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Depositional environment and provenance of the pre-glacial Słopiec Formation, Holy Cross Mountains (Poland)

Małgorzata LUDWIKOWSKA-KĘDZIA[1,*] Barbara SŁODKOWSKA[2], Barbara WORONKO[3] and Tadeusz SZYDŁAK[4]

[1] Jan Kochanowski University, Institute of Geography and Environmental Science, Żeromskiego 5, 25-406 Kielce, Poland; ORCID: 0000-0001-5747-4934

[2] Polish Geological Institute – National Research Institute, Rakowiecka 4, 00-975 Warszawa, Poland; ORCID: 0000-0003-3760-4935

[3] University of Warsaw, Faculty of Geology, ul. Żwirki i Wigury 93, 02-089 Warszawa, Poland; ORCID: 0000-0002-2763-5650

[4] AGH University of Krakow, al. Adama Mickiewicza 30, 30-059 Kraków, Poland; ORCID: 0000-0002-6516-2612

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The pre-glacial, autochthonous deposits of the Słopiec Formation represented by the Jabłonna and Radzików members, were identified in two new boreholes – Jabłonna UJK-1 and Słopiec UJK-2 – which were drilled in the Słopiec Basin in the Holy Cross Mountains. Their sedimentary environment, provenance, and environmental conditions were determined using sedimentological, mineralogical-petrographic, geochemical, geophysical and palynological methods. The boundaries of the Słopiec Formation are well defined. It lies on the Paleozoic bedrock and is overlain by glacial deposits, the precise chronostratigraphic position of which remains under discussion. The basal Jabłonna Member comprises lacustrine deposits (muds; silts and silts with interlayers of sands and with organic detritus, which overlie gravels), while the overlying Radzików Member consists of fluvial (fluvio-aeolian) deposits (sands and sands with gravels). Deposition took place in karst lakes, probably meromictic, in a cold climate. The source material came from the local weathering covers (Paleozoic, Mesozoic and Paleogene-Neogene). Palynological analysis (7 samples) revealed the presence of 118 taxa, including 23 cryptogam taxa, 20 gymnosperm taxa, 51 angiosperm taxa and 24 phytoplankton taxa, indicating significant mixing and repeated redeposition of palynomorphs from various sources. The final phase of deposition of the Jabłonna Member occurred during the Quaternary Period. The results described provide the first detailed description of pre-glacial deposits in the Holy Cross Mountains and will serve as an important reference for future regional and extra-regional lithostratigraphic correlations.

Key words: sedimentology, lithostratigraphy, pre-glacial deposit, Holy Cross Mountains.

INTRODUCTION

The pre-glacial succession (*sensu* Lewiński, 1928, 1929) in the lithostratigraphic profile of the Quaternary in the Holy Cross Mountains (HCM; facies of valley-type Pleistocene deposits after Czarnocki, 1931) directly overlies Paleozoic bedrock and/or terrestrial Paleogene-Neogene deposits. These underlie the oldest deposits of glacial origin in the region (Czarnocki, 1927, 1931; Łyczewska, 1971; Filonowicz, 1972; Lindner, 1984). This succession is described as pre-glacial due to the absence of the Scandinavian material commonly found in deposits of glacial provenance regionally (Łyczewska, 1971; Lindner, 1984). However, this is an ambiguous description with a broad temporal meaning (Kasiński and Słodkowska, 2024).

The pre-glacial deposits of terrestrial facies in the HCM have been termed Eopleistocene, indicating a period of deposition separated from that of known Pliocene deposits by an erosional boundary and followed by accumulation of glacial deposits containing material of Scandinavian origin (Lindner, 1984). They have also been referred to the Lower Quaternary (Lindner, 2004), and to the Kozienice and Krasnystaw facies (Mojski, 2005). They include: a) various types of loamy weathered bedrock materials, mainly from a karst environment (e.g., Czarnocki, 1935; Kowalski, 1958; Głazek et al., 1977; Różycki, 1978; Urban, 2013); b) colluvial deposits (slope deposits without Scandinavian material), which fill depressions of fluvial, karst and tectonic origin, and which record the activation of gravitational slope processes during the oldest Scandinavian

* Corresponding author, malgorzata.ludwikowska-kedzia@ujk.edu.pl

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glaciation (Lindner, 1984); and c) fluvial deposits constituting the upper part of the alluvial succession, and considered to be equivalent to the Pliocene-Eopleistocene valley infills in the western and central parts of the HCM, and to comprise at least two Eopleistocene fluvial units in their eastern part (Lindner, 1984, 2004).

The pre-glacial fluvial succession recognised (sandy-gravelly, composed of local rock pebbles) was interpreted as recording the functioning of the valley system in the eastern (at 190–200 m a.s.l.) and western (at 160–170 m a.s.l.) parts of the Holy Cross region during the Eopleistocene. These parts are divided by a watershed line running west of Kielce, Chęciny, and Jędrzejów (Lindner, 1984). In this palaeogeographic interpretation, in the lithostratigraphic profile of the Quaternary deposits (of the Pleistocene valley facies according to Czarnocki, 1931) in the HCM, the overlying thick series of muds (without Scandinavian material) were considered to be of Pleistocene (Glacial Pleistocene) age (Lindner, 1984, 2004). These muds were described as valley deposits accumulated in depressions that were blocked by ice masses during the pre-maximum stage of the South Polish Glaciation (Lindner, 1984) and, more broadly, during the South Polish Glaciations (Lindner and Dzierżek, 2019, Dzierżek et al., 2021). They were also interpreted as "directly drifted from the front of the approaching ice sheet or derived from loess washed down from the slopes of nearby hills and deposited on the floodplains of river and lake of that time" (Filonowicz, 1972: p. 106). It was believed that the source areas of the clayey-silty deposits were the outcrops of Krakowiec clays (the Machów Formation; Miocene deposits in the vicinity of the HCM; cf. Czapowski, 2004), from which this fine sediment was probably washed down to the valley bottoms and deposited there by rivers (Filonowicz, 1972: p. 114). As fluvial deposits filling fossil valleys (dissecting older slope and colluvial deposits), the muds overlie the Eopleistocene alluvium or rest directly on the pre-Quaternary deposits (Lindner, 1984, 2004).

