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Sedimentary record of the Dukla Basin (Outer Carpathians, Slovakia and Poland) and its implications for basin evolution

Diana DIRNEROVÁ, Marta PREKOPOVÁ and Juraj JANOČKO

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The Late Cretaceous to Oligocene strata of the Dukla Nappe, which is a part of the accretionary wedge formed in front of the Carpathian orogen, record a history of the basin development from remnant to foreland basin stages. The lower part of the succession indicates the first stage of basin evolution characterized by turbidite systems fed from the E (NE) to W (SW). The system encompasses deposits of the Łupków and Cisna formations deposited in a channel-lobe transition (Łupków Fm.) and in sandstone-rich channelized lobes (Cisna Fm.) The transitional phase is represented by deposits of the Submenilite Formation derived from two different sources (SE and N) and deposited in a submarine slope/ramp environment. The third stage of basin evolution is marked by the advancing front of the Carpathian orogen resulting in peripheral foreland basin development. Increased tectonic activity led to a switch in sediment source from the SE to the NW, more complex topography of the basin and a change in sediment distribution. The initial phase of this stage is characterized by low-density turbidites and suspension fall-out sediments of the Menilite Fm. Discrete tectonic pulses are recorded by the thick Cergowa sandstones, mostly deposited by hybrid flows and high-density turbidity currents. A decrease in tectonic activity is suggested by heterolithic deposits of the Krosno Fm. capping the sedimentary succession.

Diana Dirnerová, Marta Prekopová and Juraj Janočko, Institute of Geosciences, Technical University of Košice, Letná 9, 04001 Slovakia, e-mails: diana.dirnerova@tuke.sk, marta.prekopova@tuke.sk, juraj.janocko@tuke.sk *(received: October 12, 2011; accepted: July 17, 2012; first published online: September 06, 2012).*

Key words: Dukla Unit, facial analysis, deep-marine environment, submarine fan, basin evolution.

INTRODUCTION

New methodologies and approaches in the study of deep marine deposits, including studies of outcrops at seismic scales (e.g., Hurst *et al.*, 1999; Hodgson *et al.*, 2006), seismic investigations (Deptuck *et al.*, 2008), laboratory experiments and numerical simulations (McCaffrey *et al.*, 2003; Huang *et al.*, 2007) have brought new insights into process-response models that relate the transport process to the facies distribution and geometry of sedimentary bodies. The resulting information can be not only applied to understanding of the evolution of sedimentary systems and related sedimentary basin evolution but also to prospection for new hydrocarbon reservoirs. One of the benefits of such studies is the possibility to use complex models in regions with scarce exposures in order to complete the missing parts of a "geological puzzle".

The main aim of this article is to present a detailed facies analysis and interpretation of depositional environments of strata and to discuss the implications for the evolution of the Dukla Basin in the Outer Carpathian Flysch Belt (Fig. 1).

GEOLOGICAL SETTING, TECTONIC AND PALAEOGEOGRAPHIC FRAMEWORK

The Dukla Nappe, emerging at the surface in southeastern Poland and stretching southeastwards across Polish and Slovakian territory to the Ukraine (Fig. 1), represents a part of the the Outer Carpathians traditionally called Outer Flysch Belt in Slovakia. It belongs to the Fore-Magura group of nappes occurring between Magura to the south and the Silesian nappes to the north.

Stratigraphically, the Dukla Unit in the area studied comprises the Łupków Formation overlain by the Cisna, Submenilite and Menilite formations, which are, in turn, capped by the Krosno Formation (e.g., Leško and Samuel, 1968; Koráb and Ďurkovič, 1978; Figs. 1 and 2). Older strata have only been found in the Ukraine (e.g., Jankowski *et al.*, 2004).

