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Recent studies on the Silurian of the western part of Ukraine

PIOTR ŁUCZYŃSKI, STANISŁAW SKOMPSKI and WOJCIECH KOZŁOWSKI

Faculty of Geology, University of Warsaw, Al. Żwirki i Wigury 93; PL-02-089 Warszawa, Poland
E-mails: Piotr.Luczynski@uw.edu.pl, Skompski@uw.edu.pl, Wojciech.Kozlowski@uw.edu.pl

ABSTRACT:

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The paper summarises the effects of recent studies carried out by a team from the Department of Historical and Regional Geology of the Faculty of Geology, University of Warsaw on the upper Silurian of Podolia (western part of Ukraine).

The sedimentary history of the Silurian succession of Podolia is characterised by its cyclic pattern, with shallowing-upward cyclothems. In the traditional interpretation, the occurrence of stromatoporoid beds within each cyclothem marks the deepest (or most open-marine) sedimentary environment within the cycle. According to the results of recent studies, their occurrence is connected rather with a relatively shallow-water environment and with high energy phenomena. A substantial reinterpretation of the main sedimentary processes governing the deposition and facies distribution on the shelf is presented. Particularly, there are recognised and described high-energy sedimentary events repeatedly punctuating the generally calm sedimentation that prevailed in the lagoonal settings, some of which are interpreted as tsunami induced.

Further perspectives for studies on the Silurian successions of Podolia are also discussed. The main problem is the precise correlation of particular sections that are scattered over vast distances and developed in similar facies associations.

Keywords: Upper Silurian; Podolia; Facies; Stromatoporoid beds; Sedimentary environments.

INTRODUCTION

The aim of this paper is mainly to present the results of recent studies on the upper Silurian of the Podolia region (western part of Ukraine) performed by a team from the Department of Historical and Regional Geology of the Faculty of Geology, University of Warsaw.

The Palaeozoic of western Ukraine has traditionally been a subject of interest of Polish geologists since the end of the nineteenth century. However, for decades of Soviet rule the area was hardly accessible, and therefore more intensive studies were not carried out. The situation changed after the foundation of the Ukrainian state in 1991, and a number of Polish researchers, in collaboration with their Ukrainian partners, began new investigations (e.g. Małkowski *et al.* 2009; Racki *et al.* 2012; Środoń *et al.* 2013; Szaniawski and Drygant 2014). The team from the University of Warsaw (authors of the present paper) began their work on the upper Silurian of Podolia in 2005, with extensive help from Prof. Danyło Drygant from the State Museum of Natural History in Lviv, National Academy of Sciences of Ukraine, who introduced us to the topic and showed us the crucial localities.

The Podolia region offers excellent exposures of the upper Silurian. A wide belt of shallow-water facies is accessible for studies in numerous natural outcrops, mainly along the Dnister river and its northern tributaries, as well in a number of active quarries. The outcropping strata are almost horizontal, with only a slight dip to the west and with no distinct tectonic disruptions recognisable in field, allowing the tracing of particular horizons over long distances. This has enabled an insight into the sedimentary architecture and eventually allowed a substantial reinterpretation of the processes governing deposition on a Silurian shelf. The main topics addressed in this paper, and summarising the newly presented data and the recently proposed interpretations are:

i) recognition of numerous event phenomena punctuating deposition on the shelf, commonly manifested by the occurrence of thick stromatoporoid beds, with various geometries and lateral continuity, intercalated within fine-grained peritidal deposits;

ii) reconstruction of the processes of mass onshore transport of biogenic (mainly stromatoporoid) and lithogenic material by high-energy sedimentary events and of their deposition in calm, restricted lagoonal settings;

iii) analysis of the morphometrical features of stromatoporoids and their interpretation in terms of environmental conditions in their habitats and susceptibility to redeposition;

iv) interpretation of some of the event beds as tsunami deposits and the discussion of the possibilities of identification of palaeotsunamis in shallow-marine carbonate facies;

v) identification and environmental interpretation of *in situ* biogenic accumulations dominated by stromatoporoids.

Points i-iv listed above and discussed in the following chapters of this paper summarize the results of the studies published in the authors' consecutive papers (Skompski *et al.* 2008; Łuczyński *et al.* 2009, 2014). Our understanding of the nature of the high-energy sedimentary events and of their impact on the facies record of the Silurian successions of Podolia evolved slightly during these years, and this is also presented here. Particularly, the possible role of tsunami waves as factors responsible for onshore transport of the material has become more evident. The identification and environmental interpretation of *in situ* stromatoporoid accumulations (point v) is presented here in detail for the first time.

Further perspectives for studies of the Silurian successions of Podolia are also discussed. The main problem is the precise correlation of particular sections that are scattered over vast distances and developed in similar facies associations. Various recent attempts to create a regional stratigraphic framework were based mainly on the identification of bentonite layers and on major isotopic excursions that could be traced on longer distances. An attempted local correlation of adjacent profiles, based on the analysis of field spectral gamma ray measurements, combined with facies studies, was presented in Łuczyński *et al.* (2015). The local stratigraphic framework obtained allowed the presentation of a small scale model illustrating the reaction of carbonate sub-environments to sea level changes and showing the facies position of the stromatoporoid buildups within facies patterns on a Silurian shelf.

HISTORY OF POLISH INVESTIGATIONS OF THE WESTERN PART OF UKRAINE

In the first half of the 19th century the Podolia region was investigated mainly by Russian and Austro-Hungarian geologists (see Szaniawski 2005). The first announcements on the Palaeozoic rocks of Podolia made by Polish investigators appeared in the famous monograph of Alth (1874), published in German and later supplemented by cartographical material in the Geological Atlas of Galicia (Alth and Bieniasz 1887). More or less at the same time, the understanding of the local stratigraphy was considerably improved due to the paper of Szajnocha (1889). Simultaneously the tectonics and geomorphology of the region were the subject of several publications by Teisseyre (1893, 1894, 1900). The first synthetic descriptions of the Podolian geology, with the use of a relatively modern terminology, were presented in the first handbook of the geology of Poland by Siemiradzki (1903), and in a more detailed monograph devoted to the Paleozoic of Podolia (Siemiradzki 1906). Unfortunately it became apparent later that his views on the stratigraphy and facies architecture may be incorrect, and were criticized by subsequent investigators.

The real turning point in the understanding of the upper Silurian stratigraphy of the region were investigations carried out at the University of Warsaw in the course of the 1920s by Dr Roman Kozłowski, future world-famous expert in graptolite taxonomy and evolution. In 1924, after 8 years of work in Bolivia and 2 years of PhD studies in Paris, he came back to Poland and started to organize the Palaeontological and Geological Laboratory at the Wolna Wszechnica private high school in Warsaw. At the same time, he gave lectures in palaeontology for students of the University of Warsaw, where in 1927 the Chair of Palaeontology had been established, and R. Kozłowski became its leader for many years. In spite of enormous administrative activity, he did not neglect scientific investigations, which concentrated on the upper Silurian beds, exposed in the river cliffs of Dnister and its left tributaries, in the vicinity of Skała Podolska (Skala Podil'ska) on the eastern outskirts of Poland. The results of his palaeontological investigations were published in the form of a comprehensive monograph (Kozłowski 1929), printed as the first volume of the "*Palaeontologia Polonica*" – monograph series published to date.

