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The Dobrotiv Formation (Miocene) in the Boryslav-Pokuttya and Sambir nappes of the Ukrainian Carpathians: a record of sedimentary environmental change in the development of the Carpathian Foredeep Basin

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The upper Lower Miocene Dobrotiv Formation, a 700–800-m-thick unit, was deposited in a subsiding platform margin, which become involved in the marginal part of the Outer Eastern Carpathian accretionary wedge. The sedimentary succession from the Sloboda Conglomerate up to the Dobrotiv Formation records a transition from alluvial fan through fan-delta to deltaic deposits, followed by the fluvial plain-channel facies of the Stebnyk Formation. The deltaic deposits are mud-dominated, with poorly developed thickening-up packets of beds. Efficient sediment accumulation was balanced by subsidence caused by subsurface loading. Emerged parts of the deltaic sedimentary system include tetrapod footprints and raindrop imprints. The general absence of mudcracks in the Dobrotiv Formation suggests a humid climate. Deposits of the Sloboda, Dobrotiv and Stebnyk formations form fining- and thinning-upwards clastic wedge successions along the Ukrainian Carpathians.

Key words: non-marine, deltaic sediments, molasse, mammal and bird footprints.

INTRODUCTION

A sedimentary succession at least 2-km-thick of the remnant to peripheral foreland basin of the Boryslav-Pokuttya and Sambir nappes (Vashchenko and Hnylko, 2002; Hnylko, 2012) in the marginal part of the Eastern Carpathians in Ukraine (Fig. 1A, B) contains, in its middle part, thick, non-marine deposits. They are distinguished as the Sloboda Conglomerate, Dobrotiv Formation and Stebnyk Formation (Fig. 1C, D). The Dobrotiv Formation, dominated by fine-grained deposits, is known from spectacularly well-preserved mammal and bird footprints (Vialov, 1966). However, there has been little palaeoenvironmental interpretation of this unit. Its sedimentation, which took place after coarse clastic deposition in the alluvial fan and fan-delta of the Sloboda Conglomerate (Oszczypko et al., 2012), commenced with variegated marls, shales and sandstones of the Stebnyk Formation and records a significant change in depositional palaeoenvironment in the foreland basin. The course of the change remains unknown, but this problem cannot be satisfactorily solved without facies analysis of the Dobrotiv Formation.

The aim of this paper is to describe and interpret the palaeoenvironment of the Dobrotiv Formation, in the context of the basin development, on the basis of field research in the Prut River section, which is the best section through this formation.

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PREVIOUS WORKS

The Dobrotiv Formation (originally the Dobrotiv Beds) was distinguished by Paul and Tietze (1877). Later, it was studied by almost all the Polish and Ukrainian geologists working on the foreland of the Ukrainian Carpathians (e.g., Zuber, 1888, 1915, 1918; Teisseyre, 1927; Bujalski, 1930, 1934, 1938; Denisova, 1959, 1970; Fedushchak, 1962; Vialov, 1960, 1965, 1966 and references therein), who focused mainly on its stratigraphic position, lithology and palaeontological features. Its facies counterparts are in the Sub-Carpathian Unit in Romania are known as the Tescani Beds (Micu, 1982).

The most detailed descriptions of the Dobrotiv Formation are given by Teisseyre (1927), Bujalski (1934) and Denisova (1970). According to Teisseyre (1927), deposits of this formation are bipartite and are characterized by distinct lower and upper boundaries. Their lower part is dominated by sandstones, and the upper by claystones and marls. In general, the Dobrotiv Formation displays a fining- and thinning-upwards sequence. Vialov (1965) agreed that the Dobrotiv Formation occurs between the Sloboda Conglomerate and the Stebnyk Formation, and considered that the Sloboda Conglomerate and the Dobrotiv Formation correlate with of the lower and upper part of the Vorotyshcha Salt Formation, respectively. Vialov (1965) con-

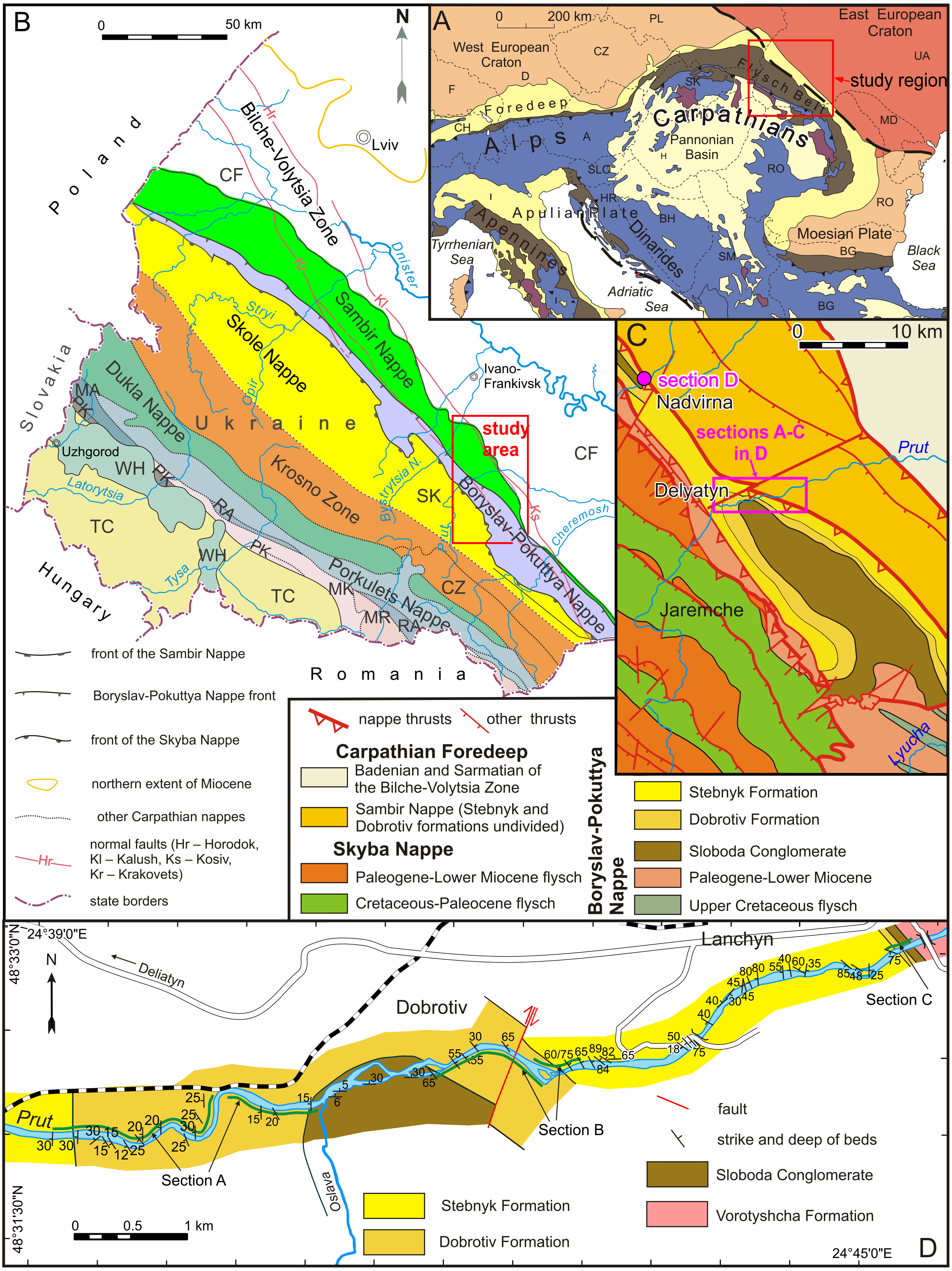

Fig. 1. Location maps

A – position of the study area in the Alpine-Carpathian system (after Picha, 1996, modified by Oszczypko et al., 2006); **B** – tectonic map of the Ukrainian Carpathians (after Ślączka et al., 2006, simplified); CF – Carpathian Foredeep, SK – Skyba (Skole) Nappe, CZ – Chornohora Nappe, RA – Rakhiv Nappe, MR – Marmarosh Massif, MK – Marmarosh Klippen Zone, MA – Magura Nappe, PK – Pieniny Klippen Belt, WH – Vihorlat-Gutin Volcanic Massif, TC – Trans-Carpathian Depression; **C** – geological map of Deliatyn-Lanchyn-Nadvirna area (after Jankowski et al., 2007), showing location of the section D; **D** – geological map along the Prut River showing location of the sections A–C sidered that the boundary between the Dobrotiv and Stebnyk formations is at the base of the first “rose marls”.

All investigators have noted the presence of well-preserved mammal and bird footprints (see Vialov, 1966) and rain-drop imprints (Teisseyre, 1927; Dimitriéva et al., 1962; Vialov, 1965; Denisova, 1972). The most detailed lithological and sedimentological studies of the Dobrotiv Formation has been made by Denisova (1959). Based on analysis of the sedimentary structures, she proposed a deltaic origin for the Dobrotiv Formation, the sediments of which, dominated by an overwhelming predominance of zircons in the heavy minerals fraction, were derived from the East European Platform.

