UPPER PLEISTOCENE AND HOLOCENE DEPOSITS AT STARUNIA PALAEONTOLOGICAL SITE AND VICINITY (CARPATHIAN REGION, UKRAINE)

Tadeusz SOKOŁOWSKI[1], Renata STACHOWICZ-RYBKA[2] & Barbara WORONKO[3]

[1] *Faculty of Geology, Geophysics and Environmental Protection, AGH University of Science and Technology, Al. Mickiewicza 30, 30-059 Kraków, Poland, e-mail: tsokol@uci.agh.edu.pl*
[2] *Władysław Szafer Institute of Botany, Polish Academy of Sciences, ul. Lubicz 46, 31-512 Kraków, Poland, e-mail: r.stachowicz@botany.pl*
[3] *Faculty of Geography and Regional Studies, University of Warsaw, Krakowskie Przedmieście 30, 00-950 Warszawa, Poland, e-mail: bworonko@uw.edu.pl*

Abstract: An abandoned ozokerite mine (= Ropyshche), where large mammal remains were discovered in the first half of the 20th century, is located in the Velyky Lukavets River valley covered with Quaternary sediments. The catchment area includes a flysch sequence unconformably overlain by salt-bearing Lower Miocene molasses of the Vorotyshcha beds. Both the Upper Pleistocene and Holocene are represented by: channel (gravel, sandy gravel) and overbank alluvium (mud, peat, biogenic mud) and colluvium (mud, sandy mud) as well as by mine wastes. The channel sediments are usually found in the lowest fragments of the borehole logs and represent mainly material deposited in the straight segments of meandering river-beds. The most common, fine-grained (Mz = 61.33 to 7.11 μm), distal floodplain sediments are locally up to 10 m thick and are dominated by massive mud lithofacies, which contain frequent burrows, root hairs or slightly larger root traces and reed rods. These sediments are characterized by rather stable grain size distribution, quite monotonous mineral composition, presence of resistant heavy minerals and quartz grains with traces of chemical weathering. Angular grains with conchoidal fractures and sharp edges also occur. Therefore, textural features show that the main sources of material were, most probably, weathering crusts of various ages developed on relatively poorly lithologically diversified Carpathian flysch strata and on Miocene deposits of the Carpathian Foredeep. With time, an increase of the content of material originating from mechanical weathering (frost action) occurred in the floodplain deposits, which can be linked to an increase of climate severity and reduction of vegetation. However, these changes are not recorded in the deposits, which developed mostly in closed hollows and accumulated mainly from suspension or from low-energy flows. This calm sedimentation was periodically interrupted by supply of more coarse-grained material (sand, gravel). A distinct predominance of overbank deposits in the sections documented by their thickness suggests that the northward flow of the Velyky Lukavets River was blocked as a result of either neotectonic movements or damming of the valley by landslide tongues. From the lithological point of view, the most favourable conditions for preservation of large, extinct mammals still exist in the two selected areas, where the total thickness of Pleistocene muds exceeds 2 metres. The first area is located in the vicinity of boreholes Nos 2, 3, 21, 22, 23, 28, 30 33 and 36N, and the other, smaller one, is placed around borehole No. 42.

Key words: Quaternary fluvial sediments, Velyky Lukavets River valley, Starunia, Carpathian region, Ukraine.

INTRODUCTION

The lithological studies of Pleistocene and Holocene sediments were part of an interdisciplinary research project focused on the Starunia area. In the years 2006–2009, such comprehensive investigations were carried out in an abandoned ozokerite (earth wax) mine in Starunia (Kotarba, 2009), about 130 kilometres southeast of Lviv, Ukraine (Fig. 1), where remains of mammoth and three woolly rhinoceroses, and one nearly completely preserved rhinoceros carcass were found in 1907 and 1929. The discovery of large Pleistocene mammals at the Starunia ozokerite mine was a spectacular scientific event on a world scale. An unique combination of oil and brine accumulated within the
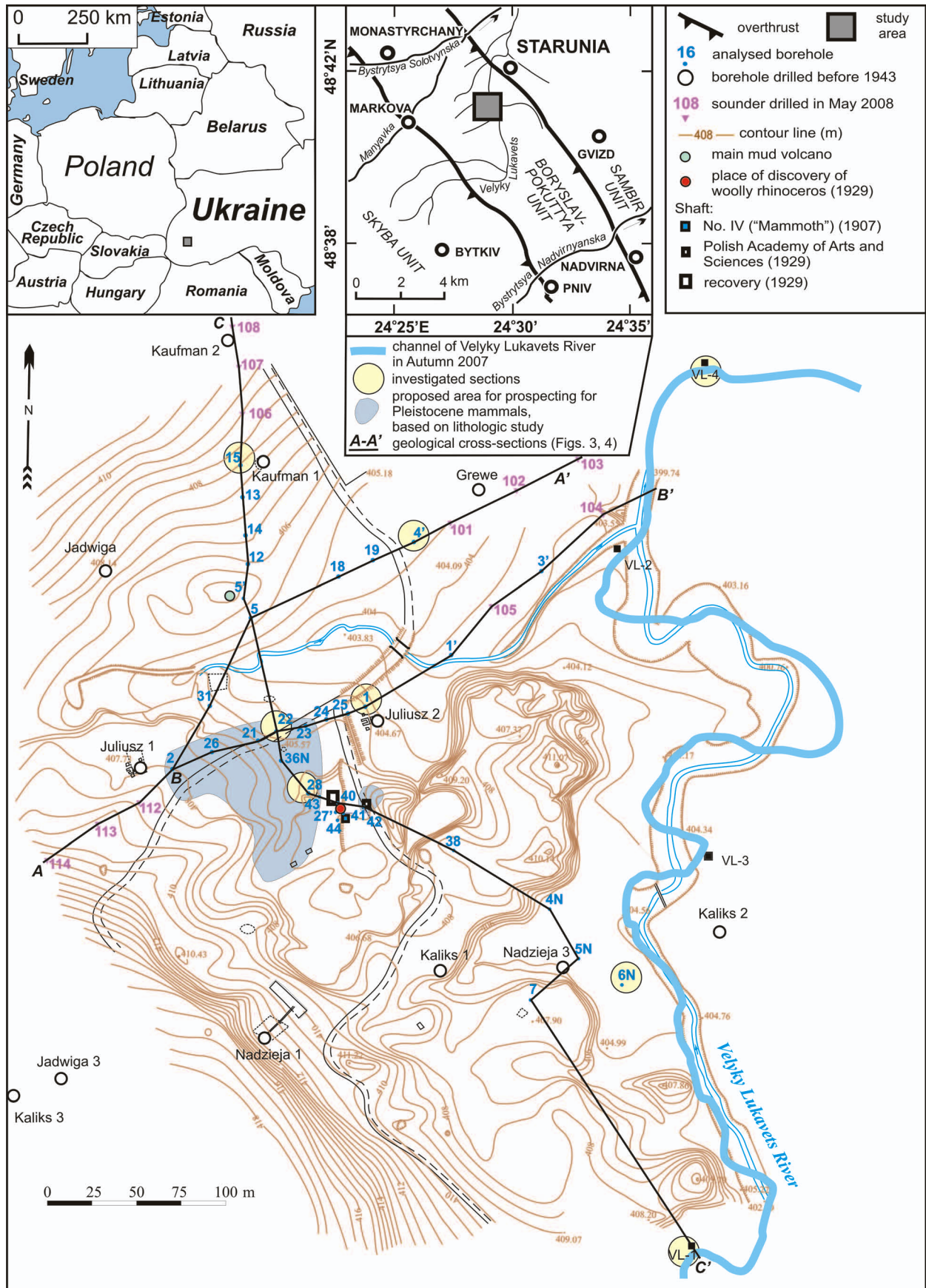
Fig. 1.   Sketch map of the vicinity of Starunia (Carpathian region, Ukraine) with the location of study area

Pleistocene clayey muds, into which the animals had sunk, resulted in near perfect preservation of these specimens (Alexandrowicz, 2004; Kotarba, 2005; Kotarba & Stachowicz-Rybka, 2008).

The problem of Quaternary deposition in the vicinity of Starunia has not been adequately studied despite many years of scientific research in the area. Lithology of both the Quaternary and older strata was presented by, *e.g.*, Zuber (1885, 1888), Rogala (1907), Bayger *et al.* (1914), Nowak *et al.* (1930), Tokarski (1930), and later by Alexandrowicz (2004), Alexandrowicz *et al.* (2005), Koltun *et al.* (2005), Korin (2005), and Stelmakh (2005).

The detailed research carried out in Starunia covered a part of an abandoned mine (=Ropyshche) located nearby the presumed site of animal remains excavation, which worked mainly ozokerite and small amounts of petroleum (Kotarba & Stachowicz-Rybka, 2008 – Fig. 1). The area is located mainly in the valley bottom of the Velyky Lukavets River valley and its tributary, the Rinne Stream, entering the slopes of the valley only on its western and north-western peripheries. Large mammals were found in fine-grained deposits of Pleistocene age. That is why more consideration was given to these deposits as well as to biogenic sediments. However, Holocene deposits were also tested (although not in detail) in order to describe the entire background and environmental changes.

The main aim of lithological studies was to identify the best conditions within the Pleistocene muds favouring the preservation and conservation of specimens of other woolly rhinoceroses and/or mammoths, apart from those discovered in 1907 and 1929. Moreover, the results of lithological studies (structural and textural features) enable the authors to reconstruct depositional conditions, post-depositional changes and the rough source of Quaternary sediments.

The watershed of the Velyky Lukavets River is located in the Outer Eastern Carpathians, from which large amounts of fine-grained material were supplied to the riverbeds by erosion of weathering crusts of the flysch strata. The Ropyshche area is located within the Boryslav-Pokuttya Unit belonging to the Carpathian Foredeep Basin. The Boryslav-Pokuttya Unit includes a flysch sequence unconformably covered by the Miocene molasse. The upper part of the molasse sequence is occupied by the salt-bearing Lower Miocene Vorotyshcha beds (Andreeva-Grigorovich *et al.*, 1997; Korin, 2005). Lithology of these beds is dominated by weathering-susceptible sandstone-shale-marl breccia cemented with clays and salt, cut by gypsum veinlets, and impregnated with single Na-K-salts crystals. Locally, intercalations of medium- to coarse-grained sandstones with poor, clay-carbonate cement, marls and ozokerite were observed. Zuber (1885) also found quartzite, limestone and schist fragments in breccias. These strata can be laterally replaced by the Sloboda Conglomerates and the Dobrotiv Sandstones.

In the Ropyshche area, Quaternary sediments presumably form at least two terraces (Sokołowski, 2009), although their boundaries were completely destroyed by mining operations.

SAMPLING PROCEDURES, MATERIALS AND METHODS

In the Ropyshche area, 44 boreholes were drilled, and 17 soundings were driven and described. The drilling works were described by Kuc *et al.* (2009). Graphical sections of most boreholes are presented in Fig. 2A, B, C. They were used both to construct geological cross-sections (Figs 3, 4) and to illustrate various types of research: geological, geochemical, etc. (see Kotarba, 2009). In the nearby scarps of fluvial terraces, several dozen outcrops were recorded and described, as well.

The material taken from 7 boreholes (Nos 1, 4, 4', 6, 15, 22 and 28) and from outcrops (Nos VL-1 and VL-4; Fig. 1) was used to describe the lithology of Pleistocene and Holocene sediments (Figs 3, 4). Due to the interdisciplinary character of conducted research, studies of lithology, absolute dating and palaeobotanical analyses, all aiming at determining the age and stratigraphy of sediments (Kuc *et al.*, 2009; Sokołowski & Stachowicz-Rybka, 2009; Stachowicz-Rybka *et al.*, 2009a, b), were carried out mostly on the same samples. Locations of samples (sections and depths) were selected in a way enabling the description of all lithofacies (except slope sediments), including their spatial variability and age. Due to the specific subject of research, the most detailed studies covered the fine-grained and biogenic sediments of Pleistocene age (for distal floodplain – terrace 1; see also Sokołowski, 2009).

In order to determine the conditions of transport and accumulation of sediments filling the Velyky Lukavets River valley within the Ropyshche area, grain-size analysis was conducted. Dry-sieving analysis was applied for gravels, while for grains of diameters below 1 mm the Laser Particle Sizer Analysette 22 Comfort apparatus was used. The obtained results were the basis for calculations of grain-size indices, according to the Folk and Ward's (1957) formulae.

The mineral composition of fine-grained deposits (6 samples) was investigated with the X-ray diffraction (XRD) using the Philips APD X'Pert PW 3020 X-ray diffractometer. Minerals were identified with the XRAYAN software based on data from the ICDD catalogue (International Centre for Diffraction Data – www.icdd.com). The XRD curves were taken for air-dry oriented and non-oriented powder mounts saturated with ethylene glycol and roasted at a temperature of 560°C. The oriented mounts were used for both qualitative determination and semiquantitative estimation of mineral composition with the internal standard method, and the non-oriented mounts were used for identification of clay minerals.