The long-term absence of sedimentological and palynological studies of the pre-glacial succession in the HCM (and also of other Quaternary deposits), together with the complicated and dynamic nature of the morpho- and lithogenetic processes in the HCM during the Eopleistocene/Early Quaternary, makes it difficult to interpret the environmental conditions and stratigraphic position of the pre-glacial succession. This also hinders placing it within current climatostratigraphic schemes of the Polish Lower Pleistocene based on palynostratigraphy (Winter, 2015), or in the broader Quaternary stratigraphic framework of Poland (Marks, 2023a, b). Therefore, identifying the diagnostic features of the pre-glacial succession in individual morphostructural units of the Holy Cross Mountains (independently of each other and at a small spatial scale) is a key issue in the Quaternary lithostratigraphy of this area. The importance of this task is justified by: a) the still debated nature of glaciations in the HCM (e.g., Liszkowski, 1976; Lindner, 1984; Ludwikowska-Kędzia, 2018; Dzierżek et al., 2021); b) the difficulty of applying morphostratigraphic criteria to distinguish between Quaternary glacial and non-glacial deposits in the HCM (which often have a similar lithology; Ludwikowska-Kędzia, 2018); and c) the very limited state of knowledge regarding the Paleogene–Neogene evolution of the HCM.

As autochthonous deposits formed in the specific environment of the HCM, the pre-glacial succession provides a unique record of the environmental conditions of the period before the diachronous (in respect of time and area) encroachment of glaciation, which is considered a "disturbance" (*sensu* Ballantyne, 2018), and before the appearance of allochthonous deposits in the HCM (Ludwikowska-Kędzia, 2018). Apart from its obvious value in understanding the Early Pleistocene palaeogeography of the HCM, determining its characteristic features is the basis for distinguishing this succession from the younger Quaternary deposits of various ages and origins that occur in the HCM and that often resemble it in terms of lithology and lithofacies. Moreover, the HCM are considered the source area of pre-glacial deposits in Central Poland (e.g., Clark et al., 2006; Bujak, 2010; Roman, 2010; Makowska, 2015; Bujak et al., 2016; Goździk and Zieliński, 2017; Zieliński, 2018), accumulating over a period from ~2.58 to 0.9 Ma (Marks, 2023b). These pre-glacial deposits occur in various facies, reflecting a mosaic of different depositional environments. They include fluvial and delta deposits, as well as deposits of alluvial fans (in fluvial, lacustrine, and fluvial-lacustrine environments), formed from the early Pliocene to the older, pre-glacial Quaternary (Middle Pleistocene), with visible cyclical deposition associated with climatic fluctuations, as in other parts of Europe (e.g., Kasse, 1990; Boenigk and Frechen, 2006; Kemna, 2008; Westerhoff et al., 2008). Pre-glacial deposits of this type are also common in the Polish Lowland (Kasiński and Słodkowska, 2024).

This article describes diagnostic sedimentological features of the pre-glacial sedimentary succession that allow its identification in the HCM as the Słopiec Formation (based on two newly drilled boreholes: Jabłonna UJK-1 and Słopiec UJK-2; Fig. 1). Additionally, it reinterprets and further characterizes the sedimentary environment and the environmental conditions within which this pre-glacial succession was deposited, and determines its sedimentary provenance.

STUDY AREA

The two new boreholes, Jabłonna UJK-1 (50°47'07"N; 20°45'44"E) and Słopiec UJK-2 (50°47'14"N; 20°47'20"E), were drilled near the villages of Jabłonna and Słopiec Szlachecki in the southern/central part of the HCM Paleozoic massif – the zone of the Chęciny–Klimontów anticlinorium of the Kielce region (the Kielce Fold Zone, according to Konon, 2008; Fig. 1A, B), and the Borków syncline, which is the eastern part of the Gałęzice–Bolechowice syncline (Filonowicz, 1976; Konon, 2008; Fig. 1C). These two boreholes were located in the Słopiec Basin (Fig. 1C), very close to the archived boreholes described by Czarnocki (1975) and Filonowicz (1972, 1976).

The bedrock in the Borków syncline is composed of Devonian dolomites and limestones and is cut by numerous faults (Filonowicz, 1976); according to Kowalski (2001) it forms part of a graben system (Fig. 1C).

The relief of the Paleozoic bedrock in the Słopiec Basin varies and is partly concealed by the Quaternary deposit cover (Tracz, 1986; Szczepański, 1995). It is characterized by karst structural palaeodepressions, which are separated by remnant hills (Fig.1D). Their spatial arrangement and size are similar to those of a polje. The Słopiec Basin is surrounded on several sides by low hills consisting mainly of Cambrian and Devonian sandstones, marls and siltstones. To the south and southeast, the basin area borders the palaeozone of Miocene sea bays (Radwański, 1969, 1973; Czapowski, 2004). The bottom of the Słopiec Basin is partly occupied by the Belnianka River valley (Fig. 1C).