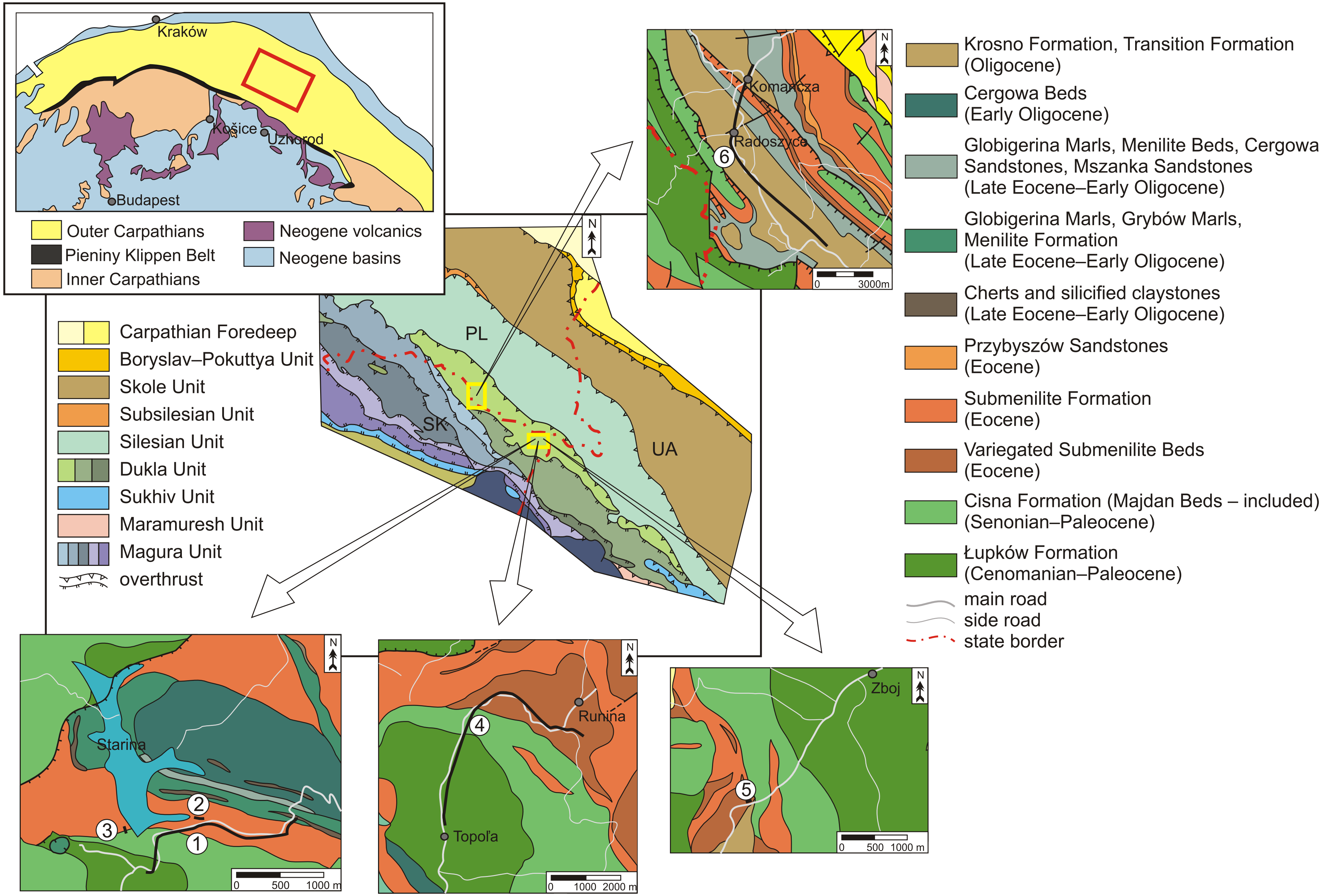


Fig. 1. Location of the study area (geology after Koráb, 1983; Kováč *et al.*, 1998; Jankowski *et al.*, 2004; modified)

Numbers 1–6 indicate the location of studied sections

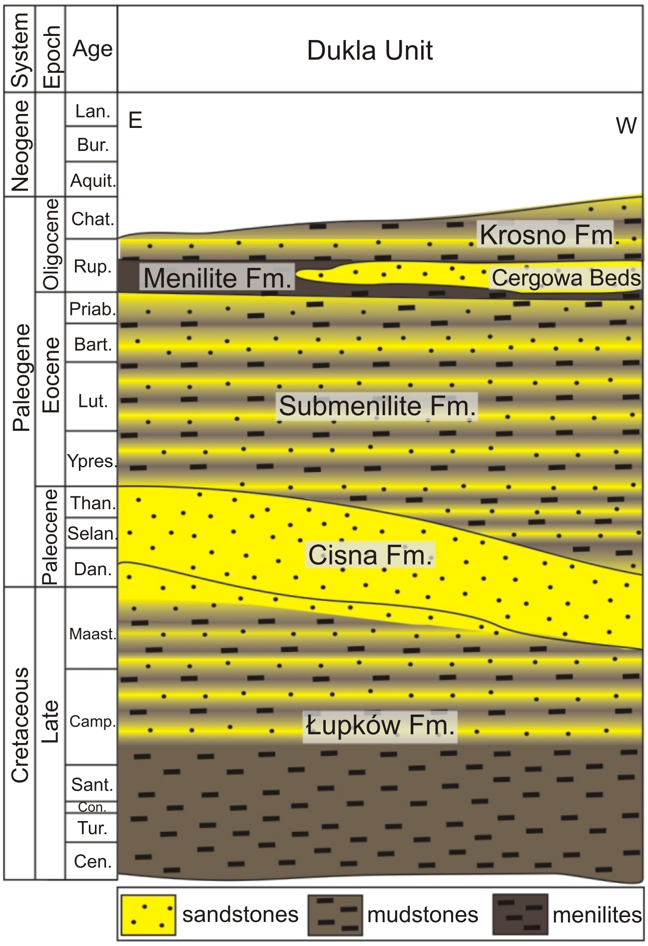


Fig. 2. Stratigraphic column of the Dukla Unit in the area studied

The Łupków Formation (Cenomanian–Paleocene) is characterized by a high content of mudstones (60–90% according to Leško and Samuel, 1968) and convolute laminated sandstones. The volume and thickness of sandstones increases upwards. Palaeoflow indicators suggest a source area located in the E (NE; Koráb and Ďurkovič, 1978).

The deposits of the Łupków Formation grade upwards into the Cisna Formation (Senonian–Paleocene) which is characterized by a dominance of thick sandstones (up to 6 m) with occasional microconglomerates at their bases (Koráb and Ďurkovič, 1978). Study of sole marks shows the main palaeoflow direction from the NE to the SW and from the N to the S (Leško and Samuel, 1968).

The Submenilite Formation (Eocene) is defined as a fining upwards succession of alternating sandstone and mudstone beds that contain many ichnofossils (Koráb and Ďurkovič, 1978). Koráb and Ďurkovič (1978) described two palaeoflow directions; a main longitudinal direction from the SE towards the NW and a minor, lateral direction from the N (NE) towards the S (SW). The sandstones deposited by different palaeoflows have different mineralogical compositions indicating diverse source areas.

The finest deposits are represented by the Menilite Formation (Early Oligocene) mostly composed of mudstones and menilite type claystones with minor occurrence of sandstones and pelocarbonates (Koráb and Ďurkovič, 1978). This fine-grained unit contains several thick (from 5 to 50 m) sandstone intervals (e.g., Mszanka Sandstone, Cergowa Sandstone, Metresa Bed; Leško and Samuel, 1968; Koráb and Ďurkovič, 1978; Ślączka and Walton, 1992).

The sedimentary succession is terminated by the Krosno Formation (Oligocene) characterized by heterolithic deposits. The clastic material of the fine-grained sandstones was delivered to the Dukla Basin from the NW (Ślączka and Kaminski, 1998).

The deposits are generally considered to have been deposited in a remnant ocean basin transformed into a peripheral foreland basin related to the evolution of the Carpathian orogen in the Late Eocene–Early Oligocene (Oszczypko, 1999; Poprawa *et al.*, 2002; Golonka *et al.*, 2011).

Two different phases were recognized during the palaeogeographic evolution of Dukla Basin. Until the end of the Late Cretaceous and the beginning of the Paleogene the Dukla Basin was a part of the Magura Basin (Cieszkowski, 2002; Oszczypko, 2006; Malata and Poprawa, 2006; Pszonka, 2009). Communication between the basins is shown by similarities of the Łupków and Cisna formations in the Dukla Unit and the Inoceramus Beds in the Magura Unit (Ślączka, 1971; Golonka *et al.*, 2000; Cieszkowski 2002). At this time, the Silesian and Bukowiec Palaeo-Ridges separated the Magura and Dukla realm from the Silesian Basin to the north (Ślączka, 2005). According to Bąk and Wolska (2005) the eastern part of the Dukla Basin was bordered by a promontory of the Marmarosh Massif that supplied sediments that now comprise the Cisna Formation during the Paleocene.