Moreover, for samples from sections Nos 4, 15, 22, 28 and VL-1, representing sediments accumulated in different periods of the close of the Weichselian and Holocene (Figs 3, 4), in order to determine the mineral composition of sediments and the character of quartz grains surfaces, mapping was carried out on a nonsputtered sample at magnification of 60–100 times, using the EDS microprobe attached to the SEM, as well as the analysis of surface micromorphology of quartz grains fraction below 0.1 mm diameter was made. The EDS microprobe recorded the presence of the following elements: Si, Al, K, Ti, Na, Fe, Mg and Ca. SEM micro-

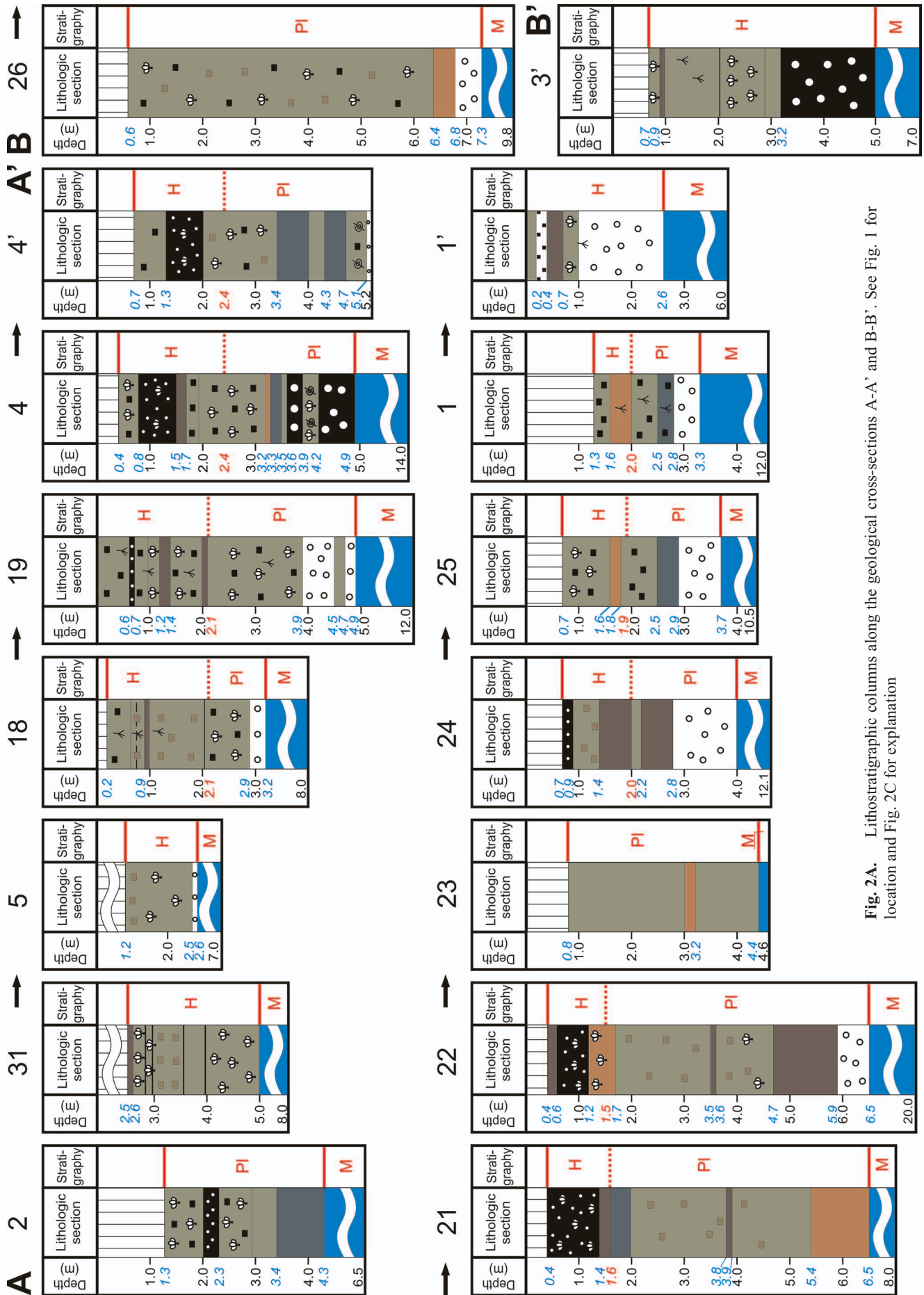**Fig, 2A.** Lithostratigraphic columns along the geological cross-sections A-A' and B-B'. See Fig. 1 for location and Fig. 2C for explanation
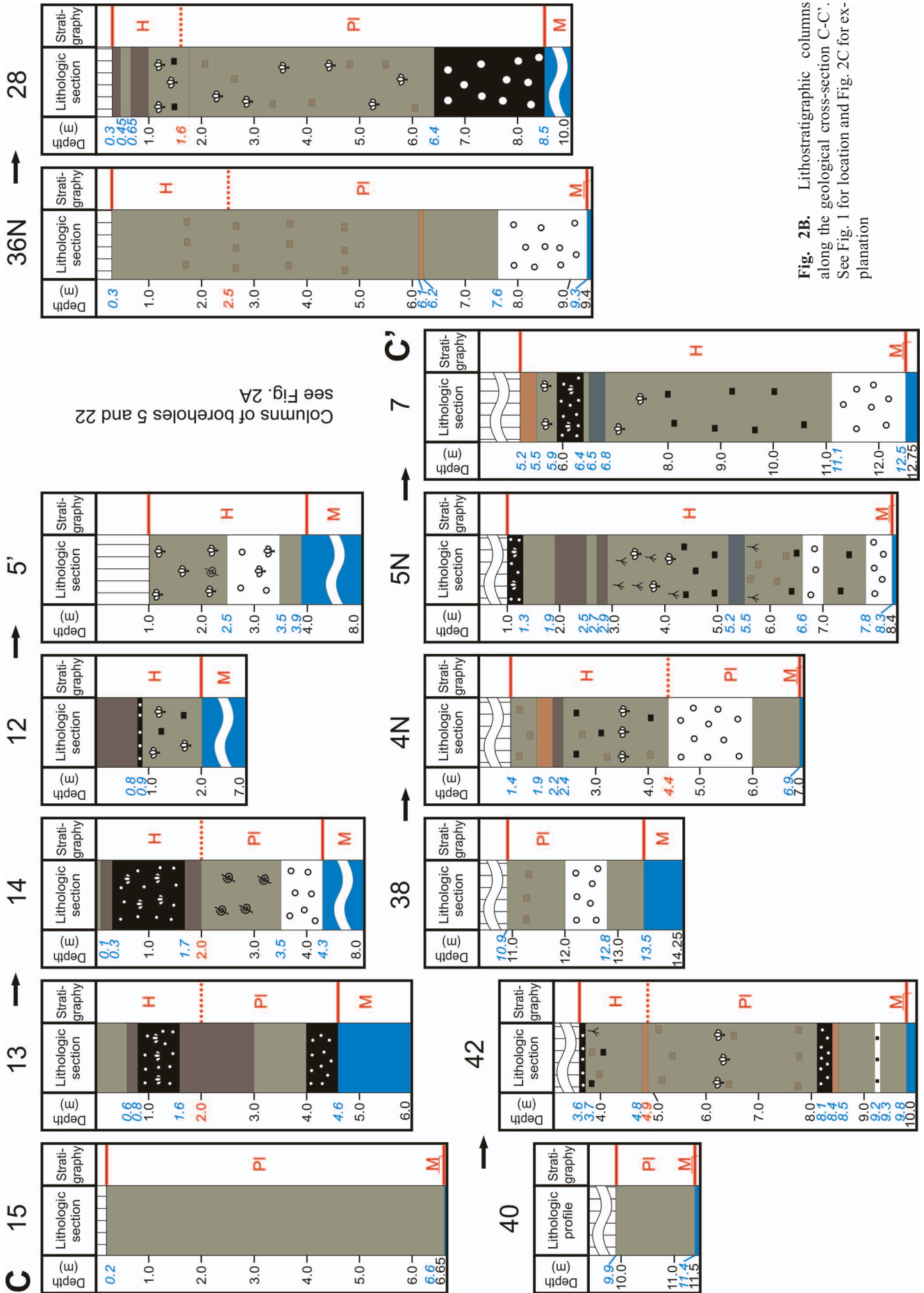
Fig. 2B. Lithostratigraphic columns along the geological cross-section C-C'. See Fig. 1 for location and Fig. 2C for explanation
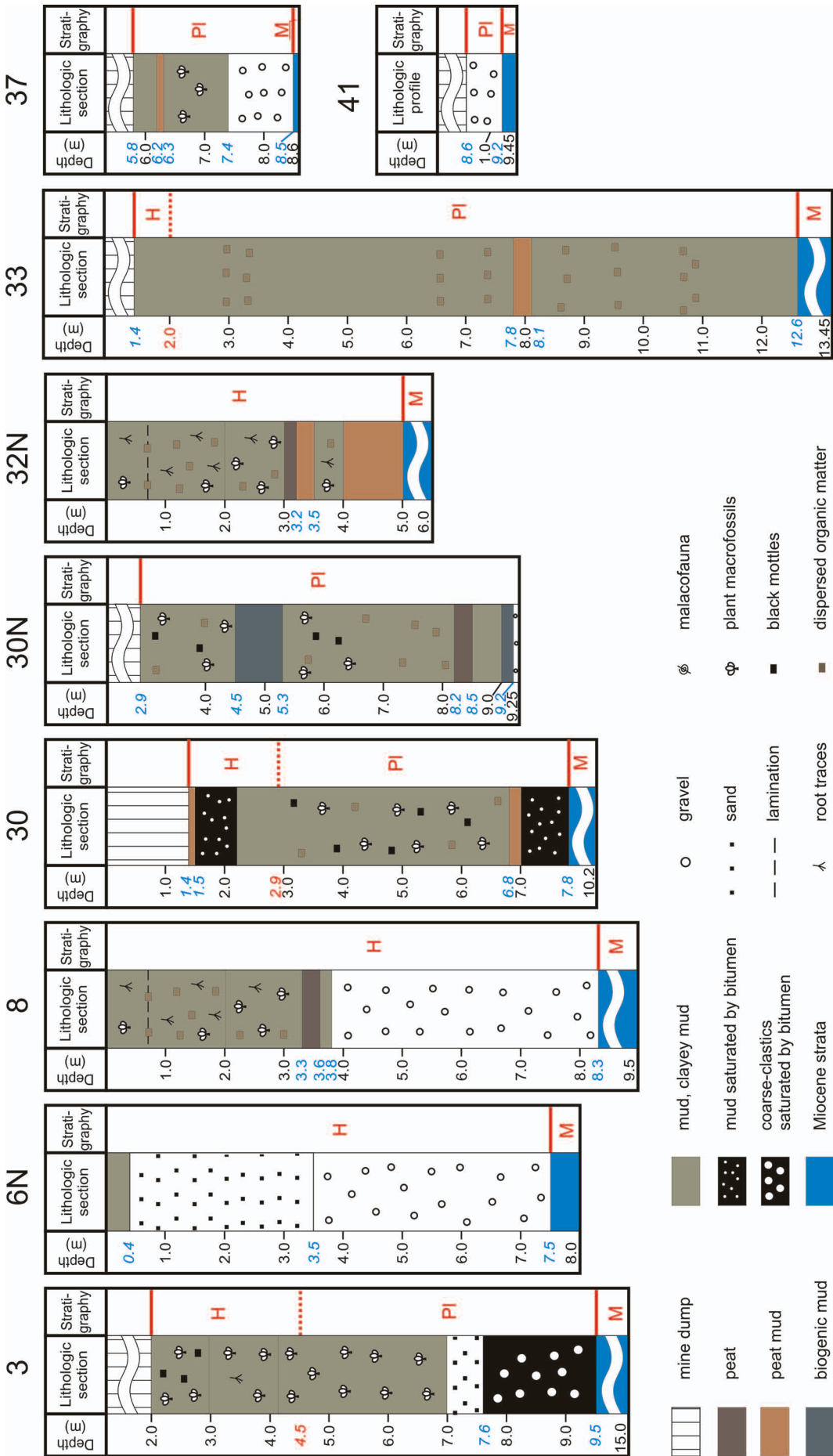
Fig. 2C. Lithostratigraphic columns of boreholes Nos 3, 6N, 8, 30, 30N, 32N, 33, 37 and 41. See Fig. 1 for location
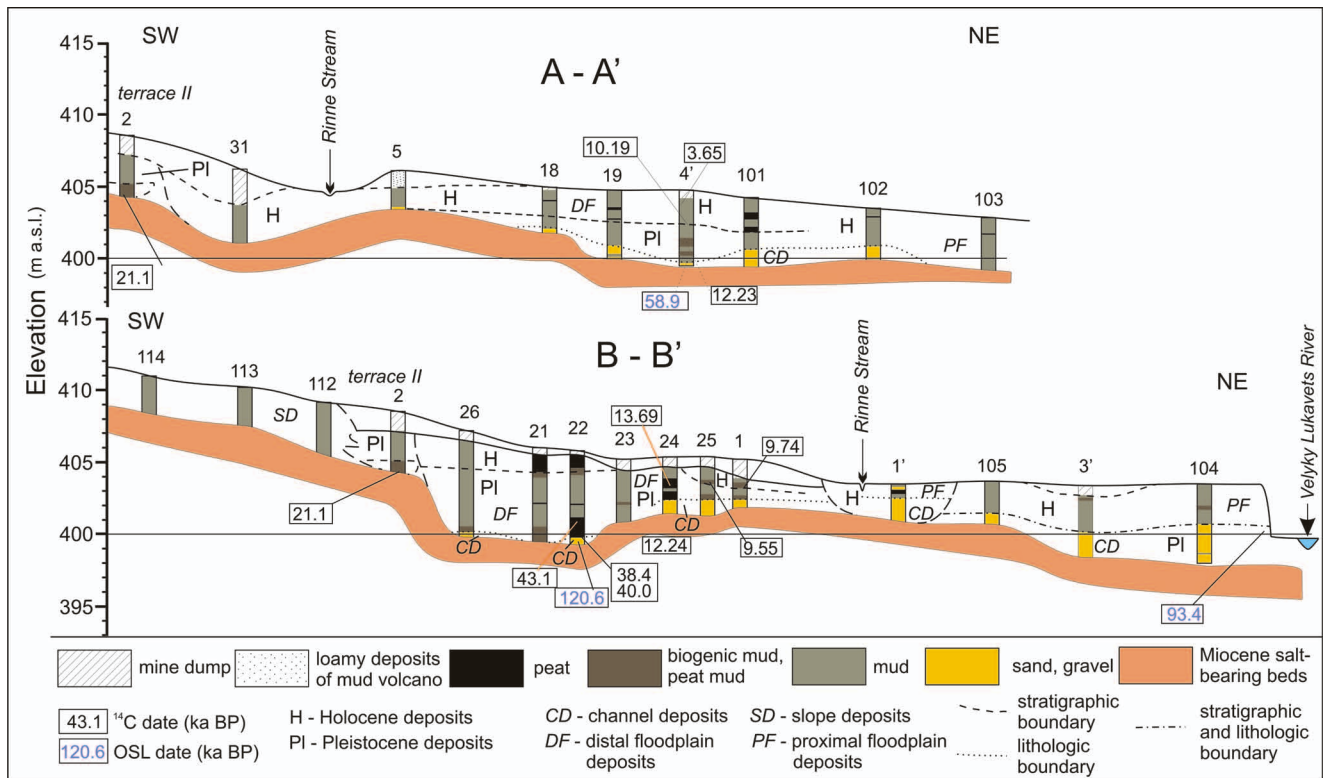
Fig. 3. Geological cross-sections A-A' and B-B'. See Fig. 1 for location

