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Sole structures as a tool for depositional environment interpretation; a case study from the Oligocene Cergowa Sandstone, Dukla Unit (Outer Carpathians, Slovakia)

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Sole structures, typically developed on basal bedding surfaces of turbidite sandstones, are commonly used as palaeocurrent indicators and indicators of the current ability to erode. Detailed analysis of types and frequency of sole structures in the 128-m-thick succession of Lower Oligocene Cergowa Sandstone (Outer Western Carpathians) also shows their potential as an indicator of flow properties during the deposition. The massive and amalgamated sandstones, predominantly containing load structures and minor grooves with unidirectional orientation, are suggested to be deposited by high-density turbidity currents and debris flows. A wide range of sole structures in thick and medium thick-bedded sandstones, suggesting oblique and reverse flows compared to the main palaeoflow direction, implies deposition from density-stratified flows where the lower, denser part has a tendency to deflect when hits a basin floor obstacle. The upper, less dense part has an ability to come over the obstacle and shows only small scatter in the palaeocurrent direction.

Key words: sedimentology, sole structures, flow properties, Dukla Unit, Cergowa Sandstone, Western Carpathians.

INTRODUCTION

Sole structures are relatively common features observed on bedding surfaces of deep-water sandstone beds intercalated with shales. Their morphology and use as an indicator for palaeocurrent direction have attracted attention of geologists for a long time (e.g., Williams, 1881; Wright, 1936; Rücklin, 1938; Hall, 1943). Qualitatively, research on sole structures widened after the first studies on turbidite sedimentation conducted by Kuenen and Migliorini (1950) and others (e.g., Kuenen, 1951; Bouma, 1962; Sanders, 1965). In addition to other locations, sole structures were intensely studied in the Polish Flysch Carpathians and the processes of their formation were confirmed experimentally (e.g., Dzulynski et al., 1959; Dżułyński and Sanders, 1962; Dżułyński and Walton, 1965; Dzulynski and Simpson, 1966). Description of individual types of sole structures with detailed interpretation of the process of their formation is well-documented in Dżułyński (1996). The classification took into account the formation time (before, during and after sedimentation of the bed covering the marks), mark morphologies and processes they originated. The division of current marks (formed by the passage of the current carrying sediment over the muddy bottom) into scour and tool marks, is widely used today. Even if the understanding of the physical behaviour of gravity flows, including early diagenetic changes of their deposits, has improved substantially since that time (e.g., Lowe and Lopiccolo, 1974; Lowe, 1976; Allen, 1982; Masson et al., 1997; Stow and Johansson, 2000; Talling et al., 2012), the application of sole structures for palaeoenvironmental analysis of ancient deposits has not changed greatly.

The aim of this study is to document the variety of sole structures preserved in the Cergowa Sandstone in the Dukla Unit of the Outer Flysch Zone of the Western Carpathians (Fig. 1) and, based on this information, to interpret the flow behaviour and position of the sediments within the turbidite sedimentary system.

GEOLOGICAL SETTING AND DEPOSITIONAL ENVIRONMENT OF THE CERGOWA SANDSTONE

Cergowa Sandstone (Lower Oligocene) is a member of the Menilite Formation in the Dukla Nappe of the Outer Western Carpathians. The Dukla Nappe crops out in the Slovakian and Polish sides of the Western Carpathians. It includes Upper Cretaceous–Upper Oligocene deep-water sediments deposited in a remnant ocean basin evolving into a foreland basin as a result of closure of the Tethys and convergence between the North European Platform and ALCAPA plate (Oszczypko, 1999, 2006; Golonka et al., 2003, 2011; Dirnerová et al., 2012). Depo-