MATERIALS AND METHODS

The deposits in the Jabłonna UJK-1 and Słopiec UJK-2 borehole profiles were investigated using the full spectrum of research methods typically employed in Quaternary stratigraphic studies (cf. Ludwikowska-Kędzia, 2018), i.e. standard

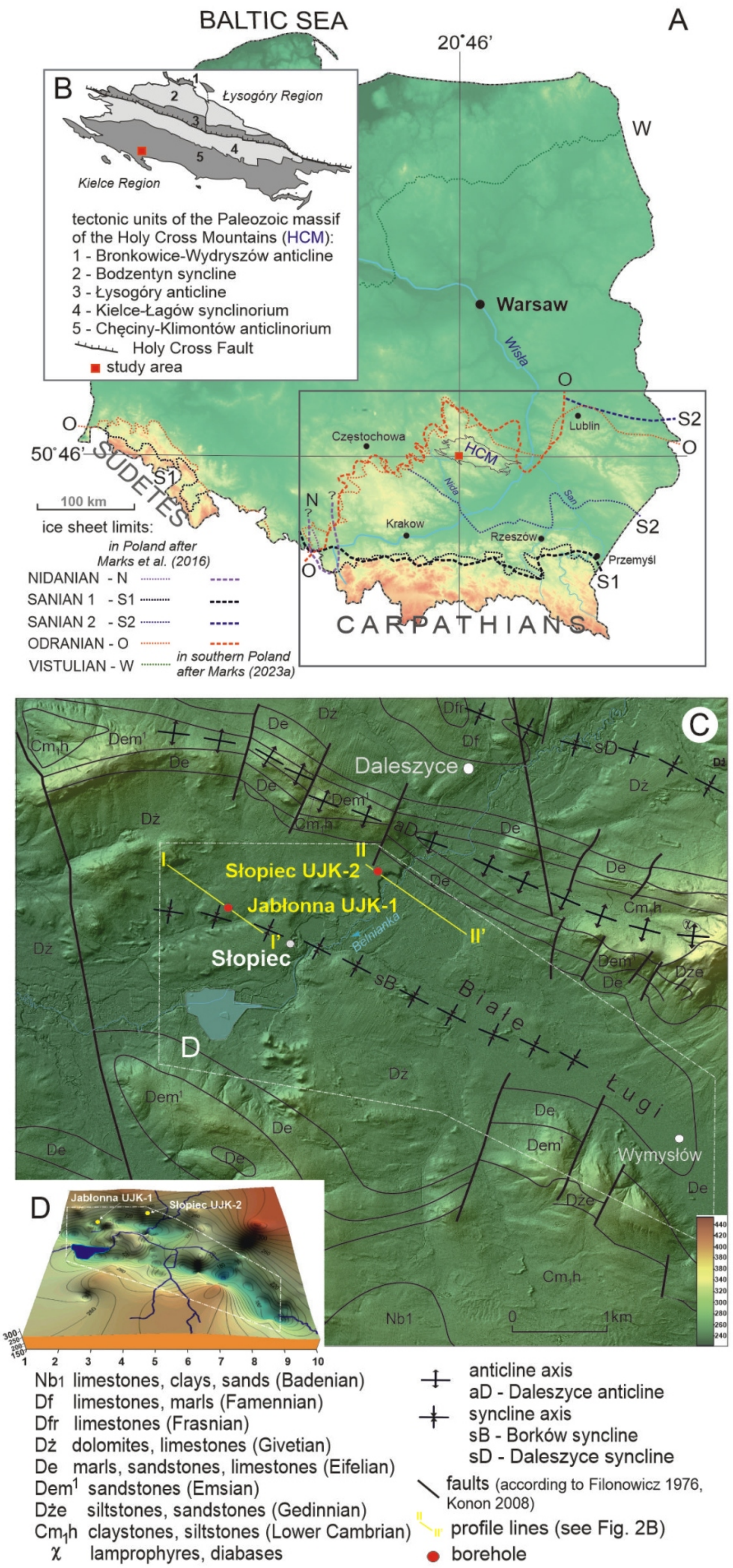

Fig. 1A, B – location of the study area in relation to the ice sheet limits in Poland (according to Marks et al., 2016; Marks, 2023a) and the tectonic units of the Paleozoic core of the Holy Cross Mountains; C, D – location of the Jabłonna UJK-1 and Słopiec UJK-2 boreholes against the background of a Słopiec Basin DEM with a geological sketch and the palaeorelief of the sub-Quaternary bedrock in the Słopiec Basin

sedimentological, petrographic, geochemical, geophysical, and palaeobotanical methods (Lindner, 1992; Mycielska-Dowgiałło and Rutkowski, 1995, 2007; Harasimiuk and Terpiłowski, 2003). They included analyses of grain size, carbonates and organic carbon content, mineral and petrographic composition, the rounding and frosting of quartz grains, magnetic susceptibility, and palynological analysis.

The sand and gravel material was dry-sieved using a column of Fritsch sieves with mesh diameter steps every 0.5 . The grain-size distribution of the silty-clayey deposits was analysed using a *Laser Particle Sizer Analyssette 22* (for fractions <1 mm). The content of carbonates was determined using the Scheibler method (Kowalkowski and Swałdek, 1994). The heavy mineral spectrum was examined in the 0.1–0.2 mm fraction after the heavy fraction was separated in bromoform with a density of 2.89 g/cm^3. The mineral and petrographic composition of the muds was determined in thin section, using an optical microscope. The rounding and frosting of quartz grains in the 0.8–1.0 or 0.5–0.8 mm fractions were analysed using the Cailleux method (1942), as modified by Goździk (1980) and Mycielska-Dowgiałło and Woronko (1998). This method combines the degree of rounding of the quartz grains according to Krumbein (1941) with the morphology of their surface. Geophysical investigations, including magnetic susceptibility and thermal analyses, were carried out at the Institute of Physics of the Polish Academy of Sciences in Warsaw.