morphology analysis involved the identification of microstructures at the surface of quartz grains of the 0.1–0.03 mm fraction, according to the classification suggested by Mahaney (2002), extended to include microforms described in papers by Goudie and Bull (1984), Helland and Holmes (1997), and Woronko (2007). Fifty randomly chosen quartz grains were analysed each time.

The analysis of heavy minerals was carried out for the fractions from 0.05 mm to 0.25 mm. The obtained concentrate was examined microscopically, identifying a minimum of 300 grains. The content of carbonates was determined with Scheibler's method, and the content of organic matter by Tiurin's method. Petrographic composition of the gravel fraction was analysed with the method after Rutkowski (1995), on the material sieved through sieves with meshes complying with the phi scale. Each fraction was treated as 100%.

Structural analysis of sediments was based on lithofacies suggested for alluvial sediments by Miall (1996) and Zieliński (1998). In the case of fine-grained and biogenic sediments (see, *e.g.*, Farrell, 1987, 2001), apart from sedimentary structures, the presence of plant remains and/or traces of larger roots, root hairs, stalks of reeds and burrows was taken into consideration, as these remains also determine the formation of specific biogenic structures. For the latter, the code proposed by above mentioned authors was retained in order to emphasize textural features, whereas in some cases the authors' own indices of structures were proposed. In determining the thickness of the scale of sets and beds visible in the outcrops, particularly with reference to coarse-grained deposits, the following values were adopted

from Zieliński (1998): up to 6 cm – small-scale, 6–30 cm – medium-scale, and over 30 cm – large-scale.

Methodology and detailed results of analysis of plant macroremains from boreholes Nos 4', 22 and 28 and outcrops No. VL-1 and VL-3 were described by Stachowicz-Rybka *et. al.* (2009b). The presented paper focuses on chosen groups of plant macroremains used to characterize the distinguished lithofacies, except for coarse-grained sediments (gravel and sand) of the river channel subenvironment.

QUATERNARY SEDIMENTS

Since the discovery of large mammal remains, a certain scheme of development of Quaternary sediments has been adopted (Nowak & Panow, 1930; Alexandrowicz, 2004; Alexandrowicz *et al.*, 2005). The lowest member was supposed to be composed of ..."diluvial muds with *Betula nana*"..., filling small hollows that used to be associated by the early authors with a palaeo-oxbow or a palaeochannel. Higher in the section, gravels overlain by clays with sand intercalations and a layer of loam were found. The section was capped by a soil, and the entire succession was covered with a mine dump.

Sometimes, a significant impediment in assigning the deposits to a given river subenvironment in the Ropyshche area is the common occurrence of oil. Locally, distinct impregnation of sediment by thickened bitumens homogenize all rocks into a black, slightly greasy mass blurring the initial sediment structure and texture. All sediments also con-
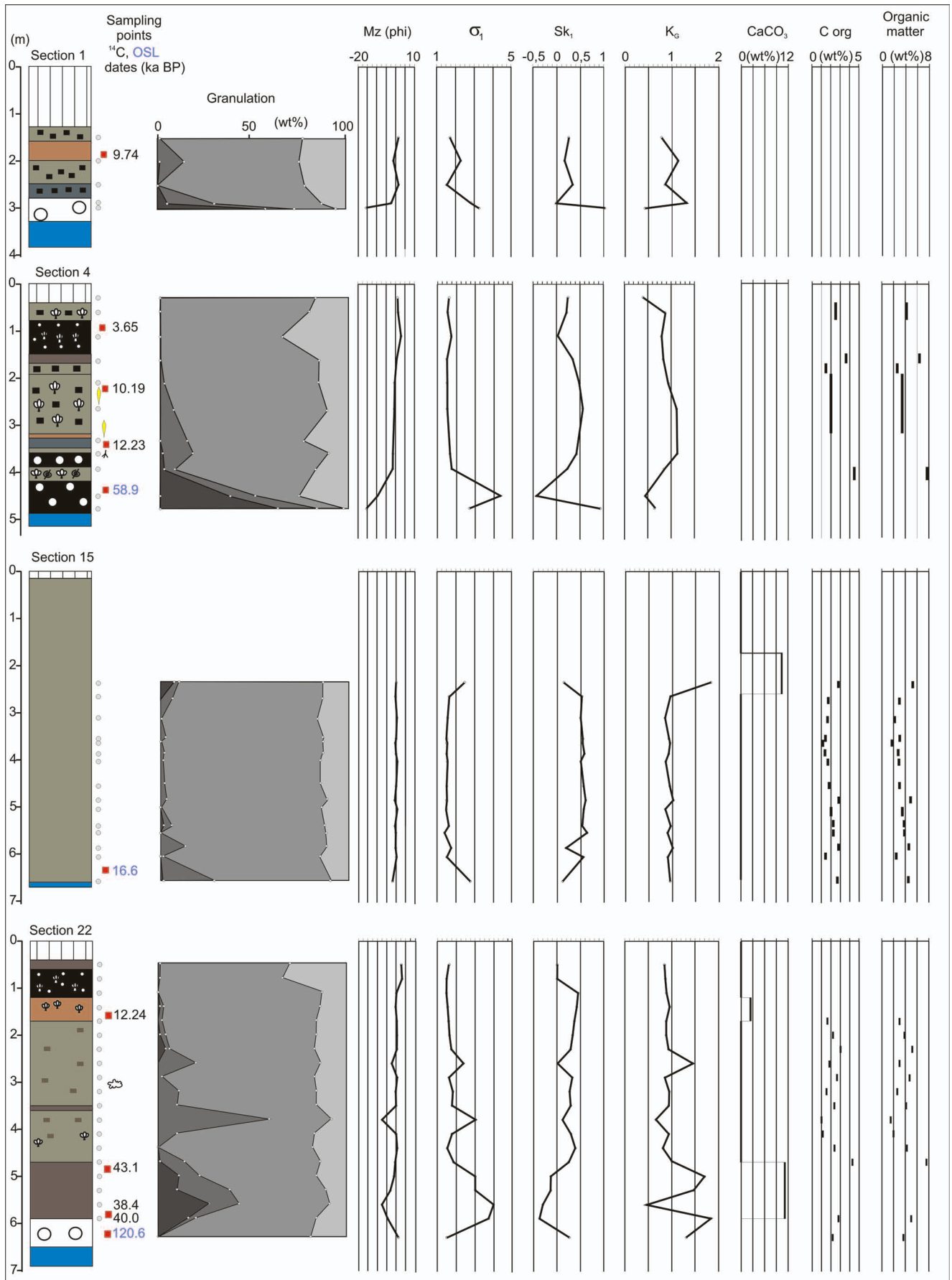
Fig. 4.   Geological cross-section C-C'. See Fig. 1 for location and Fig. 3 for explanation

tain salt occurring as small (up to 1.5 mm across) crystals, which gives the rocks a slightly salty taste.

One of the most important criteria of their distinction, which can also be applied to drill cores, is the grain size of sediments, whose changes are considered the basis for distinguishing individual subenvironments. Sedimentary structures were visible nearly exclusively in outcrops, where coarse-grained, fine-grained and biogenic deposits were distinguished. Attention was paid mostly to the two latter types as large mammals were discovered in fine-grained sediments. Hence, such sediments seemed to be favourable hosts for further discoveries.

Description

Both the textural and structural diversity of sediments filling the valley bottom of the Velyky Lukavets River and the presence of biogenic material allowed for the distinction (following Zwoliński, 1992) of a river-channel facies and of subenvironments of proximal and distal floodplains (alluvial ridge and flood basin; see Bridge, 2003).

Subenvironment of the river channel – coarse grained sediments (gravel, sand)

Coarse-grained sediments show a slightly variable grain size, quite well illustrated by the maximum particle diameter. Usually, for gravel deposits, the maximum particle diameter does not exceed 80 mm and only occasionally, in the present-day bars, cobbles up to 300 mm across can be encountered. The highest values of the mean grain diameter slightly exceed 2 mm, and the σ_1 values indicate very poorly sorted or unsorted material. The skewness value is sometimes negative (Figs 5, 6).

The beds and bed sets are usually of medium or large scale, often showing a fining-upward sequence. The sandy-muddy cementing mass is grey, yellow-grey or rusty after weathering and locally very coherent. In many places of the Velyky Lukavets River channel, strong saturation with oil results in seeps into river waters.

The petrographic composition of the Velyky Lukavets River gravels is diversified. The principal components (up to 80% of grains of 32–16 mm fraction) are the flysch sandstones, originating from the Outer Carpathians. Grey-bluish sandstones derived from the Vorotyshcha beds are found in amounts from several to a dozen or so percent. The cobbles of hornstones, originating from the Menilite beds, are very characteristic components. In the finest of examined fractions (8–4 mm) several percent quartz grains appears. Such gravel composition is very typical of rivers of the Outer Eastern Carpathians and it does not differ significantly from that of rivers in the Polish Outer Carpathians (Rutkowski, 1995).