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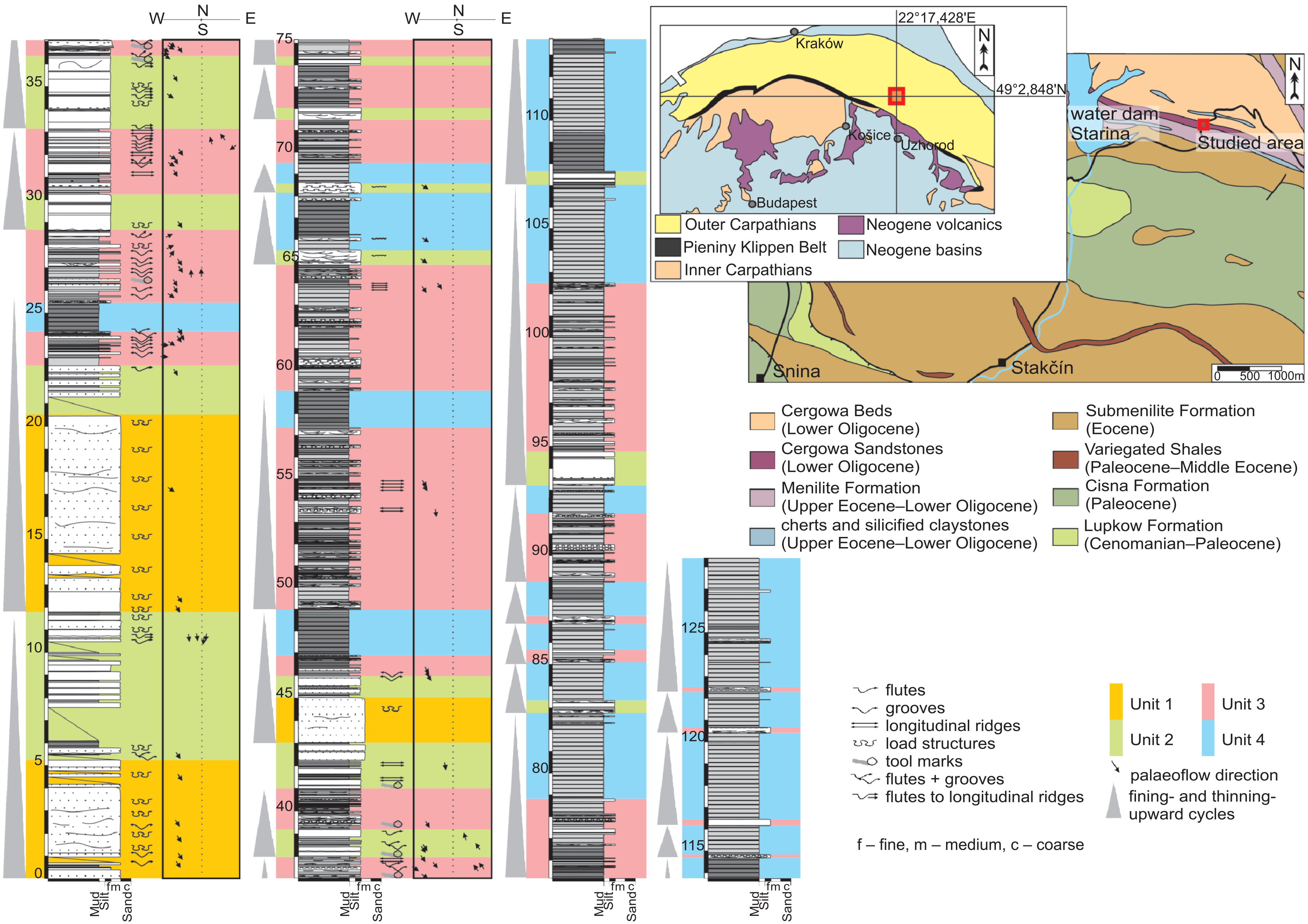

Fig. 1. Location of the study area (Koráb, 1983) and sedimentary profile of the Cergowa Sandstone

sition of the basin fill occurred during the Sarmatian thrust episode as a result of ongoing subduction (Oszczypko, 1999, 2006; Golonka et al., 2003, 2011).

At the Eocene to Oligocene transition there was increased tectonic activity related to subduction, which resulted in the formation of several depocenters in the Dukla Basin characterized by restricted circulation. It determined the deposition of the Lower Oligocene Menilite Formation which typically comprises bluish, grey and black (menilite) shales encasing a thick interval of the Cergowa Sandstone.

Cergowa Sandstone deposits consist mostly of medium- to thick-bedded, fine- to medium-grained sandstones interbedded with thin to medium-thick shale beds. They are interpreted as deep-water sediments deposited by high- and low-density turbidity currents and minor debris flows (Dirnerová et al., 2012). The sedimentary succession is up to 150 m in thickness. It comprises dark and black menilite shales passing upward into bluish and grey shales and mostly fine-grained, thin-bedded micaceous sandstones of the Krosno Formation (Fig. 2).

Deposition of sandstones interbedded with shales provided suitable conditions for the development of sole structures. An excellent exposure of the Cergowa Sandstone, located 8 km NE of Snina, shows its complete stratigraphy in a 128-m-thick section (Fig. 1). In general, a fining-upward trend of sediments can be observed in this section. The lower part comprises thick-bedded, medium-grained massive sandstones with mudstone clasts, interbedded with thin shale beds. There is a gradual transition into fine-grained sandstones with various sedimentary structures that alternate with shales. The volume of fines increases upwards and only thin-bedded sandstone intercalations are preserved in the upper part of the succession.

SEDIMENTS AND SOLE STRUCTURES OF THE STUDIED SECTION

Sole structures are preserved in the form of casts on the bases of more resistant units that were deposited after the structures had formed (Lewis and McCounchie, 1994). They may be classified to several groups (e.g., Reineck and Singh, 1980; Lewis and McCounchie, 1994; Dżułyński, 1996; Collinson et al., 2006).

Based on lithology and sedimentary structures of the studied section we divided the sedimentary succession into four lithofacies units (Figs. 1 and 3), also reflecting the quantity and types of the preserved sole structures.