In this strictly palaeontological study, the main subject was preceded by a comprehensive introduction, in which the Silurian series were arranged in order. Kozłowski confirmed the stratigraphical succession of the Skała, Dzvenyhorod, Borshchiv and Chortkiv Beds, according to the earlier descriptions of Alth (1874), Alth and Bieniasz (1887) and Szajnocha (1889), and contrary to the opinion of Siemiradzki (1906), who had treated these units as isochronous facies equivalents. He also proposed new definitions of particular units, treating them as chronostratigraphical stages (in the modern sense of the term). The Skała Stage – the oldest unit exposed in the Polish part of the Dnister section, was represented here by three lithostratigraphical sets (in stratigraphical order): Skała Limestones (Stromatoporoid Limestones) (originally *Calcaires de Skała* (ou *Calcaires à Stromatopores*)), Dzvenyhorod Marls (originally *Marnes de Dzwinogród*) and Tajna Beds (originally *Couches de Tajna*). The oldest unit – the Skała Stromatoporoid Limestones, covered the Isakivtsi Dolomites (originally *Dolomie d'Izakowce*), a unit easily distinguishable due to its petrographical characteristics.

In the context of the above presented stratigraphical scheme, the recent investigations reported in this paper concern two complexes: the Skała Limestone unit and an older Malynivtsy unit (Text-fig. 2). In the numerous papers of Russian and Ukrainian authors published after the Second World War (i.e. Nikiforova *et al.* 1972; Tsegelnjuk *et al.* 1983; Drygant 1984; Koren' *et al.* 1989) the units have been repeatedly redefined. A review of the stratigraphical changes has been presented in detail i.a. by Abushik *et al.* (1985), and in more recent papers by Małkowski *et al.* (2009), Voychyshyn (2011), Racki *et al.* (2012) and Szaniawski and Drygant (2014). Most of sedimentological, palaeoecological and geochemical investigations, inspired usually by prof. Szaniawski from the Institute of Palaeobiology of the Polish Academy of Sciences, and carried out in the beginning of the 21st century, were focused on the short intervals corresponding to global isotopic events. Their results are summarized by Szaniawski (2012) and other papers published in the same volume of *Acta Palaeontologica Polonica*.

GENERAL REGIONAL AND STRATIGRAPHICAL SETTING OF THE SILURIAN OF PODOLIA

In the Silurian, the area of present-day Podolia was a part of a vast carbonate shelf belonging to a marginal sea that rimmed Baltica from the south (Silurian orientation), with deposition governed mainly by eustatic sea-level changes (Text-fig. 1A). The shelf stretched from present-day western Ukraine, through Belarus, north-western Poland and the Baltic States, up to the island of Gotland on the Baltic sea and the Scania region in southern Sweden (Calner 2005). In its northern part, the shelf engulfed a somewhat deeper epicontinental East Baltic Basin. Over most of its length of 2000 km it had an approximately constant width of around 150-200 km and maintained a characteristic facies pattern. A central position in this pattern was occupied by a zone of shallows and barriers dominated by stromatoporoid-coral buildups developed as biostromes and bioherms, as has been described i.a. from Estonia (e.g. Kaljo 1970; Kaljo *et al*. 1983; Nestor and Einasto 1997) and Gotland (Bjerkéus and Eriksson 2001; Sandström and Kershaw 2002, 2008). This zone separated the inner shelf lagoonal environments from outer shelf and slope facies that pass into basinal graptolitic shales. In the Podolian sector, the outer shelf and slope facies are dominated by limestones and marls with an abundant and diverse open-marine fauna of stromatoporoids, tabulate and rugose corals, brachiopods and crinoids (e.g. Racki *et al.* 2012). The inner shelf facies are developed mainly as laminites and dolomicrites with ostracods and eurypterids, which are intercalated by stromatoporoid-rich beds (e.g. Skompski *et al.* 2008). During sea-level changes the exact location of particular zones shifted, but the general pattern remained unchanged.

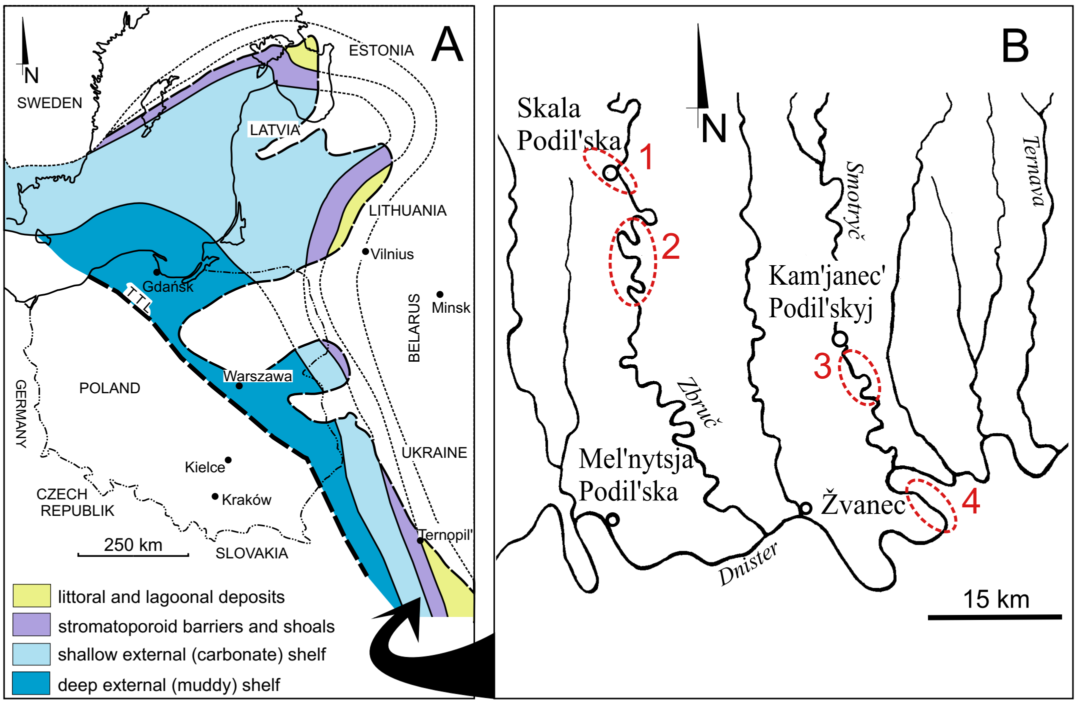
The most intensely studied parts of the Silurian shelf are the exposures on Gotland and in Estonia, where several attempts of reconstructing the facies pattern were made. However, due to a substantial tectonic tilting and the shallowness of erosional cuts, combined with a general lack of good sections perpendicular to the facies zones, the tracing of complete transects cutting the whole facies belt was impossible even in such excellent outcrops as those on the shores of Gotland (Kershaw 1990; Sandström and Kershaw

2002). Therefore, although the localities allow recognition of the evolution of the succession through time (e.g. Samtleben *et al.* 2000; Baarli *et al.* 2003), the reconstructed facies patterns are based mainly on seismic profile analyses (e.g. Flodén *et al.* 2001; Bjerkéus and Eriksson 2001) and are thus only interpretations.