The Holocene gravels of the terrace I and floodplain (Sokołowski, 2009) are exposed in numerous undercuts and were recorded in several boreholes. The lowest segments of the Holocene succession are dominated by Gh lithofacies of a large scale, trough cross-stratification (Gt) or Gh→GSh (sandy gravel) sequences, and locally by the Gt→GSt sequence. The massive gravel (Gm) lithofacies is less com-

Fig. 5.   Granulation and chemical composition of sections Nos 1, 4, 15 and 22. See Fig. 6 for explanation
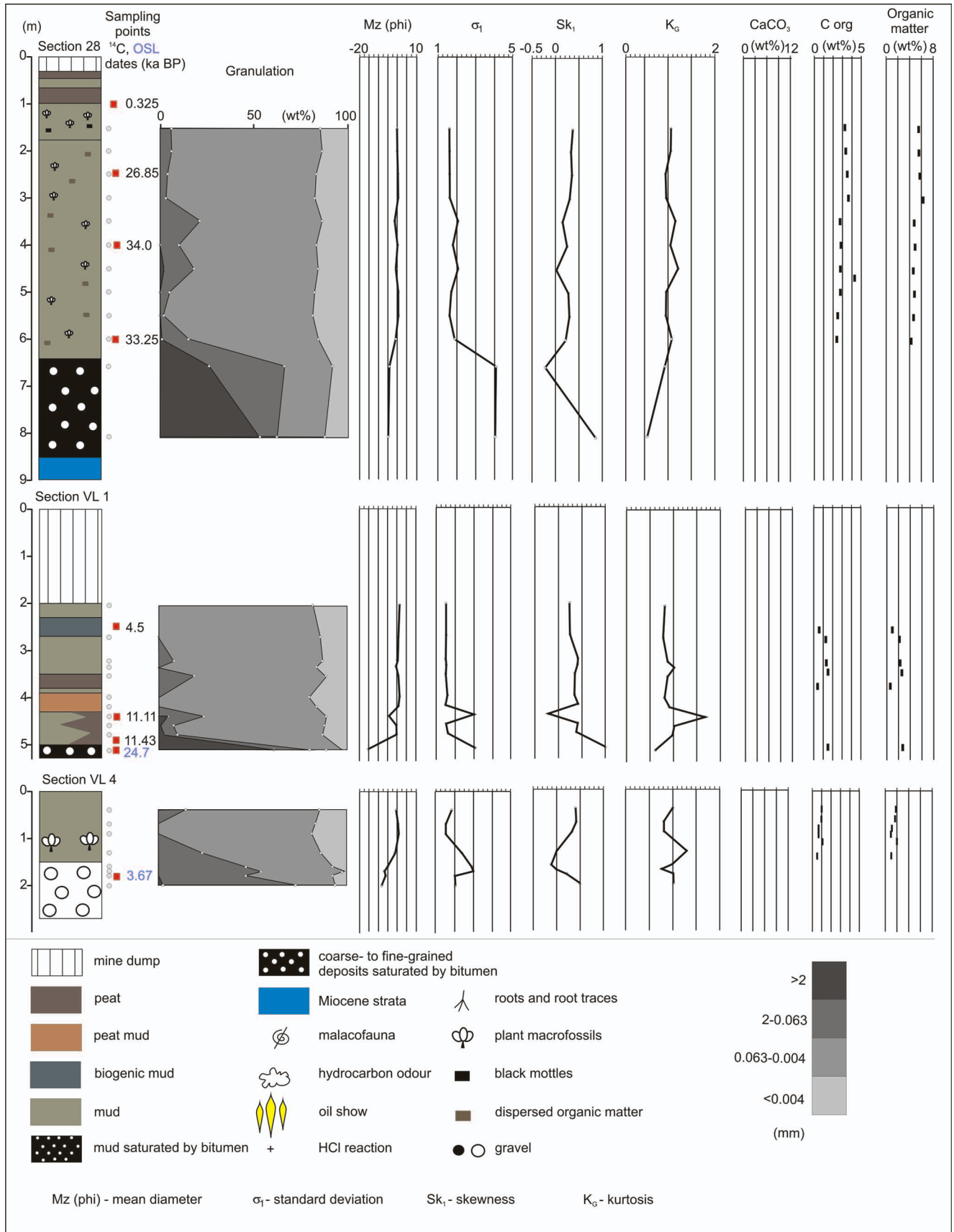
Fig. 6. Granulation and chemical composition of sections Nos 28, VL 1 and VL 4

mon. In the higher segments of the terrace section as well as within the floodplain, there appear beds composed of single sets of medium- or large-scale Gh lithofacies, or Gh→GSh sequences. The planar cross-stratifications (Gp) or Gp→GSp sequences, and even Gp→GSp→Sp sequences are also frequent. Identical sediments are also observed in the present-day river bed and these also appear at the surface of the floodplain, forming landforms that resemble splays. At the base of channel scours' infill, in turn, the medium- or large-scale Gm lithofacies appear. The coarse-grained deposits of Late Pleistocene age are significantly less thick (up to 1.7 m in section No. 36N), but thicker successions are likely to occur in the outcrops, particularly in No. VL 2. The thickness of Holocene coarse- grained sediments is 7.1 m (section No. 6N – Figs 2C, 3).

Subenvironments of overbank deposits

The structural and textural description of sediments filling the bottom of the Velyky Lukavets River valley indicates that they represent mainly the subenvironments of overbank deposits. Moreover, results of palynological studies and analyses of macroremains indicate that the accumulation of sediments was a long-lasting event, which began in the Eemian Interglacial and was continued in the Weichselian Glaciation and Holocene (see Figs 2–4 in Sokołowski & Stachowicz-Rybka, 2009).

Fine-grained sediments of the distal floodplain (mud, clayey mud)

Sediments of the distal floodplain are dominated by large-scale, massive mud lithofacies (Fm), reaching thicknesses of 10 m and occurring most frequently above coarse-grained deposits, occasionally also above biogenic sediments. Rarely, these are underlain by Miocene salt-bearing clays. Muds of the Fm lithofacies are grey-olive, rarely grey and contain more clay minerals. The admixtures of carbonates are very rare and appear almost exclusively in the bottom parts of the succession (Figs 5, 6). Single dropstones up to 5 cm in diameter, probably brought here on ice floats, are common. Siderite concretions were also found. In many places, there appear quite characteristic, black spots of oil or disseminated pyrite. Particularly the former may have developed taking the advantage of the ichnofauna burrows and root traces.

In the majority of boreholes, particularly in their upper portions (usually in Holocene sediments), there appear root hairs or slightly larger root traces (lithofacies Fb), most frequently with rusty coatings, as well as reed rods (lithofacies Frr) and burrows.

In such sediments numerous fruits of *Triglochin maritimum* and *Juncus* sp., nuts and scales of *Betula nana*, as well as nuts of *Carex* sp. and *Eleocharis palustris* occur. The first species is rather rare in Quaternary sediments and is currently in danger of extinction. It grows mainly on sea shores and on halophilic, boggy meadows, and sphagnum peat-bogs. Another halophilic species is *Zannichellia palustris*, which grows most frequently in extremely eutrophic or slightly-saline, standing or slowly flowing waters. It

grows at various depths in littoral shallows of lakes and rivers. Unusually numerous are the seeds of *Poaceae* sp., while accompanying tree remains are lacking. Simultaneous occurrence of *Cenococcum geophilum* sclerotia indicates an open character of vegetation around the sedimentary basin as well as increased solifluction processes (Ławrynowicz, 1983). The environment of arctic tundra and intensively boggy habitats are also indicated by the composition of the malacofauna assemblage (Stachowicz-Rybka *et al.*, 2009b).

The observed or interpreted thickness of Weichselian fine-grained deposits is quite variable, exceeding slightly 10 m in section No. 33 (Figs 2C, 3). The Holocene deposits are even thinner. Muds with intercalations of biogenic deposits are up to 5 m thick (section 32 N).

The muds are mostly coarse to fine silts with medium grain diameter (Mz) from 61.3 to 7.1 μm (Figs 5, 6). A fact worth emphasizing is that, apart from borehole No. 22 and outcrop No. VL 4, variability of the mean grain diameter (Mz) is very low throughout the section, as shown best by sediments from borehole No. 15 (Fig. 5). In an over 4-m-long drill core the Mz varied from 18.4 to 13.9 μm. Only in the basal part of the drilled series did the Mz increase to 28.0 μm. On the contrary, in sediments from borehole No. 22 (Fig. 5) a distinct sandy intercalation with a slight admixture of pebbles was encountered at a 3.8 m depth. This sand is associated with a noticeable water flow and probably indicates the Pleistocene/Holocene stratigraphic boundary. The top part of the core comprises finer-grained sediments. Sediments of the mud lithofacies are poorly and very poorly sorted (σ_1), showing positive skewness, as well (Sk$_1$; Figs 5, 6).

Mineralogical composition of sediments sampled from sections Nos 4, 15, 22 and 28 (Figs 2A, 2B, 5, 6) as well as from No. VL 1 outcrop (Fig. 1), determined with the EDS is highly homogeneous. Both the fine sand and silt fractions are dominated by quartz grains. In the majority of analysed samples quartz constitutes 90% of examined grains. Other components are: K-feldspar, albite and admixtures of other minerals (Table 1). In No. VL 1 and No. 4 sections variable

Table 1

Rough mineral contents (%)

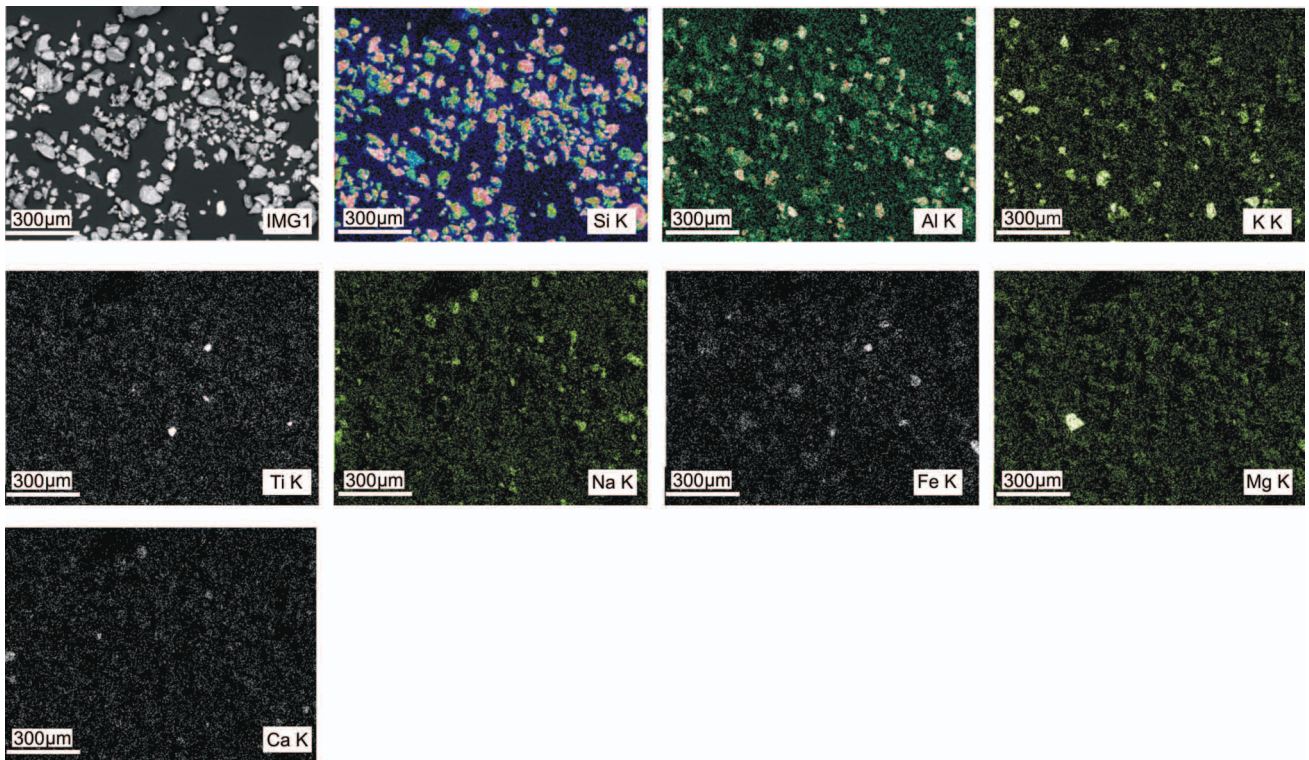| Section/depth (m)	Quartz	K-Feldspar	Albite	Fe	Ti	Plagioclase	Others
4/2.1	79.2	15.1	4.4	1.3	0.0	0.0	0.0
4/3.6	96.0	2.0	2.0	0.0	0.0	0.0	0.0
15/4.5	91.6	6.8	1.2	0.0	0.0	0.0	0.4
22/2.0	96.0	2.6	1.3	0.0	0.0	0.0	0.0
22/3.5	90.0	4.2	4.2	0.8	0.0	0.0	0.8
22/4.7	93.9	3.8	1.1	0.0	0.4	0.0	0.8
28/2.0	95.2	3.5	1.3	0.0	0.0	0.0	0.0
28/3.5	91.7	4.8	3.6	0.0	0.0	0.0	0.0
28/6.0	95.7	2.9	1.4	0.0	0.0	0.0	0.0
VL 1/4.5	96.2	0.0	1.9	0.0	0.0	1.9	0.0
VL 1/3.7	84.1	9.8	5.0	0.0	0.8	0.3	0.0