During the Eocene and Oligocene, the emerging Grybów Palaeo-Ridge resulted in at least partial separation of the Dukla and Magura basins (e.g., Ondra and Hanák, 1989; Cieszkowski, 2002). However, the subsiding Silesian Palaeo-Ridge facilitated communication between the Dukla and Silesian basins at that time (e.g., Ślączka and Walton, 1992; Cieszkowski, 2002). Relative sea level fall as a result of eustasy and tectonics (e.g., Poprawa *et al.*, 2002; Oszczypko *et al.*, 2002; Oszczypko, 2006; Soták, 2010) around the Priabonian Rupelian boundary (e.g., Oszczypko, 1999; Oszczypko *et al.*, 2002; Poprawa *et al.*, 2002; Golonka *et al.*, 2003) controlled palaeogeographical changes influencing water circulation, with resulting deposition now mostly represented by fine-grained strata of the Menilite Formation, typical of a larger part of the Outer Carpathian realm (e.g., Oszczypko *et al.*, 2002).

The present-day position of the Dukla Nappe is a result of Late Oligocene to Early Miocene tectonic events (Oszczypko *et al.*, 2002; Golonka *et al.*, 2003; Oszczypko-Clowes and Oszczypko, 2004; Nemčok *et al.*, 2006), resulting in detachment of the Late Cretaceous to Oligocene strata from their substrate and their removal towards the N and NE (e.g., Nemčok *et al.*, 2006; Oszczypko, 2006).

LOCALIZATION OF STUDY AREA

Six sedimentary profiles of strata belonging to the Dukla Unit with a total length of 757 m were analysed "bed-by-bed" on the Slovakian (5) and Polish (1) territories (Fig. 1). The first three profiles lie close to the dam at Starina (8 km NE of Snina, NE Slovakia, Fig. 1) and amount to 502 m in thickness. Profile 1 records strata of the Cisna, Submenilite and Menilite formations exposed along the main road from Stakčín to Príslop. The strata of profiles 2 and 3 crop out on the right and left sides of the dam, respectively and comprise a succession of Submenilite Formation overlying the uppermost part of the Cisna Formation. The fourth profile is located along the main road between Runina and Topoľa (23 km from Snina, NE Slovakia, Fig. 1) and comprises 125 m of strata assigned to the Łupków, Cisna and Submenilite formations. Around the villages of Zboj and Uličské Krivé the fifth, 15 m long profile occurs and shows strata of the Submenilite Formation. A 115 m thick succession (profile 6) belonging to the Menilite and Krosno formations occurs 25 km S of Sanok in Poland (Fig. 1).

The sections described provide the best exposures of the Dukla Unit and were used for detailed bed-by-bed logging with a resolution of 1 cm. Where possible, lateral trends of facies were documented. Facies descriptions and interpretations are given in Table 1 and Figures 3, 4 and 5. Interpretation is given of depositional processes of the facies associations distinguished and interpretation of the depositional environment is made (see Table 2 and Fig. 6).

Table 1

Sedimentary facies distinguished in the study area with their descriptions and interpretations of depositional process

Name of the facies	Code	Description	Depositional process
Debrite	D1	– medium-grained sandstone containing mudstone clasts chaotically distributed throughout whole bed – mudstone clasts up to 7 cm, chaotically arranged – sharp and erosional base bed thickness up to 20 cm	– en-masse freezing from debris flows (Lowe, 1982; Nemec and Steel, 1988)
	D2	– fine- to medium-grained sandstone – amalgamated beds with thickness up to 190 cm – subangular to suboval chaotically dispersed mudstone clasts of 0.2-0.8 cm size – locally aligned mudstone clasts up to 6 cm – mostly sharp bases, occasionally with sole marks and load casts	
Massive sandstone	Sm	– fine- to medium-grained amalgamated sandstone – variable bed thickness, for fine-grained sandstone between 1-10 cm, for medium-grained sandstone up to 300 cm – sharp or wavy bases locally with sole marks – locally aligned mudstone clasts of 0.5 - 7 cm diameter	– frictional freezing from hyperconcentrated density flow (Mulder and Alexander, 2001) – frictional freezing and suspension fall-out from concentrated density flow (Lowe, 1988; Mulder *et al.*, 2001) – continuous aggradation from sustained high density turbidity currents (Kneller and Branney, 1995; Stow and Johansson, 2000; Plink-Björklund and Steel, 2004) – collapse fall-out beyond the hydraulic jump from concentrated density and turbidity flow (Stow and Johansson, 2000)
Normal graded sandstone	Sg	– fine- to medium-grained sandstone – highly variable thickness of beds from 6 to 110 cm – sharp or scoured bases, locally with sole marks	– suspension fall-out within decelerating and waning flow, i.e. Ta division in Bouma sequence (Amy and Talling, 2006) – progressive aggradation from concentrated flow (Kneller and Branney, 1995)
Parallel-laminated sandstone	Spl	– fine-grained sandstone – bed thickness not exceeding 35 cm – sharp or scoured bases, locally with sole marks	– deposition from tractional flow (Pickering *et al.*, 1986) – Tb division in Bouma sequence (Bouma, 1962)
Ripple and trough cross-laminated sandstone	Srcl/tcl	– fine- to medium-grained sandstone – bed thickness between 1 to 19 cm – sharp or scoured bases	– result of migration of 2D or 3D ripples (Reineck and Singh, 1980) – Tc division in Bouma sequence
Hummocky cross-stratified sandstone	Shcs	– fine-grained sandstone – bed thickness to 20 cm – wavelenght of hummocks exceeding 60 cm – sharp bases	– deposition via waves forming on the contact of the flow with the ambient water (Prave and Duke, 1990; Mulder *et al.*, 2009)
Convolute-laminated sandstone	Scl	– fine- to medium-grained sandstone – thickness of beds up to 78 cm	– transformation of metastable sediment (Dżułyński, 1996)
Massive mudstone	Mm	– bed thickness up to 39 cm – dark grey to black – sharp bases	– fall-out from suspension, i.e. pelagic/hemipelagic sedimentation – Te division in Bouma sequence
Parallel-laminated mudstone	Mpl	– highly variable bed thickness from 1 to 73 cm – light to dark grey color – sharp bases	– fall-out from suspension – Te division in Bouma sequence
Ripple-laminated muddstone	Mrcl	– very thin to thin beds from 2 to 13 cm – light grey to black color – sharp bases	– deposition from very fine-grained turbidity flow – reworking by bottom current
Menilite-type claystone	Me	– thickness of beds up to 710 cm – black color – sharp bases	– fall-out from suspension, i.e. pelagic/hemipelagic sedimentation under anoxic conditions (Puglisi *et al.*, 2006)

Fig. 3. Photos of facies and facies associations described in the Cergowa Beds (profile 1)

