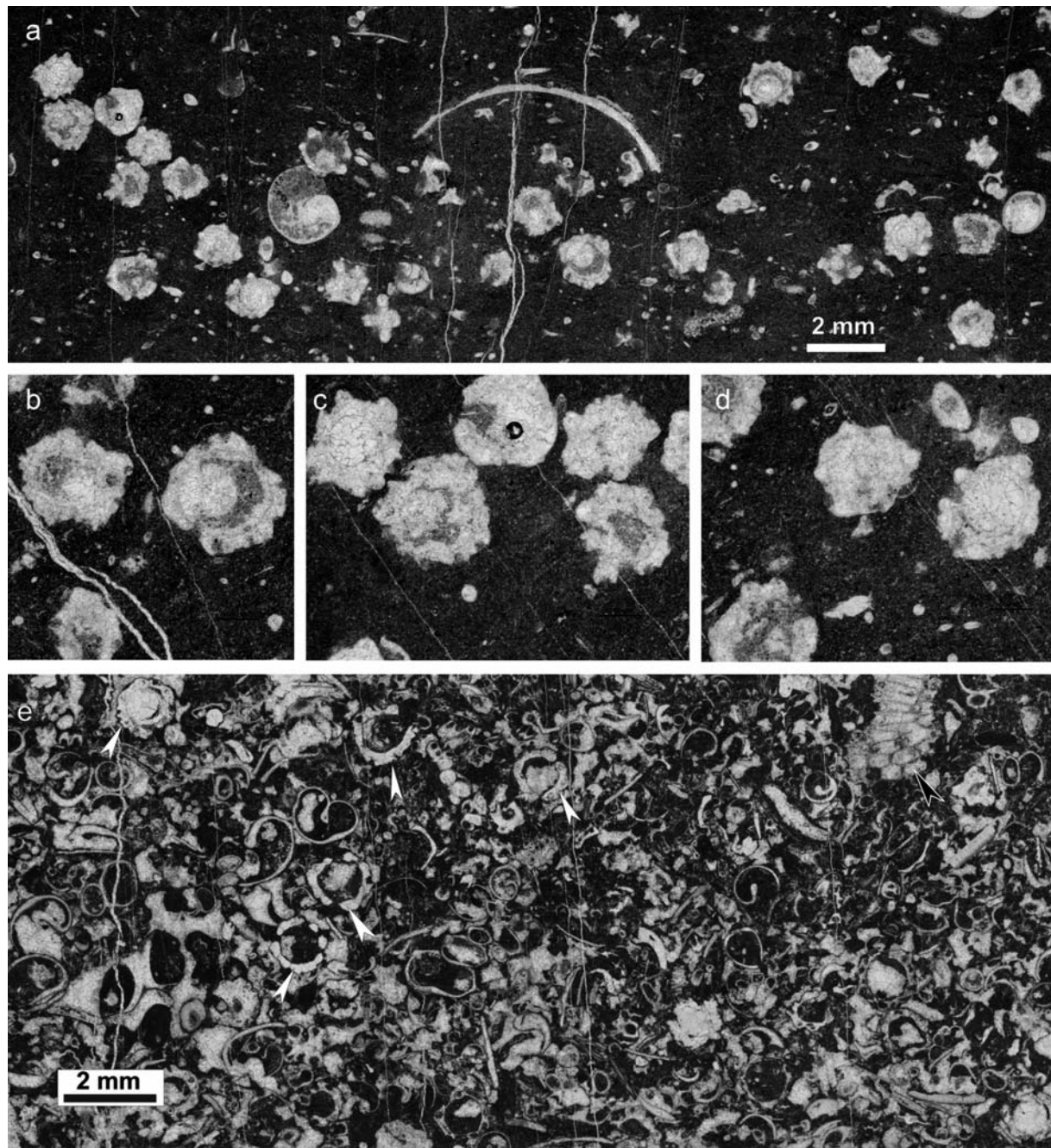
Flat-pebble conglomerates

Flat-pebble conglomerates

Flat-pebble conglomerates are developed as individual layers, usually around 20 cm thick or less (Text-fig. 5d, e). In the sections, they often occur directly above the stromatoporoid beds (outcrops no. 213, 217). The lithoclasts that do not exceed 1 cm are elongated or isometric, whereas all the larger lithoclasts, reaching a length of 10 cm, are distinctly elongated. In extreme cases, the length/thickness proportion equals 30:1 (in section). Size spacing is random, and the orientation of elongated clasts is predominantly horizontal (Text-fig. 8a).