UNIT I

Unit I, occurring mostly in the lower part of the section, typically comprises medium- to thick-bedded, massive and sporadically parallel laminated fine- to medium-grained sandstones containing chaotically dispersed granule-sized mudstone clasts (Figs. 1 and 4). A common feature is the occurrence of amalgamated sandstone beds up to 340-cm-thick. Thin beds of massive and planar parallel laminated shales separating the sandstone

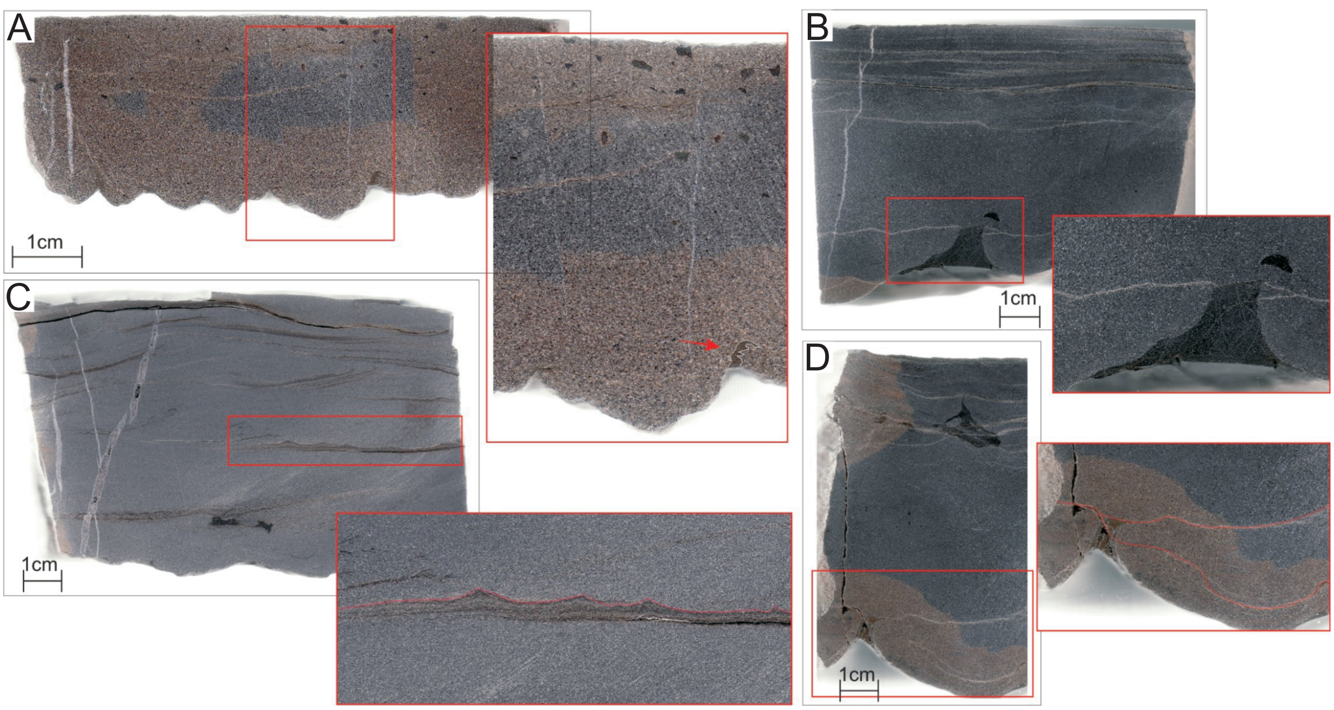

Fig. 2. Cross-sections of the sandstone beds with preserved sole structures at their bases

A – longitudinal ridges with tiny mud tongues dragged into the sandstone and subsequently fragmented to small mud clasts deposited in the upper part of the bed; **B** – flame structure with the top broken away during deposition of overlying sandstone bed; **C** – small-scale flame structure preserved at the contact of sandstone bed and thin mudstone laminae; **D** – amalgamated sandstone beds (boundaries marked red) with load structures on their bases