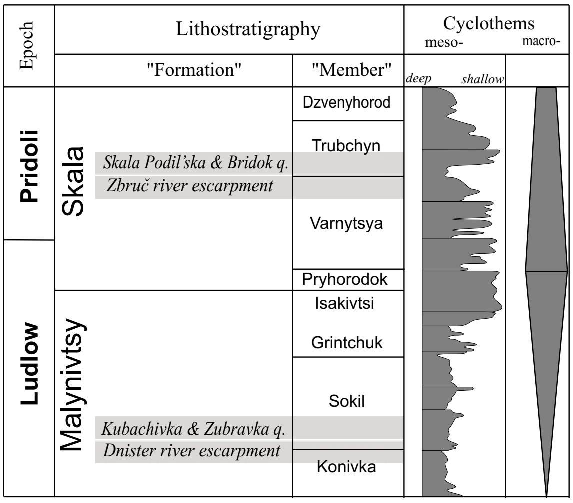
Attempts at creating a facies model of the Silurian carbonate shelf on Baltica were carried out also by Estonian researchers and were based on numerous boreholes penetrating the Baltic States (Nestor and Einasto 1977; Einasto *et al.* 1986; Einasto and Radionova 1988; Hints *et al.* 2008). However, the large distances between individual boreholes made it necessary to extrapolate the data, and therefore the reconstructions presented contain no detailed information about the width of particular facies zones and about their spatial relations. Most of the interpretation is provided here by the analyses of vertical succession, which according to the Walther's principle registers the changing position of particular zones governed by changes in sea-level.

In this context, the excellent exposures of the Silurian in Podolia offer a unique opportunity for studies and verification of the mentioned models. The region provides probably the best access to a wide-spread facies belt of the marginal sea that rimmed the East European Craton along its whole length. The Silurian succession is exposed in the high banks of the deeply incised valley of the Dnister River, between its left side Ternava tributary on the east and the village of Dnistrove on the west (where a parastratotype of the Silurian/Devonian boundary is located), and along its northern tributaries – mainly the Zbruč and Smotryč rivers. Several active quarries operate in the river valleys. The strata are close to horizontal with only a slight dip to the west and with no distinct tectonic disruptions recognisable in field. The almost continuous exposures along the generally latitudinally flowing Dnister River enable examination of the whole Silurian profile, whereas the banks of the meridionally flowing tributaries allow tracing particular horizons over long distances.

The Silurian succession of Podolia is 370- to 430 m thick, and is best characterised by its cyclic pattern (Text-fig. 2). The cyclothems are arranged into three orders of units: elementary cyclothems, mesocyclothems and macrocyclothems (Tsegelnjuk *et al.* 1983; Predtechensky *et al.* 1983). The two older macrocyclothems represent regressive successions, while the latest, which passes into the Devonian, is transgressive. In terms of local lithostratigraphy the Silurian is divided into four informal units – Kitaigorod, Bahovytsia, Malynivtsi and Skala (for a most complete and recent scheme see: Racki *et al.* 2012), the recognition of which is based on a mixture of lithos-



Text-fig. 1. Distribution of the upper Silurian. A – upper Silurian facies along the margin of the East European Craton (after Einasto *et al.* 1986, simplified). B – Location of the sections studied: 1 – Skala Podil'ska and Bridok Quarries (detailed location in Skompski *et al.* 2006, 2008); 2 – Zbruč river escarpment (detailed location in Łuczyński *et al.* 2014); 3 – Kubachivka and Zubravka quarries (detailed location in Łuczyński *et al.* 2009); 4 – Dnister River escarpment (detailed location in Łuczyński *et al.* 2015)



Text-fig. 2. Stratigraphic position of the sections studied. Lithostratigraphy and chronostratigrapical correlation according to Tsegelnjuk *et al.* 1983; Drygant 1983; Koren' *et al.* 1989; Racki *et al.* 2012; cyclothem interpretation after Predtechensky *et al.* 1983. Stratigraphic position of the studied sections indicated by shadow bars

tratigraphical and biostratigraphical criteria (Nikiforova *et al.* 1972; Tsegelnjuk *et al.* 1983; Drygant 1984; Koren' *et al.* 1989; Kaljo *et al.* 2007). The complexes can be treated as "para-formations" – units corresponding to formations, but never properly defined in their formal sense. Therefore, in the presented studies, the Ukrainian original terms of "horizon" and "suite" (e.g. Abushik *et al.* 1985), commonly treated as chronostratigraphic units, have been replaced by the English terms "formation" and "member", as proposed by Koren' *et al.* (1989) and Huff *et al.* (2000). The Bahovytsia Formation, represented mainly by shallow-water facies, separates the somewhat deeper Kitaigorod and Malynivtsy formations. The youngest Skala Formation is dominated by shallow-water deposits, however with a deepening upward tendency. During sea-level changes, most probably eustatic in nature, the exact position of the above mentioned facies zones shifted landward and seaward, however their general pattern remained unchanged and is recognisable in every unit.

The detailed studies presented in this paper concentrate on selected intervals embracing parts of the Konivka and Sokil members (Ludlow) of the Malynivtsy Formation and parts of the Varnytsya and Trubchyn members (Pridoli) of the Skala Formation (shadow bars on Text-fig. 2). For detailed description of the two formations see Skompski *et al.* (2008). The main studies were carried in outcrops along the Smotryč River south of Kam'yanets' Podil'skyi, along the Zbruč River, around and south of the town of Skala Podil'ska, and along the Dnister River**,** on its both banks, between the villages of Voronovytsia and Konivka (Text-fig. 1B).

FACIES RECORD OF HIGH-ENERGY SEDIMENTARY EVENTS IN LAGOONAL SUCCESSIONS

High-energy sedimentary events, such as storms, hurricanes, etc., may cause redeposition of material laid on the sea bottom in shallow-water areas both shoreward and basinward. In the case of carbonate shelves and ramps without barriers, most of the material is finally transported into deeper zones and deposited as tempestites around the storm wave base. In the case of shelves with reef-type barriers, the storms often destroy the barrier and the material is transported into the lagoons (e.g. Tucker and Wright 1990). However, in the Silurian, the barriers were mainly represented by stromatoporoid-coral buildups, which usually did not constitute reefs in the ecological sense of the term, and which are mainly developed as biostromes (Kershaw 1990, 1994; Sandström and Kershaw 2002). The problem of how these buildups acted as barriers and responded to high-energy sedimentary events still remains unsolved.