The clasts are represented mainly by wackestones originating from laminated limestones, with small amounts of biotritus (Text-fig. 8d). The edges of the clasts are rounded (Text-fig. 8c). Apart from lithoclasts, bioclasts of red algae and stromatoporoids are

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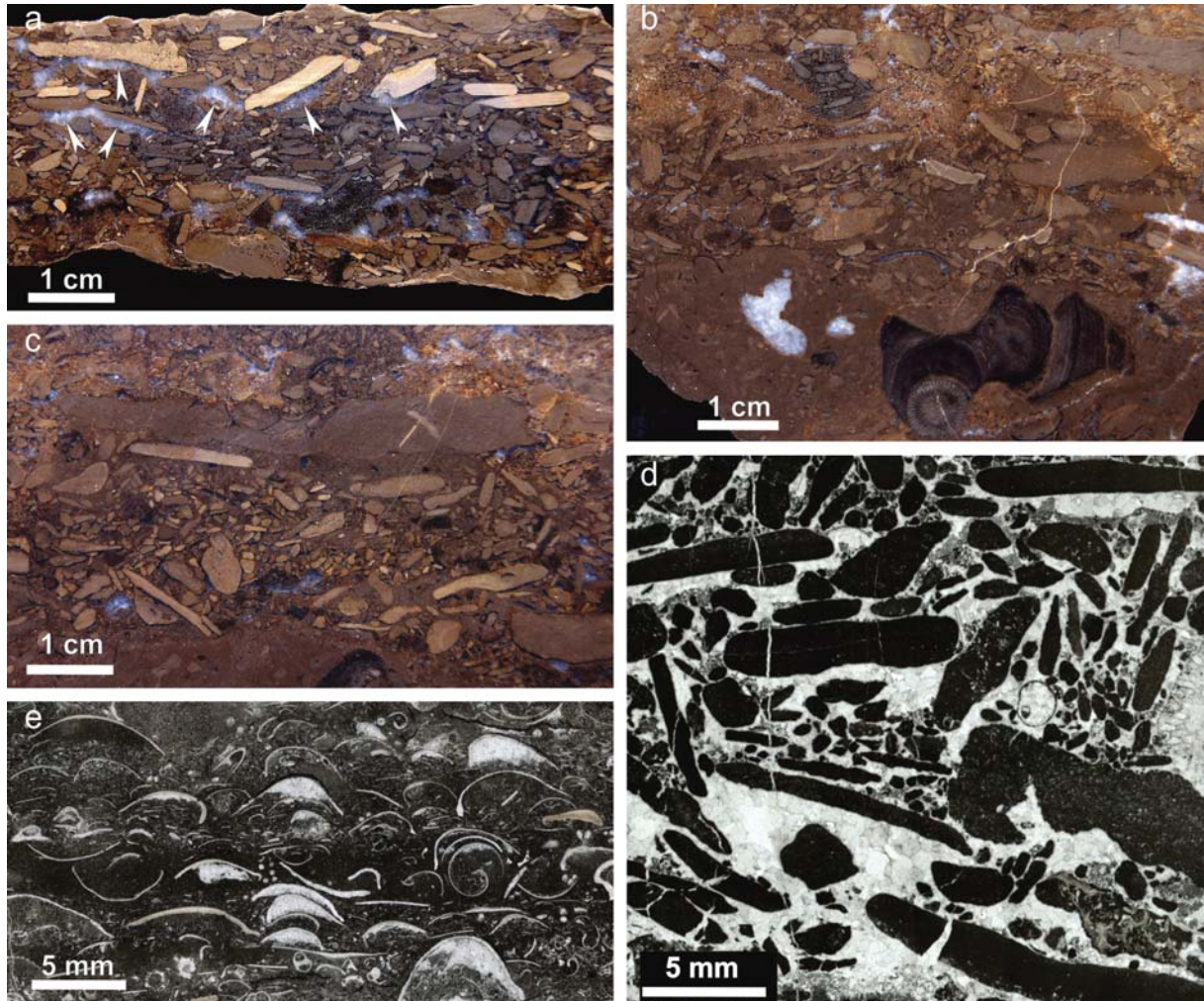
Text-fig. 7. Dasycladacean remains from a limestone bed from interval P (see Text-fig. 4); **a-d** – wackestones with dasycladacean whorls; **e** – gastropod-dasycladacean packstone; arrowed are dasycladacean remains (white arrows) and solenoporacean fragments (black arrow)

also common (Text-fig. 8b), sporadically accompanied also by a detritus of bryozoans and ostracods. Another typical feature is the occurrence of fenestral umbrella structures with blocky calcite infillings under the clasts (arrows on Text-fig. 8a). The shapes of these infillings resemble microstalactitic druse cements, but cathodoluminescence observations revealed no characteristic lamination.

INTERPRETATION

Low-energy facies

All of the above-distinguished low-energy facies fit well to the sedimentary environmental scheme proposed for coeval deposits of the upper part of the Rashkov suite by Skompski *et al.* (2008, fig. 11). Lam-



Text-fig. 8. Details of flat-pebble conglomerates and shell coquinas; **a** – calcite druse infillings (arrowed); **b** – large stromatoporoid bioclast between flat pebbles originated from laminitic limestones; **c** – large intraclast in the upper part of the slab; **d** – thin section of a conglomerate with numerous “umbrella structures” (calcite infillings below clasts); **e** – gastropod-bivalve coquina with shells deposited in convex-up position with geoptal infillings

inated limestones with desiccation cracks and fenestral structures were typical of the near-shore intertidal zone. Nodular marly limestones with an impoverished faunistic assemblage were characteristic of deeper, subtidal parts of the shelf, which were separated from the more open sea by a zone dominated by stromatoporoids. The nature and sedimentary role of this zone (biostromal, biodetritic shoals or a zone of stromatoporoid mounds) is still debated, but it is undisputable that it separated open marine environments from the more restricted areas of the internal shelf, as illustrated by Einasto and Radionova (1988). The third subfacies, dominated by enigmatic plants, most probably of algal origin, developed in small and local depressions of the sea bottom. According to Skompski (2010) *Tuxekanella* grew in lagoons extending between the shoals dominated by stromatoporoids and the near-shore intertidal zones.