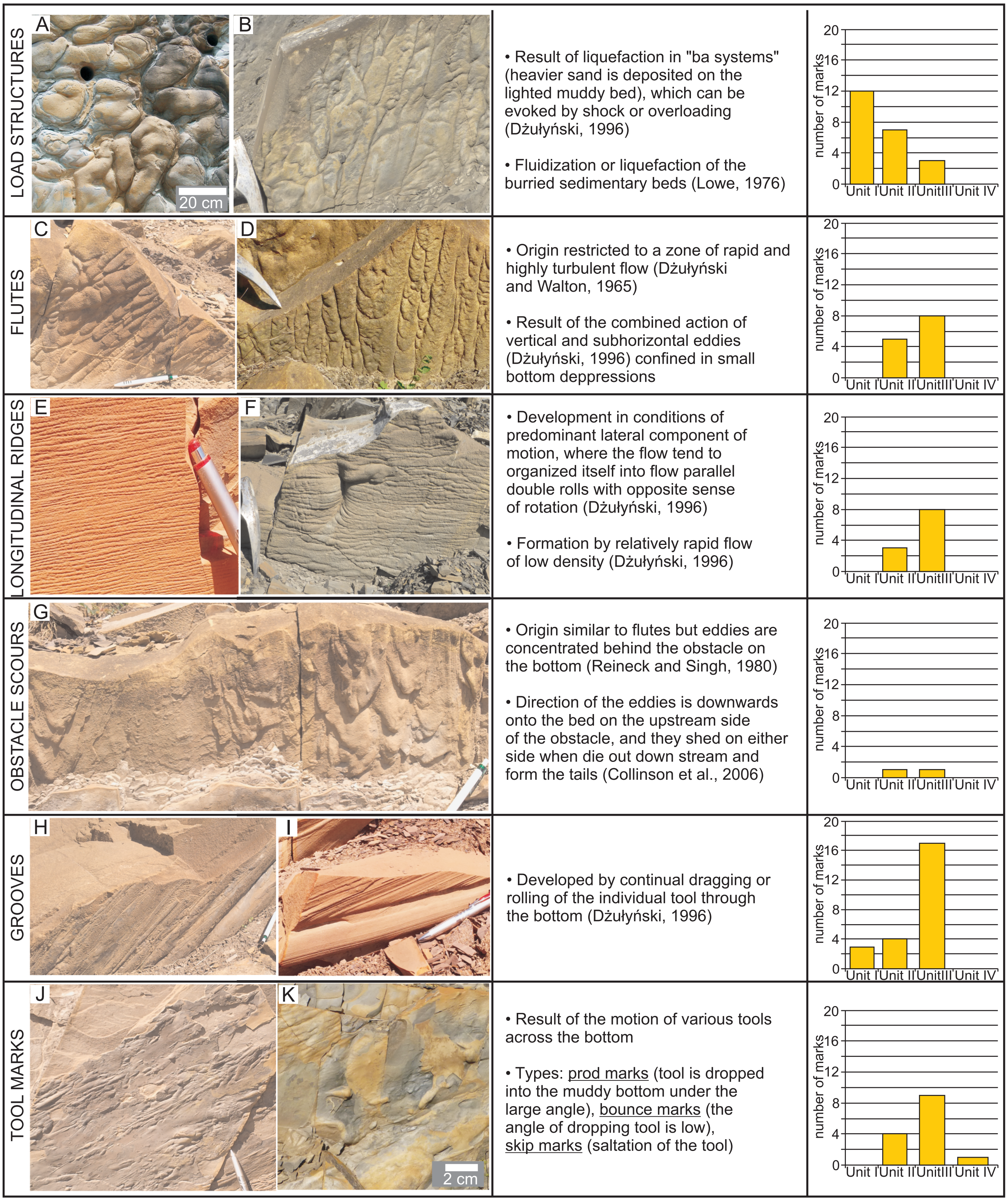

Fig. 3. Examples of sole structures recorded in the study area with description of their origin

Frequency of different sole structures with reference to each unit is also shown; **A**, **B** – load structures characteristic for massive sandstones. Note the remnants of mud injected into the sand (B); **C**, **D** – flutes preserved in different forms: aligned side-by-side (C) and in rows (D); **E**, **F** – longitudinal ridges. Note rounded noses in some ridges indicating transitional forms from flutes (F); **G** – obstacle scours; **H**, **I** – grooves occurring most frequently in the studied section; **J**, **K** – tool marks represented by prod, bounce and skip marks

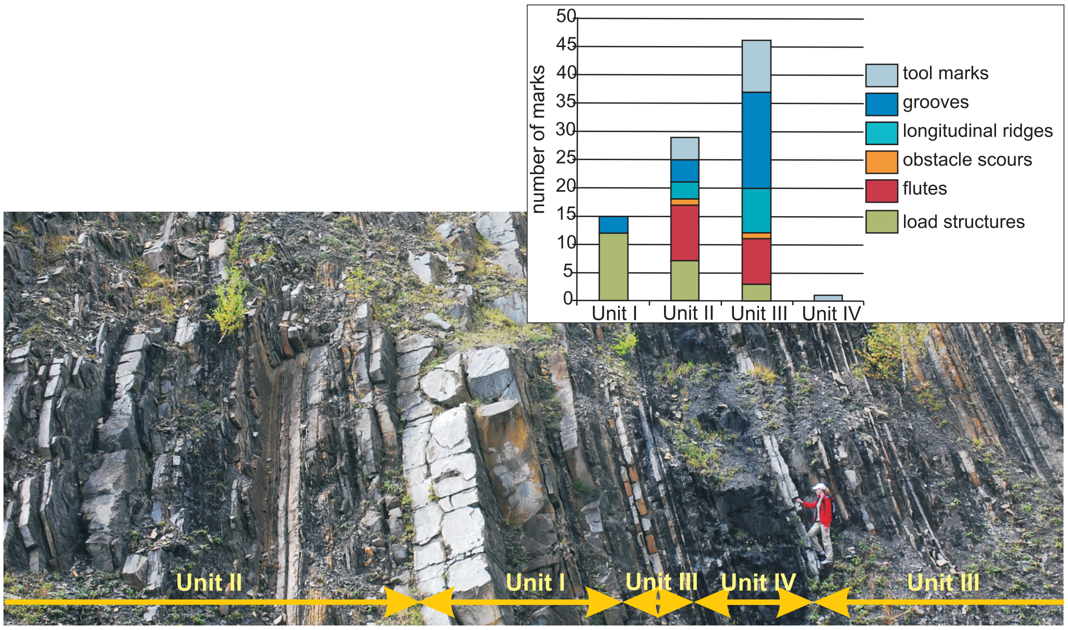

Fig. 4. Four units of the Cergowa Sandstone and a summarizing graph showing volume and diversity of preserved sole structures in each unit

beds occur rarely. The sandstone to mudstone ratio is 33:1. Based on all these features, the sediments of Unit I are interpreted as high-density turbidites and/or debrites (e.g., Haughton et al., 2009; Hodgson, 2009; Talling et al., 2012; Dirnerová et al., 2012; Talling, 2013).