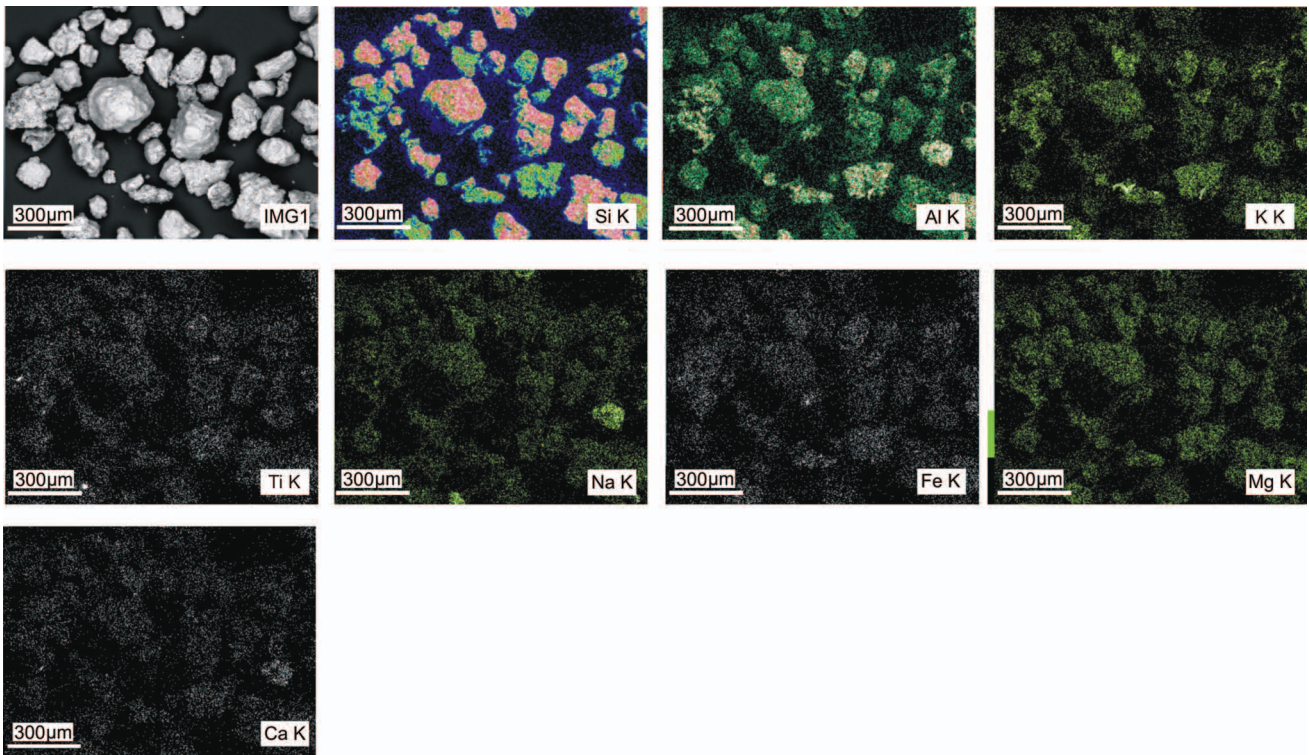**Fig. 7.**   Single element scans and BSE image of VL-1/1.36 sample

Fig. 8.   Single element scans and BSE image of VL-1/2.2 sample

proportions of individual minerals are found (Table 1, Figs 7, 8). It is worth noting that in the deposits sampled in borehole No. 22 (mainly at 4.7 m depth) the presence of glauconite grains was recorded.

Homogeneity of mineral composition of the lithofacies is also confirmed by the results of XRD analyses (Table 2). Clay minerals compose up to 50% of the total minerals and mostly are of mixed-layer structure (smectite-illite – S-I).

Chlorite-vermiculite (Ch-V), micas and illite (about 15%), kaolinite (about 10%), and chlorite (about 3%) were identified, as well. Apart from clay minerals, the samples contain quartz (about 20%), plagioclases (about 10%), K-feldspars (about 7%), and halite (5–10%) as well as occasional pyrite and gypsum. In section No. 28 no visible changes of mineral composition with the depth were encountered (section No. 28; Table 2); all samples contain a similar set of both clay and non-clay minerals. The polymineral assemblage of clay minerals indicates their detrital origin and the similarity in composition shows that the material originated from the same source area, *i.e.* the Carpathian flysch shales or clays of the Carpathian Foredeep Basin. The presence of chlorite-vermiculite assemblage in alluvial sediments can be presumably associated with post-depositional soil processes developing in a cool and moderately humid climate.

The composition of heavy minerals is variable (Table 3). In the upper part of section No. 28 small globules and rounded grains of clayey siderites were observed. Less frequent are fine, isometric, mainly angular grains, occasionally somewhat rounded or even coated with garnets and amphiboles. Down the section, isometric grains were found, mainly resistant to weathering garnets and primary iron oxides (ilmenite and magnetite), together with zircon, and a small amount of poorly and very poorly coated minerals, non-resistant to destruction and low-energetic (easily mobilized and slowly deposited). In a specific part of No. 28 section large amount of resistant staurolith was encountered (Table 3). In the upper part of section No. 4 the amount of heavy minerals is low, the most frequent being hydrated iron oxides and transient phases formed during pyrite decomposition (goethite, limonite) as well as single garnets and numerous quartz grains, highly infiltrated with iron compounds. Below, clayey siderites and spherosiderites dominate, accompanied by small amounts of pyrite and rare garnet grains.

Table 2

Mineral composition of fine grained deposits, calculated half-quantitatively by radiography method

Section			28		15	4
Mineral composition (wt%)	Depth (m)					
	2.2	4.0	5.0	6.2	3.3	2.2
Quartz	20	20	22	22	22	23
Plagioclases (9-466)	10	10	10	10	12	10
K-feldspars (12-703)	7	10	7	7	7	7
Halite (5-628)	5	5	7	5	5	1
Pyrite (6-710)	1	1	1	1	3	0
Gypsum (33-311)	0	0	0	0	0	7
Kaolinite (6-221)	10	12	10	10	10	10
Micas/illite (26-911)	15	17	15	15	13	10
Chlorite (16-362)	3	2	2	3	3	3
Illite-smectite, chlorite-vermiculite and amorphous phases	29	23	26	27	25	29
Total of clay minerals	57	54	53	55	51	52

Numbers of standards in ICDD base are put in brackets

These sediments are usually devoid of carbonates, except local occurrences. Rare malacofauna is one of the indicators of carbonatization. Considerable concentration of carbonates (even up to 13 wt%; Figs 5, 6) present in lower segments of No. VL-1 and No. 22 sections points to both the leaching from the upper segments and secondary concentration.

The described deposits contain variable but high amounts of organic carbon and organic matter (up to 3.6 and

Table 3

Contents of heavy minerals

Sample section/ depth (m)	Number of grains	Content of minerals (%)																	
		amphiboles	pyroxenes	biotite	chlorite	epidote	garneta	tourmaline	zircon	rutile	titanite	disthene	staurolite	apatite	siderite	ilmenite, magnetite	glauconite	geothite, limonite	pyrite
28/2.5	945	2.33	0.42	0.00	0.42	0.11	6.56	0.63	1.27	0.11	0.00	0.00	0.21	0.11	87.83	0.00	0.00	0.00	0.00
28/3.5	490	5.31	0.41	0.00	0.00	0.00	38.78	3.06	11.02	3.27	0.00	0.82	1.63	0.00	0.00	28.57	0.00	2.24	4.90
28/4.5	608	4.93	0.49	0.00	2.63	0.00	41.78	0.82	1.64	0.49	0.00	0.66	9.54	0.00	30.43	5.43	0.33	0.00	0.82
28/5.5	482	4.36	0.62	3.53	4.56	0.00	52.28	1.66	1.87	0.00	0.41	0.00	8.51	0.21	13.49	5.81	0.83	1.45	0.41
28/6.8	478	3.35	0.42	1.05	0.84	0.00	33.89	6.07	2.51	0.84	1.46	1.26	5.44	0.63	0.00	39.12	0.00	1.88	1.25
4/1.3	139	0.00	0.00	0.00	0.00	0.00	6.47	0.00	0.72	1.44	0.00	0.72	0.72	0.00	0.00	0.00	0.00	89.3	0.00
4/2.2	331	0.00	0.00	0.00	0.00	0.00	2.42	0.00	0.00	0.00	0.00	0.00	0.60	0.30	0.00	0.00	0.00	21.5	75.53
4/3.5	436	2.06	0.23	0.46	1.61	0.46	15.83	0.00	0.69	0.00	0.00	0.46	0.00	0.23	73.39	0.00	0.00	0.00	4.59
4/4.2	384	1.04	0.00	0.00	0.00	0.00	1.82	0.00	0.00	0.00	0.00	0.78	0.00	0.00	0.00	0.00	0.00	0.00	96.35
15/4.7	583	0.51	0.17	0.17	0.17	0.00	9.78	0.00	0.34	0.00	0.00	0.00	1.03	0.17	0.00	0.69	0.00	86.6	0.00

Type of structure/ sample (borehole/depth)	4 (2.1m)	4 (3.6m)	15 (4.5m)	22 (2.0m)	22 (3.5m)	22 (4.7m)	28 (2.0m)	28 (3.5m)	28 (6.0m)	VL-1 (4.5m)	VL-1 (3.7m)
low relief	○	•	•	•	•	○	●	•	∘	•	●
medium relief	●	•	●	●	●	●	○	●	●	•	•
high relief	○	○	∘	∘	∘	○		∘	○	○	
high frequency fractures	○		○				○	○	○	○	○
low frequency fractures	○	•	•	•		○	○	○	•	∘	○
edge rounding	●	●	●	•	●	●	●	●	●	●	●
sharp features	•	•	•	○	○	○	∘	○	•	○	○
abrasion fatigues		∘	•				○		●		∘
abrasion feature	•			∘			○	•	•	∘	○
fresh surface	•	•	•	○		∘	○	•	•	○	•
overgrowth quartz	○	∘		∘		•	○	•	●	•	○
dissolution surface	●	•	●	•	●	•	•	●	●	●	○
dulled surface			∘	∘		○			●	∘	
platy ppt.	•	●	●	●	•	●	●	●	•	•	•
smooth ppt.			•	•	●	○	•	∘	∘	○	•
lattice shattering								○	●		
oriented etch pits				∘		○			○		
solution crevasses	○	∘		•	○	•		○	○	○	○
solution pits	•	○	•	•	•	●	○	•	•	○	∘
arc-shaped steps			∘		○				○		○
breakage blocks (<0.010 mm)	○		○		∘	○	∘	○			○
breakage blocks (>0.010 mm)								○			
chattermarks											
conchoidal fractures (<0.10 mm)	•	○	○	∘				•	○	○	•
conchoidal fractures (>0.010 mm)	∘	∘	○	∘			∘	○	○	○	○
fracture faces		○		○		∘	○		•		•
linear steps	∘	○			∘			•	○	∘	∘
subparallel linear fractures	○	∘							∘	∘	○
micro steps											∘
parallel ridges										∘	
radial fractures											
sawtooth fractures											
craters											
crescentic gouges											
V-shaped percussion cracks										∘	
mechanically upturned plates											
bulbous edges											
curved grooves	∘	∘				∘					
deep trough	○		∘	∘		∘				○	
straight grooves											
depressions	○	○		○	○	○	○	○		∘	∘
elongated depressions				○	○	○					
scaling							∘				
adhering particles	●	●	●	●	●	●	●	●	●	●	●

● 75-100　　● 50-74　　• 25-49　　○ 24-5　　∘ 4-1 (%)

Fig. 9. Microstructures of grains of the sandy fractions in SEM

5.8 wt%, respectively). These increased values may be associated with the Fb and Frr lithofacies. Significantly lower amounts of these components are found in the PF fine-grained sediments (Figs 5, 6), what probably results from both quick deposition preventing the development of vegetation and the young age of deposits (Sokołowski & Stacho-wicz-Rybka, 2009). Still lower values of organic carbon and organic matter (0.5 and 0.8 wt%, respectively) are observed in the Recent sediments.

The results of SEM grain surface micromorphology analysis of the 0.1–0.03 mm quartz fraction show that the grains are characterized by a medium or low relief (Fig. 9).