Detailed mineralogical study of the Dobrotiv Formation was carried out by Tkachenko (1961), who showed that the heavy mineral fraction of the sandstones is distinctly different from that of other Lower Miocene units by a high predominance of chlorite and zircon over other heavy minerals. Similarly, mudstone intercalations show a dominance of chlorite with small amounts of hydromicas, while other Lower Miocene units are dominated by hydromicas.

GEOLOGICAL SETTING AND SECTIONS INVESTIGATED

Along the marginal part of the Ukrainian Carpathians, a wide zone of folded Miocene strata belongs to the Boryslav-Pokuttya and Sambir nappes (Fig. 1B, C). The Boryslav-Pokuttya Nappe, known also as the Marginal Fold Unit or the Boryslav-Pokuttya Folds, is exposed in a narrow (up to 10 km) belt located between the Skyba and Sambir nappes. This nappe may be traced from Romania in the SE to the Polish border in the NW. This nappe is built of a complex set of superimposed thrust sheets (Koltun et al., 2005). The Boryslav-Pokuttya Nappe, composed of flysch and molasse deposits is overlain by the frontal Carpathian thurst, overthrust on the Sambir Nappe, which comprises exclusively molasse deposits. Some authors (Burov et al., 1978; Smirnov et al., 2000) consider the Boryslav-Pokuttya and Sambir nappes as representing the inner part of the Carpathian Foredeep. Both nappes are overthrusted onto the Middle Miocene (Badenian and Sarmatian) autochthonous deposits of the Bilche-Volytsia Zone, which rests directly on the foreland platform basement.

BORYSLAV-POKUTTYA NAPPE

This nappe is subdivided into the Deliatyn and Runhury Sloboda sub-nappes (Kulchytsky et al., 1997). The Deliatyn Sub-nappe is composed of Cretaceous-Lower Miocene flysch, which is similar to that of the Skyba Nappe. The youngest Lower Miocene flysch succession belongs to the Polyanytsia Formation, which is overlain by the Vorotyshcha Formation (NN3–?NN4 Zone; Andreyeva-Grigorovich et al., 2008a). The Vorotyshcha Formation (Fig. 2), up to 700-m-thick, composed of grey mudstones and siltstones intercalated with coarse-grained sandstones and conglomerates, contains large blocks of impure halite and anhydrite (Gurzhyi, 1969; Andreyeva-Grigorovich et al., 2008a). Locally, the upper part of the Vorotyshcha Formation is replaced by the Sloboda Conglomerate (Oszczypko et al., 2012 and references therein).

The Deliatyn Sub-nappe is overthrusted upon the Runhury Sloboda Sub-nappe. The latter is built mainly of the Sloboda Conglomerate, Dobrotiv Formation and Stebnyk Formation. Several boreholes show that the Sloboda Conglomerate is underlain by the Vorotyshcha Formation, while the flysch deposits, mainly of the Lower Menilite Formation, are represented by the olistoliths and olistostromes, and olistoplaques (Kolodiy et al., 2004).

On the southern limb of the Runhury Sloboda Anticline, the Sloboda Conglomerate is underlain by the Menilite Formation shales (Oligocene), and on its northern limb by the salt-bearing clays of the Vorotyshcha Formation (Tołwiński, 1950). The Sloboda Conglomerate (Fig. 2) contains exotic blocks, boulders and cobbles of Upper Proterozoic-Lower Paleozoic green phyllite, black schist, dolomite, Jurassic white limestone, and rare flysch-derived olistoliths and olistostromes (Fedushchak, 1962; Oszczypko et al., 2012). The thickness of the Sloboda Conglomerate increases from 450–500 m in the Nadvirna area up to 1400 m at Runhury Sloboda. The Sloboda Conglomerate passes into the ?Ottnangian Dobrotiv Formation, which is up to 800-m-thick. This formation is overlain by the variegated mudstones, marls and sandstones of the Stebnyk Formation (Karpatian–Early Badenian; see Andreyeva-Grigorovich et al., 1995, 1997, 2008a). On the northern limb of the Runhury Sloboda Anticline at Jabloniv, gypsum layers up to 100-m-thick are sandwiched between the Sloboda and Dobrotiv formations (Tołwiński, 1950).

SAMBIR NAPPE

The Sambir Nappe, up to 24 km wide and composed of several thrust-sheets (Fig. 1), is correlated with the Sub-Carpathian Unit in Romania and the Stebnik Nappe in Poland (Oszczypko et al., 2006, 2008). This unit is overthrusted upon the Badenian-Sarmatian deposits of the outer zone of the Carpathian Foredeep (Kolodiy et al., 2004). The Sambir Nappe succession is composed mainly of the thick succession of “lower” Miocene molasse of the Stebnyk and Balych formations. The lithostratigraphy of its basal part is still under discussion. Several authors (Koltun et al., 2005; Andreyeva-Grigorovich et al., 2008b and references therein) regard the Vorotyshcha Formation as the oldest division of the Sambir Nappe succession. This opinion is supported by boreholes, e.g. Hvizd 1 near Nadvirna and Urizh 6 (NE of Boryslav), where the Vorotyshcha Formation was penetrated (Andreyeva-Grigorovich et al., 1997, 2008a). At the same time, poorly developed coarse clastic deposits of the Sloboda Conglomerate and Dobrotiv Formation occur locally in this unit. The Dobrotiv Formation is followed by variegated marls, mudstones and sandstones of the Stebnyk Formation (Late Karpatian–Early Badenian; NN4–NN5 zones; Andreyeva-Grigorovich et al., 1997, 2008a). The Stebnyk Formation passes up into greenish and grey clays, mudstones and poorly cemented sandstones of the Balych Formation, regarded by Bujalski (1930) as the northern facies of the upper part of the Stebnyk Formation (see also Vialov, 1965). In the village of Sadzhavka, 2 km E of Lanchyn, Berlavsky (*fide* Vialov, 1965) distinguished a succession of massive sandstones in the upper part of the Stebnyk Formation, which are 40-m-thick. Also two units of dacitic tuffite are known from the villages of Krasna and Seredniy Maydan near Lanchyn (Bujalski, 1938), each 40–45-m-thick (Vialov, 1965). Moreover, a number of brine springs related to the “younger” Miocene salt deposits of the Stebnyk Formation are known from the area (Bujalski, 1938).

In the Kalush area, the Stebnyk and Balych formations are undivided and they pass upwards into the Bohorodchany Formation, composed of 100–250-m-thick grey marly mudstones and sandstones, which contain abundant Badenian planktonic foraminifera and calcareous nannoplankton of the NN5 Zone (Andreyeva-Grigorovich and Kulchytsky, 1985; Andreyeva-Grigorovich et al., 2003). In the southern sector of the Kalush area, the Bohorodchany Formation passes up into the evaporitic salt sequence of the Kalush Formation, or gypsum and salt deposits of the Tyras Formation, which belong to the NN5–NN6 zones (Andreyeva-Grigorovich et al., 2003).

The youngest deposits belonging to the Kosiv (Upper Badenian) and Dashava (Sarmatian) formations have been documented near Dobromyl. These deposits are terminated by the Radych Conglomerate, which contain flysch clasts and is dated to the NN6–NN9 zones (Andreyeva-Grigorovich et al., 2008a).

SECTIONS STUDIED

The sections studied crop out in the Prut River valley (Fig. 1D), north of Deliatyn, between the villages of Zarichchya and Lanchyn, where almost continuous exposures are present for about 8 km along the river banks. These exposures display folded Miocene deposits of the Runhury Sloboda Anticline within the Boryslav-Pokuttya Nappe. The core of the anticline is formed by the Sloboda Conglomerate, while the limbs are occupied by the Dobrotiv and Stebnyk formations. Moreover, the transition between the Sloboda Conglomerate and the Dobrotiv Formation was studied in the Nadvirna area, as shown in Oszczypko et al. (2012).

In the Prut valley, the boundary between the Boryslav-Pokuttya and Sambir nappes is not clear. Geological maps (Jankowski et al., 2007; see also Hnylko, 2012) show this boundary within the Stebnyk Formation on the north limb of the Runhury Sloboda Anticline, ca. 6 km north of Deliatyn.

The sections studied of the Dobrotiv Formation in the Boryslav-Pokuttya Nappe are as follows (Fig. 1C, D):

- section A – southern limb of the Runhury Sloboda Anticline, south of the of the Oslava Stream inflow to the Prut River at Dobrotiv (GPS coordinates: from N48°32.161'; E24°41.080' to N48°32.156'; E24°40.819') towards Deliatyn (GPS coordinates: from N48°32.049'; E24°38.854' to N48°33.033'; E24°45.282'). This section displays a transition of the uppermost part of the Sloboda Conglomerate into the Dobrotiv Formation and continues through the Dobrotiv Formation up to the Stebnyk Formation;
- section B – right and left banks of the Prut River between the Oslava Stream inflow to the Prut River to the cable bridge at Dobrotiv (GPS coordinates: from N48°32.161'; E24°41.080' to N48°32.336'; E24°43.461').
- section C – left bank of the Prut River at Lanchyn near the bridge (GPS coordinates: N48°33.015'; E24°45.155' to N48°33.117'; E24°45.117'). This section displays a transition from the uppermost part of the Vorotyshcha Formation through the Sloboda Conglomerate and the Dobrotiv Formation type sandstones, which display strongly reduced thicknesses, up to the base of the Stebnyk Formation represented by rose-coloured marly shales;
- section D – cliffs along the left bank of the Bystrytsia Nadvirnanska River at Nadvirna (GPS co-ordinates: N48°32.240'; E24°41.012'). A transition from the Sloboda Conglomerate to the Dobrotiv Formation can be observed here.