Sole structures are mainly represented by load structures (load casts of Boggs, 2001; Collinson et al., 2006; polygonal ridges of Dzulynski and Simpson, 1966) and minor grooves. The load structures have various sizes and shapes. Common are irregular concave bulges, 2–40 cm across (Fig. 3A, B). However, elongated forms resulting from deformation of the primarily evolved load structures due to forward current motion upon polygonal compartments (Dzulynski and Simpson, 1966; Dżułyński, 1996) were also described. Their width ranges from 1 to 4 cm, length is up to 40 cm and depth is about 0.5 cm (Fig. 3B). Their occurrence indicates the first stage in a laminar-turbulent flow transition (Sparrow and Husar, 1969). The margins of the bulges are often accentuated by flame structures (Fig. 2). Depth of the bulges is from 0.5 to 5.0 cm depending on the bulge size. The load structures are mostly developed on the surface between the sandstone and underlying shale. However, they are also found between adjacent amalgamated sandstone beds (Fig. 2). Grooves have a limited occurrence in Unit I and are always found on different bedding planes like load structures. They are 0.5–5.0 cm wide and 0.5–1.5 cm deep and have smooth surfaces (Fig. 3H, I).

The sandstones belonging to Unit I are thought to be deposited by high-density turbidity currents and/or debris flows (Dirnerová et al., 2012). Thick, massive sandstones, a small number of shale interbeds, sandstone bed amalgamations and frequent load structures are signs of abrupt sand deposition triggering water escape from underlying mud and squeezing the underlying mud into overlying sand. Predominating load structures suggest rapid sand deposition typically related to free horizontal flow expansion at the mouth of submarine canyons and channels or to hydraulic jumps frequently occurring in base-of-slope settings (Kneller and Branney, 1995; Stow and Johansson, 2000; Baas, 2004).

UNIT II

Unit II consists predominantly of thin to medium-thick (1–40 cm) sandstone beds separated by very thin and thin (1–30 cm) mudstone beds (Figs. 1 and 4). The sandstone to mudstone ratio is 6:1. Sandstones are massive, fine, planar laminated and ripple-cross laminated. Locally, they contain mudstone clasts up to 5 cm across. Based on the internal structures, these deposits are interpreted as high- and low-density turbidites (e.g., Mutti, 1992; Talling et al., 2012).

The sole structures in Unit II are more varied than those in Unit I and include flutes, load structures, longitudinal ridges, tool marks such as groove, prod, bounce and skip marks, as well as obstacle scours. Flutes typically have both symmetrical and asymmetrical forms and are aligned side-by-side or in rows (Fig. 3C, D). The width of the flutes may vary from 0.5 to 3.0 cm and their upstream depth is 0.2–1.0 cm. We can often observe tightly superimposed flutes above each other on the same bed base, showing the same orientation and suggesting a stable palaeocurrent direction. Obstacle scours are characterized by their crescent shape, 1–3 cm wide and 0.5–1.0 cm deep, and are associated with another type of tool marks. Grooves are 0.5–5.0 cm wide and 0.2–2.0 cm deep. They have smooth or striated surfaces depending on the morphology of dragged tool. Longitudinal ridges (*sensu* Dżułyński, 1996) also termed as longitudinal furrows and ridges by Reineck and Singh (1980) or longitudinal scours by Collinson et al. (2006) are commonly 0.5–1.5 cm wide and 0.2–0.5 cm deep. Individual ridges have rounded noses analogous to flutes. Tool marks are usually associated with some other sole structures like flutes or grooves.

Load structures are not as frequent as in Unit I. Individual bulges are irregular to gently elongate and their widths vary from 3 to 10 cm and depths from 2 to 3 cm. Load structures are often associated with flame structures marking paths of water escape. The asymmetric shape of the flame structures and occasionally torn-off segments suggest their formation during the active flow of turbidity current (Fig. 2).

Unit II is comprised of massive, planar- and ripple-cross laminated sandstones alternating with mudstones and is thought to be deposited by high- and low-density turbidites. Planar-laminated sandstone with less than 2-mm-thick laminae formed through deposition from near-bed layers with high sediment concentration (Leclair and Arnott, 2005; Sumner et al., 2008). Increasing flow concentration resulted in a higher sediment fallout rate and the formation of massive sandstones. Ripple-cross laminated sandstone is a result of decreased flow concentration supporting bedload transport. The variety of sole structures in Unit II suggests that such deposits have the best formation and preservation potential. The main difference to Unit I, deposited mainly by high-density turbidity currents, is a greater abundance of erosional forms like flutes and longitudinal ridges, but fewer load structures. Skipping and bouncing marks suggest more dilute currents allowing free movement of transported material.