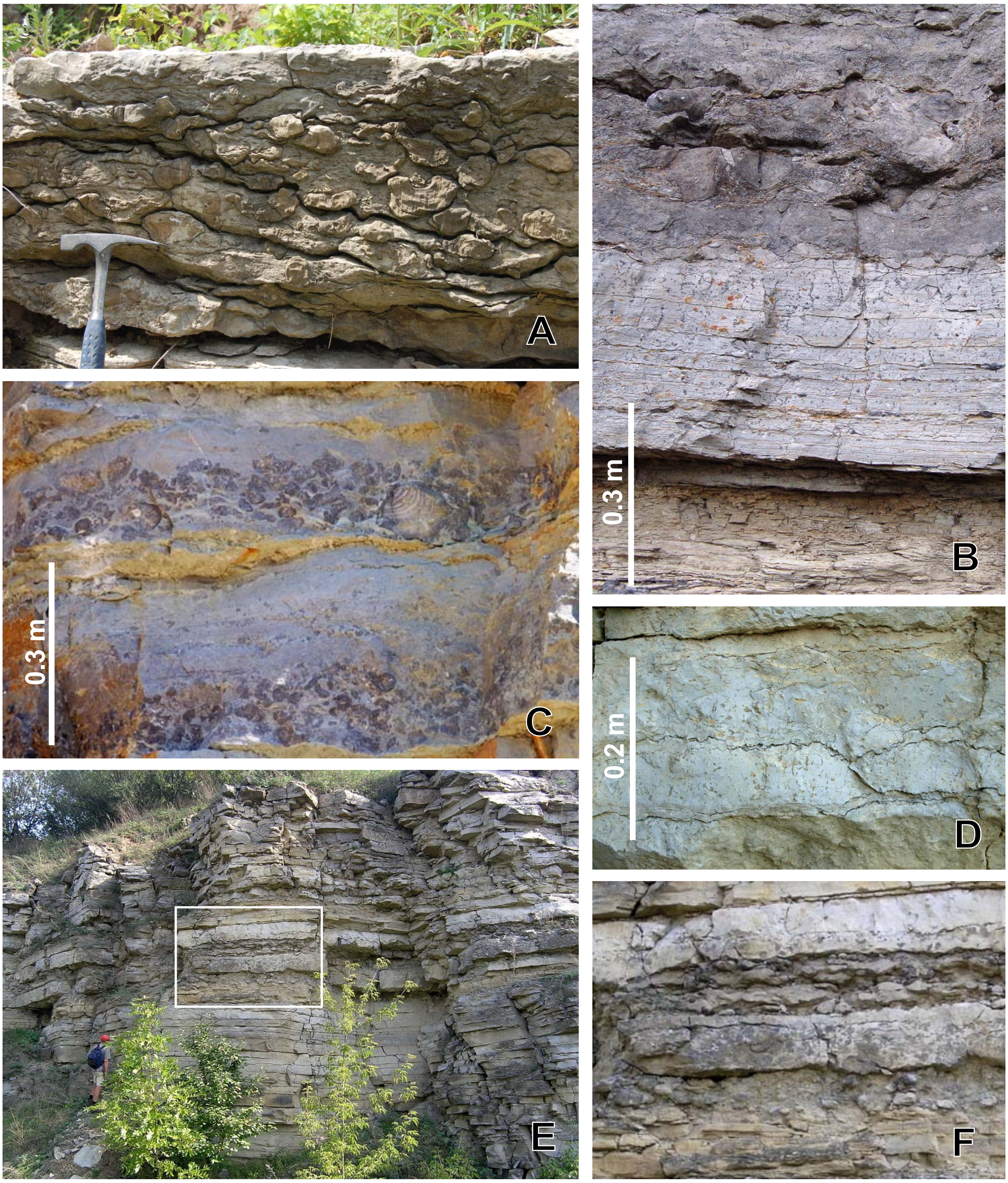
In the Podolia region, the upper Silurian (Ludlow and Pridoli) shallow-water inner shelf facies are represented mainly by fine grained peritidal laminites and dolomicrites with ostracods and eurypterids. Laminated limestones contain desiccation cracks and fenestral structures univocally indicating an extremely shallow-water environment. These deposits are commonly intercalated by variously developed stromatoporoid beds (Text-figs 3, 4). Traditionally these beds were interpreted as marking the deepest environment in a peritidal cyclic pattern (e.g. Predtechensky *et al.* 1983; Abushik *et al.* 1985). The latest studies have revealed the need to revise this interpretation.

The first studies (Skompski *et al.* 2008) were carried in the Sokil Member of the Malynivtsy Formation (Kubachivka Quarry) south of Kam'yanets' Podil'skyi, and in the Trubchyn Member of the Skala Formation (Skala Podil'ska Quarry and Zbruč River escarpment) around Skala Podil'ska (Text-fig 1B):

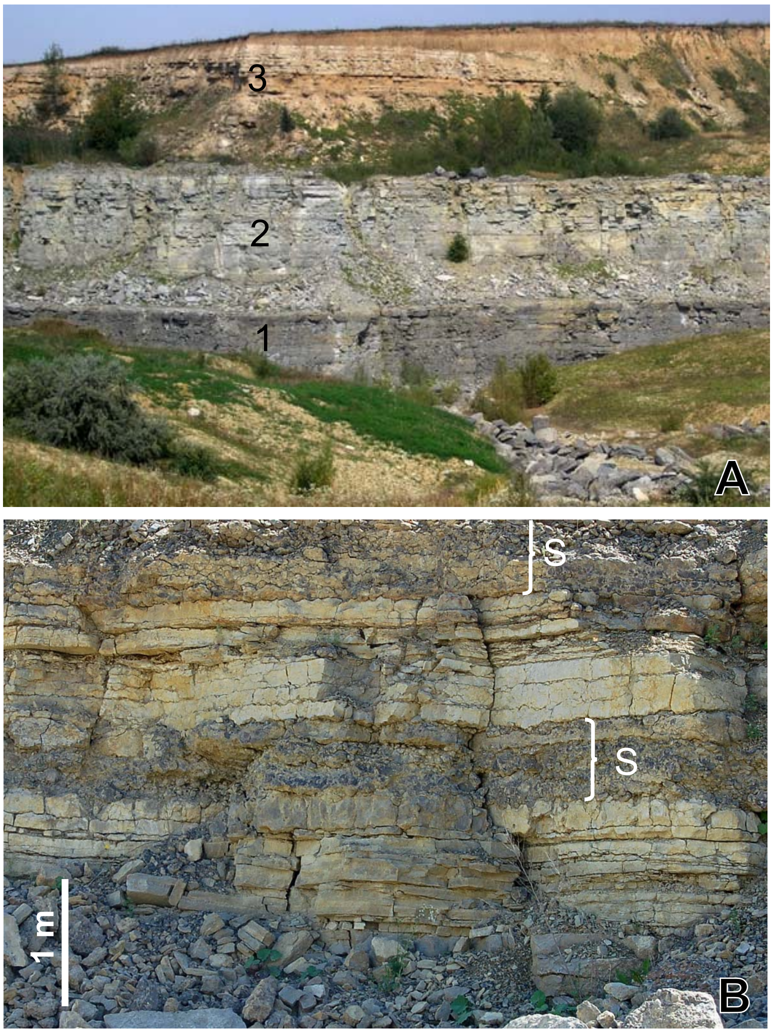
- The section exposed in the Kubachivka Quarry is composed of two thick stromatoporoid complexes separated by laminites with fenestral structures. The laminitic fenestral complex contains fragments of redeposited stromatoporoids and tabulates.
- In the Skala Podil'ska Quarry, a generally unfossiliferous dolomicritic complex outcrops, charac-

terised by the occurrence of desiccation polygons and weathering surfaces interpreted as initial regoliths. However, surprisingly, some of the beds contain a redeposited open marine benthic fauna, mainly in their upper parts.

- In the Zbruč River escarpment north of the castle in Skala Podil'ska, a large lenticular erosional channel filled by redeposited massive stromatoporoids is incised into a cyclic, shallowing-upward succession of light-coloured fine grained mi-



Text-fig. 3. Details of stromatoporoid beds intercalating intertidal deposits. A – Stromatoporoid biostrome composed of reworked specimens; locality Trubchyn, Dnister escarpment near Zbruč river mouth; B – Typical boundary between light grey intertidal bed with vertical calcite-filled tubes (lower part) and dark grey stromatoporoid biostrome; locality Podpilip'e, Zbruč river escarpment; C – Stromatoporoid layers deposited during high-dynamic events; locality Bridok Quarry, complex D; D – Typical intertidal bed with fenestral structures and vertical calcite-filled tubes; locality Skala Podil'ska, Zbruč river escarpment; E, F – Stromatoporoid beds intercalated by marly limestones; Skala Podil'ska southern quarry, inset shows the part enlarged on the Fig. F



Text-fig. 4. Bridok Quarry. A – General view of the northern wall. 1 – Stromatoporoid complex C; 2 – Complex D of laminated intertidal beds intercalated by stromatoporoid layers; 3 – Cretaceous/Neogenian cover of the Silurian complexes. B – Uppermost part of complex D: grey stromatoporoid beds (S) within light grey laminated intertidal beds

critic limestones with fenestral structures and restricted fauna.