Investigations of sections A and B enabled preparation of two sedimentary logs of the Dobrotiv Formation on both limbs of the Runhury Sloboda Anticline. The log of the southern limb is continuous, covering the profile described by Vialov (1965, p: 54–59). The log of the northern limb of the anticline is combined due to tectonic displacement along the Prut River, where the section is obscured over a distance of 450 m (GPS coordinates: from N48°32.445'; E24°42.558' to N48°32.407'; E24°42.876').

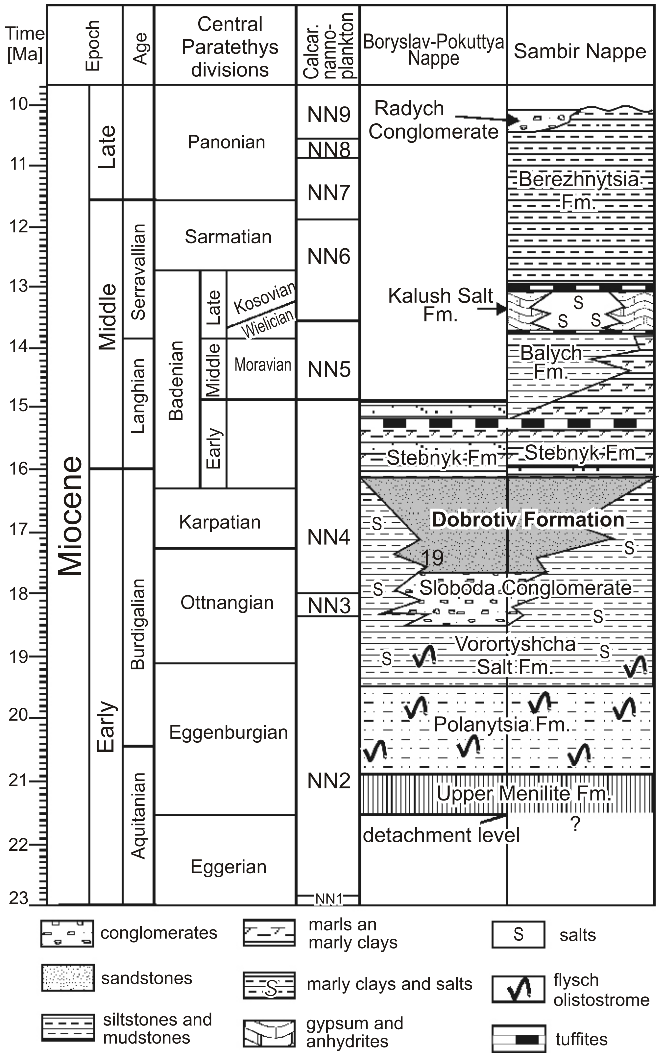

Fig. 2. Lithostratigraphic scheme of the Borislav-Pokuttya and Sambir nappes (based on Andreyeva-Grigorovich et al., 2003, 2008a, b; Oszczypko et al., 2006, supplemented)

This area is crossed by a transverse NW–SE fault, which displaces the limb of the anticline northwards by approximately 500 m. This resulted in duplication of thickness on the northern limb for about 350 m.

Section C displays the core of the Lanchyn Anticline, probably belonging to the Sambir Nappe. The southern limb of the anticline is composed of grey brecciated mudstones of the Vorotyshcha Formation (see Andreyeva-Grigorovich et al., 2008a). This formation is overlain by the Sloboda Conglomerate and Dobrotiv Formation of strongly reduced thickness: 25–30 m and 22–25 m respectively. The Sloboda Conglomerate begins with grey matrix- and clast-supported medium-grained conglomerates with sharp-edged and semi-rounded clasts, 2–5 cm across, the beds of which dip subvertically towards the south. The clasts are composed of grey sandstones and mudstones with small admixtures of quartz and carbonates. These conglomerates, deposited by debris flows, are 10–15-m-thick. They are overlain by a 15-m-thick succession of thick-bedded (0.7–1.0 m) fine conglomerates, with a muddy-sandy matrix. Their beds show a transition to fine- to coarse-grained sandstones, in beds 10–30-cm-thick. Lower surfaces of the conglomerate beds are usually flat and only locally channelized. These beds are overlain by 10 m of, thick-bedded, coarse-grained, structureless sandstones, which are followed by 12 m of thin- to medium-bedded, fine-grained sandstones with intercalations of dark or grey mudstone, resembling these from the uppermost part of the Dobrotiv Formation. Directly above the Dobrotiv Formation-type deposits, grey and rose-coloured shales of the basal portion of the Stebnyk Formation are exposed. Such a large reduction in thickness of the Sloboda and Dobrotiv formations in section C can be caused by both tectonic truncation and sedimentary pinching out.

Beneath the bridge, on the northern limb of the anticline, the Vorotyshcha Formation is overlain by a sub-vertical SW-dipping, overturned packet of blue-grey, non-calcareous shales with thin anhydrite lenses (GPS coordinates: from N48°33.066'; E24°45.375' to N48°33.125'; E24°45.528'). This succession is known as the "Lanchyn blue complex" (Vialov, 1965), which sporadically contains intercalations of thick-bedded, coarse-grained, amalgamated sandstones, with palaeotransport from the ESE (110°; see also Andreyeva-Grigorovich et al., 2008a).

FACIES CHARACTERISTICS

LITHOLOGY AND SEDIMENTARY STRUCTURES

The lowest part of the Dobrotiv Formation (unit A in this paper) was regarded as a transition from the Sloboda Conglomerate (Koliadnyi, 1951). It is 123-m-thick on the southern limb of the Runhury Sloboda Anticline (Fig. 3), 90-m-thick on its northern limb (Fig. 4) and at least 30-m-thick in the Nadvirna section (Fig. 5). It contains beds of grey or brownish polymictic conglomerates of the same type as in the Sloboda Conglomerate (for details see Oszczypko et al., 2012), but mostly finer and commonly matrix-rich. These beds are up to a few metres thick, and at Nadvirna up to 10-m-thick. There are also brownish or grey, thin- to thick-bedded, medium- or coarse-grained, poorly-sorted, locally muddy sandstones. Some cross-laminated beds display a transition from conglomeratic sandstone or fine conglomerate at the base to coarse-grained sandstone at the top. Inverted graded bedding (Fig. 6), from coarse-grained sandstone to fine-grained conglomerate, is less common. Some of beds show large-scale (over 30 cm) cross-bedding. Thicker sandstone beds are intercalated with packets of grey or reddish, thin- to medium-bedded, fine-grained, massive, parallel- or ripple-laminated sandstones, which are intercalated with grey or reddish calcareous mudstones.

The main part of the Dobrotiv Formation (unit B in this paper or the lower part of the formation in Koliadnyi, 1951) is 540-m-thick on the southern limb of the Runhury Sloboda Anticline (Fig. 3), and 645 m or 690-m-thick on the northern limb (Fig. 4). It displays monotonous light grey, calcareous deposits. A few sandstone beds and rare marlstone beds are yellowish on weathered surfaces. Three basic lithofacies of these deposits include (Fig. 7):

1 – very thin- and thin-bedded mudstone-siltstone intercalations, in which beds are 1–2 cm or 2–5-cm-thick;
2 – mudstone-siltstone intercalations interbedded with very fine- and fine-grained, thin-bedded sandstones;
3 – very fine- and fine-grained, medium- to thick-bedded sandstones interbedded with mudstones and siltstones.

These lithofacies change through the sections, with gradual transitions in most cases. Moreover, the higher part of the formation – southern limb of the Runhury Sloboda Anticline (Fig. 3) contains thin and medium beds of marlstone (see also Vialov, 1966: fig. 9), which are composed of marly silt or very fine-grained calcareous sandstone at the base and muddy passing up into grey marlstone at the top. The beds are yellow on weathered surfaces.

Cross-sections and surfaces of beds display (Fig. 8) depositional, erosive, deformational and biogenic sedimentary structures (for their origin and classification see Allen, 1982; Dżułyński, 1996, 2001). Many of these were recognized by Denisova (1959) and Vialov (1965, 1966) but described using other nomenclature. The sedimentary structures are represented mostly by parallel or gently wavy lamination, which is visible in sandstones and finer deposits. However, some beds are macroscopically massive. Larger scale cross-bedding is rare, ripple lamination is more frequent.