A – debrite (facies D1) – note the thin bed of sandstone at its base (arrow). Flute casts at the base indicate its deposition from turbulent flow, which created a scour later filled by debrite; **B**, **C** – linked debrites consisting of massive and normally graded sandstone at the base, capped by debrites. The debrite in Figure 3 is capped by parallel-laminated fine sandstone with alternation of darker and lighter laminae suggesting segregation of clay aggregates; **D** – massive sandstone with dispersed mudstone clasts (facies D2), the arrows mark the shear bands formed during the freezing of sediment; **E** – thick amalgamated beds of massive sandstone with dispersed mudstone clasts (facies D2) – close-up showing the composition of the sandstones; **F** – massive sandstone with floating mudstone clasts (facies Sm), arrows mark sandstone top bed injection of mud resulting from rip-down of the overlying mud and mudstone clasts deposited by continuous aggradation from high-density turbidity currents; **G** – deposit of low-density turbidity currents with divisions of the Bouma sequence; **H** – menilite-type claystones (facies Me), the black colour is due to high organic (>4%) content

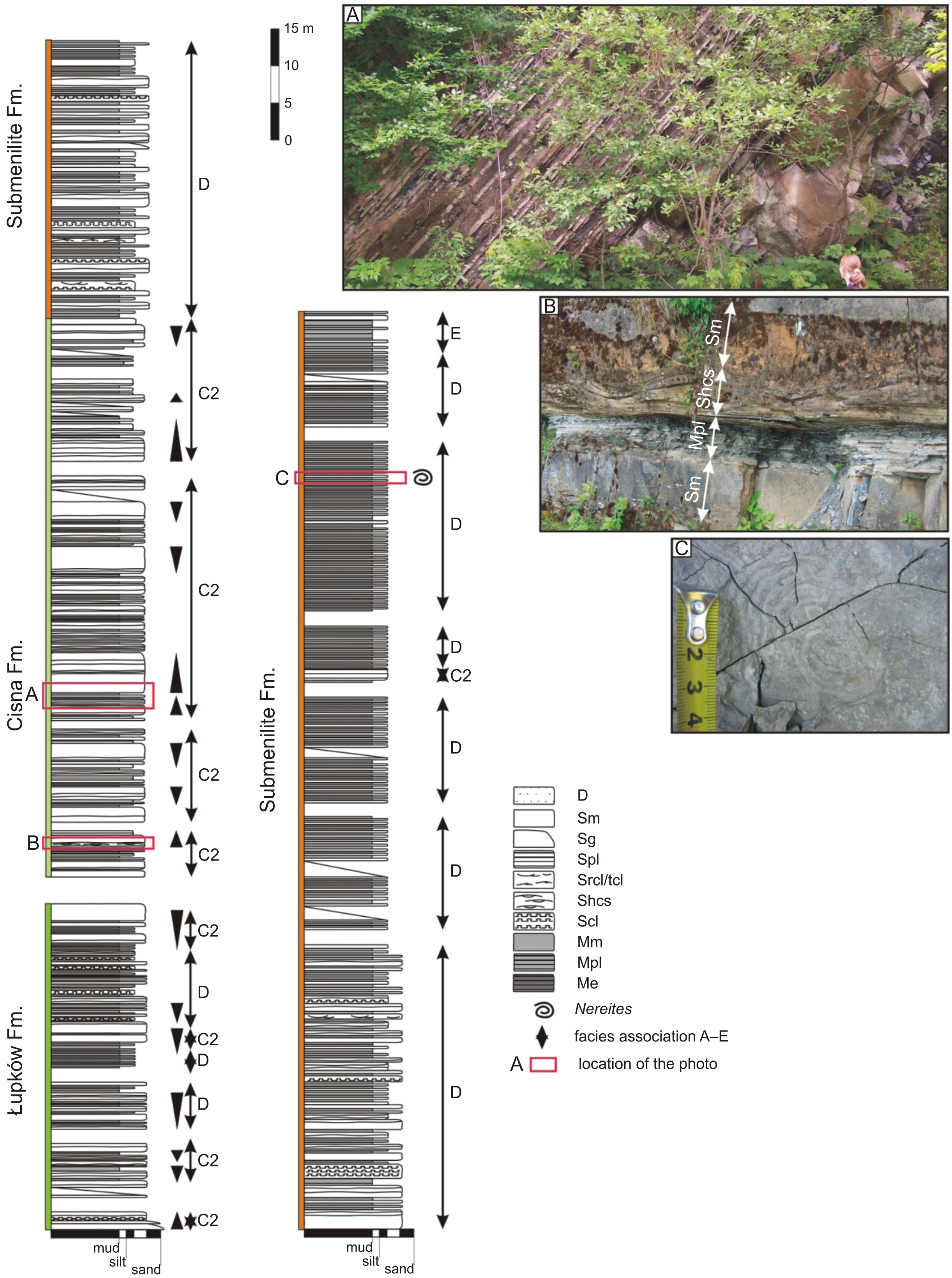


Fig. 4. Simplified composited sedimentary profiles of the Łupków (profile 4), Cisna (profiles 1 and 3) and Submenilite (profiles 1 and 3) formations

A – rhythmic alternation of thin beds of sandstone and mudstone interpreted as interlobe deposits, passing upwards into thick sandstones indicating channelized lobes; **B** – hummocky cross-stratified sandstone whose origin is related to the interface between the flow and ambient water; **C** – the ichnofossil *Nereites* as one of the indicators of a deep-water environment; for explanation of facies codes see Table 1