The three localities correspond to three different sedimentary sub-environments within the peritidal zone (fig. 11 in Skompski *et al.* 2008). The section in Kubachivka Quarry represents a zone of tidal flats that developed in the vicinity of stromatoporoid shoals located at a considerable distance from shore. The channel exposed in the Zbruč River escarpment is developed in a near-shore tidal flat. The Skala Podil'ska Quarry succession represents the shallowest environment of those occurring in the Silurian of Podolia – a transition zone between intertidal and supratidal environments.

All the situations described indicate that the inner-shelf peritidal environments with generally calm sedimentation were punctuated by very high-energy events causing onshore redeposition of material derived from open marine settings. Transported were mainly stromatoporoids, which were relatively light during transport, as this happened before crystallization of sparry calcite in the internal voids of their skeletons, and after destruction of the soft tissue, and they were probably filled with water (Stearn and Pickett 1994). However, in some cases the stromatoporoids are accompanied by redeposited tabulate and rugose corals and by crinoids. The sedimentary effect observed is the co-occurrence of facies that in palaeoenvironmental reconstructions are usually located far away from each other. The high-energy events influenced sedimentation in a large and diversified area of lagoons sheltered by shoals and barriers dominated by stromatoporoids. The biogenic material derived from the shoals, or even from shallow open shelf areas, was swept into the lagoon and laid down in various peritidal settings. In Kubachivka Quarry, it was situated in the intertidal zone located on the lee sides of stromatoporoid shoals (according to a model of tidal flats proposed by Pratt and James (1986)). In Skala Podil'ska Quarry the transported material reached the onshore supratidal zone on the other side of the lagoon.

The most complex scenario is proposed to explain the development of a large erosional channel filled by stromatoporoids and incised in intertidal deposits, which is exposed on the bank of the Zbruč River. The time of channel formation and the time of its infilling by stromatoporoids must have been separated, as is indicated by the occurrence in the matrix of small lithoclasts with bioerosional coats. Therefore, the large erosional structure is interpreted as a tidal channel, as in its dimensions and orientation it resembles modern examples (e.g. Shinn *et al.* 1969; Rankey and Berkeley 2012). Its infilling is however different, as the modern tidal channels are usually filled by a basal lag of intraformational clasts accompanied by skeletal debris. In the presented case, the structure is filled mainly with stromatoporoids derived from offshore settings and swept into the lagoon. The material transported onshore finally accumulated in tidal channels, which focused the energy of flow, particularly during backwash flows, during which the water receded from inundated areas.

DETAILED ANALYSIS OF STROMATOPOROID BIOSTROMES BASED ON STROMATOPOROID MORPHOMETRICAL STUDIES

Stromatoporoid biostromal accumulations were studied in detail in two isochronous sections of the Malynivtsi Formation, in two active quarries – Kubachivka and Zubravka, closely located to each other (~ 2 km) along the banks of Smotryč River south of Kam'yanets' Podil'skyi (Łuczyński *et al.* 2009). The exposed facies succession can be subdivided into three units: an oncolitic-fenestral complex, and the stromatoporoid complexes that underlie and cover it. The sections represent the zone of shoals located at a considerable distance from shore, and its transition to back-shoal tidal flats, with Zubravka Quarry located in a slightly more offshore setting. The stromatoporoid beds are developed as autoparabiostromes (*sensu* Kershaw 1994) with disrupted skeletons, but still retaining the impression of having previously been an autobiostrome (20-60% in place) in the lower complex, and as parabiostromes with large amount of debris of autobiostome constructors (< 20% in place) in the upper complex.

The studies focused on morphometrical analysis of massive stromatoporoids. Various attributes of stromatoporoid skeletons have been interpreted in terms of their growth environment. Studied have been such features as the external shape, living surface profile, surface character and arrangement of latilaminae (major growth bands) etc., and the main reconstructed environmental factors are the rate of sediment accumulation, water turbulence and substrate consistency (e.g. Kershaw 1981, 1990, 1998; Łuczyński 1998, 2003, 2006, 2008, 2009). For detailed description of the parameterization method see Kershaw and Riding (1978) and Łuczyński (2005).

In the referred study both *in situ* and redeposited specimens from the stromatoporoid complexes were analysed, as well as specimens from non-biostromal facies. Various morphometrical attributes of redeposited stromatoporoids proved not only to be indicators of the environmental conditions in their original settings, but also could be interpreted in terms of susceptibility to exhumation and transport, which is a new approach. This group of features embraces i.a. burial ratio, type of initial surface, overall shape and capacity (volume).

The variability of stromatoporoid accumulations is shown by the range in the stromatoporoid morphometric features, as well as by the difference of the studied assemblages in the two quarries. The studies confirmed that a process of onshore redeposition of material, mainly consisting of massive stromatoporoid skeletons, strongly influenced sedimentation on the shallow shelf, which finds its reflection both in the characteristics of particular facies and in facies patterns, as was postulated by Skompski *et al.* (2008). Stromatoporoids deposited in parabiostromes were mostly derived from outer shelf areas. All their basic morphometric features, such as the domination of nonenveloping latilaminae arrangements, and the presence of low overall shapes, point to an environment in which calm episodes were only exceptionally interrupted by events with a high energy and deposition rate, most probably located well below wave base. The relatively light stromatoporoids inhabiting a soft bottom at such depths were vulnerable to exhumation and redeposition. The main process governing the composition of parabiostromal stromatoporoid beds is fractional (weight) segregation, which resulted in the occurrence of generally larger specimens in the direct vicinity of the zone of shoals (Zubravka) than in the inner part of the lagoon (Kubachivka). The autoparabiostromes, on the other hand were inhabited mainly by morphotypes better adapted to permanent wave action, which developed adaptations that prevented their exhumation and redeposition. The high-energy events had therefore less effect on the stromatoporoid communities inhabiting the zone of shoals. The biostromes building the shoals suffered loss of only some of the specimens, which results in their residual character. A characteristic *in situ* assemblage of flat laminar stromatoporoids from lagoonal non-biostromal facies is typical of muddy bottoms.

TSUNAMI INTERPRETATION OF STROMATOPOROID BEDS AND FLAT-PEBBLE CONGLOMERATES

Tentative suggestions that the high-energy sedimentary events causing onshore redeposition of the stromatoporoid material can be identified as tsunamis were expressed already in Skompski *et al.* (2008) and Łuczyński *et al.* (2009). However, new arguments allowing the presentation of the tsunami interpretation of particular stromatoporoid beds and flat pebble conglomerates (Łuczyński 2012; Łuczyński *et al.* 2014) came from the studies of the Silurian sections along the banks of Zbruč River.