Some upper bedding surfaces display different ripple-marks (preserved also as casts; see Zuber, 1888, 1915; Teisseyre, 1927; Denisova, 1959; Dimitriéva et al., 1962), which can be symmetrical or asymmetrical, with straight, winding or bifurcating crests. Linguloid ripples are very rare. Vialov (1965, 1966) called the Dobrotiv Formation a "museum of ripple-marks". The symmetrical ripples are interpreted as wave ripples. Moreover, interference ripples have been found, including combinations of current and wave ripples.

Some sandstone display sharp lower bedding surfaces, while others show diffuse transitions. Most sandstone beds gradually pass up into finer sediments. Almost all beds are tabular at outcrop scale (over a distance of up to 20 m). Erosional structures are generally rare. Small scour casts occur very rarely in the fine-grained, heterolithic deposits as do shallow channel-fills at bed scale. The infilling sandstones pinch out and can contain rip-up mud clasts.

Fine erosional structures are represented by groove marks (Fig. 8). Some of these display secondary grooves along the main one. Rarely, flute casts have been observed. These occur on lower bedding planes of sandstones and indicate transport to the east.

Deformational structures (Fig. 9) are represented primarily by ball-and-pillow structures (called "rounded concretions" by Zuber, 1888, or curved and twisted bedding by Vialov, 1966), which are present in some thicker beds. Some sandstone pillows are dismembered and "float" in finer matrix. Smaller load structures can be seen on some lower bedding surfaces, occasionally in association with groove marks and other erosional structures. Moreover, a few beds of debrite (1–2-m-thick) occur in the middle part of the units. They are composed mostly of muddy matrix with floating blocks of sandstone. Ball-and-pillow structures are referred mostly to loading processes (Allen, 1982), which can be triggered by seismic shock (e.g., Rodríguez-Pascua et al., 2000).

A few sandstone beds contain muddy intraclasts and larger, carbonized plant fragments.

Finer deformational structures include raindrop imprints and their casts (see also Teisseyre, 1927; Koliadnyi, 1951; Denisova, 1959), which occur at several horizons, commonly in association with invertebrate and vertebrate trace fossils.

The higher part of the Dobrotiv Formation passes into the Stebnyk Formation, that is characterized by reddish mudstones and fine-, medium-, and coarse-grained sandstones, that are less well sorted than in those in the Dobrotiv Formation (Fig. 3). The boundary between the formations is normal and may be placed at the base of the first reddish mudstone layer or the first coarse-grained sandstone bed. The latter is preferred, because the occurrence of the coarse-grained, poorly sorted sandstones indicates an important facies change, associated with sedimentation in fluvial channels. Such sandstones begin in the grey and dark grey mudstones of Dobrotiv Formation type. The reddish mudstones can occur a few tens of metres above. Moreover, the top of the Dobrotiv Formation (ca. 100-m-thick) that is shale-dominated, contains mudcracks, and a few beds of cross-bedded, medium-grained sandstone have been distinguished by Koliadnyi (1951) as within the upper part of this formation.

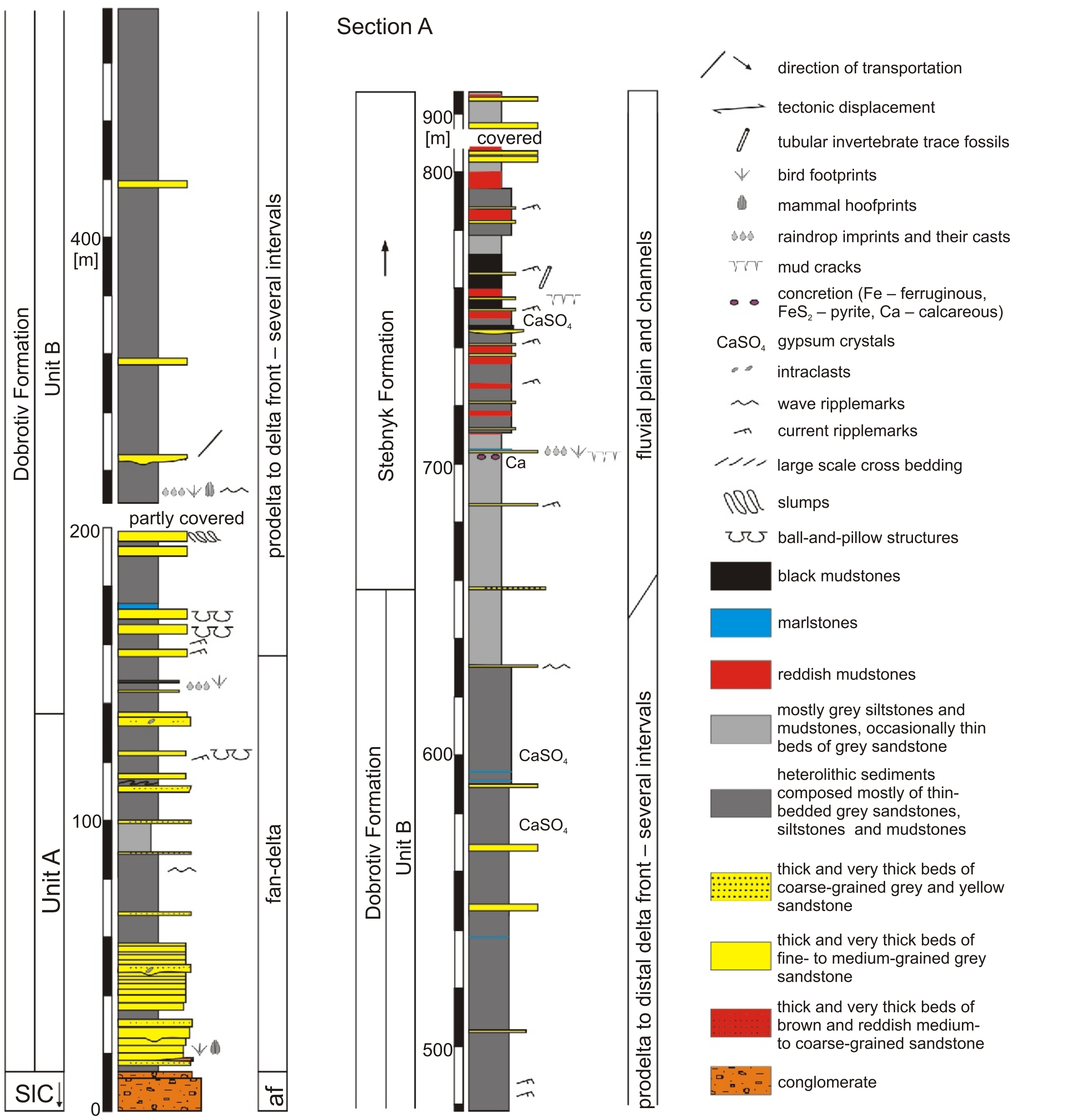

Fig. 3. Sedimentary log of the Dobrotiv Formation along the Prut River, southern limb of the Runhury Sloboda Anticline (section A)

TRACE FOSSILS

Vertebrate trace fossils (Fig. 10) from the Dobrotiv Formation have were noted and illustrated by Koliadnyi (1951) and described in detail by Vialov and Flerov (1952, 1953, 1954), Hizhniakov (1954), Denisova (1959, 1970) and Vialov (1960, 1966) and illustrated by Dimitriéva et al. (1962). They include footprints and trackways of artiodactyl mammals (one ichnospecies of *Gazellipeda* Vialov, one ichnospecies of *Cervipeda* Vialov and two ichnospecies of *Pecoripeda* Vialov), angulate mammals (one ichnospecies of *Hippipeda* Vialov), carnivorous mammals (two ichnospecies of *Bestiopeda* Vialov), and several footprints and trackways of birds (three ichnospecies of *Avipeda* Vialov).

During the fieldwork, several mammal footprints (*Gazellipeda*) and bird footprints (*Avipeda*) have been found. They are preserved on the upper sandstone surfaces of or as casts on their lower surfaces, commonly in association with raindrop imprints or their casts. Moreover, a low-diversity assemblage of simple, horizontal invertebrates burrows has been found. These were noted by Teisseyre (1927). All these trace fossils are the subject of a separate paper in preparation.