High-energy event beds

In previous papers (Skompski *et al.* 2008; Łuczyński *et al.* 2009; Łuczyński 2011), we have described lenticular stromatoporoid beds from the Upper Silurian of Podolia and attributed their origin to onshore redeposition of stromatoporoid material, tentatively suggesting their tsunami origin. Recent field studies have revealed that several sections exposed along the Zbruch River abound in stromatoporoid horizons that can be traced over distances of several kilometres. In many ways, they are similar in character to the earlier-described lenticular beds; i.e. they contain densely packed large, massive (non-dendroid) redeposited stromatoporoids and show erosional contacts with the underlying deposits; however, they maintain a more constant thickness. Presented below are arguments pointing to a pos-

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sible tsunami origin of the stromatoporoid beds and flat-pebble conglomerates.

Stromatoporoid beds – source of redeposited material and erosion depth

The stromatoporoid beds are composed almost solely of stromatoporoids. Other benthic faunal elements, such as tabulate and rugose corals, occur only occasionally. This may be an effect of the relatively low specific weight of the stromatoporoids (Stearn and Pickett 1994) enhancing their buoyancy. Moreover, their ecological strategy of ‘soft substrate platform dwellers’ (Wood 1995) enabled colonization of vast areas but, on the other hand, it made the stromatoporoids highly susceptible to exhumation and redeposition. The stromatoporoids in the Silurian of Podolia usually did not constitute reefs in the ecological meaning of the term. They were predominantly developed as biostromes with the individuals growing separately, and thus not constructing a rigid framework. Similar growth patterns of Silurian and Devonian stromatoporoid-coral communities have been recognized in numerous carbonate complexes (Flügel and Flügel-Kahler 1992; Flügel and Kiessling 2002), and were studied in detail e.g. on Gotland (Kershaw 1990; Sandström and Kershaw 2002) in the Holy Cross Mountains (Kazmierczak 1971; Łuczyński 2003, 2008) and in Morocco (Königshof and Kershaw 2006).

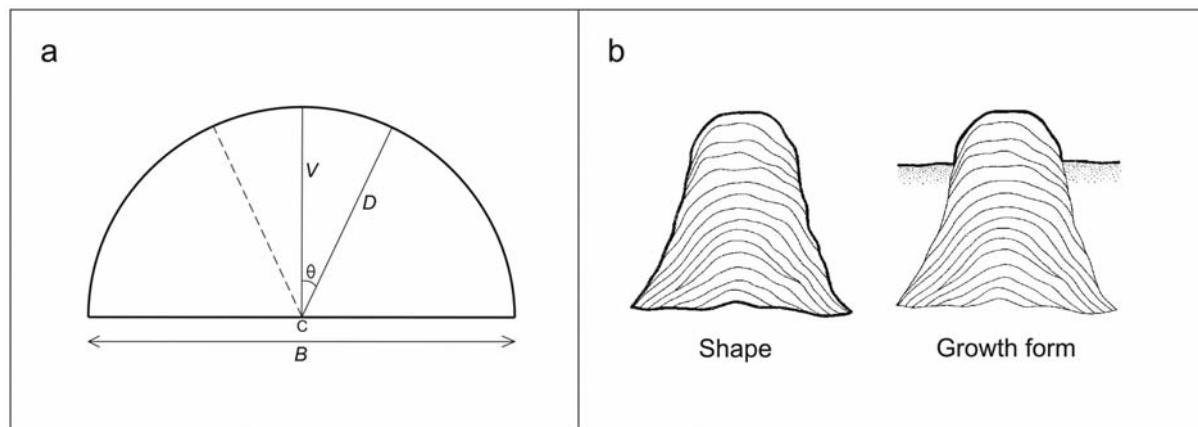
Stromatoporoids occur in a variety of shapes, and their morphometric features can be interpreted in terms of sedimentary conditions in their growth environment (e.g. Kershaw 1984, 1998; Łuczyński 2003, 2005, 2006, 2008, 2009; Königshof and Kershaw 2006). A detailed morphometric analysis has been made of the stromatoporoids from Podpilip’e (section 215-1). Features such as the dimensions of the skeleton (capacity), its overall shape, the arrangements of the latilaminae (growth bands), and the character of the upper and lower surfaces have been determined (Table 1; for details of the method see Łuczyński 2006) and interpreted not only in terms of the organisms’ growth environment, but also in terms of their susceptibility to exhumation and redeposition. Stromatoporoids from other exposures were not studied in such detail; however, their morphometric features are generally the same.