UNIT III

Unit III consists of alternating sandstone and mudstone beds at a ratio of 1:2 (Figs. 1 and 4). Fine- to medium-grained sandstones are characterized by various sedimentary structures (complete or individual Bouma divisions) and occur in beds from 1 to 48-cm-thick. The massive and parallel-laminated mudstone beds are up to 68-cm-thick. Based on the sandstone grain size, sedimentary structures and occurrence of mudstones representing Bouma Te division and hemipelagites, we think that the sediments of Unit III were deposited predominantly by low-density turbidity currents.

Similarly to Unit II, sole structures are represented by a great variety of types. In contrast to Units I and II, no load structures occur and flutes are smaller (1–2 cm wide and 0.5–1.0 cm deep). Longitudinal ridges are characteristic by dying out through mutual coalescing (Fig. 3E, F) or they could be transformed into polygonal or pillow-like structures (after Dżułyński, 1996). This transformation is probably related to bottom irregularities and/or a change of the sediment flow velocity (Dżułyński, 1996). Besides longitudinal ridges, various tool marks are characteristic for Unit III. They are represented by grooves as well as prod, bounce and skip marks. The width of these marks varies from 0.5 to 5.0 cm and their depth is from 0.3 to 1.5 cm. The occurrence of Bouma divisions in the fine- to medium-grained sandstones, absence of load structures (typically reflecting high sedimentation rate) and small flutes suggests that Unit III was deposited mainly by a low-density turbidity current with a weaker erosional ability.

UNIT IV

Unit IV is represented by mudstones only sporadically interbedded with thin sandstone beds. The majority of sediments occur in the uppermost part of the Cergowa Sandstone sedimentary succession characterized by its fining and thinning-upward trend (Figs. 1 and 4). The sandstone to mudstone ratio is 1:25. The 1–30-cm-thick sandstone beds, showing Tb, Tc, Td Bouma divisions, are sandwiched by thick and very thick (up to 350 cm) mudstone beds. Massive and parallel laminated mudstones are thought to be Te turbidite divisions and hemipelagites.

Only a few tool marks have been recorded from this unit. They are represented by bounce, prod and skip marks, 0.5–1.5 cm wide and 0.3–1.0 cm deep.

Minority or absence of sole structures indicate either a slow depositional current that was too weak to scour the bottom or a faster one in which a traction carpet was completely effective in shielding the bottom from turbulent eddies (Dżułyński and Sanders, 1962). According to the lithology as well as character and size of sole structures preserved in Unit IV, we interpret the sediments as deposited by a dilute turbidity current typical for distal parts of turbidite systems and interdistributary areas (Mutti and Ricci Lucchi, 1978; Sumner et al., 2012).

IMPLICATION FOR INTERPRETATIONS OF DEPOSITIONAL ENVIRONMENT

The formation of sole structures depends on complex factors including velocity and density of sedimentary flows as well as properties of the basin floor (Dżułyński and Walton, 1965). Sediment gravity flows often transform from either dense, sediment-rich and laminar to less dense, watery and often turbulent currents or *vice versa*: from less dense, turbulent to denser flows as they slow down (Felix and Peakall, 2006; Felix et al., 2009; Haughton et al., 2009; Talling et al., 2012; Talling, 2013). This also governs the transformation of sole structures depending on the flow character implying the possibility to use these structures, i.e. their type, size and frequency in relation to sediment lithology, for deducing depositional environment.

DEPOSITIONAL SETTINGS

The analysed sedimentary succession shows an overall fining- and thinning-upward trend. This is reflected by the arrangement of the units forming several smaller cycles with a similar trend. The lower cycles start with thick massive sandstone of Unit I at the base and fine upwards passing into medium-bedded sandstones separated by shales (Unit II), or pass through Units II and III to Unit IV with prevailing mudstones. In the middle part of the succession, the cycles typically start with Unit II (medium-bedded sandstones separated by thin shales) and fine upwards into Unit III or IV. Finally, the uppermost part of the succession is mainly composed of cycles of alternating sandstones and mudstones at the base (Unit III), passing to mudstones (Unit IV; Fig. 1). Such an arrangement implies a gradual change of flow properties from prevailing high-density turbidity currents and debris flows in the lower part of the succession to dilute turbidity currents in its upper part. The change of flow properties affects not only the sedimentary facies but also the geometry of resulting deposits (shape, thickness) and the proximity – distality trend. The deposition of the Cergowa Sandstone is associated with depositional lobe environments in a peripheral foreland basin developed during the advance of the Carpathian orogen (Oszczypko, 1999; Prekopová and Janočko, 2009; Dirnerová et al., 2012). The described fining-upward trend in the sediments is thought to reflect a decreasing sediment supply as a result of changes in the hinterland, triggering retrogradation of the lobes.