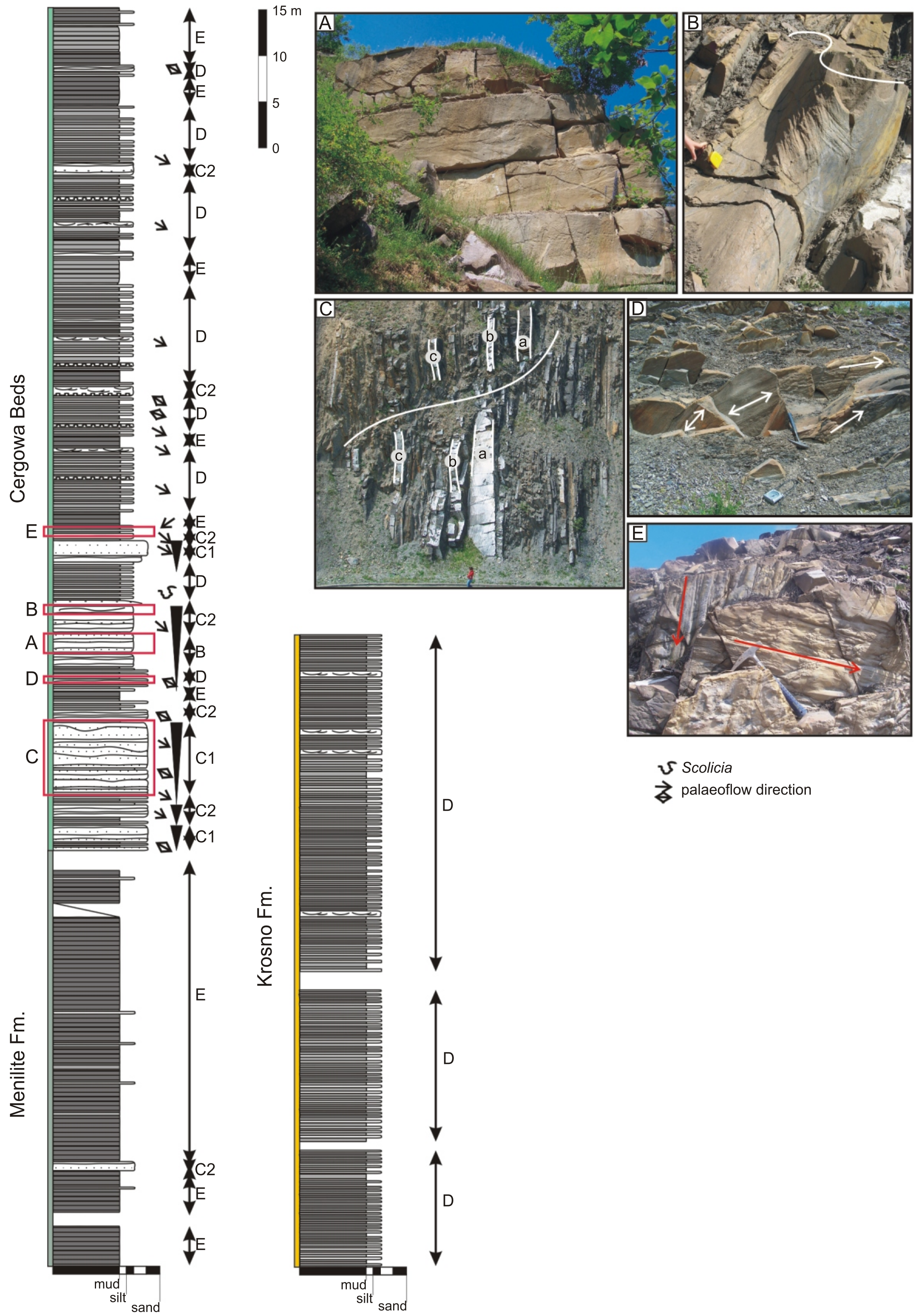
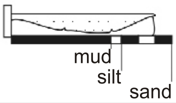
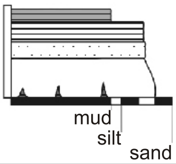
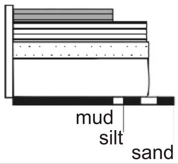
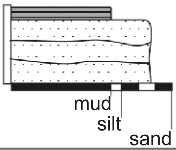
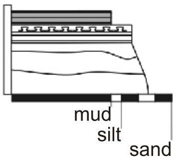
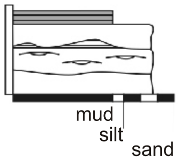
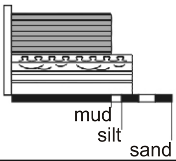
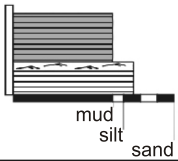
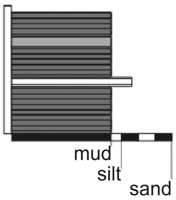


Fig. 5. Simplified composite sedimentary profiles of the Menilite (profiles 1 and 6) and Krosno (profile 6) formations

A – thick channelized sandstones of the Metresa Bed; **B** – synsedimentary fold; **C** – facies association C2. The fault throw is indicated by beds marked by letters a,b,c; **D** – palaeoflow indicators at the bases of Cergowa sandstone beds suggest gradual deviation of the flow due to local topography; **E** – two perpendicular palaeoflow directions of the Cergowa sandstones (arrows) resulting from dissected topography of the basin floor; for explanations see Figure 4

Table 2

Facies and facies associations distinguished in the sedimentary record analysed with their descriptions and interpretations

Code of facies/association				Interpretation
A			D1	Deposits of debris flows
B		 	Mpl Spl D2 Sm/Sg	Deposits of hybrid flows
C	C1		Mpl D2	Deposits of high-density turbidity currents
	C2	 	Mpl Spl/Scl/Sm Sm/Sg/Shcs	
D		 	Mpl/Mm Srcl/Stcl/Scl Sm/Spl	Deposits of low-density turbidity currents
E			Me Mpl/Mm Me Sm/Spl Me	Hemiturbidites to hemipelagites/pelagites

For explanation of facies codes see Table 1

SEDIMENTS AND SEDIMENTARY ENVIRONMENTS

The sedimentary succession studied consists of debrites, sandstones and mudstones with varying net-to-gross ratio, together with ichnofacies and foraminifera assemblages suggest different positions in a turbidite system and related deep-water environment in the evolving Dukla Basin during the Paleocene to Oligocene interval. Based on general indicators of palaeobathymetry, we here use the term "deep-water deposits" for the sediments deposited below storm-wave base.

Bed-by-bed description of the succession revealed 11 lithofacies based on grain size and sedimentary structures (Table 1 and Fig. 3): the debrites are represented by (1) matrix-supported conglomerates composed of pebble- to cobble-sized mudstone clasts within a sandstone matrix and (2) medium-grained sandstones with occasional granule-sized mudstone clasts. The sandstone facies includes (1) massive, fine- to medium-grained sandstone and massive sandstone with chaotically dispersed granule-sized mudstone clasts; (2) normally graded medium- to fine-grained sandstone; (3) fine-grained sandstones with various traction structures and (4) convolute laminated sandstone. The mudstone facies is composed of massive, parallel and ripple laminated mudstones. A specific facies, occurring in the upper part of the succession studied, is menilite-type claystone (Table 1).

The sediments analysed were deposited by several processes as suggested by the individual facies and by the facies associations (Table 2). Hence, we were able to recognize the following deposit types:

DEPOSITS OF DEBRIS FLOWS

Medium-grained, mud-rich sandstone with chaotically distributed mudstone clasts are interpreted as the product of cohesive debris flows. The mudstone clasts varies from 0.5 to 10 cm across, and are often contorted. The base of debris flow beds is sharp and loaded with common flame structures.