This petrographic research was supplemented with a palynological analysis of seven mud samples taken from the Jabłonna Member in two boreholes: three samples from the Jabłonna UJK-1 borehole at depths of 42.2 m, 48.8 m and 49.3 m, and four samples from the Słopiec UJK-2 borehole at depths of 48.5 m, 51.0 m, 54.0 m and 55.0 m. The samples underwent laboratory processing using standard palynological maceration methods, involving the disaggregation of ~5 g of material from the centre of each sample. This material was then treated with 10% HCl to remove the carbonates. Next it was boiled with 7% KOH to remove humus compounds. The mineral and organic fractions were separated in heavy liquid, i.e. a water solution of zinc chloride with a density of 2.31 g/cm^3. The organic material was then macerated using a modified acetolysis method (Erdtman, 1954). Glycerine microscopic slides (20 x 20 mm) were prepared from the obtained macerate and analysed using a *Leica ARISTOPLAN* biological microscope in transmitted light at 400x magnification.

All of the palynological material was analysed: palynomorphs (sporomorphs and phytoplankton) and phytoclasts (wood fragments, cuticles, etc.). The frequency of sporomorphs (spores and pollen grains) was generally satisfactory. The palynological analysis carried out was qualitative. The poor state of preservation of the specimens (pollen grains were broken, deformed, with signs of corrosion on their surfaces) made precise identification and dating of the sporomorph assemblage difficult. Spores and pollen grains were identified using morphological systematics, combined with the botanical classification of the taxa where possible (Ziembińska-Tworzydło et al., 1994a, b; Stuchlik et al., 2001, 2002, 2009, 2014). Marine phytoplankton also constituted a significant group in some samples and were identified using the taxonomy of Williams et al. (2017a, b).

RESULTS

DESCRIPTION OF THE JABŁONNA UJK-1 AND SŁOPIEC UJK-2 BOREHOLES

Solid bedrock was reached in the Jabłonna UJK-1 and Słopiec UJK-2 boreholes at a depth of 50.2 m and 57.6 m, respectively (Fig. 2A, B). Comprehensive studies of the Jabłonna UJK-1 and Słopiec UJK-2 borehole profiles enabled the identification of four lithogenetic units (each divided into subunits): two autochthonous, i.e. fluvial-lacustrine FR (17.5–19.2 m thick) and/or fluvial-aeolian FA (8 m thick), and two allochthonous, i.e. glacigenic GLG (17.5–31.0 m thick) and/or fluvial-slope-aeolian FSA (14.6 m thick; Ludwikowska-Kędzia, 2018; Fig. 2B).

The autochthonous lithogenetic FR and FA units do not contain Scandinavian erratics (Ludwikowska-Kędzia, 2018). The FR unit (in both boreholes) consists of muds – primarily grey-green and blue silts, as well as silts with sand interlayers and organic matter – overlying gravels and sandy silts, and lacks a molluscan fauna (see Figs. 2B, 3, 4A, B1–10, C). The FA unit consists of sands with fine gravels (or silty-clayey intraclasts; Figs. 2B, 3, 4B11-12, C).

The allochthonous GLG and FSA units are characterized by the presence of Scandinavian rocks. The GLG glacial unit consists primarily of glacial diamictons separated by glaciofluvial deposits and the deposits of local ice-dammed lakes. Their heavy mineral composition is typical of Quaternary glaciogenic deposits in Poland (see Racinowski, 2010). By contrast, the FSA unit deposits are a mixture of local fluvial, slope, and redeposited glaciogenic deposits. Their heavy mineral spectrum reflects the duality of the material sources (weathered local rock covers and glaciogenic material) and the diverse conditions of their transport and deposition (slope, fluvial and aeolian environments).

In this study, the name pre-glacial Słopiec Formation (named after the village near the boreholes) was adopted for the autochthonous pre-glacial FR and FA units (in both boreholes, i.e. Jabłonna UJK-1 and Słopiec UJK-2) considered together in relation to the overlying GLG unit (Fig. 2B). Within the Słopiec Formation (17.5–27.5 m thick, occurring at 200–226 m a.s.l.), two units were distinguished: the Jabłonna Member (corresponding to the FR unit in both boreholes) and the Radzików Member (corresponding to the FA unit in the Słopiec UJK-2 borehole), an analogue of the ‘Radzików series’ described by Makowska et al. (1976).