Based on the lithofacies, the sedimentary profile of the Cergowa Sandstone was divided into four units. Each unit hosts different sets of sole structures that differ in type, frequency and orientation (Figs. 3 and 4).

In Unit I, showing thick-bedded amalgamated sandstones deposited by high-density turbidity currents and/or debris flows, load structures predominate (Figs. 3 and 4). Unit II is characterized mainly by load structures and flutes. However, other sole structures are also common. Medium and thick-bedded sandstones separated by mudstones, forming Unit II, are interpreted as deposits of high- and low-density turbidity currents. The greatest abundance of sole structures is found in Unit III (Figs. 3 and 4) that contains sediments deposited mostly by low-density and, in minority, by high-density turbidity currents. It may suggest increased distality within a turbidite system or interdistributary and interlobe environment (e.g., Mutti and Ricci Lucchi, 1978; Stow and Mayall, 2000; Remacha and Fernandez, 2003; Kneller and McCaffrey, 2003). The most frequent are grooves, longitudinal ridges, flutes and tool marks. In contrast to Unit I, load structures are absent. Unit IV, composed mainly of mudstones, does not show almost any sole structures as is typical for the most distal part of turbidite systems (Bouma, 1962; Pickering and Hiscott, 1985; Wynn et al., 2002; Sumner et al., 2012).

PALAEOCURRENT DIRECTIONS

Several of the observed sole structures may also serve as palaeocurrent indicators. They suggest that unidirectional currents toward the south-east prevailed during the deposition of Unit I massive sandstones (Fig. 5). In Unit II, palaeocurrent toward the south-east predominates. However, some sole structures also suggest oblique palaeocurrents from north to south, and even a direction opposite to the main south-east trend. The palaeocurrent indicators of Unit III show slight variation in their direction that is generally toward the south-east (Fig. 5). The recorded directions and directions from the published studies (e.g., Koráb and Ďurkovič, 1978; Ślączka and Walton, 1992; Slaczka and Kaminski, 1998) show the main palaeocurrent direction during the deposition of the Cergowa Sandstone toward the south-east.

The palaeoflow directions of turbidity currents are strongly affected by the basin topography, and their behaviour around obstructing topography varies with the forward velocity of the current, the obstacle height, the current density and density stratification within the current (Kneller and Buckee, 2000 and