This means that the microrelief of the grain surfaces is insignificant. Only in sediments from No. VL-1 (3.7 m depth) and No. 28 (3.5 and 6.0 m depths) sections, were grains of a high relief observed. The surfaces of the vast majority of quartz grains are dominated by microstructures associated with chemical weathering, both etching and coating (Fig. 9). Abrasional microstructures are observed only at the surfaces of single grains and are associated with low frequency fractures. Moreover, their variability is limited to only a few microforms (conchoidal fractures, fracture faces, arc-shaped steps and breakage blocks), which can be regarded as a characteristic feature of such fine grains (Woronko, 2007). The process of quartz surface etching is observed in the majority of grains, but with variable intensity. Usually, these are irregular surfaces (dissolution surfaces, Fig. 10A) or irregularly shaped solution pits (Manker & Ponder, 1978; Fig. 9). In section No. 22, the process is so advanced in single grains that the resulting microrelief can be described as a spongy surface (Friedman *et al.*, 1976). Moreover, both point and linear concave microforms (solution pits and crevasses) are observed. The former are oval holes or V-shaped pits. Oriented etching pits, reflecting defects in the crystallographic network of quartz grains, occur at the surfaces of single grains from section No. 22.

The process of surface coatings is visible in all analysed grains irrespectively of sampling depth (Fig. 9) but with variable intensity: from the initial (Fig. 10B) to the advanced, the latter completely masking the pre-existing microrelief (Fig. 10C). Two types of crusts were distinguished: platy ppt and smooth ppt (Fig. 10B & D) (Woronko, 2007). These are formed mostly by amorphous silica, potassium alumosilicates, and ferric oxides (Figs 7, 8). The first type forms fuzzy, uneven surfaces (Woronko, 2007). In the initial form this type of crust is observed only within microhollows, leaving all the convex grain fragments uncrusted (Woronko, 2007). In contrast, the smooth ppt type crust forms continuous and smooth coats evenly covering the whole grain surface, regardless of how advanced are the processes and the grain micromorphology (Fig. 10D). Most of the examined grains (60% to over 90%) reveal the platy ppt-type crust (Fig. 9). The participation of grains with a smooth ppt crust usually does not exceed 35% (Fig. 9) and exceptionally amounts up to 76% of the analysed grains (section No. 22/3.5 m). There is a significant participation of grains with surfaces coated with both the platy and smooth crusts. In microhollows we observed the crust of platy ppt type, whereas at the edges and over all convexes the smooth ppt type occurred. Apart from coated surfaces of grains, fresh and uncoated surfaces were also seen (Fig. 10E). The processes of crusting and etching are responsible for rounding the grain edges. There also occur grains of overgrowth silica (Figs 9, 10F), showing different stages of crystallization, from an initial one to a complete idiomorphic crystal. Moreover, some of the grains show amorphous forms with well developed crystal planes (Fig. 10G & H). Grains of such type are found in variable amounts, from 0 to about 65%. In sediments from borehole No. 28, grains of this type were recorded at both 5.0 m (28%) and 6.0 m (65%) depths. A slightly lower amount was recorded in borehole No. 22, within sediments at 4.5 m depth (39%), and in No. VL-1 outcrop, at 3.7 m depth (28%). In other analysed samples the percentages of this type of grains did not exceed 10% or the grains were absent (Fig. 9).

Proximal floodplain fine-grained sediments (mud, sandy mud, silty sand)

The fine-grained sediments are of Holocene age and occur exclusively in exposures along the Velyky Lukavets River bed, also overlying the coarse-grained sediments. To some extent, sediments from sections Nos 5N and 7 (Figs 1, 2B) are of a similar position and development. Thus, their sections did not appear in Figs 3, 4. The sediments show high variability. Dominant are brown muds (F), silty sands (SF) and sandy muds (FS) with horizontal (SFh, FSh), wavy (SFw, FSw), flaser (SFf) and ripple-cross (SFr) laminations. In the higher parts of the sections massive muds (Fm) and horizontally laminated muds (Fh) were frequently recorded. The rhythms of fining-upward sequences appear, as well, often including three segments: SFh→FSh→Fh, sometimes SFh→FSh→Fm or SFr→SFw(FSw)→SFf(FSf). Cycles of a pennsymmetric sequence (Teisseyre, 1988) with the SFh member were also observed. Locally, the top of the sequence is occupied by a massive mud (Fm) lithofacies. In these sections intercalations of medium- and even large-scale Gp, GSp and, occasionally, GSh and GSl lithofacies locally appear. Their thickness rarely exceeds 2 m.

These deposits are in many places dissected by palaeo-oxbows and crevasses. Such washouts are filled with silty sand and sandy mud, developed as SFr, SFw and FSr lithofacies, and in the lower parts occasionally as St or even Gt lithofacies. The latter lithofacies is accompanied by small mud balls and numerous plant remains (branches, leaves, and seeds).

Above the valley bottom and at the base of slopes surrounding the valley, yellow and greyish-yellow muds and sandy muds (lithofacies Fs) appear, usually less than 1.5 m thick.

Biogenic sediments (peat, peat mud, biogenic mud)

Biogenic sediments appear in various segments of the analysed sections and in various morphological positions. Rarely, the sediments rest directly upon the salt-bearing Vorotyshcha beds, but commonly form several, independent intercalations within overlying silty strata. Moreover, these are located at very shallow depths, just below a thin layer of overburden or even at the surface.

The peat (lithofacies Cp) is usually brown or dark brown, occasionally almost black, with plant remains at different stages of decomposition. Peat always contains some mud admixture. Quite characteristic is peat with numerous *Phragmites* remains, usually found in the top parts of the sections. However, palaeobotanical research did not confirm high contents of reed seeds within these horizons and outcrop examinations indicate that rhizomes of *Phragmites australis* grew into the deposit down to about 1.5–2 m depth. Peat, which occurs at shallow depths (usually down to 1.5 m), contains rhizomes of *Phragmites australis* and is commonly highly saturated with bitumen.
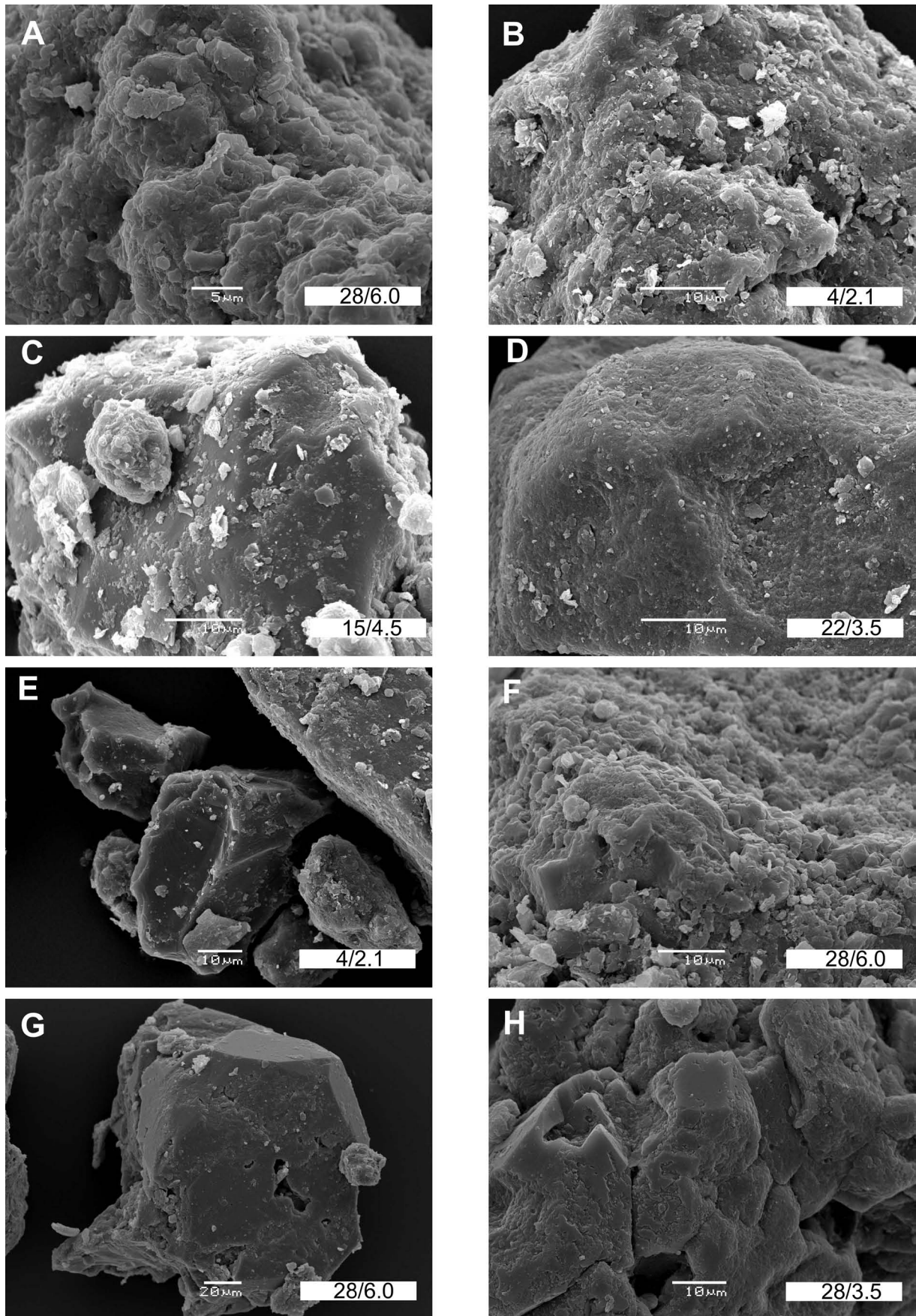
Fig. 10. Microstructures on quartz grain surfaces in SEM. **A** – dissolution surface (section 28/6.0), **B** – platy ppt coating (4/2.1), **C** – initial form of platy ppt coating (15/4.5), **D** – smooth ppt coating (22/3.5), **E** – new conchoidal fractures (4/2.1), **F** – quartz grain with overgrowths quartzes (28/6.0), **G** – amorphous grain (28/6.0), **H** – intensive etching of overgrowth quartz (28/3.5)

Locally, this peat contains a high admixture of dispersed mud (peat mud – Cm lithofacies) or grades into a mud (sometimes silty) with a noticeable admixture of fine plant remains (biogenic mud – Co lithofacies). In such rocks plant remains are usually strongly decomposed and often hard to identify macroscopically. Biogenic origin of these deposits is confirmed by the highest contents of organic carbon and organic matter, reaching 4.5 and 7.8 wt%, respectively.

Thickness of biogenic deposits varies from a few to some tens of centimetres but locally, especially in the vicinity of the Rinne Stream, interbeds of biogenic sediments reach thickness even up to about 1 m (*e.g.*, sections Nos 13, 14, 22, 23 and 24; Figs 2A, 2B, 3, 4).

In young erosional cuts observed in outcrops, accumulations of largely diversified plant macrofossils were found as intercalations in silt or silt-sandy deposits. The macrofossils do not show advanced humification processes and form isolated, medium-scale sets (Cd). Analysis of plant macroremains (Gałka, 2009) from such deposits in the Dashevets Stream valley points to the presence of numerous tree remains, the species composition of which indicates a warm period of the Holocene. These are: fruits of *Carpinus betulus*, needles, seeds and flower-bud scales of *Picea abies* and *Pinus sylvestris*, needles of *Abies alba*, as well as fruits of *Alnus glutinosa*. Such abundance of tree remains may evidence sedimentation coeval with the period when the area was covered by a forest of high species diversity. A similar type of flora was also described by Rogala (1907) from the adjacent Maly Lukavets River valley.

Slope deposits

Yellow, grey-yellow and occasionally grey muds and sandy muds of slope deposits (SD) appear above the valley bottom and at the base of slopes surrounding the valley (sections Nos 106, 107 and 112–117, Figs 1, 3, 4) and mostly do not exceed 3.6 m in thickness. Lithology of such sediments was not investigated in detail; only a field description of drill cores was recorded.

Mine dump

The mine dump forms a continuous layer of wastes in the SE part and a discontinuous layer in the northern and NW parts of Ropyshche area, overlying the above described, natural sediments. In the wastes, which have been accumulating at a large scale since the 19th century, breccia-like material was identified comprising quartz grains, sandstones, marls, gypsum and ozokerite fragments together with bricks, concrete, ceramics, slag, wood and metal fragments embedded within silty cement. In the northern part of the Ropyshche area (starting from geological cross-section B-B'; Fig. 1) mine wastes form a discontinuous layer, less than 2.5 m thick (section No. 31). Southward, the thickness of wastes abruptly increases and reaches almost 11 m (section No. 38; Figs 5, 6). In some boreholes even thicker wastes were encountered but it is probable that these wells were spud in old shafts.