The muds (the Jabłonna Member), overlying sandy gravels and sandy silts, are the distinctive unit within the lithostratigraphic profile of the Quaternary deposits in the HCM (Czarnocki, 1931, 1950; Lindner, 1984). They are easily identifiable based on their lithology and lithofacies and have been found in numerous boreholes (e.g., Czarnocki, 1975; Filonowicz, 1972, 1976; Lindner, 1984). The Jabłonna Member deposits can be correlated with the lithological units no. 1 and 4–6 (Lindner, 1984) in the most complete lithostratigraphic profile of Quaternary deposits of the Pleistocene valley facies in the vicinity of Daleszyce (after Łyczewska, 1971, as modified by Lindner, 1984), in the southern part of the HCM. However, as deposits of this type (muds) occur in various morphogenetic environments of different ages in the HCM (e.g., fluvial, slope, lac-

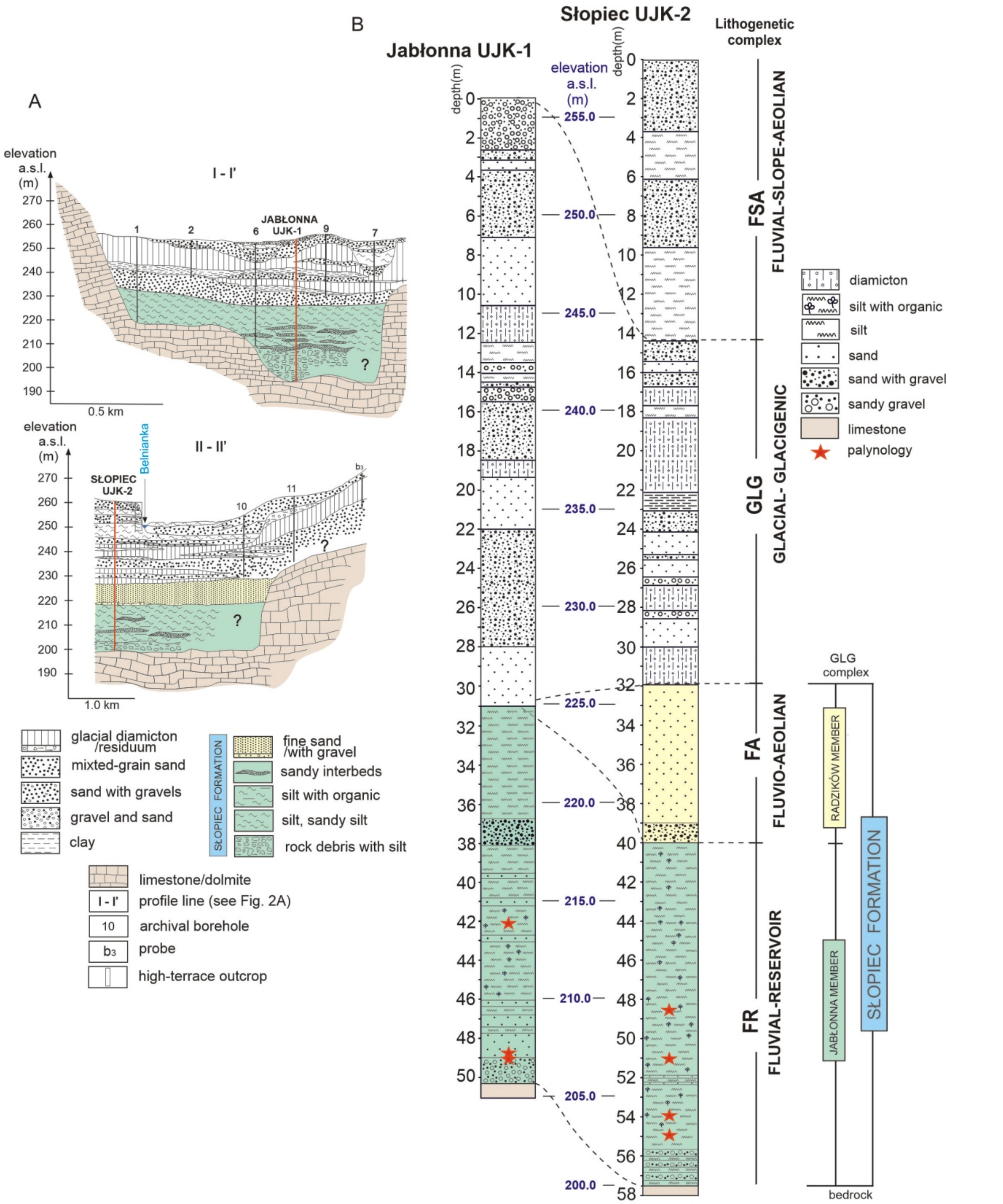

Fig. 2A – geological cross-sections through Quaternary deposits in the Jabłonna and Słopiec area (according Ludwikowska-Kędzia, 2018, modified); B – lithological profiles of the Jabłonna UJK-1 and Słopiec UJK-2 boreholes (according Ludwikowska-Kędzia, 2018)