BEDDING TRENDS

Long intervals of the sections studied are monotonous, without distinct thickening or thinning trends in the arrangement of beds. In some intervals, only a few metres-thick, thicken-

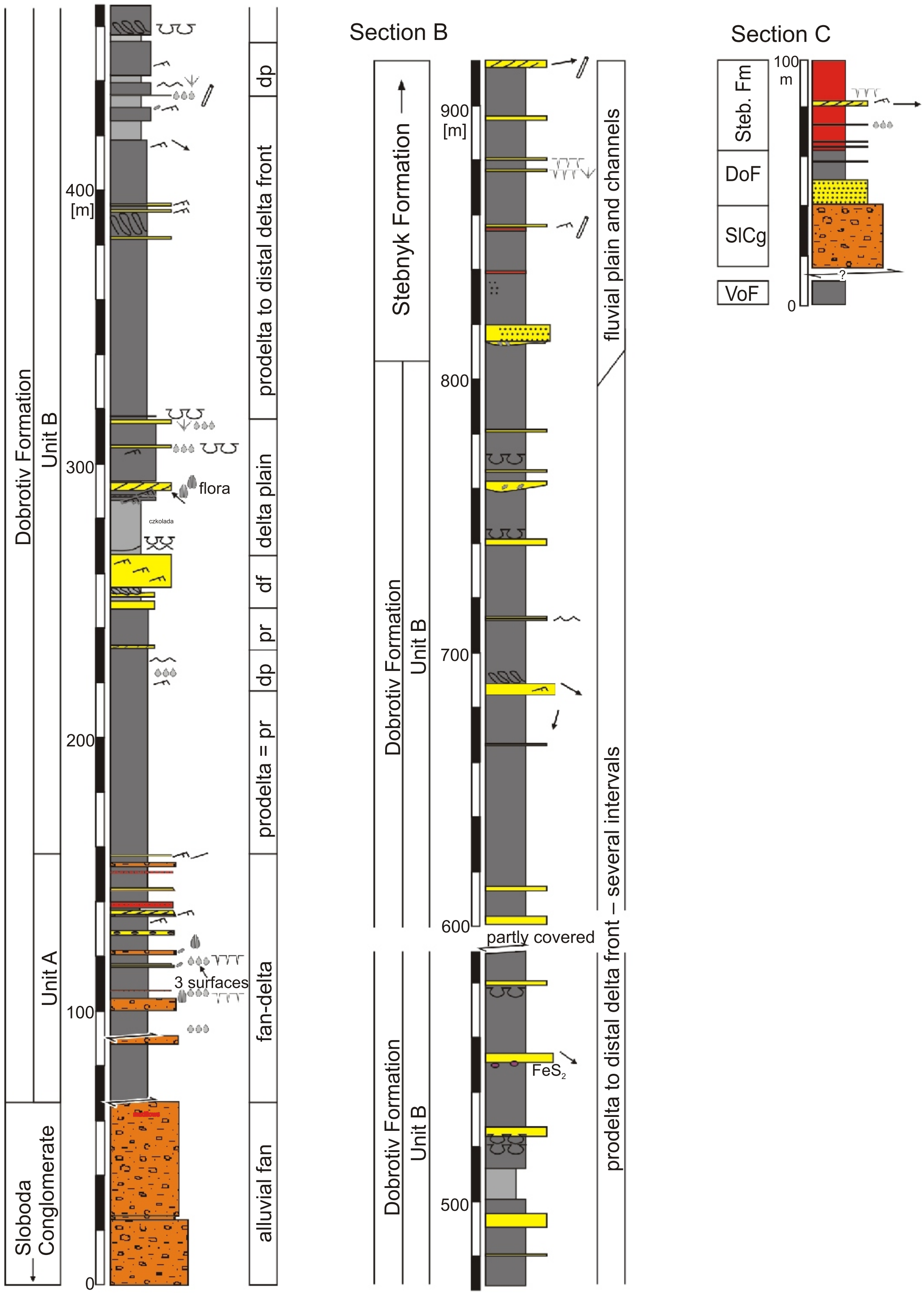

Fig. 4. Sedimentary logs of the Dobrotiv Formation along the Prut River, northern limb of the Runhury Sloboda Anticline (section B) and southern limb of the Lanchyn Anticline (section C)

VoF – Vorotyshcha Formation, SlCg – Sloboda Conglomerate, DoF – Dobrotiv Formation, Steb. Fm. – Stebnyk Formation; df – delta front, dp – delta plain; for other explanations see Figure 3

ing-up or thinning up trends can be observed, as well as symmetrical trends or isolated, thicker beds without any trend context. Alternations of sets of thicker and thinner beds can be also observed, without any order.

However, there are a few exceptions. At the base of the formation (unit A), a thickening-up packet can be seen near the Oslava River inflow to the Prut River (Fig. 11). It is ca. 10-m -thick. Thick beds at the top display erosional bases with shallow incision into the underlying deposits, pinching out, cross--bedding and load structures. The tops of some beds are convex-up, while their bases are flat. This interval is capped by thin- and medium-bedded rhythmic intercalations of sandstones and siltstones and mudstones.

Another thickening interval can be seen at 237–264 m of section A (N limb of the Runhury Sloboda Anticline; Fig. 4), where beds at the top display common ball-and-pillow structures. At some places, packets of sandstone about 10-m-thick rest on thin- or medium bedded strata without any gradual transitions.

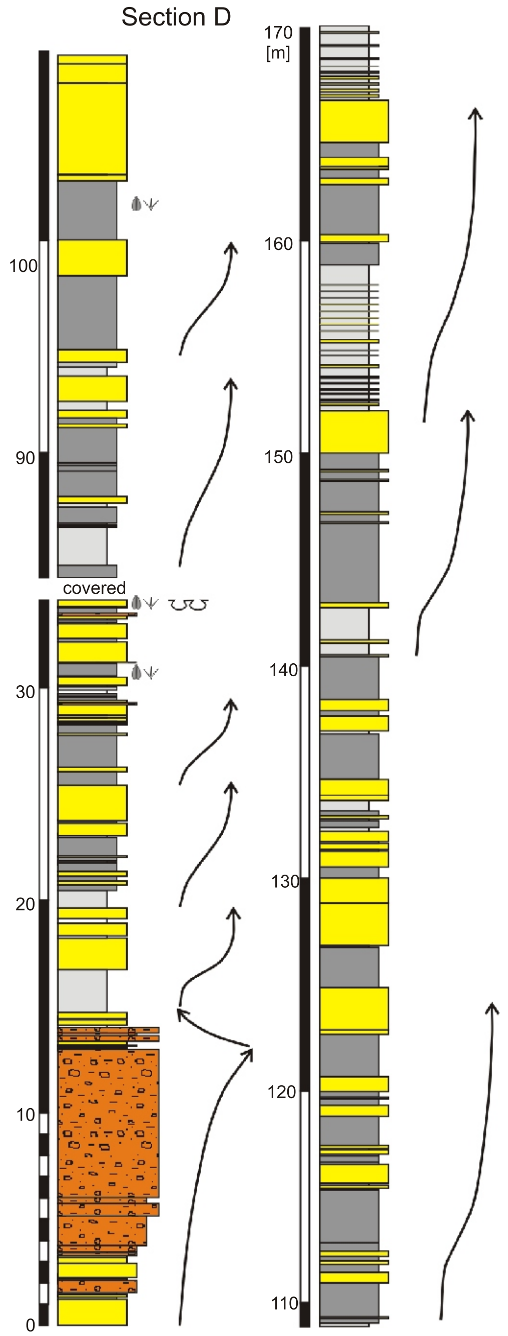

Fig. 5. Sedimentary logs of the Sloboda Conglomerate – Dobrotiv Formation transition, along the Bystrytsia Nadvinanska River at Nadvirna (section D)

For explanations see Figure 3

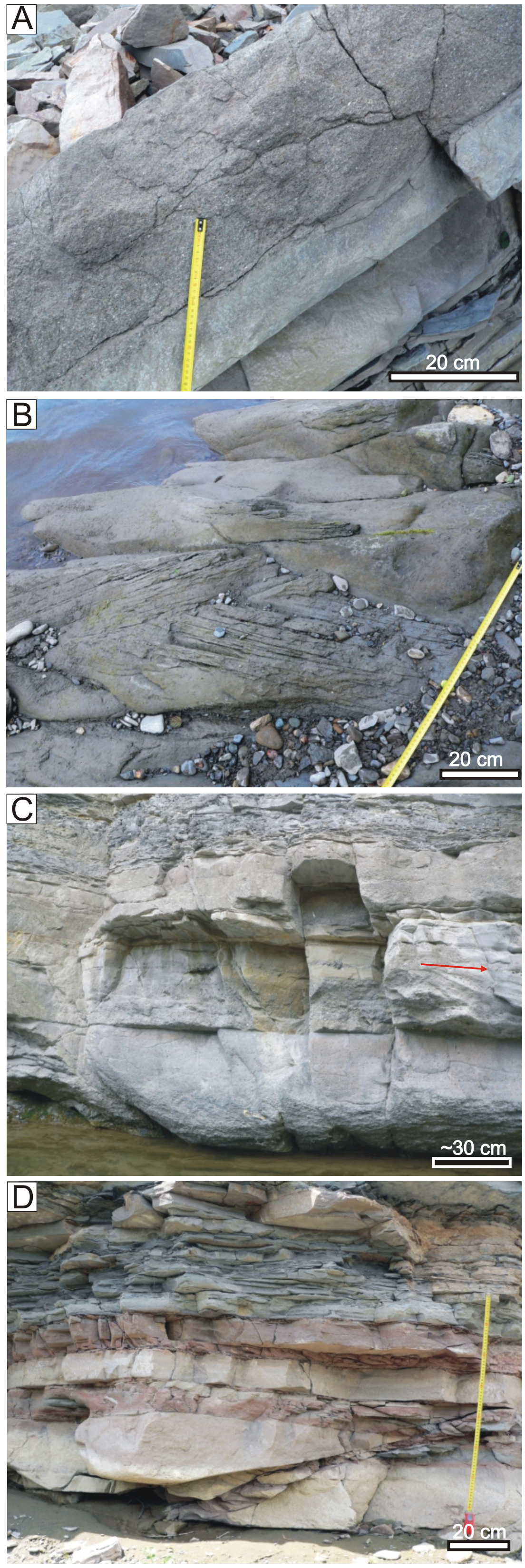

Fig. 6. Examples of fan-delta facies

A – bed showing inverted graded bedding from coarse-grained sandstone to fine-grained conglomerate; **B** – large-scale cross-bedding in a bed of coarse-grained muddy sandstone; **C** – in the lower part, two fine-grained conglomerate to coarse-grained sandstone beds showing cross-bedding, which indicate transport from the south; **D** – intercalation of sandstone and reddish-grey mudstones

DISCUSSION

SEDIMENTARY ENVIRONMENT

The sedimentary environment of the Dobrotiv Formation was determined as deltaic by Denisova (1959), but without analysis or discussion.