Tsunamis are a natural phenomenon induced by such recurring events as submarine earthquakes or great mass movements, and there is no reason to assume that they were any less frequent in the geological past than they are today. Yet, tsunami deposits are relatively rarely identified in fossil sedimentary successions (e.g. Łuczyński 2012; Goff *et al.* 2012), which is somewhat surprising. This is mainly caused by their vulnerability to erosion (particularly those deposited onshore; e.g. Dawson and Stewart 2007), and by their susceptibility to early diagenetic changes that overprinted the original sedimentary features (Szczuciński *et al.* 2006, 2012). Lists of sedimentary features characteristic of palaeotsunami deposits have been presented by some authors (e.g. Sakuna *et al.* 2012); however, none of them can be treated as a single indicator of a tsunami origin, as in many cases the tsunami deposits showed no distinct characteristics, which allow them to be distinguished from other sediments (Shanmugam 2006). The aim of the referred studies was to describe a new type of palaeotsunami deposit and to add new arguments to the discussion on the sedimentological features of ancient tsunamis.

The outcrops studied are natural exposures located along the deeply incised meandering valley of the southwards flowing Zbruč River, south of the town of Skala Podil'ska (Text-fig. 1B). The beds are close to horizontal and devoid of tectonic disruptions, which allows the tracing of particular horizons over long distances – even several kilometres. The analysed transect is probably oblique to the palaeoshoreline (for detailed location see fig 2. in Łuczyński *et al.* 2014), with the shore located in the north-east, and so the northern group of exposures (Berezhanka, Podpilip'e and Verbovka) represents a slightly shallower and nearshore setting than the southern group (Baryshkovtsy).

The lithological succession studied is represented by low-energy facies interbedded by a number of high-energy event beds. The sections are of Pridoli age (Abushik *et al.* 1985) and belong to the Varnytsya Member of the Skala Formation (Text-fig. 2). The low-energy facies are developed mainly as laminated limestones with desiccation cracks and fenestral structures (Text-fig. 3B, D) and as marly nodular limestones and dolomites, in places accompanied by shales with floral remains and the accumulations of the microproblematicum *Tuxekanella* (Skompski 2010). The event beds are represented by stromatoporoid and bioclastic parabiostromes (Text-fig. 3A, C) and by flat-pebble conglomerates. The beds are laterally continuous over large distances, which differentiates them from the mainly lenticular stromatoporoid bodies described from other areas (Skompski *et al.* 2008; Łuczyński *et al.* 2009). The tsunami interpretation of the event beds given here is based mainly on: (i) the supposed depth at which the erosion of the material redeposited shoreward took place, (ii) the lateral distribution and internal structure of the stromatoporoid beds, and (iii) the character and composition of flat-pebble conglomerates.

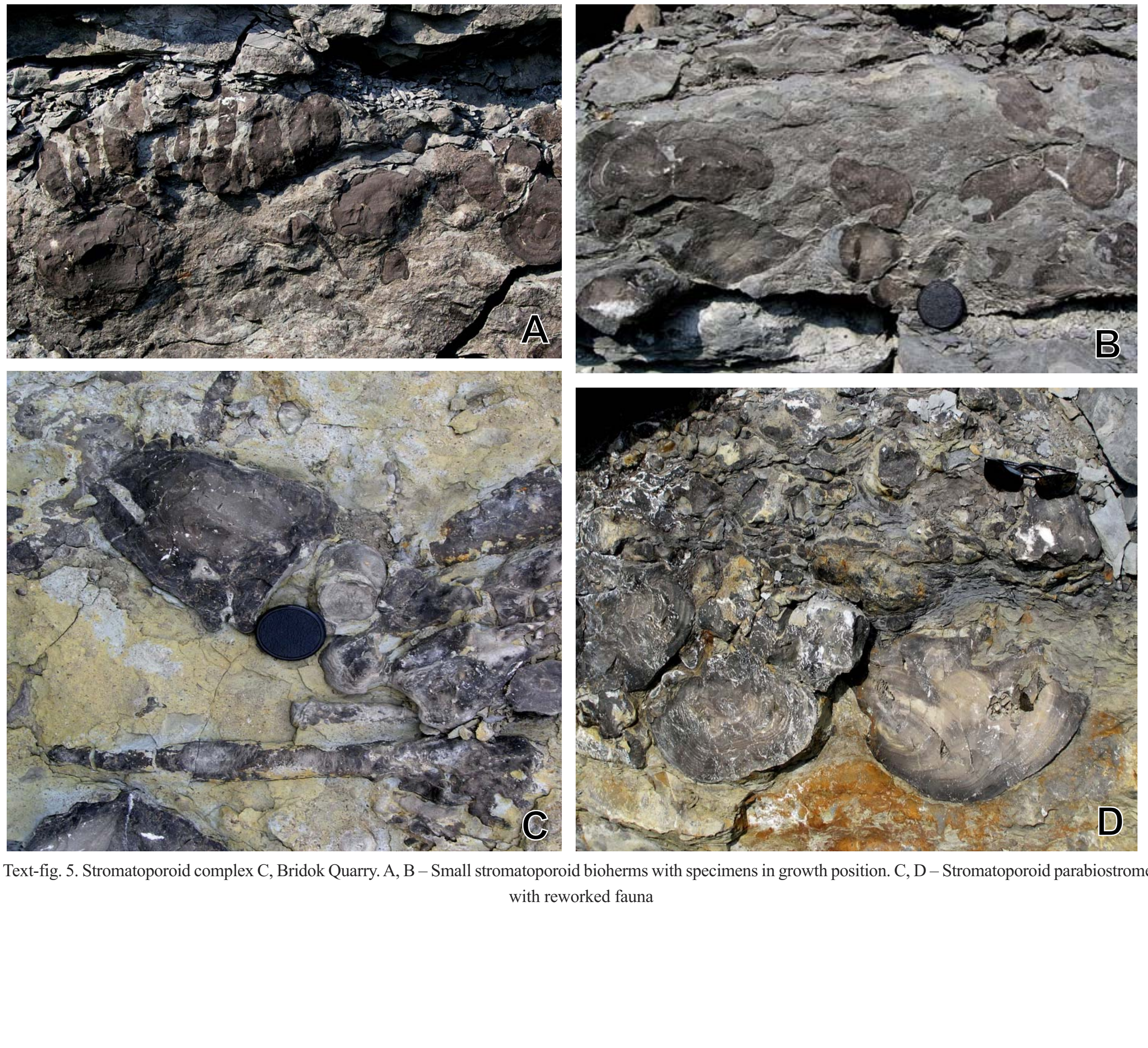
Important arguments concerning the tsunami origin of the stromatoporoid beds come from morphometrical analysis of the redeposited specimens. All the main stromatoporoid features, such as the domination of high shape profiles, enveloping latilaminae arrangements, low burial ratios and smooth upper surfaces indicate a calm original growth environment located below storm wave base. On the other hand, the same features made the skeletons vulnerable to redeposition by high-energy events, if such occurred. Tsunamis are the most probable factor that could cause redeposition from such a setting. A tsunami wave, with its very long period, causes movement throughout the water column, and is capable of setting in motion sediment at great depths (e.g. Weiss 2008; Paris *et al.* 2009).