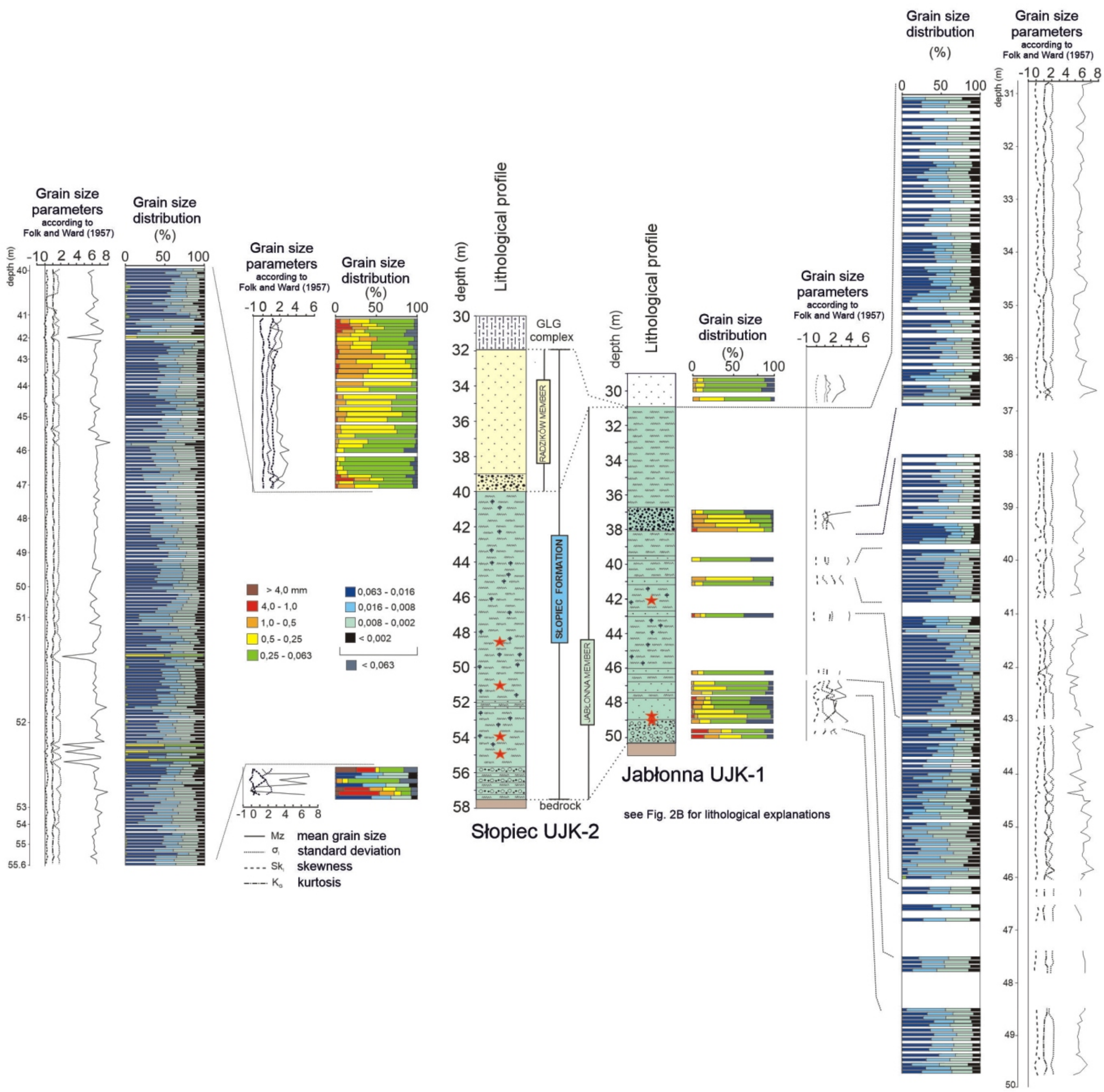

Fig. 3. Grain size distribution of the Słopiec Formation in the Słopiec UJK-2 and Jabłonna UJK-1 boreholes (based on Ludwikowska-Kędzia, 2018)

ustrine, glacial), they can be incorrectly interpreted and correlated, particularly in boreholes (Ludwikowska-Kędzia, 2000, 2018). To minimize errors in interpretation and, above all, to indicate the features identifying this depositional sequence, further palynological studies of the Jabłonna Member deposits have been made. Such analysis is often critical to determining the chronostratigraphic position of muds of various ages in the HCM (Ludwikowska-Kędzia, 2018).

DIAGNOSTIC FEATURES OF THE SŁOPIEC FORMATION

The diagnostic features of the Słopiec Formation in the Jabłonna UJK-1 and Słopiec UJK-2 borehole profiles are summarized in Tables 1, based on the results published by Ludwikowska-Kędzia (2018). These features included textural characteristics (grain size, rounding and frosting of quartz grains and their packing), and sedimentary structures (depositional, deformational and erosional ones), mineral and petrographic composition, heavy mineral spectrum, calcium carbonate content, and magnetic susceptibility of the deposits (Figs. 3–6).

DESCRIPTION OF THE PALYNOLOGICAL SPECTRUM IN THE JABŁONNA MEMBER

The results of the palynological studies of the Jabłonna Member in the Jabłonna UJK-1 and Słopiec UJK-2 borehole profiles are summarized in Tables 2 and 3 (Figs. 7–9). Palynological analysis (7 samples) revealed the presence of 118 taxa, including 23 cryptogam taxa, 20 gymnosperm taxa, 51 angiosperm taxa, and 24 phytoplankton taxa. Phytoclasts occurred in the form of brown and black wood fragments and cuticles. Inorganic debris consisted of glauconite aggregates.