In the lower part of the formation (unit A), above the Sloboda Conglomerate, coarse-grained to fine-grained conglomeratic sediments were deposited. The upper part of the conglomerate was deposited on an alluvial fan and the topmost part on a

Fig. 7. Examples of deltaic facies

A – heterolithic deposits – rhythmic intercalations of mudstone, siltstone and very fine-grained sandstone; **B** – small channel-fill in heterolithic deposits; **C** – intercalations of mudstone, siltstone and very fine-grained sandstone, thicker than in A or B; **D** – beds composed of very fine-grained sandstone at the base with a transition to marlstone at the top; **E** – packet of thick-bedded fine-grained sandstone intercalated with thinner-bedded clastic deposits; **F** – packet of thick-bedded fine-grained sandstones intercalated with thinner-bedded clastic deposits; note pinching out of two thinner beds intercalated between two thick beds; the higher thick bed truncates the two thinner beds; **G** – channel bed wedge, which contains rip-up mudstone clasts

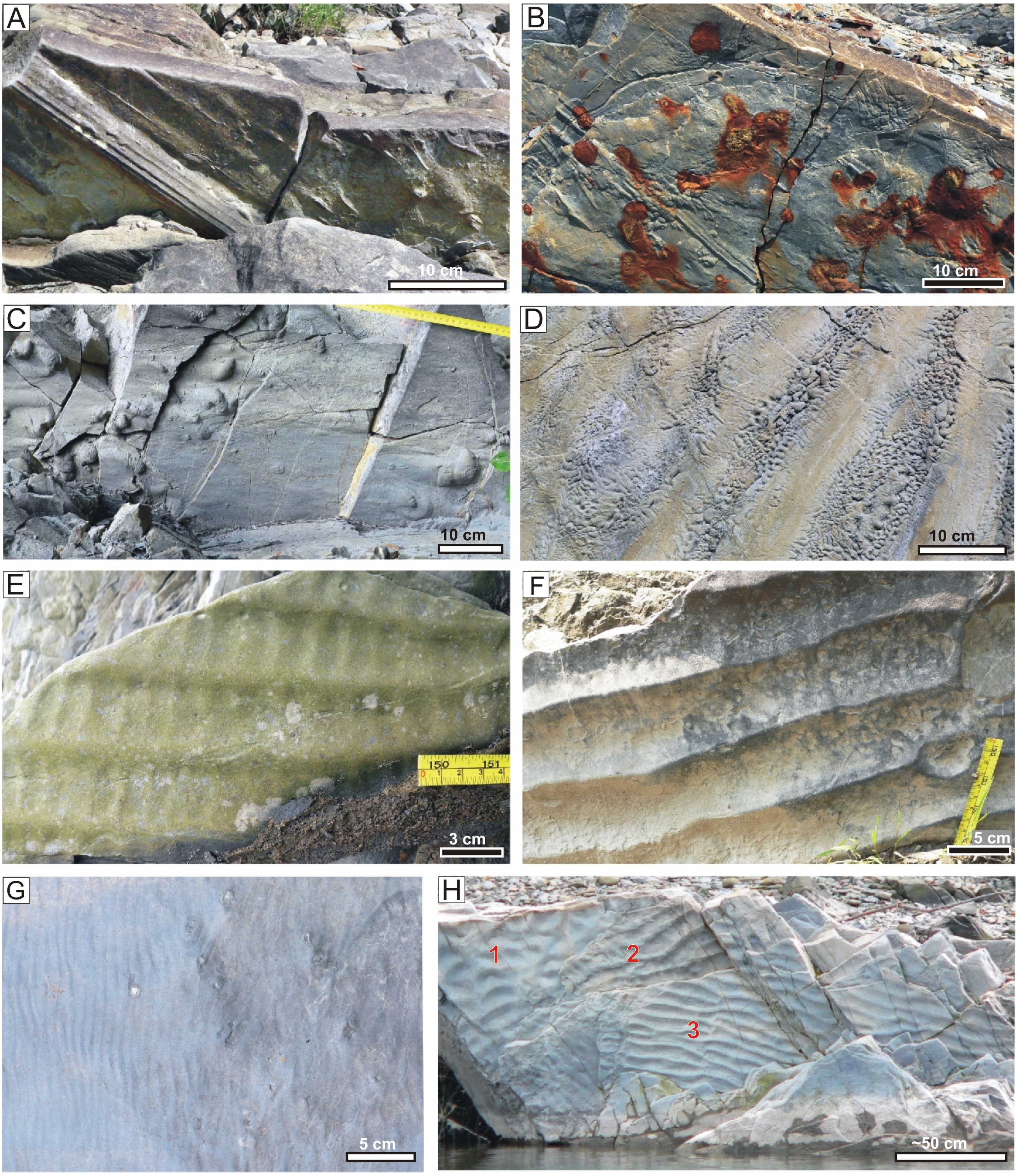

Fig. 8. Some bedding-surface structures

A – groove marks; **B** – groove marks, load structures and ferruginization after pyrite concretions; **C** – flute casts; **D** – load structures; **E** – interference of current (smaller) and wave (larger) ripples; **F** – large wave ripples; **G** – very small current ripples punctuated by vertical burrows; **H** – three surfaces (1–3) of different current ripples showing different directions of flow

fan-delta (Oszczypko et al., 2012). The lowest part of the formation, where coarse sediments can be found, was likely deposited in a moribund fan-delta, with a well-developed delta plain, in which tetrapod footprints and raindrop imprints are preserved. Fine conglomerates and coarse sandstones were deposited in fluvial channels (as debris flows?). Increasing numbers of fine-grained rippled sandstones and finer clastics point to deposition under water (subaqueous part of the fan-delta).

The interpretation of the main part of the Dobrotiv Formation (unit B) as deltaic sediments can be maintained. However, several details need to be clarified. The sedimentary structures point to flowing water as the main mechanism of sediment transport and deposition, mainly in the lower flow regime, in which sediment was transported by traction. These were occasional gravity flows, which resulted in the deposition of debrites. Sporadic occurrences of symmetrical ripplemarks suggest