Interpretation

In the Velyky Lukavets River valley all subenvironments typical of fluvial valleys were developed: river channels and floodplains with hollows filled with biogenic deposits. Analysis of landforms accompanied by textural and – for outcrops – structural studies of sediments allow us to determine the conditions present at the time of sediment transport and deposition, as well as the character of post-depositional processes affecting the sediments. Significant pieces of information were also provided by palaeobotanical and malacological studies (Stachowicz-Rybka *et al.*, 2009a, b).

Rare outcrops with sometimes only fragmentarily exposed coarse-grained gravels, which build layers of channel sediments (CS), did not allow the authors to run more detailed sedimentological analysis. However, all the distinguished lithofacies should be regarded as river channel deposits. The Gm lithofacies, locally resting directly upon the erosional surface, can be associated with the beginning of the decline of flood waters. The Gh, Gp and Gt lithofacies, including the above mentioned vertical sequences of sediments, probably indicate deposition during downstream migration of riffles and their filling of the pools (*cf.* Nemec, 1984; Brierley, 1989). Moreover, such forms are found in the present-day bed of the Velyky Lukavets River. Rarely occurring Gl and Gl→GSl lithofacies can be regarded as the effects of river outwash scouring.

Both the textural and structural diversity of fine-grained deposits, and the presence of biogenic material allowed for the distinction (following Zwoliński, 1992) of subenvironments of proximal and distal floodplains (alluvial ridge and flood basin; see Bridge, 2003).

The proximal floodplains (PF) sediments were found only in the top of the Holocene terrace I, close to the Velyky Lukavets River bed (Figs 3, 4) and in the recent floodplain. However, because of their young age, these deposits were not the main subject of the study, and their analysis was not detailed.

On one hand, the described sediments resemble those of floodplains of meandering gravel-bed rivers (Teisseyre, 1988) but on the other hand, the succession of sedimentary structures makes them somewhat similar to floodplains of sand-bed braided rivers (*e.g.*, Abdullatif, 1989; Singh & Bhardwaj, 1991; Zieliński, 1998). Nevertheless, these sediments are more fine-grained in comparison to the latter. Moreover, plant remains of different size tend to appear throughout the studied sections. The topmost parts of the sections, a few tens of centimetres thick, host anthropogenic material: brick fragments, mine wastes, fragments of boards, bottles, plastic wraps, etc. The intercalations of medium- and even large-scale Gp, GSp and, occasionally, GSh and GSl lithofacies probably represent sediments of crevasse splays and/or deltaic cones (Zwoliński, 1992).

The distal floodplain (DF) sediments, represented by lithofacies Fm, Fb, Fr, also Cp, represent both the Pleistocene and the Holocene. The former are more frequently found in borehole logs, especially in the western part of the Ropyshche area. These were also recorded in No. VL-1 and VL-3 outcrops. Holocene sediments are usually exposed in outcrops.
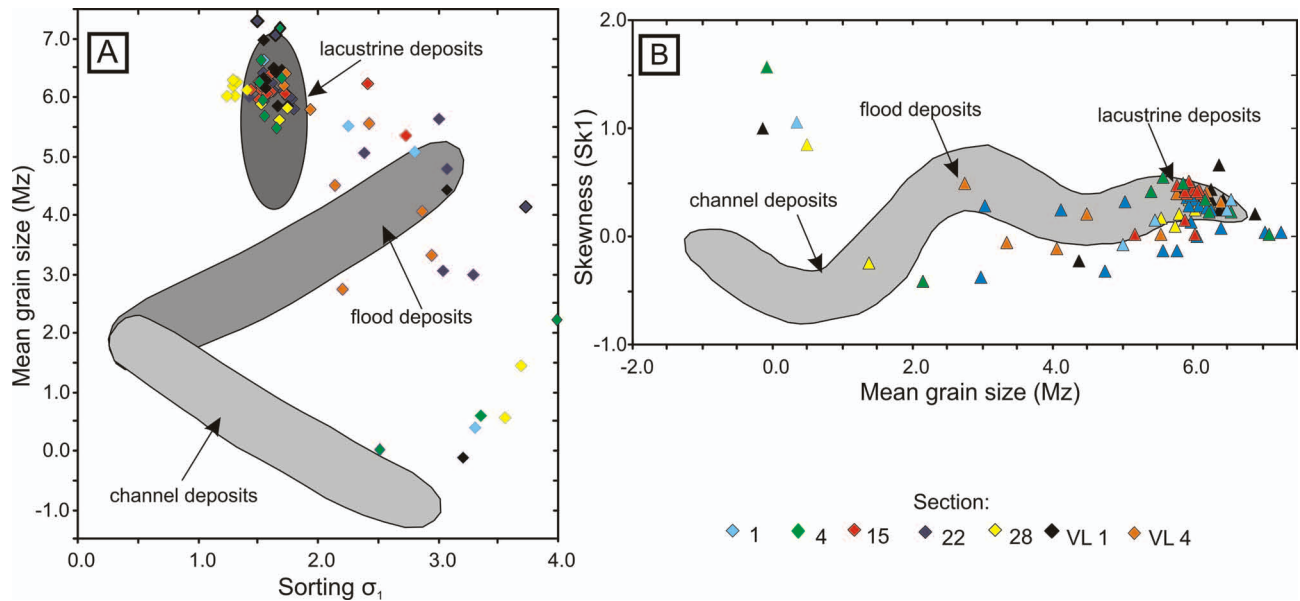
Fig. 11.   Relationship between mean grain diameter (Mz), standard deviation (σ_1), and skewness (Sk_1) with reference to examination of the Belnianka River deposits (grey contour – according to Ludwikowska-Kędzia, 2000)

For the DF sediments, the graphs of mutual relationships of selected indices after Folk and Ward (1957), *i.e.*, the mean grain diameter (Mz), sorting (σ_1) and skewness (Sk_1), show unequivocally that the majority of examined silt deposits accumulated in standing water, either from suspension or from very calm flow (Fig. 11). Referring to the results of the Ludwikowska-Kędzia's (2000) study of deposits filling the Belnianka River valley (the Holy-Cross Mountains, Poland), the examined sediments represent basin fill. It should be emphasized that during the whole time of their accumulation the environmental conditions remained constant throughout most of the investigated area. This is reflected by a very narrow range of sediment fraction changes. Rarely and only locally (*e.g.*, section No. 22), episodes are marked of the supply of sandy material or fine gravels (Figs 5, 6). The character of these lithofacies and the fact that clear erosion surfaces are rarely found point to a non-channelized sheet flow of a very low stream power. On the other hand, when plotted in Mz vs. σ_1 and Sk_1 vs. Mz graphs, the sediments form a cloud of points scattered in the upper parts of graphs (Fig. 11). This is probably an effect of turbidity currents or a representation of highly fine-grained river-channel sediments. Sediments attaining the largest mean diameters of grains (Mz) in graphs of relationships of indices are also worth consideration (Fig. 11). It is likely that these are scoured sediments of a fine-grained river-bed pavement. Taking into account the fine grain size of deposits, it can be assumed that their accumulation occurred in the distal part of the basin. The shallow basin is also indicated by vegetation of the Cp and Fp lithofacies (section No. 22). In the lower part, small amounts of seeds of aquatic plants were identified: *Zannichellia palustris*, *Batrachium* and *Potamogeton filiformis*, which prefer shallow depths (less than 2 m of highly trophic water). At boggy sites or on muddy, drying shore fragments, plant communities with *Bidens tripartita* were likely to occur. In the strip of land

surrounding the lake, the rushy plant communities were dominated by *Juncus* sp. and *Eleocharis palustris*, and more drier habitats contained grasses, particularly the halophytic *Puccinellia distans*. Palynological studies recorded minor amounts of pine, birch, alder and larch pollen grains. In both micro- and macroanalysis there is a record of *Betula nana*, the presence of which, together with *Juniperus* sp. and *Salix herbacea*, proves that the landscape around the lake had a character of a shrub tundra.

The deposition of muds probably occurred in a cool climate, as revealed by both palaeobotanically examined boreholes (No. 22 and mostly in No. 28), where only single plant remains were found or where no plant remains occurred. A likely explanation might have been quick sediment deposition preventing development of more luxuriant vegetation. The presence of stagnating waters is also indicated by the character of malacofauna (Stachowicz-Rybka *et al.*, 2009a, b). Deposition in swamp conditions, with periodic and episodic energetic flows (indicated by single CS intercalations) continued in the Holocene and has lasted almost to the historical times (*cf.* Sokołowski & Stachowicz-Rybka, 2009).

The results of micromorphological analysis of quartz grain surfaces carried out for fine sands and silts show that the detrital material was supplied from environments shaped by different processes. Most of examined grains bear traces of intensive chemical weathering, but completely angular grains with conchoidal fractures and sharp edges also occur. The former dominate mostly in coarse silts or fine sands, whereas fresh grains typify the finest deposits. Chemical weathering affected the grain surfaces in various ways. Chronologically, the first stage of the surface shaping in the majority of grains was associated with intensive etching (Fig. 12A). As an effect, a rough, irregular surface (*dissolution surface*) was formed and every edge and corner of the grain became rounded. According to Gautier *et al.* (2001), the etching in these places was relatively easy
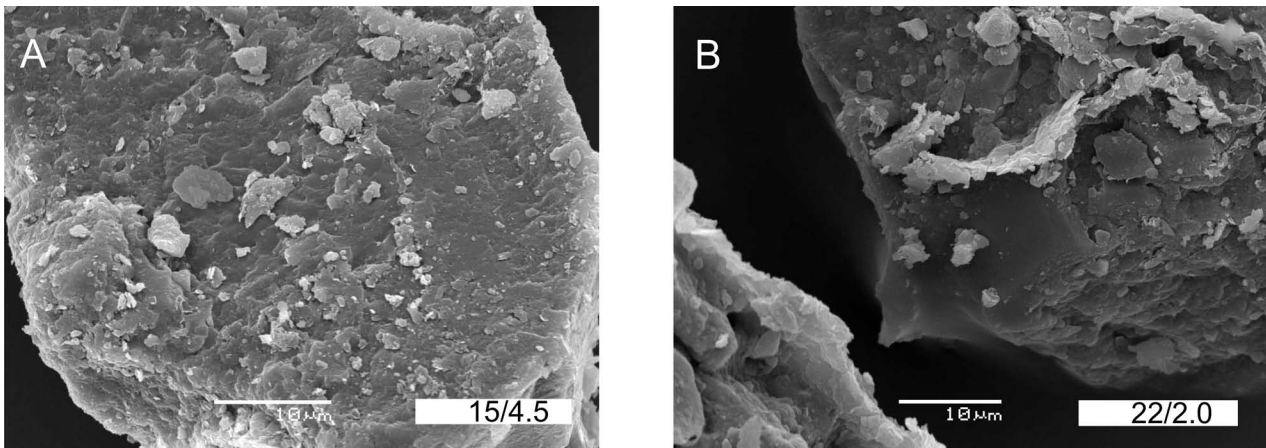
Fig. 12. Microstructures on quartz grain surfaces in SEM. **A** – intensive etching quartz grain with platy ppt coating (15/4.5), **B** – coated grain with new conchoidal fracture (22/2.0)

because of quartz crystal structure. This process might have occurred in various environments, provided that the pH of the solution was above 9 or below 3.5 (Dove & Rimstidt, 1994; Brehm *et al.*, 2005). The process intensity increased with the presence of humid acids (Kamiya *et al.*, 1974; Howard *et al.*, 1995) and with the decreasing grain size (Margolis, 1968; Schulz & Whrite, 1999). In the next stage, chemical weathering led to encrustation with smooth ppt crusts. Most probably, this type of crust was associated with high mineralization of circulating solutions and low amounts of clay fraction within the deposits (Woronko, 2007). Hence, a change in environmental conditions occurred associated with pH lowering. Preferably, in the case of a very high supersaturation of the solution with silica a simultaneous crystallization of overgrowth quartz took place (Subramanian, 1975; Higgs, 1979). In the subsequent stage the grains were also subjected to encrustation; however, the resulting crust was of platy ppt type (Fig. 9). Most probably, encrustation of that type took place in environments of low aggressiveness of solution and of high participation of the clay fraction in the sediment (Woronko, 2007). The final process which shaped the examined grain surfaces was mechanical weathering recorded by fresh conchoidal fractures (Figs 10E, 12B). High variability of grain surfaces and, most of all, different degree of encrustation prove that the grains originated from different sources, for instance from various parts of drainage basin. The presence of single glauconite grains in the deposits may indicate that the main sources of material, which comprise the basal parts of above mentioned sections, were waste covers of different ages, including those developed on marine sandstones (Mørk & Moen, 2007). This is obvious when considering the geological structure of the drainage basin. Such origin of the material is also supported by the composition of the heavy fraction, which is clearly dominated by minerals highly resistant to weathering (Table 3). Moreover, a high proportion of intensively etched grains, with overgrowth quartz at the surface and the presence of amorphous silica, may also indicate weathering crusts as sources of material (Kim & Lee, 2004; Mørk & Moen, 2007). Finally, the representation of weath-

ering covers of the different ages within the examined deposits may be proved by different degrees to which overgrowth quartz surfaces are weathered, as shown in sediments from sections No. 28 (mainly at the depths of 3.5 m and 6.0 m) and No. 22 (mainly at a depth of 4.5 m). The sediments were accumulated in the Middle Pleniglacial, in cold climatic conditions, in which a vegetation typical of a dwarf shrub tundra was developed (Sokołowski & Stachowicz-Rybka, 2009). Severity of climate is evidenced by the presence of grains with a fresh surface (particularly in sediments originating from basal parts of the section), being an effect of mechanical weathering. Deterioration of old weathering covers is indicated by the dominance of highly etched grains, including overgrowth quartz, in the sediment. In upper parts of sections, sediments of that age bear grains with a higher degree of encrustation, that are likely to be associated with an improvement in environmental conditions. Such an improvement is confirmed by results of palynological analysis (Sokołowski & Stachowicz-Rybka, 2009). The presence of pyrite in top sediments representing this period (Tables 2, 3) indicates their short-distance transport (Barczuk & Nejbert, 2007).