Vertical crosscuts through complete stromatoporoid skeletons were measured in three dimensions – vertical (V), horizontal (B) and diagonal (D) at an angle of 25° from the vertical (Text-fig. 9a). The shape profile is described by the V/B ratio. Studies of the arrangements of the latilaminae – major, macroscopically seen internal bands within the skeleton marking its growth development – allowed determination of the burial ratio (BR) of the specimens in their final growth stage. This ratio expresses the relationship between the overall shape of the stromatoporoid’s skeleton and its growth form above the sediment surface (living surface profile), and is described by the formula $BR=(V_s-V_g)/V_s$, where V_s is the vertical height of the skeleton, and V_g is the vertical height of the individual’s final growth form. As the stromatoporoids grew during accumulation of sediment around them, these are two different features (Text-fig. 9b). The capacity (size) of stromatoporoids was calculated using the formula $C=4/3\pi(B/2)^2V$, in which the stromatoporoid shape is approximated by a half of a rotatory ellipsoid.

In all three stromatoporoid beds exposed at Podpilip’e, the stromatoporoid assemblages are dominated by forms with high shape profiles. The mean V/B ratio ranges between 0.67 and 0.93 for specimens measured from particular beds (Table 1) and equals 0.78 for the whole measured population, which corresponds to a high domical shape (see Łuczyński 2005). The skeletons show mainly enveloping arrangements of the latilaminae (with the following latilamina covering the preceding) and smooth (not ragged; i.e. without sediment increments on sides) upper surfaces. Consequently, the calculated burial ratios are close to 0 (Table 1). The most common initial (lower) surface is flat. The only important feature that distinctly differs between particular beds is the mean capacity of the stromatoporoids. A positive correlation between the mean volume of the skele-

Stromatoporoid beds		Bed I	Bed II	Bed III
Studied parameters				
N (Number of studied specimens)		28	18	16
B (cm) (Basal length)	Mean	16.7	8.5	16.6
	Confidence interval	(± 1.1)	(± 1.4)	(± 2.1)
V (cm) (Vertical height)	Mean	11.9	13.7	7.1
	Confidence interval	(± 1.0)	(± 1.8)	(± 0.9)
D (cm) (Diagonal distance)	Mean	11.9	13.4	6.6
	Confidence interval	(± 1.0)	(± 2.0)	(± 0.8)
V/B (Shape profile)	Mean	0.72	2.03	0.50
	Confidence interval	(± 0.05)	(± 0.50)	(± 0.12)
C (cm ³) (Capacity)	Mean	1934	656	1233
	Confidence interval	(± 249)	(± 250)	(± 353)
Latilaminae arrangement	Enveloping	2 (5%)	20 (66%)	8 (23%)
	Non-enveloping	42 (95%)	11 (34%)	27 (77%)
Burial ratio	Mean	0.11	0.14	0.10
	Confidence interval	(± 0.03)	(± 0.04)	(± 0.03)
Surface character	Smooth	4 (9%)	22 (71%)	10 (29%)
	Ragged	40 (91%)	9 (29%)	25 (71%)
Initial surface	Flat	1 (2%)	16 (52%)	26 (74%)
	Initial elevation	19 (43%)	9 (29%)	4 (11%)
	Anchor	24 (55%)	6 (19%)	5 (15%)

Table 1. Results of stromatoporoid measurements

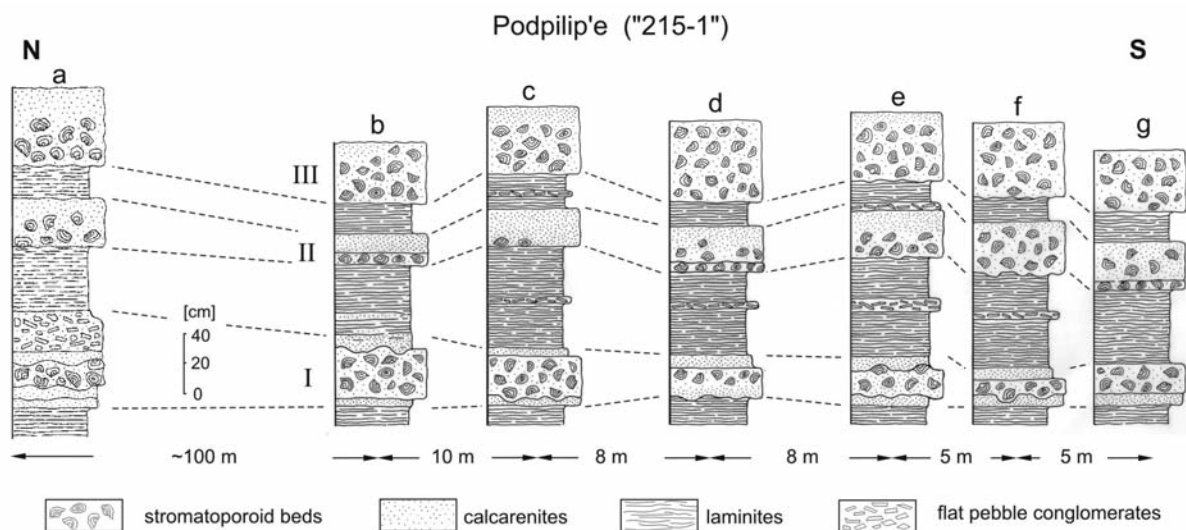


Text-fig. 9. Stromatoporoid morphometry; **a** – basic parameters describing a stromatoporoid shape, B – basal length, V – vertical height, D – diagonal distance, $\theta = 25^\circ$; **b** – shape of the skeleton and growth form (living surface profile) of a stromatoporoid specimen

ton and the bed thickness is observed, with the largest specimens occurring in the thickest bed (bed III on Text-fig. 10).