The stromatoporoid beds studied by Łuczyński *et al.* (2014) rest on low-energy facies and have distinct erosional bottom surfaces (Text-fig. 3B). The stromatoporoid material is usually fractionally unsorted and shows clast-supported textures, however laterally, in some beds the stromatoporoids are restricted to the lower part of the layer, with the upper part developed as bioclastic limestone. The flat-pebble conglomerates are composed mainly of elongated, horizontally oriented lithoclasts originating from laminated limestones of the low-energy facies. Both the lateral distribution, as well as the internal structure and composition of the described event beds find its analogues in modern tsunami deposits. The vastness of the area covered by the parabiostromal beds and the lack of stromatoporoid lateral size segregation resembles the distribution of modern tsunami-derived material and differs from storm derived deposits (comp. Paris *et al.* 2009; Goto *et al.* 2007, 2013). The material was transported both by traction by the oncoming tsunami waves (clast supported varieties), and from suspension, probably during backwash flows (bioclastic limestones with the material derived from shallow-water areas) (comp. e.g. Jaffe *et al.* 2012). Another feature that is typical of modern tsunami deposits is the occurrence of rip-up mud clasts within fine grained deposits (Goff *et al.* 2012; Yawsangratt *et al.* 2012). The flat-pebble conglomerates described here are interpreted as an accumulation of such clasts.

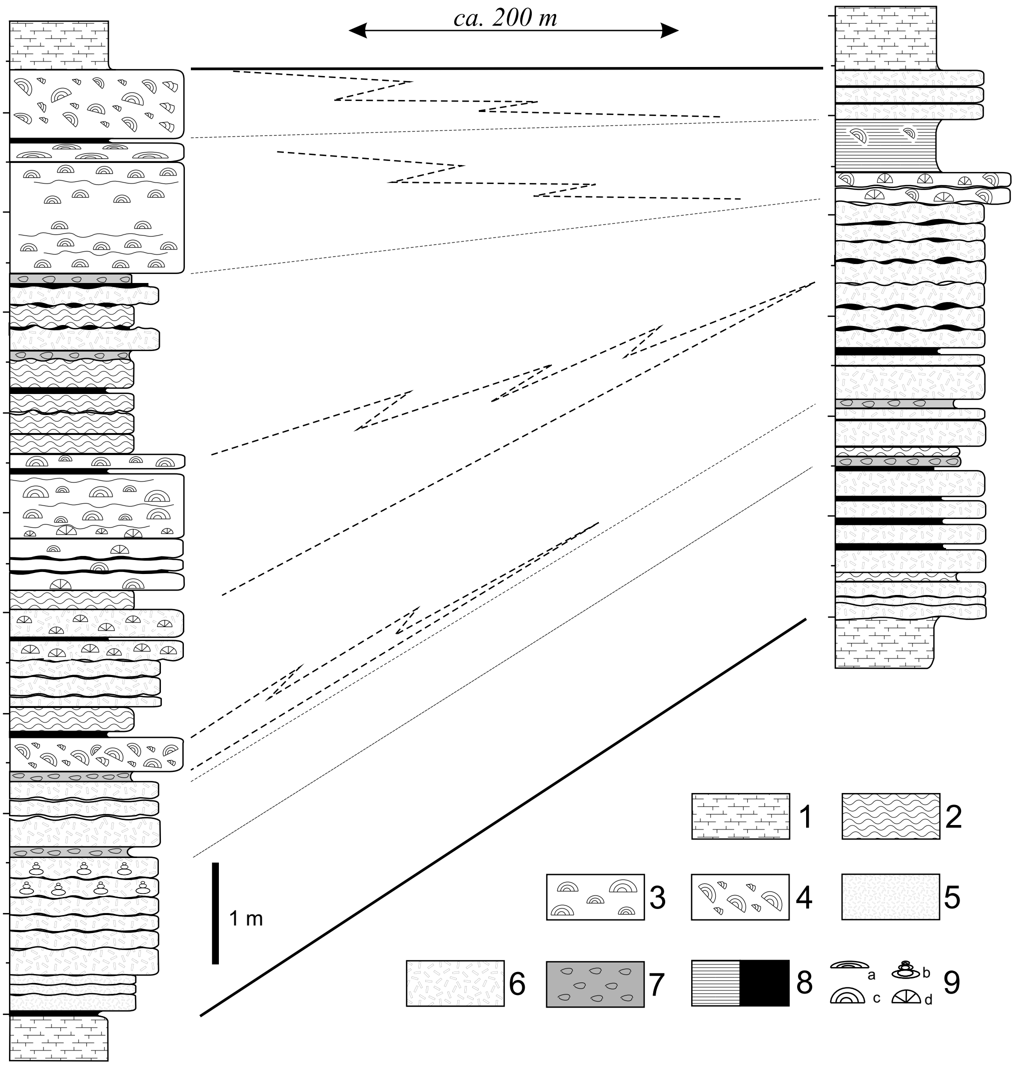
IDENTIFICATION OF *IN SITU* BIOGENIC COMPLEXES DOMINATED BY STROMATOPOROIDS IN THE LAGOONAL SUCCESSIONS

The above presented facies record of high-energy sedimentary events in lagoonal successions, and particularly the identification of a prominent process of onshore redeposition of stromatoporoids by tsunamis and/or storms, may suggest that all the stromatoporoid beds intercalating the shallow-water facies in the upper Silurian of Podolia can be treated as event beds. This is however not the case. Stromatoporoid beds developed as autoparabiostromes (*sensu* Kershaw 1994) have been described e.g. from Zubravka Quarry (see above), however the best examples of *in situ* formation of beds dominated by stromatoporoids come from Bridok Quarry on the northern outskirts of Skala Podil'ska town.

The Silurian succession exposed around Skala Podil'ska is represented by the Trubchyn Member of the Skala Formation, and has been divided into four complexes (Skompski *et al.* 2006). The two lower complexes (A and B), developed mainly as laminated



Text-fig. 5. Stromatoporoid complex C, Bridok Quarry. A, B – Small stromatoporoid bioherms with specimens in growth position. C, D – Stromatoporoid parabiostromes with reworked fauna



Text-fig. 6. Correlation of stromatoporoid beds between two sections in the Bridok Quarry. 1 – Flat-laminated mudstones/wackestones with fenestral structures; 2 – Wavy-laminated mudstones/wackestones with fenestral structures; 3 – Biohermal limestones with stromatoporoids in growth position; 4 – Biostromal limestones with redeposited stromatoporoids; 5 – Fine-grained calcarenites with brachiopods; 6 – Coarse-grained crinoid-brachiopod calcarenites with nautiloids and ostracods; 7 – Brachiopod (*Camartoechia, Delthyris*) coquinas; 8 – Black claystones/mudstones; 9 – Mass occurrences of: a – tabular stromatoporoids, b – gastropods, c – high domical stromatoporoids, d – rugose and tabulate corals

micritic dolomites with desiccation polygons and initial palaeosoils, outcrop in Skala Podil'ska Quarry and contain beds with redeposited stromatoporoids and tabulates (see above). The uppermost complex D (Bridok Quarry) is characterised by the occurrence of typical stromatoporoid parabiostromes intercalating the laminated intertidal lagoonal facies (Text-fig. 4B), and thus represents yet another example of the facies record of high-energy events punctuating the shallow-water shelf. The underlying complex C is however developed differently, and is represented by an almost 10 m thick horizon of dark limestones, distinctly contrasting from the surrounding sequence (Text-fig. 4A).