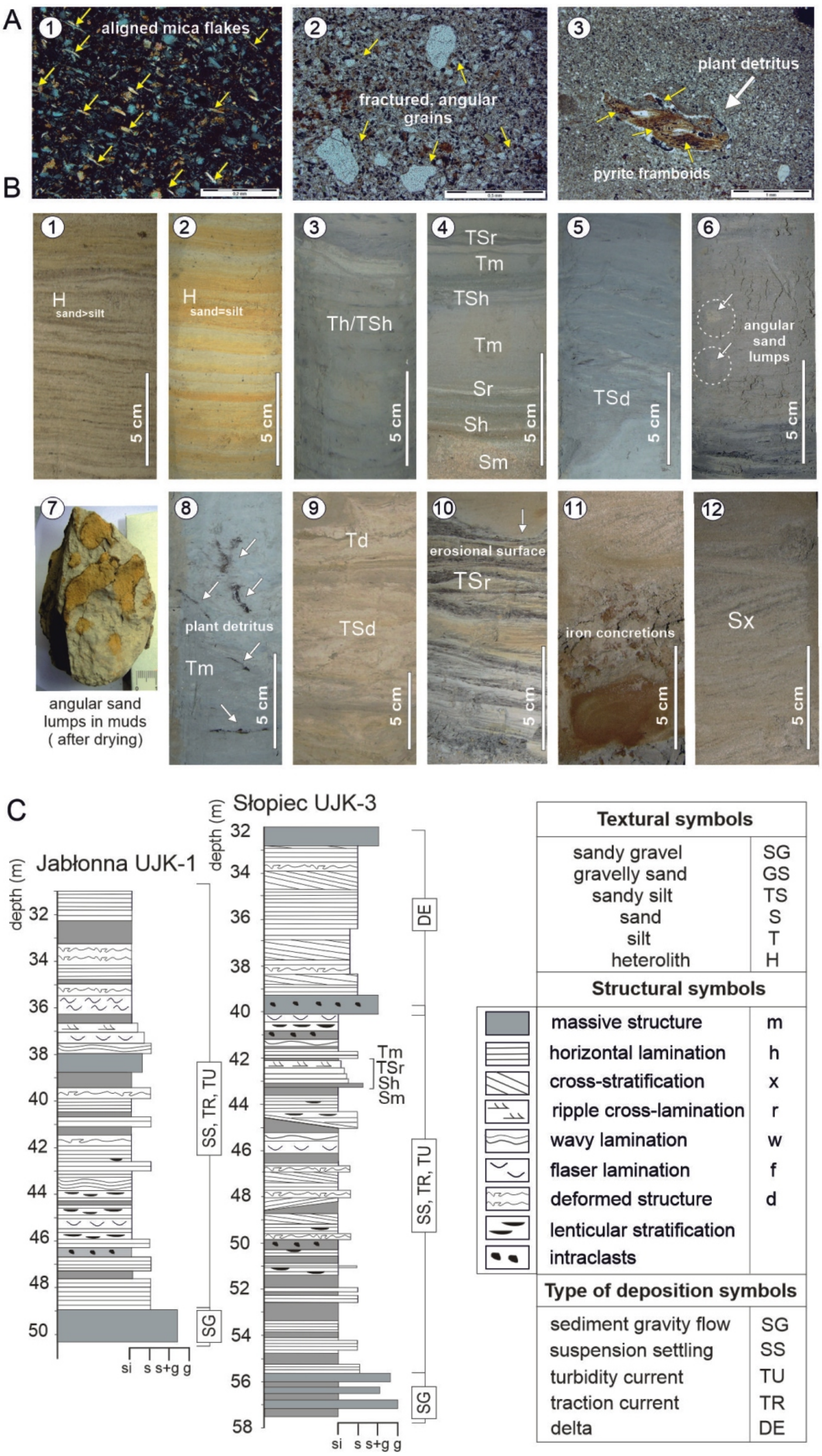

Fig. 4A – muds of the Jabłonna Member in thin section; B – sedimentary structures of the Jabłonna (1–10) and the Radzików members (11–12) deposits; C – simplified sedimentological logs of the Słopiec Formation (Słopiec UJK-2 and Jabłonna UJK-1 boreholes)

Symbols of the lithofacies and lithogenetic code according to Zieliński (2014)

Table 1

Diagnostic features of the Słopiec Formation divided into the Jabłonna and Radzików Members (based on Ludwikowska-Kędzia, 2018)

		SŁOPIEC FORMATION		
ALTITUDE		**200.0–225.0 m a.s.l.**		
THICKNESS (m)		**16.0–28.0**		
BOUNDARY		lower: Paleozoic bedrock; upper: glacial deposits; sharp, distinct		
MEMBER		**JABŁONNA**		**RADZIKÓW**
LITHOLOGY		gravel, sand, silt	muds: silt and silt with sand interlayers	sand, sand with gravel
THICKNESS (m)		1.0–2.0	15.0–18.0	8.0
ENVIRONMENT		lacustrine		fluvial (fluvio-aeolian)
		• gravel, sandy silt: record of the subaqueous flows and, indirectly, subaqueous landslides (through secondary flows; remobilisation) • muds: record of the oscillatory deposition from traction and suspension (turbidity currents)		• the subaerial (and/or subaqueous?) river-sediment accumulations near the mouth of a stream or river (delta)
TEXTURE (Figs. 3 and 5)	**grain size**	• gravels (fine and coarse), sand, silt • poorly and very poorly sorted	silt: • mainly coarse, fine and sandy silt, poorly and very poorly sorted –- grain size of detrital material is very diverse – grains of 0.01–0.06 mm predominate, with numerous quartz grains of 0.1–0.5 mm scattered among them (in thin sections); sand interlayers within silt: •fine and silty sand, poorly sorted but better than silt • multiple changes in grain size, which are a record of the conditions of sediment deposition in the lake	• coarse-grained sand with fine gravel and silty-clayey intraclasts (up to 5 mm) in the bottom part, overlain by medium- and fine-grained sand • well and moderately sorted deposit
	morphology	• angular, sporadically well-rounded gravel	silt: •angular and weakly rounded grains of detrital material predominate in silt, sand interlayers within silt: • predominance of quartz grains of EL (very well-rounded with smooth and shiny surface) type (43–61%) and/or EM/EL (moderately rounded with smooth and shiny surface) type • bottom part of the profile – high diversity of quartz grains: high content of O (other) type (43.4–60.6%), NU (fresh) type (13.1–14.4%) and C (cracked) type (11.7%); irregular quartz grains occur • middle part – very high content of C (cracked) type grains (22.8%) is accompanied by spherical iron concretions • upper part – high content of O (other) type grains, grains of RM (very well-rounded with matt surface) and EM/RM (moderately rounded, with matt surface only on convex parts of grains) types appear	• quartz grains of RM (very well-rounded with matt surface) and EM/RM (moderately rounded, with matt surface only on convex parts of grains) types predominate (totaling 76–92%); fluvio-aeolian deposits; • up the profile: grains of EM/EL (moderately rounded with smooth and shiny surface) and C (cracked) types disappear, the content of O (other) type grains decreases, and grains of EL (very well-rounded with smooth and shiny surface) and NU (fresh) types are absent.
SEDIMENTARY STRUCTURES (Fig. 4)	**depositional**	• massive structure • clast-supported gravel with silty-clayey matrix	• predomiantion of thin laminae (from several milimeters to 2 cm thick, with uneven lower and upper boundaries) – horizontal lamination, less often ripple cross-lamination, flaser, wavy and lenticular lamination – accentuated by grain size changes; thin interlayers of sandy silt streaks (up to 5 mm) and clay laminae (up to 0.2 mm) • sets of laminae with full or partial sequence of Bouma structures, recurring in different intervals throughout the profile of the muds; • thick laminae (up to 10 cm) and layers (10–40 cm) – massive structure, locally with sandy, angular and/or partially rounded lumps of yellow, carbonate-free, fine-grained sand (visible in deposits after they have dried) • normal (sporadically inverse) grading occurs within the sets of laminae, and is also visible in single thicker laminae	• horizontal lamination and cross-lamination predominate, massive structure occurs in places • frequency of cross-stratification increases up the profile but in the upper part only massive structure occurs