All the above-mentioned morphometric features of the stromatoporoids indicate a calm original growth environment. Low burial ratios are indicative of settings with a slow and stable sediment deposition rate (Łuczyński 2005). Enveloping latilaminae and smooth upper surfaces show that the growth had not been interrupted by any rapid depositional events. The same is indicated by the general lack of sediment increments within the skeletons. High shape profiles together with enveloping latilaminae and low burial ratios indicate that the stromatoporoids stood high above the sediment surface, with their skeletons exposed. Flat lower surfaces are typical of stromatoporoids growing on soft bottoms and not encrusting hard elements.

The original habitats of the redeposited stromatoporoids were situated in areas with prevailing calm conditions, which enabled their undisturbed growth. This resembles the situation described from the autoparabiostromes (*sensu* Kershaw 1984) from Zubravka quarry (Łuczyński *et al.* 2009). Such settings were most probably located in outer shelf areas, below the storm wave base, and therefore were not interrupted by recurring high-energy events, such as storms. Single stromatoporoid skeletons grew for up to several tens or even hundreds of years (Young and Kershaw 2005) and their growth remained undisturbed during that time. On the other hand, their high profile, low burial ratio and flat lower surfaces made them vulnerable to redeposition (Kershaw and Brunton 1999). During extreme events, which interrupted the generally calm environment, the stromatoporoid growth was terminated, and



Text-fig. 10. Correlation of the stromatoporoid beds in the Podpilip'e (215-1) section; I-II-III – stromatoporoid beds intercalated within low-dynamic layers

the skeletons were transported landward and finally deposited in the described parabiostromes.

A tsunami wave, with its very long period, causes movement throughout the water column and thus tsunamis, unlike wind-generated waves, can “feel” the seabed even at great depths (Ward 2001; Weiss 2008). The back and forth water movement is therefore capable of setting in motion sediments at depths well below the storm wave base. Of course, correspondingly large flow velocities are needed to move larger fractions, such as reef boulders and large stromatoporoids. Modern tsunami-derived boulders are represented mainly by light, porous reefal limestones (Goto *et al.* 2007; Paris *et al.* 2009) which, like the stromatoporoids, are characterized by a low specific weight. The depths, from which the modern tsunami boulders and other tsunami-genic material were derived, exceed 20 m (Szczeniński *et al.* 2006; Paris *et al.* 2009). Many authors, however, both those studying modern and fossil tsunami deposits, report an admixture of open-marine fauna (microfauna) characteristic of deeper parts of the shelf (Każmierczak and Goldring 1978; Cantalamessa and DiCelma 2005; Dawson and Stewart 2007).

The postulated original habitat of the stromatoporoids building the parabiostromal beds, most probably located below the storm wave base, makes a tsunami the most probable factor that could have caused their redeposition.

Stromatoporoid beds – distribution

Individual stromatoporoid beds are present in all of the sections studied. Their continuity can be traced at the small scale of particular exposures (Podpilip’*e*, Text-fig. 10), as well as between them, in high inaccessible walls along the banks of the Zbruch River. Correlation between adjacent exposures can be made bed-by-bed, based on the number of beds and their position in the succession. The correlation of particular beds between the northern group of sections, exposed around the villages of Verbovka, Podpilip’*e* and Berezhanka, and the southern, exposed near Baryshkovtsy is more speculative, but all the sections represent the same interval with a number of characteristic stromatoporoid layers, directly overlying the sharp boundary between yellowish dolomites and grey limestones (Text-fig. 4). Particular beds usually maintain a comparable thickness and composition in terms of stromatoporoid sizes and distribution. Thickness differences are most probably governed by minor palaeotopographic relief of the sea bottom. The northern group of exposures represents a setting located closer to the palaeoshoreline, which was probably situated farther to the northeast, whereas the

southern group was located more offshore; nonetheless, all of the sections are developed in inner shelf shallow-water facies. The distance between the sections indicates that the area occupied by intertidal facies was vast, and therefore the shore profile was very flat, although the exact geometrical relationship (angle) between the transect represented by the sections and the palaeoshoreline is difficult to determine.

Direct comparison of the stromatoporoid beds with modern high-energy event deposits is impossible due to the unique character of stromatoporoids as shelf inhabitants and constructors of carbonate buildups, without a good modern analogue. Today, large bodies redeposited shoreward by such events are represented mainly by reefal limestones. However, the vastness of the area covered by parabiostromal beds, as indicated by the distance between the northern and southern group of outcrops, in some aspects resembles the distribution of tsunami-derived material.