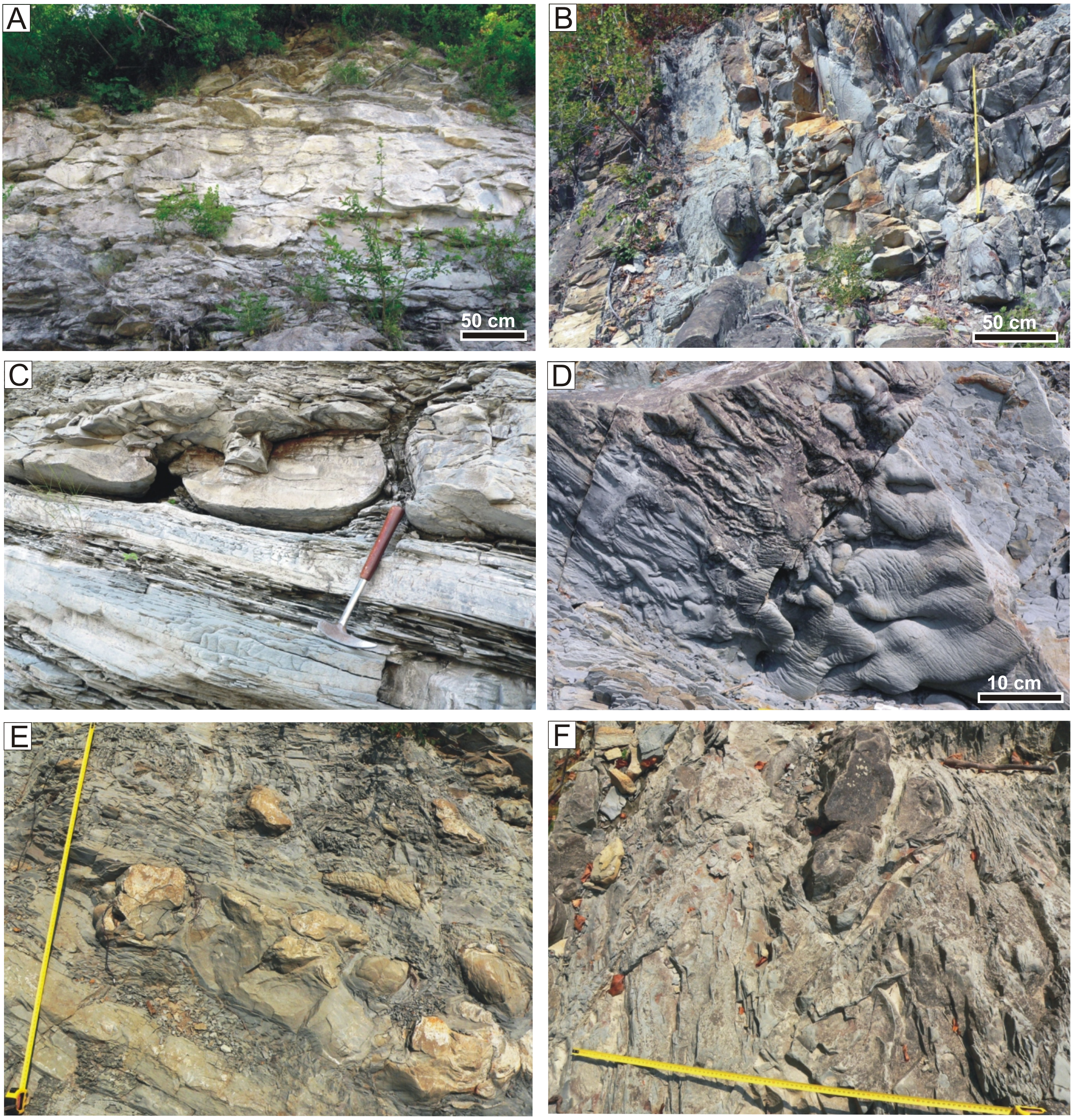

Fig. 9. Deformational structures

A – ball-and-pillow structures in a packet of thick-bedded sandstones; **B** – a few levels of ball-and-pillow structures in thick-bedded sandstones; **C** – ball-and-pillow structures; **D** – initial pillowing on a bedding surface; uprooted pillows in mudstone; **E** – chaotic mudstone with deformed fragments of sandstone beds – a slump

wave action in shallow water. Thickening-up trends in bed sets from mudstone-dominated to sandstone-dominated packets, mostly 10–20-m-thick, though very rare, are typical of deltaic sediments. They reflect a progradation of delta from prodelta to delta-front sands. The ball-and-pillow structures also are the characteristic feature of deltaic deposition (e.g., Hubert et al., 1972; Flores and Erbenbeck, 1981; Rajchl, 1999). Generally, the delta-front sands are poorly represented in the Dobrotiv Formation. Such a situation might be caused by erosional truncation at the tops of thickening-up parasequences (Einsele, 2000), but this is not the case in the Dobrotiv Formation, because the thicker sandstone beds and their adjacent deposits, interpreted as delta-front sands, are capped by heterolithic deposits containing mammal footprints and raindrop imprints indicating drying terrestrial conditions, which can be referred to a delta plain. Some thicker sandstone beds on the delta plain are probably fluvial channel fills and thinner sandstone beds were likely deposited in crevasse splays.

Soils did not develop on the exposed areas, probably due frequent episodes of sedimentation. We saw no signs of desiccation, such as mudcracks, though Vialov (1965: pl. 11) noted some in an unspecified part of the formation. This indicates a

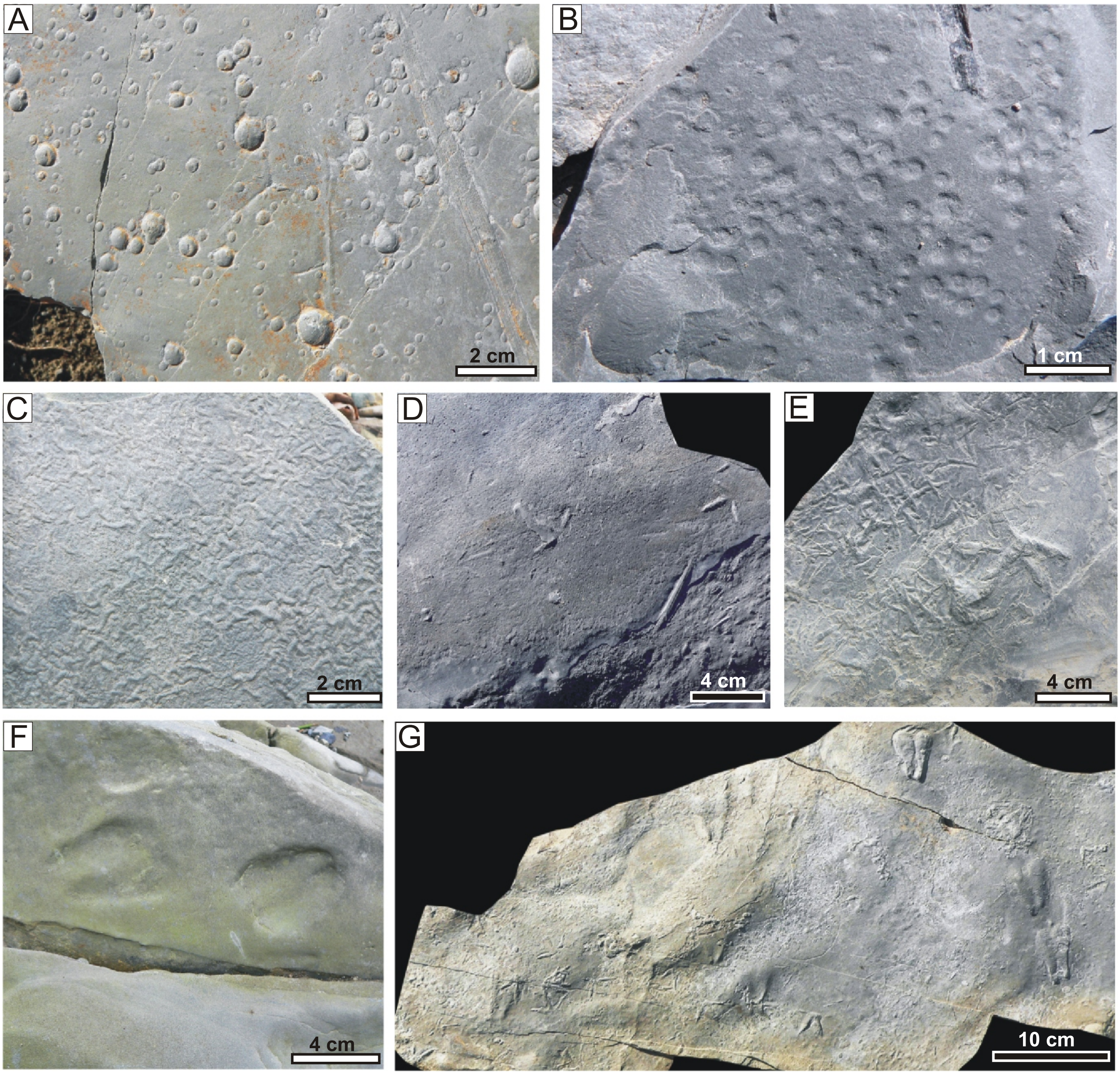

Fig. 10. Raindrop structures and trace fossils

A – raindrop casts; **B** – raindrop imprints; **C** – winding invertebrate burrows; **D, E** – bird footprints; **F** – *Gazellipeda* – mammal footprint; **G** – mammal trackway *Gazellipeda*, bird footprints, raindrop casts

humid climate as shown by common raindrop imprints. The presence of structures related to ice crystals (Vialov, 1965; Denisova, 1970), suggests a moderate climate.

The coastal part of the delta was probably a migration path for herbivorous mammals. Abundant plant detritus indicates vegetated areas behind the site of deposition.

Interestingly, there is almost no exiting bioturbational disturbance of the fine-grained sediments interpreted as prodelta. Significant bioturbation of prodelta sediments, with the occurrence of typically marine trace fossils such as *Chondrites* or *Phycosiphon* is common (Hovikoski et al., 2008). The most convincing explanation is brackish conditions in the basin, and maybe oxygen deficiency. It is significant that marine microfossils are almost absent from the Dobrotiv Formation. Only Koliadnyi (1951) noted poorly preserved and low-diversity foraminifers but it is not clear if they are autochthonous or exhumed from older sediments. All the samples we collected appeared barren of foraminifers and nannoplankton.