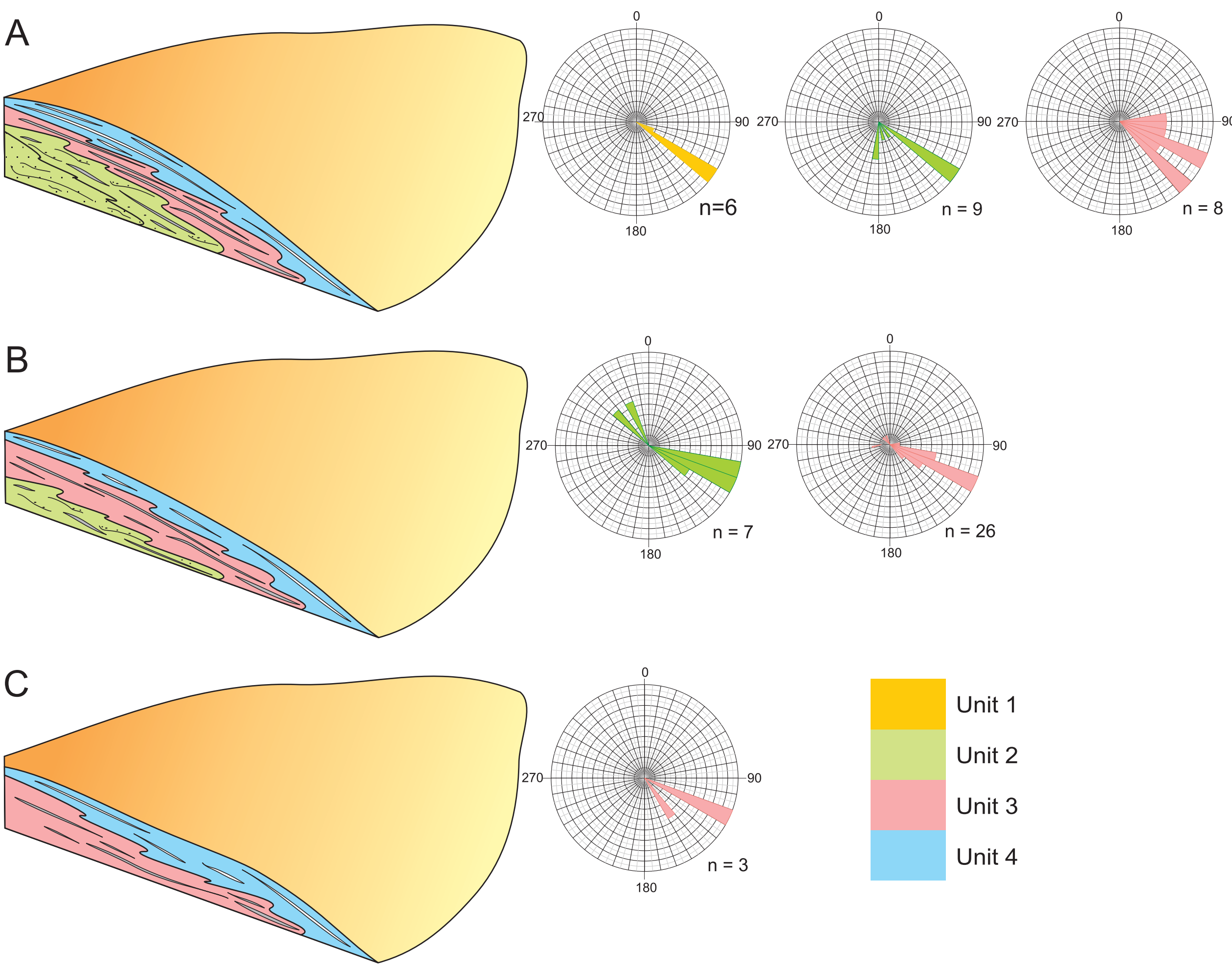

Fig. 5. Fining- and thinning-upward cycles in the Cergowa Sandstone with rose diagrams showing palaeocurrent directions of each unit indicated by preserved sole structures

references therein). Multiple palaeocurrent directions within single beds have been described from many turbidite systems and interpreted as a result of topography on the current direction (e.g., Pickering and Hiscott, 1985; Kneller and McCaffrey, 1999; Remacha and Fernandes, 2003). Highly turbulent, unstratified turbidity currents with a high value of Froude number have tendency to move over the obstacle (Baines, 1979). Stratified flows (Pickering and Hiscott, 1985; Kneller et al., 1991; Kane and Hodgson, 2011) are much more controlled by topography, which often triggers the flow separation (Lawrence, 1993; Gladstone et al., 2004). The upper, less dense part of the flow moves over the obstacle whereas the lower, denser part is deflected and/or reflected (Hunt and Snyder, 1980; Kneller and Buckee, 2000). The sole structures of the sandstones belonging to units II and III suggest occasional flow deflection and, in case of Unit II, even reflection (Fig. 5). This implies uneven topography of the basin and/or occurrence of obstacles on the basin floor. The alternation of sandstone and mudstone beds, typical for these units, and manifestation of different palaeoflow directions by sole marks suggest deposition from stratified currents with effective flow stripping where the lower (denser, sandier) part was deflected and/or reflected and the upper (less dense, muddier) part was able to overcome the obstacle.

CONCLUSIONS

Sole structures represent sedimentary structures occurring on bedding surfaces of sandstones overlying mudstones (Dżułyński and Sanders, 1962; Dżułyński, 1996). The sole structures are most frequently used as palaeocurrent indicators. However, the dependence of their formation on flow properties and basin floor characteristics (lithology and topography) makes them useful for palaeoenvironmental analysis. A detailed analysis of sole structures in deep-water sediments of the Cergowa Sandstone shows how their types depend on the facies and facies associations. The massive, amalgamated, thick sandstones (Unit I) contain mainly load structures and minor grooves. The palaeocurrent direction is unidirectional and toward the south-east (Figs. 1 and 5). The thick and medium thick-bedded sandstone beds separated by mudstones (Unit II) are characterized by a large variety of sole structures that are mainly flutes and grooves (Fig. 3). Prevailing palaeocurrent directions in the unit are toward the south-east. However, some flutes show currents trending toward the south and in the opposite direction compared to the main palaeoflow direction (Figs. 1 and 5). The thinner sandstone beds alternating with mudstones at a ratio of 1:2 (Unit III) show abundant sole structures with predominant grooves, flutes, longitudinal ridges and various tool structures. The orientations of the marks show prevailing south-east palaeocurrent directions with variation toward the east, and only few deviations toward the west and north-west (Figs. 1 and 5). Finally, Unit IV that consists mostly of mudstones and minor sandstones is almost barren in sole structures.

Based on types, preservation and orientations of sole structures, we suggest:

1. Predominance of load structures and occasional grooves is associated with thick-bedded massive sandstones reflecting deposition from high-density turbidity currents and/or debris flows. Such conditions are most common in isolated slope channels in muddy slope aprons, channel-lobe complexes and stacked lobe complexes of turbidite systems (Mutti and Ricchi Lucchi, 1972; Mortimore, 1979; Stow and Johansson, 2000; Etienne et al., 2013). Unidirectional palaeoflow, recorded in Unit I, may be due to a flat basin topography or ability of flows to overcome topographic obstacles.

2. Flutes, grooves and other types of sole structures are common in thin to medium-thick sandstone beds alternating with mudstones (units II and III). They are associated with high- to low-density turbidity currents common in interlobe and channel interdistributary areas and/or middle to outer parts of turbidite systems. The wide range of palaeoflow directions, including directions opposite to the main palaeoflow, imply deflection and reflection of flows on obstacles. Such deflection is typical for stratified flows (Gladstone et al., 2004).

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