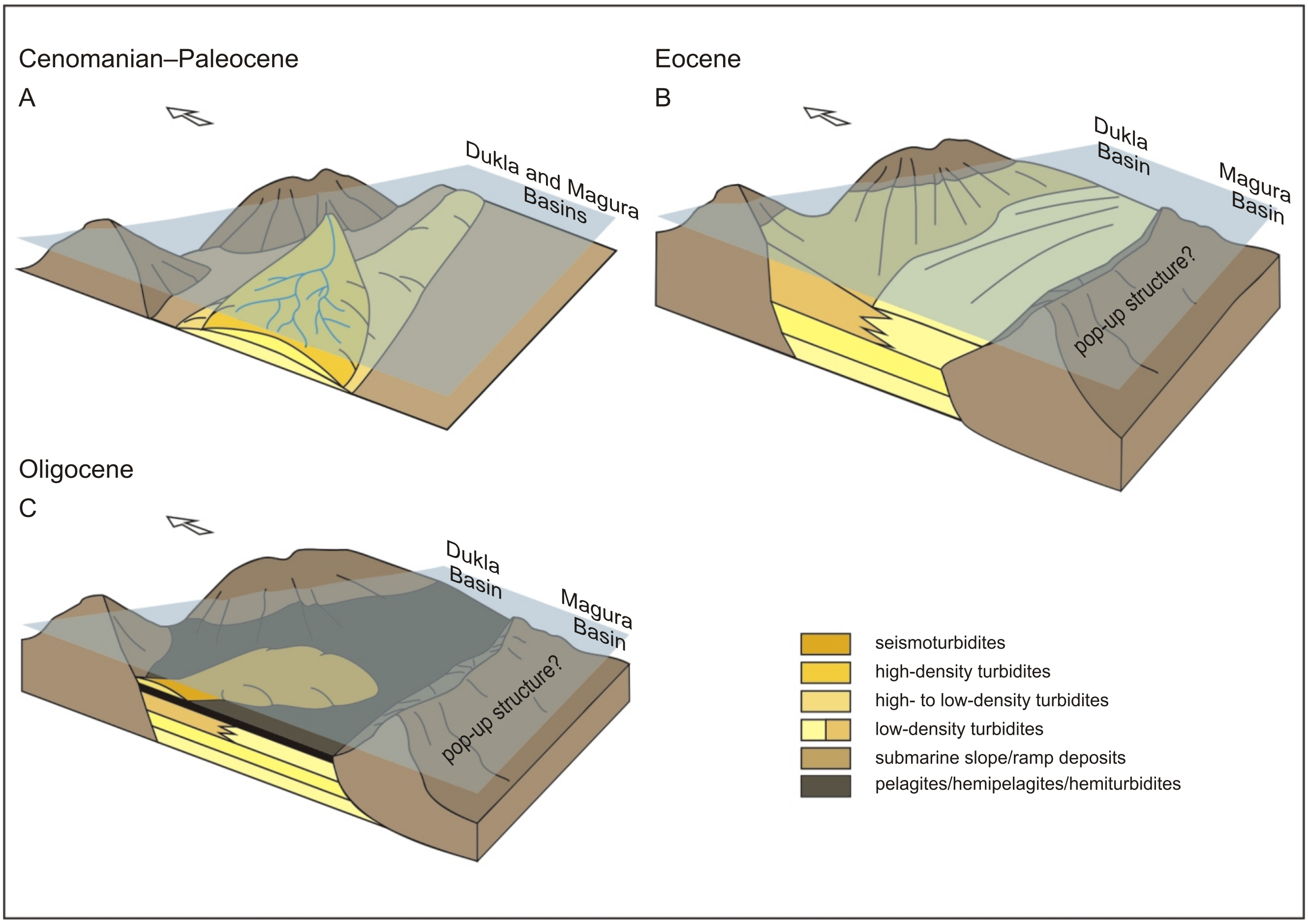


Fig. 6. Evolution of the Dukla Basin based on the deposits analysed

A – first stage of evolution interpreted as a remnant ocean basin with deposition of high- to low-density turbidites in a channel-lobe transition (Łupków Fm.) and channelized lobe (Cisna Fm.); **B** – transitional stage from remnant ocean to peripheral foreland basin with deposition of the Submenilite Fm. from two different sources; **C** – third stage of evolution recorded by the Menilite Fm. deposited in a peripheral foreland basin. Fines represent a starved phase of basin evolution, and the Cergowa sandstones are interpreted as seismoturbidites representing seismic/tectonic activity

DEPOSITS OF HYBRID FLOWS

These deposits are characterized by couplets of massive or normally graded sandstone overlain by medium-grained sandstone containing small mudstone clasts (debrite). This couplet may rarely be overlain by parallel laminated fine sandstone showing alternations of darker and lighter laminae, thus comprising triplets of sandstone – debrite – sandstone (e.g., McCaffrey and Kneller, 2001; Haughton *et al.*, 2009; Fig. 3). Organic matter is common on the bedding planes of the upper sandstones. The entire association is sandwiched between mudstone. The massive and graded sandstones have sharp or loaded bases with water escape structures (flame structures) and a distinct boundary with the overlying debrite.

The deposits described are interpreted as deposits of hybrid flows (e.g., Haughton *et al.*, 2003) consisting of high-density turbidite sandstone at the base, overlying linked debrite, which is, in turn, capped by low-density turbidite sandstone (e.g., Ito, 2008; Felix *et al.*, 2009; Pritchard and Gladstone, 2009). The massive or graded sandstone at the base is correlated with the H1 division of Haughton *et al.* (2009), while the overlying debrite and laminated fine sandstone corresponds with H3 and H4 divisions, respectively.

Similar hybrid beds are recognized widely at the distal and lateral margins of turbidite systems (Haughton *et al.*, 2009). The common association with abundant carbonaceous matter indicates probable linkage to the contemporaneous shelf.

DEPOSITS OF HIGH-DENSITY TURBIDITY CURRENTS

The deposits of high density turbidity currents (according to Lowe, 1982) are represented by three facies associations. The first association, C1, consists of massive sandstone with dispersed mudstone clasts overlain by thin beds of parallel-laminated mudstone. The sandstone to mudstone ratio is 12:1. The base of the sandstone beds is sharp, scoured or loaded and frequently shows a variety of sole marks. The beds are often amalgamated, building bedsets up to 9 m thick.

The deposits described are interpreted as products of high-density turbidity currents due to widespread sole marks indicating turbulence (e.g., Hodgson, 2009). The massive structure of the sandstones results from suppression of turbulence most probably when turbulent flow slowed e.g., due to a hydraulic jump at a change in slope angle (Talling *et al.*, 2007) or as a result of erosional bulking as suggested by the small mudstone clasts dispersed in the sandstones (e.g., Ricci Lucchi and Valmori, 1980; Talling *et al.*, 2004). Thin caps of parallel-laminated mudstone reveal subsequent deposition from following dilute turbidites.