Paris *et al.* (2009) point out that tsunami boulders deposited in the moat in Lhok Nga (western Banda Aceh, Sumatra, Indonesia) are evenly distributed in shallow waters, whereas boulders left by tropical storms build distinct ridges due to repeated reworking by turbulent waters. The boulders are composed of reefal limestones with weights reaching tens of tons, incorporated within sandy deposits. No such large elements are found in the Silurian of Podolia; where the largest stromatoporoid specimens reach diameters of only around 0.5 m. This grain size difference is, however, not a result of smaller energy of the transporting factor, but rather an effect of different source material. A truism which needs to be borne in mind is that a tsunami may only deposit material that the propagating wave has earlier moved from the sea bottom.

Distribution of event deposits has been thoroughly studied on the Ryukyu Islands (e.g. Goto *et al.* 2013), which are frequently exposed to both tsunami waves and tropical storms. Boulders of tsunami origin were transported there over a distance of more than 1 km landward from the reef crest, whereas the occurrence of those deposited by hurricanes is limited to a narrow strip (~ 200m) on the leeward side of the reef (Goto *et al.* 2010a). Moreover, the size of boulders deposited by storms decreases with increasing distance from the reef crest, whereas the tsunami boulders show no lateral size segregation. This is an effect of different kinematics of the water movement in near-shore areas during tsunamis and storms. In the case of a tsunami, which is a wave with an extremely long period, the horizontal component of the water flow is close to constant throughout the water column (Ward 2001; Dawson and Stewart 2007). Storms induce turbulent

water movement, quickly fading after passing a barrier (Rankey *et al.* 2004). The tsunami boulders on Ryukyu Islands were deposited abruptly, irrespective of their size, which points to a rapid decrease of the flow velocity, possibly when the oncoming wave met the backwash flow (Goto *et al.* 2010b). Their distribution was governed mainly by minor changes in topography.

On land, the tsunami deposits are characterized by thinning and fining landward (e.g. Dawson and Shi 2000). Offshore, the tsunami-derived material is distributed more evenly and occupies broader areas than the sediments deposited by tropical storms (Paris *et al.* 2009; Goto *et al.* 2013). A comparable thickness of the stromatoporoid beds between the sections and a lack of lateral size segregation of the stromatoporoids resemble the above-described modern boulder distribution, governed mainly by sea bottom topography. The vastness of the area covered by the stromatoporoid beds, as compared with modern boulders, is an effect of the very low profile of the Silurian shelf in the Podolia region.

Unlike the modern examples, the stromatoporoid specimens were transported separately, and not as reef fragments. However, in many cases during tsunamis entire small patch reefs are torn out from offshore waters and deposited in moats and on the beaches (Goto *et al.* 2007). These small buildups constituted separate bodies that were already partly covered by loose fine-grained sediments before redeposition, very much the same way as the individual stromatoporoids in the Silurian. In both cases, the exhumation and transport by an oncoming tsunami wave did not have to be linked with breaking and disintegration of any larger structures, as the clasts already lay on the sea bottom “waiting” for redeposition.

Stromatoporoid beds and flat-pebble conglomerates – internal structure

The different development of the high-energy event beds, represented by the stromatoporoid and bioclastic limestones and by the flat-pebble conglomerates, is a reflection of two main factors – mode of transport of the redeposited material, and its source. The stromatoporoid limestones most probably represent deposition mainly by traction. The stromatoporoids are overturned and in some cases fragmented. Unsorted stromatoporoids of various dimensions are evenly distributed throughout the thickness of the beds, forming clast-supported textures. No individuals show continuation of growth after redeposition, which is a common feature of stromatoporoids (Kershaw and Brunton 1999; Łuczyński 2006). This indicates that they

were totally buried by sediment after deposition in the parabiostromal bed.

In some sections, the stromatoporoids are restricted to the lowermost parts of the beds, which pass upwards into bioclastic limestones, with the whole layer showing graded bedding. In this case, the finer material was probably deposited from suspension. The same can be inferred for the gastropod-bivalve coquinas with shells in convex-up position and with geopetal infillings (Text-fig. 8e).

The main biotic components of the bioclastic limestones are disintegrated bryozoans and gastropods, accompanied by ostracods, solenoporacean red algae and *Tuxekanella*. The same elements are also present in the matrix of the stromatoporoid limestones. This material was derived from shallow water areas, most probably located landward from the place of their final deposition. The same has been postulated for the matrix of lenticular stromatoporoid beds preserved in palaeotopographic lows, such as tidal channels, exposed in other Silurian sections of Podolia (Skompski *et al.* 2008; Łuczyński *et al.* 2009).