The most conspicuous feature of the dark horizon is the occurrence of a number of small stromatoporoid buildups (mainly bioherms) with specimens in growth position (Text-fig. 5A, B). The stromatoporoids, reaching the dimensions of up to 50 cm, are accompanied by tabulate and rugose corals, a diversified assemblage of brachiopods, as well as by gastropods and occasional nautiloids. In terms of their morphometric features, the stromatoporoids are dominated by large bulbous, and high domical forms with enveloping latilaminae arrangements and smooth upper surfaces, sometimes forming coalescent structures with protruding columns. In some cases, the biohermal sequence is overlain by a layer composed of tabular stromatoporoids forming a kind of a mat. Apart from the bioherms, complex C is composed of a large variety of differently developed beds, including: stromatoporoid parabiostromes with a reworked fauna (Text-fig. 5C, D), crinoidal limestones, calcilutites with ostracods, brachiopods and gastropods, as well as characteristic brachiopod coquinas. The brachiopod assemblage is dominated by small rhynchonellids (*Microsphaeridiorhynchus*), accompanied by larger forms (*Delthyris*). All these facies are interbedded by variously developed calcarenites with ostracods, brachiopods and bryozoans (Text-fig. 6).

The sedimentary conditions, in which complex C has been deposited differ distinctly from those represented by the underlying and overlying deposits. The complex lacks any symptoms of emersion and of mass redeposition of biogenic material, which are so evident in other parts of the succession, and thus it represents a calm period characterised by a relatively high sea level. The occurrence of a fauna indicating normal salinity, such as crinoids and corals, suggest open-marine circulation and the location of the area relatively far from the shore. On the other hand, the characteristic poorly diversified brachiopod association, resembling that described from the Tofta beds on Gotland, and ascribed by Watkins (1992) to back-reef settings, common *Leperditia* ostracods and monospecific gastropod accumulations, as well as the dark colour of the deposits, all point to some isolation of the area.

FINAL REMARKS AND STUDY PERSPECTIVES

The studies presented concentrated on two relatively short time intervals of the upper Silurian succession of Podolia represented by parts of the Malynivtsy and Skala formations. The analysed sections were selected mainly for their excellent exposures of stromatoporoid beds that allow the lateral tracing of particular strata over long distances, which in turn has enabled the identification of the described high-energy sedimentary events. However, in terms of facies assortment, the intervals are generally representative of the whole Ludlow and Pridoli succession, and therefore the presented interpretations can be treated as applying to the whole upper Silurian of Podolia.

The main problem in the studies on the Silurian succession of Podolia is the need for a precise correlation of numerous sections that are scattered over vast distances and developed in similar facies associations. The hitherto dominant interpretation, according to which particular facies, commonly treated as isochronous units, are arranged into three orders of cyclothems (Tsegelnjuk *et al.* 1983; Predtechensky *et al.* 1983), has to be revised. The characteristic horizons, even if they exist, were connected with high-energy sedimentary events with a limited spatial extend, and as such cannot be used as correlation levels on a larger regional scale. The biostratigraphy based on conodonts can provide only a general stratigraphic framework (e.g. Drygant 1984). Recent improvements in the upper Silurian stratigraphy of Podolia are summarised in Kaljo *et al.* (2014).

Attempts to find recognisable correlation levels in the Silurian of Podolia have concentrated on two issues. First is the recognition of bentonite layers, which occur within the succession (Tsegelnjuk *et al.* 1983; Huff *et al.* 2000; Kiipli *et al.* 2000; Środoń *et al.* 2013). However, bentonites, although recognised in some sections, in the dominant high-energy and extremely shallow-water facies are very vulnerable to washing out and destruction, and thus cannot be traced over longer distances. Second is the identification of major Silurian isotopic excursions (e.g. Kaljo *et al.* 2007, 2012; Małkowski and Racki 2009; Małkowski *et al.* 2009; Racki *et al.* 2012). Further detailed studies of these excursions in the Podolian sections may open new interpretational perspectives both in the fields of stratigraphy and palaeoceanography. Their analyses in Polish and Ukrainian sections (Kozłowski and Munnecke 2010; Kozłowski and Sobień 2012; Jarochowska and Kozłowski 2014) revealed a possibility of correlation on a local scale, as well as over long distances. Recently Kozłowski (2015) has linked the kozlowski/Lau event, studied in the material from Poland, to eolian dolomite dust influx and massive whitings. Similar phenomena can possibly be recorded also in the Silurian sections of Podolia, which however requires further studies.

All the studies described above point to the necessity of a thorough reinterpretation of the Silurian successions of Podolia. Issues that particularly need to be readdressed are: the finding of the means of local correlations between the numerous outcrops, the understanding of the response of carbonate depositional sub-environments to sea level changes, and the determination of the facies position of the stromatoporoid buildups within the facies pattern on the shelf. An attempt to address these problems in a small scale study polygon was undertaken in the outcrops on the banks of the Dnister River (Łuczyński *et al.* 2015).

Selected for analysis were nine sections, located on both sides of the river, between the villages of Voronovytsia, Sokil and Konivka (Text-fig. 1B), and together offering an almost continuous transect, about 4 km long and roughly perpendicular to the palaeoshoreline. The observation polygon embraces an interval only a dozen or so meters thick, but encompasses a complete regressive-transgressive cycle. The represented sub-environments include a stromatoporoid bioherm and the adjacent areas from both the sea and the shore sides. The array of facies ranges from shallow-water peritidal dolomites to open-marine nodular limestones. The exposed succession belongs to the Malynivtsi Formation of Ludlow age (Text-fig. 2).

A classic macro- and microfacies analysis, and bed-to-bed correlation was supplemented by field spectral gamma ray (SGR) measurements. Although the total gamma signal mainly duplicates the macroscopically visible lithological differences, the measured values of particular components, coming from potassium (K), thorium (Th) and uranium (U), enabled the identification of several correlation horizons, which can be interpreted as isochronous. Moreover, the quantitative relations of some components, especially the Th/K ratio and the biogenic uranium content (U_{bio}), are useful palaeoenvironmental indicators (e.g. McLennan *et al.* 1993; Lüning and Kolonic 2003; Taboada *et al.* 2006; Carpentier *et al.* 2013). The complex application of facies analysis and gamma ray measurements allowed the presentation of a scenario of sedimentary development in a sequence stratigraphic context. Seven correlation levels have been identified based on spectral gamma ray measurements. The SGR data were used for lateral tracking of relatively easily interpretable sedimentary events visible in particular sections and for discovering their less evident counterparts.

The use of SGR measurements (common in deep boreholes) in shallow-water, partly high-energy carbonate facies is a relatively new approach (e.g. Bábek *et al.* 2007) and can therefore serve as a reference for other studies in similar facies. In the presented study the analysis proved to be a useful tool for correlation purposes and for identification of depositional systems.

The new, dynamic interpretation of the processes taking place on the shelf has also revealed the necessity of reinterpreting the cyclicity curves of the Silurian succession of Podolia. The occurrence of stromatoporoid beds, the origin of which has been attributed to high-energy events (some of them probably even to tsunamis), is related rather to relatively shallow-water conditions, and not to the deepest environments in a peritidal cycle, as was postulated e.g. by Predtechensky *et al.* (1983). A correct interpretation of the nature of particular stromatoporoid beds is crucial also due to the fact that the various types are differently oriented in relation to the general facies pattern. In the case of the *in situ* developed autobiostromes, their elongation is usually parallel to the facies zones and to the shoreline, whereas e.g. the bodies of channel origin, such as described from the bank of Zbruč, are elongated perpendicular to that direction. This has to be taken into account e.g. when identifying and localising hydrocarbon collectors in similar facies, especially when basing the interpretation solely on borehole data. All these indicates that an accurate facies history of the upper Silurian of Podolia is still to be presented.

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