The second association, C2, is characterized by thick-bedded massive or normally graded sandstone, or by convolute-laminated sandstone overlain by parallel-laminated sandstone and mudstone. The base of beds is sharp, scoured and loaded. Beds are often amalgamated with a mean thickness of 3.2 m; however, the thickness may reach 10 m locally. The mean sandstone to mudstone ratio is 5:1.

The association is interpreted as a turbidity current deposit due to basal scours and sole marks indicating flow turbulence, normal grading and tractional structures at the top of the succession. The thick massive sandstone interval at the base of the succession suggests high flow concentration and probably is analogous to the S_3 interval of high-density turbidity currents described by Lowe (1982).

DEPOSITS OF LOW-DENSITY TURBIDITY CURRENTS

The deposits of low-density turbidity currents are characterized by an association of fine- to medium-grained sandstone passing into mudstone, and mostly represented by heterolithic deposits. The sandstone shows a wide range of tractional structures from parallel-laminated, ripple/trough-cross-laminated and convolute-laminated ones. The overlying mudstone is ripple- and/or parallel-laminated. The sandstone to mudstone ratio is 2:1 to 1:5. The mean thickness of strata in the association is 4 m with a maximum of 25 m.

The abundance of tractional structures points to deposition by turbiditic curents with preservation of Bouma Tb, c and d divisions (Bouma, 1962; Hiscott *et al.*, 1997).

HEMITURBIDITES AND HEMIPELAGITES/PELAGITES

These deposits are represented by brownish dark to black claystone including black, hard, fissile and siliceous claystone with a high organic content (menilite) and massive and/or parallel-laminated mudstone. The strata described are locally interrupted by thin beds of parallel-laminated fine- to medium-grained sandstones.

The texture and structure of these beds suggest deposition by suspension fall-out and and hemiturbidites. The few thin beds of sandstone are thought to have been deposited by low-density turbidites.

INTERPRETATION OF DEPOSITIONAL ENVIRONMENT

The sedimentary section analysed is one of the best preserved sections in the Dukla Unit showing the succession of the basin fill from the base to the top. The geological background (e.g., Koráb and Ďurkovič, 1978; Oszczypko, 1999; Malata and Poprawa, 2006), sedimentary structures, ichnofossil indices (Uchman *et al.*, 2006) and palaeobathymetry defined on the base of foraminiferal assemblages (Olszewska and Malata, 2006) strongly suggest deposition in a turbidite system developed in the range of outer shelf (?) to abyssal zones.

The section studied starts with the uppermost part of the Łupków Formation (Cenomanian–Paleocene), which mainly consists of high- and low-density turbidity deposits (Fig. 4). The sandstone beds with occasional scoured and fluted beds show several upwards thickening cycles several metres thick consisting of thin (5–10 cm) beds at the base and medium-thick (40 cm) beds at the top. The sandstone to mudstone ratio is 3:1. Flutes on the base of the sandstone indicate a palaeoflow direction from E(NE) to W(SW).

Thin- and medium-thick sandstone beds deposited by high- and low-density turbidity currents, erosional features such as scours and flutes and thickening-upwards cycles indicate deposition at the channel-lobe transition with an overall progradational trend (Postma *et al.*, 2009). Medium- to coarse-grained sandstones, in places containing granules at the base and convolute lamination, suggest high competence of the currents and high sedimentation rates. Such conditions can be assumed to occur in a channel-lobe transitional area.

The interval of upward thickening cycles of sandstone beds separated by mudstones (Łupków Fm.) passes upwards into sandier deposits belonging to the Cisna Formation (Senonian–Paleocene, Figs. 1 and 4). The interval is typified by predominant medium- to coarse-grained, thick, often scoured sandstone beds. The palaeoflow directions based on flute marks are from NE to SW. The frequently amalgamated sandstone beds with a maximum measured thickness of 12 m are separated by thin mudstone intervals. The sandstones are mostly massive or built of a succession of massive/normal graded, parallel- and convolute-laminated intervals (Bouma Ta, b, c divisions), where the upper interval of tractional structures is rarely replaced by hummocky-cross stratification (Fig. 4). Foraminiferal assemblages show deposition in the lower bathyal zone (e.g., Oszczypko, 2004; Uchman *et al.*, 2006).

The thick, frequently scoured sandstone beds, amalgamation and massive sandstones suggest deposition by high-density turbidity currents close to the channelized part of a turbidite system. The occurrence of structures resembling hummocky-cross stratification are thought to be a result of up-current migrating waves (antidunes) triggered by high-energy turbidity currents that are common close to main turbidity current conduits (e.g., Mulder *et al.*, 2009).

The sandy interval of the Cisna Formation passes into thin (3–7 cm) sandstone beds alternating with mudstones (Fig. 4) assigned to the Submenilite Formation (Eocene). The transition between thick sandstone beds of the Cisna Formation and the overlying strata of the Submenilite Formation is gradual and marked by an increase in mudstone beds. The sandstone:mudstone ratio varies from 2:1 in the lower part to 1:5 in the upper part. The sandstone shows mostly Tb, c, d divisions of Bouma suggesting deposition mainly by low-density turbidity currents (Lowe, 1988). The succession contains the *Nereites* and *Ophiomorpha rudis* ichnofacies.

Deposition by low-density turbidity currents and thin sandstone beds alternating with mudstones are typical of the distal environment in a turbidite system (e.g., Remacha and Fernandez, 2003) or of on intrafan environment (e.g., Hodgson, 2009). However, evidence for gradual shallowing based on the foraminiferal assemblages (Olszewska, 1984; Uchman *et al.*, 2006) may also be suggesting deposition on a submarine slope/ramp after shut-down of the source of the sand-prone turbidite system of the Cisna Formation. The varying sandstone:mudstone ratio in the section studied probably reflects changes in sediment supply due to shift of deltaic lobes on a shelf, irregular tectonic activity and climate changes (Leszczyński, 1996).

Alternating sandstones and mudstones of the Submenilite Formation gradually pass into a 150 m thick succession of mudstones, menilitic cherts and fine-grained sandstones. These deposits represent the Menilite Formation (Early Oligocene) with the sandstone-rich member of the Cergowa Beds. The fine-grained part of the formation contains 4 to 7.1 m thick intervals of organic-rich, dark menilite-type claystones separated by intervals of pale to dark gray mudstone and thin fine-grained sandstone beds. These sediments sandwich a 50 m thick interval of Cergowa sandstones. They are characterized by alternations of thick-bedded, amalgamated and often scoured medium-grained sandstones and dark mudstones and black menilites showing an upwards thinning trend. In the lower part of the interval the sandstones are mostly massive and contain scattered small mudstone clasts. There are a few sandstone – debrite – sandstone triplets indicating hybrid flows. Upwards, this succession is gradually replaced by fine-grained sandstones showing tractional structures. The sandstone to mudstone ratio changes from 4:1 to 1:2 as the Cergowa sandstones passes into the menilite shales. Frequent sole marks indicate a palaeoflow direction from NW to SE with minor flutes suggesting flow from NE to SW. The sandstones are locally deformed by synsedimentary faults and folds (Fig. 5) crossing part of the sedimentary succession. At the base of the sandstones the ichnofossil *Scolicia* was found.