The increase in the amount of fresh grains or grains with the platy ppt encrustation (*e.g.*, in sediments conformable with the Weichselian Late Pleniglacial and Younger Dryas) may indicate material supply from the sources dominated by mechanical weathering, for instance frost action, with simultaneous material supply from old weathering covers. An effect of frost action is the production of quartz grains of the silt fraction (Wright *et al.*, 1998). It may be associated with a period of severe climatic conditions and reduction of vegetation cover. In such conditions a supply of mineralogically more diversified material occurred, including deposits unaffected by intensive chemical weathering. Based on the fact that fresh, non-encrusted grains are found mainly in fine- and medium-grained silt fractions, one cannot exclude that a part of sediments filling the valley bottom was transported by wind and accumulated in places of higher humidity or on the leeward sides of large field obstacles. Both factors might have been involved here. An alter-

ation in the composition of heavy minerals, recorded in topmost parts of sections (*e.g.*, section No. 28; Table 3), may also support this assumption.

The above mentioned climatic changes are not recorded in many properties of the sediment, like grain size and grain surface microrelief. However, as van Huissteden *et al.* (2001) and Vandenberghe (2002) showed in their studies, climatic changes, especially of short duration, are not recorded in fluvial deposits. Comparison of present-day and older sediments, including the Weichselian ones, indicates that in the past the Velyky Lukavets was a river of considerably lower energy.

The curious feature of the Velyky Lukavets River (in fact, a foreland river) is the high thickness of overbank deposits. In the Ropyshche area, the floodplain deposits constitute 50 – 100% of total thickness in most of examined sections. So far, such proportions have not been recorded in deposits filling the river valleys of the Outer Eastern Carpathians and the Carpathian Foreland in the Ukraine (*cf.* Raskatov, 1966; Kravchuk, 1999). Even in the large Ukrainian river valleys, where higher amounts of fine-grained material are deposited, the participation of overbank deposits is estimated as 10–20% (Matoshko *et al.*, 2004).

It seems likely that the Velyky Lukavets River was a meandering or anastomosing (anabranching) river (*cf.* Teisseyre, 1992; Gradziński *et al.*, 2000; Vandenberghe, 2001), as indicated by both lithological data and the presence of peat-forming vegetation. Some species recorded at Starunia (*e.g.*, *Phragmites australis*, *Typha latifolia* and *Bidens* sp.) are also encountered in river channels and on side bars of anastomosing rivers, and contribute greatly to the formation of peat-bogs and to the deposition of mineral sediments (Gradziński *et al.*, 2003a, b).

Also, it is possible that the large thickness of overbank deposits can be associated with damming of the outflow of the Velyky Lukavets River to the north, which resulted in an increase of water level, reduction of river bed gradient as well as formation of swamps and a periodical lake or lakes. The dam probably occurred in a narrowing of the alluvial terrace I and the recent floodplain, close to a cone-like hill. It cannot be excluded that during the last glaciation, when the majority of described deposits were formed under conditions controlled by the permafrost (Sokołowski & Stachowicz-Rybka, 2009), the lakes could have had the character of thermokarst lakes. However, the reasons of the wetlands formation should be searched for beyond the periglacial processes. There are a few possibilities, though none of them can be proved unequivocally. The resistance to denudation of the salt-bearing Vorotyshcha beds and the Sloboda Conglomerates, which build the bedrock in this part of the valley, does not allow for linking the described valley narrowing to lithological differences. Another reason could be either strike-slip or oblique-slip tectonic movements along one of the perpendicular faults that are marked on the geological maps of Koltun *et al.* (2005) and Korin (2005). Perhaps, one such fault runs along the northern side of the Dashevets Stream valley, causing a minor, SW-directed shift of the ridge on which Starunia is located. Similar cases of wetlands development in fluvial valleys upstream of cross-cutting fault zones were described by Sołtysik (2000)

from the Holy Cross Mountains. Landslides descending down the right slope of the valley to the north of the previously mentioned hill cannot be excluded, either. Minor slope movements are observed in this area up today. Landslide tongues connected with seismic shocks during fault reactivation might have periodically dammed the outflow of river waters. Such damming must have lasted until historical times (Sokołowski & Stachowicz-Rybka, 2009) when sedimentation was more and more affected by human activity, causing an increase in the grain size of overbank deposits (Fig. 11) and an admixture of anthropogenic material.

GEOLOGICAL FUNDAMENTALS OF FURTHER EXPLORATION FOR LARGE MAMMALS IN STARUNIA

Among many geological criteria pertinent to prediction of the sites where large mammals can be discovered, the most important are: (i) Pleistocene age of sediments, (ii) lithology limited to muds, clayey muds and biogenic deposits (peats, peat muds and biogenic muds), and (iii) thickness of these sediments. It must be emphasized that each of above mentioned sediments can be locally saturated with bitumens and brines (Kotarba *et al.*, 2009b).

The absolute age datings as well as the character of plant remains and malacofauna (Kuc *et al.*, 2009; Sokołowski & Stachowicz-Rybka, 2009; Stachowicz-Rybka *et al.*, 2009b) undoubtedly show that sediments filling the bottom of the Velyky Lukavets River valley are of Late Pleistocene (Eemian Interglacial – Late Weichselian) and Holocene ages (OIS 5e – 1) (Figs 3–5). The crucial factor in exploration for particular fauna species is the localization of Pleistocene/Holocene boundary. As the environmental conditions during most of the Holocene did not differ from those during the Weichselian, and as deposition was continuous, no lithological differences exist between sediments from both stages.

This lack of differences precludes the application of lithostratigraphic (Sokołowski & Stachowicz-Rybka, 2009) and morphostratigraphic (Sokołowski, 2009) procedures. Hence, in sections lacking the age determinations, the Pleistocene/Holocene boundary was interpreted (Figs 2A, 2B, 2C, 3, 4) using various criteria. Usually, the boundary was positioned at a depth similar to adjacent boreholes, for which age documentation of drilled sediments was completed. In some cases the boundary was located close to the bottom of biogenic sediments. In the authors' opinion possible estimation error of the depth to the Pleistocene/Holocene boundary varies from 0.5 to 1.0 m. Such a method of Pleistocene/Holocene boundary positioning was applied for the majority of sections (Nos 4N, 28, 30, 30N, 33 and 36N; Fig. 3). Most precisely, the boundary was determined in sections for which palynological studies were completed (Nos 4', 22, 28 and VL 1). For the remaining sections, for which absolute ages were determined (sections Nos 1, 2, 3, 13, 23, 24, 25 and 42), the estimation error is less than 0.5 m.

Pleistocene muds form individual layers only in sections Nos 15 and 28. In the remaining sections the intercala-

tions of biogenic deposits were found, which constitute in the extreme up to 75% of thickness of Pleistocene sediments (section No. 24). Moreover, Pleistocene muds and biogenic sediments were encountered in most of studied sections except for the vicinity of the Rinne Stream, east of Nos 1 and 4 boreholes, and in the southern part of Ropyshche, in boreholes Nos 5N, 6N, 7 and 8. The thickest Pleistocene muds and biogenic deposits (10.6 m) were observed in section No. 33 and thicknesses exceeding 6 m were measured in Nos 15, 26, 28, 30N and 36 boreholes, while in Nos 3, 21, 22 and 30 boreholes thicknesses of these strata were close to 5 m.

A commonly quoted statement of Olszewski (see Zuber, 1885) on the presence of plant remains in the shafts at depths exceeding 35 m was later repeatadly linked with a large thickness of Quaternary deposits. Also during excavations in 1907, in shaft No. IV (Fig. 1), in a mud close to mammoth and rhinoceros remains found at 17.6 m depth, numerous fruit, leaves and wood fragments were found (Raciborski, 1914a, b; Szafer, 1914). However, the type of this vegetation did not correspond to the Pleistocene flora, it rather indicates recent (Holocene) flora from nearby. Later excavations revealed that both mammal and plant remains were found in secondary ground (Nowak & Panow, 1930; Szafer, 1930), but the concept of the Miocene top surface located at least at 17 m depth has remained in the literature until now (Pawłowski, 2003).

In the Ropysche area, the top of the salt bearing Lower Miocene Vorotyshcha beds occurs at depths from 2.0 to 13.5 m, mostly about 10 m (Figs 2A, 2B, 2C, 3, 4).

The obtained results support the views of Mitura (1944). Undoubtedly, the deposits described in older papers were mine wastes filling old shafts. Moreover, low lithological diversity of studied sediments intensified by saturation with both the brine and bitumen cause distinct homogenization of their physical and geochemical properties (Kotarba *et al.*, 2009a, b, c; Sechman *et al.*, 2009; Mościcki *et al.*, 2009; Mościcki & Sokołowski, 2009).

Despite genetic and sedimentary aspects, the lithology of studied sediments and their thickness are crucial factors for future exploration leading to further discoveries of large mammals. Fossils found in 1929 were hosted in above mentioned …"muds with *Betula nana*"… (Nowak & Panow, 1930), which should be regarded as an equivalent of fine-grained sediments of Weichselian age. Moreover, it should be assumed that the thickness of these strata had to be at least 2 m in order to preserve the buried carcasses in horizontal position. These factors supported by the degree of disturbance of strata by mining operations limit the area of further exploration to only two small fragments located in the western part of Ropyshche. The larger area includes the vicinity of boreholes Nos 2, 3, 21, 22, 23, 28, 30 33 and 36N. The smaller one is located in the neighbourhood of borehole No. 42. Their locations are shown in Fig. 1.

CONCLUSIONS

The results of lithological studies of the Pleistocene and Holocene sediments in the Starunia area indicate that:

– older data concerning the thickness of Quaternary sediments are not credible. Boreholes drilled for the purpose of this study revealed thicknesses rarely and only slightly exceeding 10 m;

– therefore, considering the recognized thickness of Weichselian fine-grained DF sediments and the age of mammals, it seems likely that areas suitable for further exploration exist only in the western part of Ropyshche area;

– Quaternary sediments filling the Velyky Lukavets River valley bottom were deposited in the river-bed (gravel, sandy gravel sediments), overbank, and slope (mud, sandy mud) subenvironments. The entire succession is covered by mine wastes. The largest thicknesses are typical of the overbank sediments and their sections are dominated by fine-grained pool deposits. Accumulation of the latter proceeded mainly from suspension or due to very calm flows. Quiet sedimentation was periodically interrupted by the supply of more coarse-grained material;

– poorly differentiated grain size and mineral compositions, and predominance of resistant heavy minerals within fine-grained sediments indicate that, most probably, the principal sources of the material were weathering crusts of different ages, developing on poorly lithologically differentiated Carpathian flysch strata and Miocene deposits of the Carpathian Foresee;

– following sediment deposition, the amount of material produced due to mechanical weathering, *e.g.*, frost action, increased. This may indicate increasing severity of climate and reduction of vegetation cover. However, such a change in environmental conditions was not recorded in accumulated sediments;

– predominance of overbank sediments in the studied sections, as far as sediment thickness is concerned, suggests that the Velyky Lukavets River was periodically an anastomosing river or experienced damming of the outflow. Recent reactivation of strike-slip or oblique-slip faults and/or landslide tongues entering the valley bottom are likely reasons;

– from the lithological point of view the most favorable conditions for preservation of large, extinct mammals still exist in the two selected areas, where the total thickness of Pleistocene muds exceeds 2 metres. The first one is in the vicinity of boreholes Nos 2, 3, 21, 22, 23, 28, 30 33 and 36N, and the other, smaller one, spreads around borehole No. 42.

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