The above-presented sedimentary features resemble in many aspects those of modern and fossil tsunami deposits. Tsunami waves can transport material both onshore and offshore – in traction, suspension and due to saltation (e.g. Paris *et al.* 2009). Combination of sediments deposited from traction and suspension by one or more waves has been documented from several recent examples of tsunami deposits (e.g. Moore *et al.* 2011; Jaffe *et al.* 2012; Szczuciński *et al.* 2012). Takashimizu and Masuda (2000) have identified a sequence of tsunami deposits from the Upper Pleistocene of central Japan, with its lower part dominated by tsunami-generated tractional currents and an upper part composed of sediments deposited from suspension. Mixing of faunal elements derived from open marine settings and from shallow waters, often with an admixture of terrestrial material, has been identified in deposits with a postulated tsunami origin e.g. by Kaźmierczak and Goldring (1978), Bussert and Aberham (2004) and Cantalamessa and Di Celma (2005). The appearance of elements transported offshore can be attributed to backwash flows of waters receding from the inundated areas after propagation of the tsunami wave. However, the area investigated here is characterized by a very gentle gradient, in which case the backwash flow is usually not significant (e.g. Goto *et al.* 2011).

A distinct type of high-energy event beds present in the investigated sections is developed as flat-pebble conglomerates, which overlie the stromatoporoid beds, or occur individually, but as their lateral equivalents (Verbovka; text-fig. 4). The clasts are represented mainly by elongated fragments of laminated limestones, mi-

crofacially identical to light-grey laminites of the low-energy facies occurring in the sections, with a small admixture of bioclasts.

Different types of flat-pebble conglomerates have been variously interpreted; i.a. as effects of storms (e.g. Wignall and Twitchett 1999), mass movements (e.g. Szulczewski 1968, 1971; Spaletta and Vai 1984), seismic shocks (e.g. Pratt 2002) and also of tsunamis (e.g. Kaźmierczak and Goldring 1978; Kullberg *et al.* 2001; Myrow *et al.* 2004). The composition of the flat-pebble conglomerates described here, their position in the sections and their spatial relationship to the stromatoporoid beds makes the tsunami interpretation the most probable.

The propagating tsunami waves, which caused exhumation and onshore redeposition of the stromatoporoids forming parabiotomes, led in other parts of the seabed to erosion of semi-lithified thin-layered limestones. A tsunami is usually composed of several waves, and therefore the loose sediments resting on the sea bottom were removed by the preceding wave, exposing the lower strata to erosion by the following wave. The disintegrated parts of semi-lithified laminae forming elongated clasts with rounded edges were transported landward and redeposited to form flat-pebble conglomerates. This explains the typical position of the conglomerates in the sections, in which they usually rest on stromatoporoid beds. In some cases, the lithoclasts were accompanied by stromatoporoids (Text-fig. 8b) and other biotritus.

Typical of tsunami deposits is the occurrence of ripped-up mud clasts within fine-grained deposits (e.g. Morton *et al.* 2007; Goff *et al.* 2012; Yawsangratt *et al.* 2012), which are generally absent in modern storm-generated deposits. Turbulent water movements during storms leads to disintegration of soft clasts, whereas during tsunamis, characterized by the domination of horizontal water flow throughout the water column, they are often incorporated into fine sediments deposited onshore or in shallow water areas. The clasts of the above-described flat-pebble conglomerates can be treated as a specific type of such clasts. Fenestral umbrella structures with blocky calcite infillings and with shapes resembling microstalactitic druse cements under the clasts may suggest cementation of the conglomerates under sub-aerial conditions, which means that they became exposed for some time after deposition.

DISCUSSION – POSSIBLE TSUNAMI SOURCE

Looking for an analogy to the stromatoporoid beds among modern high-energy event deposits is difficult due mainly to the unique character of Palaeozoic stromatoporoids as shelf inhabitants and constructors of

organic buildups. Moreover, the effects of modern catastrophic events are studied mainly onshore, with relatively little data on their character and distribution available from offshore settings. Nonetheless, several attributes of the high-energy event beds described in this paper allow a tsunami interpretation of their origin to be presented.

Tsunami deposits are dependant on local sediment sources and interaction between the waves and the nearshore bathymetry. Commonly even large catastrophic events leave little sedimentary imprint and are limited to single layers of coarse-grained material or re-deposited mud (e.g. Szczuciński *et al.* 2012a, b). This may explain why no other, analogous high-energy event beds have so far been described from coeval deposits from other sectors of the continuous shelf fringing the East European Craton from the west (comp. Kaljo *et al.* 1983; Einasto *et al.* 1986; Bjerkéus and Erickson 2001; Sandström and Kershaw 2002). Perhaps the intercalations of mudstones and cm-thick layers of coarse-grained material present in the low-energy facies (laminated limestones) are yet another manifestation of tsunamis. Such deposits, if present in other areas, are not remarkable enough to be interpreted as effects of big events.

The disturbance of the water column causing a tsunami can be triggered either “bottom-up” – by displacements of the seabed caused by submarine earthquakes, volcanic eruptions and landslides; or “top-down” – by asteroid or comet impacts and coastal landslides (Dawson and Stewart 2007).