The lower part of the succession, consisting of mudstones and thin beds of sandstone, reflects quiet hemipelagic/pelagic deposition occasionally interrupted by low-density turbidites. The thick sandstone beds of he Cergowa sandstones record increased tectonic activity related to the advancing orogen (e.g., Oszczypko and Oszczypko-Clowes, 2009). The common association with abundant carbonaceous matter indicates probable linkage to the contemporaneous shelf (e.g., Haughton *et al.*, 2009). This is also supported by the occurrence of thick, often amalgamated sandstones with loaded bases suggesting high sediment input and proximity to the source area. The thick sandstone beds are intercalated with menilite cherts interpreted as condensed horizons. Their presence could represent significant intervals of time during which the turbidite pathways on the slopes were steepened by faulting (e.g., Fugelli and Olsen, 2007). A similar succession in the Dukla Unit, interpreted as a seismoturbidite, was described by Ślączka and Walton (1992). The fining-upward trend of the whole succession may be interpreted as gradual smoothing of the equilibrium profile that had been disrupted by an earlier tectonic event, resulting in gradual replacing of of high-density turbidity currents and hybrid flow deposits by deposits of low-density turbidity currents.

The menilite shales are overlain by heterolithic of deposits the Krosno Formation (Oligocene) that terminates the sedimentary succession of the Dukla Unit. The formation is characterized by thin-bedded, parallel-, ripple- and trough cross-laminated sandstones alternating with thin to medium parallel-laminated mudstone beds. The sandstone to mudstone ratio is about 1:2.

Thin sandstone beds with tractional structures overlain by mudstones represent the Tb, c, d interval of Bouma sequences deposited by low-density turbidity currents.

DISCUSSION AND CONCLUSIONS

It is generally accepted that the Outer Carpathian basins during their history represented constituents of distinct, but genetically consecutive basins (e.g., Oszczypko, 1999; Oszczypko *et al.*, 2002; Golonka *et al.*, 2003). The Cretaceous, Paleocene and Eocene strata are generally interpreted as sediments deposited in a remnant oceanic basin while the Oligocene sediments were deposited in a foreland basin that opened during the advance of the Carpathian orogen (e.g., Oszczypko, 1999, 2006; Golonka *et al.*, 2011). The final phase of deposition occurred in wedge-top basins in some places (e.g., Oszczypko *et al.*, 2002).

Based on the sedimentary record in the succession studied we interpret the following stages in the evolution of the Dukla Basin:

FIRST STAGE

The first stage is recorded by deposits of the Łupków and Cisna formations (Fig. 6). The base of the sedimentary succession recorded is typified by thickening-upward intervals of sandstones separated by mudstones, gradually passing to thick-bedded sandstones. The lower interval of high- to low-density turbidites deposited in a channel-lobe transition zone (Łupków Formation) and in the form of channelized lobes (Cisna Formation) implies progradation of the depositional system. Sources of these material lay to the NE and E of the basin, thus indicating the north-east promontory of the Marmarosh Massif (Bąk and Wolska, 2005) as well as the Bukowiec Palaeo-Ridge (in the case of the Cisna Formation, Ślączka, 2005) as their possible source.

SECOND STAGE

Lobes of the Cisna Formation were overlain by thinning- and fining-upwards strata of the Submenilite Formation deposited by low- and, to lesser amount by high-density turbidity currents (Fig. 6). Two perpendicular palaeoflow directions (dominant SE to NW and minor N and NE to S and SW) recorded by Koráb and Ďurkovič (1978) as well as different sandstone mineralogical compositions (Koráb and Ďurkovič, 1978) indicate two depositional systems fed from different sources. Shallowing of the environment indicated by foraminiferal assemblages (Olszewska, 1984) suggests deposition on a submarine slope/ramp. The change in sediment input and shallowing probably results from increased tectonic activity connected with a new source area emerging between the Dukla and Magura basins (the Grybów Palaeo-Ridge, Cieszkowski, 2002).

THIRD STAGE

The third stage is characterized by deposition of dark to black mudstones of the Menilite Formation in the Early Oligocene (Fig. 6), during which significant changes of relative sea level took place as a result of eustatic fluctuation and tectonic activity (e.g., Oszczypko, 1999; Oszczypko *et al.*, 2002; Poprawa *et al.*, 2002; Golonka *et al.*, 2003). The black mudstones containing much organic material suggest hemipelagic/pelagic and hemiturbidite sedimentation in anoxic conditions (Bessereau *et al.*, 1996) resulting from sea level fall and related isolation of the basin. This quiet sedimentation changed abruptly, as recorded by the thick-bedded Cergowa sandstones interpreted as seismoturbidites (Fig. 6). The main NW to SE direction of palaeoflows transporting coarser-grained sediments indicates that the possible source of the material was the activated thrust belt of the Carpathian orogen (Silesian Palaeo-Ridge?). Finally, low-density turbidity currents entered the basin from the same direction and deposited the youngest synorogenic sediments of the unit terminated by the Krosno Formation. We assume that the increased tectonic activity is linked with the zipping of the subduction zone between the Carpathians and the adjacent European platform.

Based on this, we suggest that: (1) the sediments of Łupków and Cisna Formation were deposited in conditions of a closing remnant basin; (2) the sediments of the Submenilite Formation, with a bipolar palaeoflow direction, represent a transitional phase between the remnant basin and the peripheral foreland basin and (3) deposition of Menilite and Krosno Fm. is associated with peripheral foreland basin that originated due to advance of the Carpathian orogen (Oszczypko, 1999; Poprawa *et al.*, 2002; Golonka *et al.*, 2011). This phase was characterized by periods of quiet sedimentation related to basin isolation and subsequent circulation slowdown ("menilitic deposition") interrupted by deposition of thick-bedded sandstones triggered by seismic events related to growth of the thrust belt in the hinterland of the Carpathian orogen front (deposits of Cergowa sandstone in the area studied and the Metresa Bed of Ślączka and Walton, 1992). Terminal sedimentation is represented by thin-bedded, low-density turbidites of the Krosno Formation.

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