The poor development of the delta-front sands, with their mostly very fine- and fine-grained nature, finer than in many mouth bars of different types (commonly medium- and coarse-grained sand; cf. Fielding et al., 2005), including many lacustrine deltas (e.g., Thomas et al., 2006), suggests a mud-dominated delta on a mud-dominated coast. Such depositional settings are still poorly understood, but known from recent and fossil examples (Augustinus, 1980; Hovikoski et al., 2008). Delta-

Fig. 11. Trends in bedding

A – generally thickening-up succession of beds interpreted as a mouth bar; outlet of Oslava; square indicates detail in B; **B** – detail of A – concave-up lithosome of thick-bedded sandstone; **C** – lateral equivalent of A on the left side of the Prut River, opposite to the Oslava River outlet; top of the Sloboda Conglomerate by hammer; **D** – a succession of thin and medium beds of sandstones intercalated with mudstones and siltstones; here, mammal footprints, bird footprints and raindrop imprints occur; this succession is interpreted as of delta plain facies; thick sandstone at the top may be a river channel-fill; **E** – a succession of beds without any distinct thickening or thinning trends

-front facies in such deltas can be composed mostly of mud (Tanabe et al., 2003). Delicate sedimentary structures, such as parallel and cross-lamination in mudstones and siltstones in the Dobrotiv Formation, resemble those from mud banks of the Surinam coast (NE South America), where mud-dominated shelf sediments prevail, though these are partly bioturbated (Rine and Ginsburg, 1985). Deltaic sediments that accumulated in shallow lakes, with very limited accommodation space, do not form typical thickening-up trends (Tye and Coleman, 1989).

BASIN DEVELOPMENT CONTEXT

The intra-Burdigalian folding and uplift of the Outer Carpathians were related to the north-eastwards translation of the Alcapa and Tisza-Dacia microplates in response to the roll-back of the Carpathian subduction slab (Zoetemeijer et al., 1999; Ziegler et al., 2002; Rasser et al., 2008). This was accompanied by north- and north-east-directed nappe transport and the development of the peripheral flexural Carpathian Foredeep along the advancing (marginal) part of the accretionary prism as well as on the platform (Oszczypko, 1998, 1999; Oszczypko and Oszczypko-Clowes, 2012; Fig. 12).

In many cases, the estimated weight of the orogen thrust overload and foredeep deposits (i.e. surface and topographic loads) is not sufficient to explain the observed flexural bending of the foreland (lower) lithospheric plate (Royden, 1988). Flexural modelling studies for the Polish and Ukrainian Carpathians (Royden and Burchfiel, 1989; Krzywiec and Jochym, 1997) suggest that deep processes and associated subsurface loads were most important for the observed present-day flexural bending of the foreland lithospheric plate in this orogenic belt (see also Kováč et al., 1989; Oszczypko et al., 2006 and references therein). The subsidence of the initial (Ottnangian–Karpatian) foreland basin was related to the deep subsurface load. At that time the rate of subsidence at the front of the Ukrainian Outer Carpathians reached at least 2000 m/Ma (Oszczypko, 1998). Such rapid subsidence was compensated by a high rate of accumulation as reflected by terrestrial and shallow-water sedimentation of the Sloboda Conglomerate and the Dobrotiv and Stebnyk formations.

Deposition of the underlying Sloboda Conglomerate as an alluvial fan and fan-delta is related to high-relief forebulge elevation that originated at an early stage of Carpathian Foredeep development (Oszczypko et al., 2012). The transition from alluvial fans via a short fan-delta phase to fine-grained sedimentation reflects a significant change in sediment supply from coarse clastic to very fine clastic deposits. This suggests that the relief in the source area became much lower (Vialov, 1965: p. 80); however, the source area was still efficient and supplied the basin with fine and very fine sand, silt and clay, which may have derived from eroded Carpathian flysch, though this is an open question.

The basin was shallow, with commonly exposed muddy surfaces as indicated by the tetrapod footprints and rain-drop imprints. The small water depth and large accommodation space may explain the poor development of thickening-up deltaic cycles, which generally result from progradation. The large accommodation space was caused by tectonic subsidence which balanced sediment accumulation. The subsidence was probably caused both by subsurface as well as by thrust uploading of advancing Carpathian nappes during the initial stage of development of the Carpathian Foredeep (Oszczypko et al., 2006); however, the subsidence may have been enhanced by local loading of the Sloboda Conglomerate, which is up to 1400-m-thick, underlies the Dobrotiv Formation and is limited to the same area (Oszczypko et al., 2012). As a result of such stacking thick sequences (800 m) could accumulate in a small area.

The delta of the Dobrotiv Formation passed into fluvial environments, which are represented by the Stebnyk Formation. The latter displays well-developed fluvial channel facies of coarse-grained, poorly sorted sandstones occurring within fine-grained overchannel sediments, which cover much larger areas than does the Dobrotiv Formation. Their red colour and the common presence of mudcracks indicate a change to a drier climatic. The first marine ingressions are marked at the top of the Stebnyk Formation by the occurrence of marine microfossils.

A similar though older succession of sediments is known from the Molasse Foreland Basin of the Northern Alps (Rasser et al., 2008). The Polyanytsia and Vorotyshcha formations (Late Aquitanian–Burdigalian) correspond to the Lower Marine Molasse (Rupelian), while the Sloboda Conglomerate and Dobrotiv and Stebnyk formations (Late Burdigalian–Early Langhian) may be referred to the Lower Freshwater Molasse (Chattian–Aquitanian) in the Molasse Foreland Basin. In particular, the Sloboda Conglomerate and Dobrotiv Formation form a clastic wedge which shows a fining and thinning upwards megasequence (Vialov, 1965), similar to that of the Lower Freshwater Molasse. The stratigraphic shift of this type of sedimentary development is consistent with west-east migration of folding and thrusting of the Alpine-Carpathian orogens (Kováč et al., 1989).

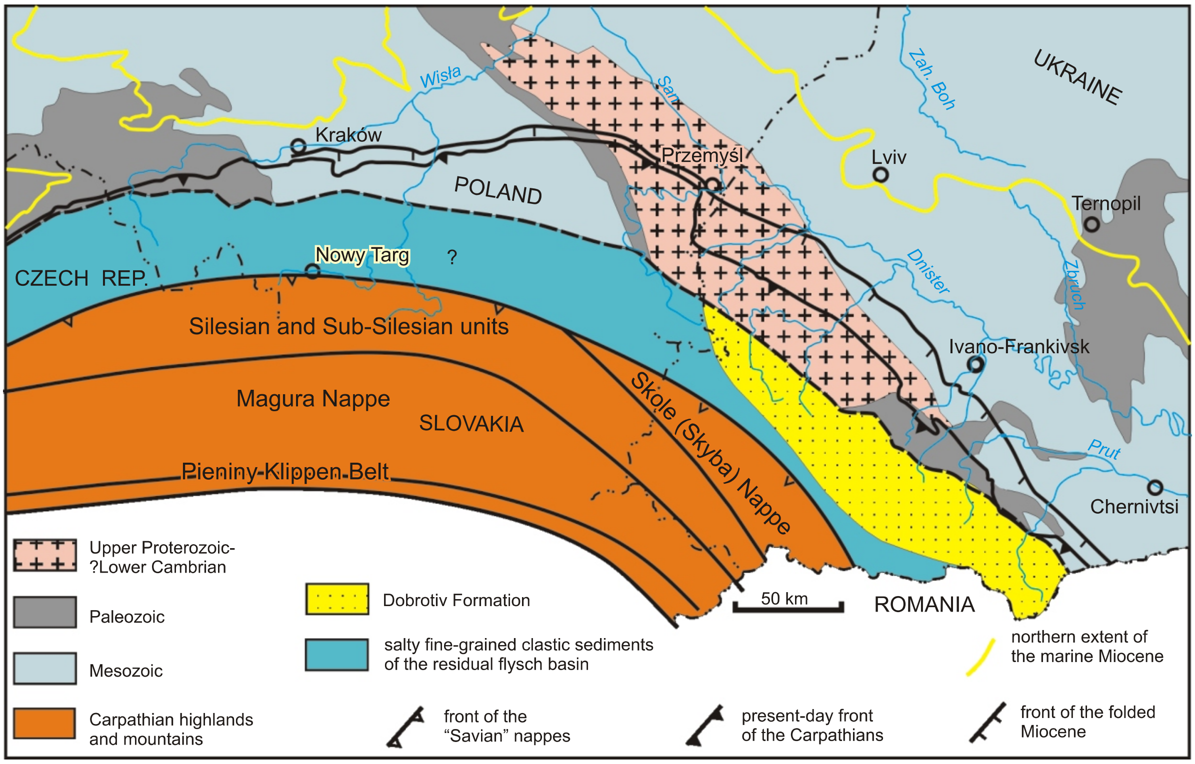

Fig. 12. Late Ottnangian-?Karpatian palinspastic palaeogeography of the foreland of the Polish and Ukrainian Carpathian Foredeep (based on Oszczypko and Oszczypko-Clowes, 2003; Oszczypko et al., 2006, 2012, supplemented)

CONCLUSIONS

The Dobrotiv Formation (upper Lower Miocene Miocene; 700–800-m-thick) is interpreted as a deltaic succession showing a transition from a fan-delta (top of the Sloboda Conglomerate) to a fluvial coastal plain (Stebnyk Formation). It was deposited on subsiding, marginal part of the Outer Eastern Carpathians. The delta was mud-dominated, with poorly developed thickening-up trends, and deposited in shallow water under a humid climate. Episodes of sediment emergence are indicated by tetrapod footprints and raindrop imprints. The underlying Sloboda Conglomerate, and the Dobrotiv and Stebnyk formations, form a clastic wedge of thinning- and fining-upwards successions.

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