Impact-triggered palaeotsunami deposits have been described e.g. by Simms (2007) and Purnell (2009), and impact-generated tsunamis are postulated to have contributed to the Cretaceous/Paleogene (e.g. Albertão and Martins 1996) and Frasnian/Famennian (see. discussion in Racki 1999) mass extinction events. However, an impact-related origin of the beds described here seems highly improbable. The recurrence of the event beds intercalating the low-energy facies show that the postulated tsunami waves hit the shelf of Baltica several times and that consecutive tsunamis were separated by calm periods, during which the low-energy facies were deposited. This cannot be attributed to a single bolide impact. The frequency of different-sized bolide impacts has been estimated by Yabushita and Hatta (1994), who calculated that a 200 m diameter asteroid is likely to hit the Pacific Ocean once in 15000 years. It is most unlikely that impacts large enough to have a geological imprint (with wave height > 5 m; Ward and Asphaug 2002) would hit the same area a number of times during the deposition of the strata exposed in the sections, although the approximate time represented by the successions is very difficult to estimate.

Another “top-down” source of tsunami – coastal landslides on the nearby shores of Baltica, can also be excluded. In Podolia the tsunami waves clearly propagated onshore through the zone of shoals and lagoons, and thus their source must have been located offshore. Moreover, the shore profile was very flat, with a wide peritidal zone, as indicated by the occurrence of desiccation cracks, karstic emersion surfaces and even initial palaeosoils in numerous sections (Skompski *et al.* 2008), which excludes the possibility of large scale gravity movements. No evidence of mass movements or synsedimentary faulting is observed in the sections.

“Bottom-up” tsunamis, induced by rapid displacements of the sea floor, are therefore the most probable process responsible for the formation of the stromatoporoid and conglomerate beds. The southwestern (actual orientation) edge of Baltica generally functioned as a passive continental margin in the Silurian. Although some synsedimentary tectonic activity took place along the mobile Teisseyre-Tornquist Zone (Text-fig. 1; Poprawa *et al.* 1999), the tsunami source was most probably located on the other side of the sea, in a foreland basin.

The Ludlow–Lochkovian succession of the Łysogóry region of the Holy Cross Mountains (Central Poland) located within the Trans-European Suture Zone (TESZ), with flysch-like sediments in its lower part, represent an infill of a Caledonian foreland basin situated at the south-west margin of Baltica (Narkiewicz 2002; Kozłowski 2008). The sediment source area was located south-west from the basin (Malec 2001) in an arc-continent orogen that originally represented the continuation of the Avalonia–Baltica suture (Kozłowski *et al.* 2004). The Łysogóry region was separated from the shallow-water facies fringing Baltica by a narrow belt of neritic sediments. In this active foreland basin all major processes responsible for triggering “bottom-up”-induced, recurring tsunamis could occur, including submarine earthquakes, volcanic activity, and large underwater landslides. The resulting waves travelled across the epicratonic sea, growing rapidly in height when they reached the shallow waters of the Podolian shores. However, taking into account the scale of modern tsunami events (e.g. the 2004 Sumatra tsunami, which caused damages all around the Indian Ocean), the tsunami source could also have been located in other, more distant regions.

CONCLUSIONS

The studies of Upper Silurian sections along the Zbruch River allow the following conclusions to be presented:

1. Stromatoporoid beds with fragmented open-marine fauna and flat-pebble conglomerates embedded within shallow-water, peritidal, lagoonal facies point to high-energy sedimentary events punctuating the otherwise calm environment.
2. The stromatoporoid beds are developed as parabiostromes composed of overturned and often fragmented massive skeletons. They indicate large scale onshore transport of mainly biogenic material, and can be attributed to phenomena with energy levels exceeding those of storms.
3. Morphometric features of the redeposited stromatoporoids point to a calm original growth environment with a low deposition rate, which enabled their undisturbed growth. The stromatoporoid habitats were most probably located at depths well below storm wave base, in which the bottom waters were interrupted only by very high-energy phenomena. Tsunami waves are the most probable factor that could have caused redeposition of the stromatoporoids from such a setting. The depth at which the erosion took place is one of the most important features distinguishing tsunami- and storm-derived deposits (see above).
4. The vastness of the area covered by the parabiostromal beds, as indicated by the distance between the northern and southern group of outcrops, and the lack of lateral size segregation of the stromatoporoids, resembles in some aspects the distribution of modern tsunami-derived material and differs from the typical distribution of storm-derived deposits.
5. The clast-supported, densely packed stromatoporoid beds with unsorted specimens represent transport in traction by the oncoming tsunami waves. The bioclastic limestones with graded bedding and material derived from shallow water areas (*Tuxekanella*, ostracods and plant remains) were deposited from suspension, probably during backwash flows by waters receding from the inundated areas towards the open sea.
6. The composition of the flat-pebble conglomerates, their position in the sections and their spatial relationship to the stromatoporoid beds makes the tsunami interpretation the most probable. The propagating tsunami waves, led to erosion of partly lithified thin-layered limestones, their fragmentation into flat clasts and redeposition as conglomerates, which is a process resembling the formation of rip-up mud clasts in modern tsunami deposits.
7. The tsunami was most probably “bottom-up”-induced, with its source located on the other side of the epicratonic sea, in a Caledonian foreland basin that was situated at the south-west margin of Baltica, within the Trans-European Suture Zone.

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