Tabl. 1 cont

	deformational and erosional	not observed	• in places convoluted structures • small erosional dissections in the top of layers and thick sandy laminae	not observed
MINERAL AND/OR PETROGRAPHIC COMPOSITION (Figs. 5 and 6)		debris of Scandinavian rocks is absent		
		• gravels are only local rocks (sandstones, limestones, lydites)	• mineral composition of muds is similar, throughout the profile, in clayey matrix there are: -numerous quartz grains, -plates of micas (mainly muscovite, less frequently biotite), -subordinately feldspars (mainly potassium feldspars, plagioclase is very rare), -numerous monocrystalline carbonate grains (<0.06 mm), -slightly larger, authigenic aggregates of micrite in the upper part of the complex, -single grains of glauconite, -pyrite framboids and microconcretions of fine-crystalline pyrite (up to 2mm) and -carbonized plant detritus, dinocysts • plates of micas (size: up to 0.3 mm) weathered to varying degrees, they usually show a distinct orientation consistent with deposit lamination (mainly in lower part of muds); • numerous angular quartz grains (0.01–0.03 mm) occur within the microconcretions of massive pyrite with irregular, less frequently oval shapes; microconcretions show a significant degree of oxidation, which is manifested by the presence of brown iron hydroxides; • precise identification of clay minerals that form the matrix is impossible due to the very small grain sizes (<10 μm)	• gravels are only local rocks
HEAVY MINERALS (Figs. 5 and 6)		• variable amount and low diversity of heavy mineral spectrum • angular and unsorted grains of heavy minerals • predominance of resistant minerals: zircon, staurolite, tourmaline, kyanite (also rutile, andalusite and topaz) • sequence of main transparent minerals: zircon, zircon>garnets or muscovite (chlorites) and garnets, garnets>muscovite • pyroxenes are absent or occur in low content while low amount of amphiboles distinctly increases in the upper part of the deposit profile • high proportion of micas (muscovite, biotite) and chlorites, i.e. minerals with low aero- and hydrodynamic equivalents – especially in the bottom part of the profile • the proportion of primary iron oxides (i.e. ilmenite and magnetite) decreases while the proportion of secondary iron oxides (i.e. limonite and goethite) increases up the profile • carbonates (calcite and/or dolomite) occur as plates or irregular aggregates, white-grey or honey-coloured, with an admixture of iron compounds • in places higher concentration of pyrite (as aggregates of pyrite and pseudomorphs after pyrite, oxidized to various degrees), especially in zones of organic material accumulation		• complete and diverse heavy mineral spectrum; • occurrence of slightly rounded, sporadically angular, well sorted grains of carbonate crystals, light yellow, light brown and honey-coloured •typical sequence of main transparent minerals: zircon>garnets> amphiboles (staurolite, tourmaline); •diverse sequences of main minerals: bottom part: tourmaline>staurolite>garnets (zircon), middle part: amphiboles>zircon>staurolite (garnets), upper part: garnets>zircon>amphiboles (staurolite); • predominance of resistant transparent minerals: zircon, staurolite and tourmaline or topaz • diverse but complete spectrum of moderately resistant minerals: mainly garnets as well as apatite and syllimanite • content of non-resistant minerals is low in the deposit series
CALCIUM CARBONATE (Figs. 5 and 6)		• deposits with an admixture of carbonates • content of carbonates decreases in a pulsating manner up the deposit profile (average value in the range of 7%-11%) or they disappear		• average content of carbonates decreases up the profile until they disappear
MAGNETIC SUSCEPTIBILITY (Figs. 5 and 6)		• variable values of magnetic susceptibility in the range of 13.8-1934.7 [10-9m^3/kg], in places high values 360-1935[10-9m^3/kg]; • the main carrier of magnetization is greigite (Fe_3S_4) but also magnetite (Fe_3O_4)		low values of magnetic susceptibility in the range of 8.0–351 [10-9 m^3/kg] • magnetite (Fe_3O_4) is main carrier of magnetization
OTHER		• lack of gastropod shells in the deposits		

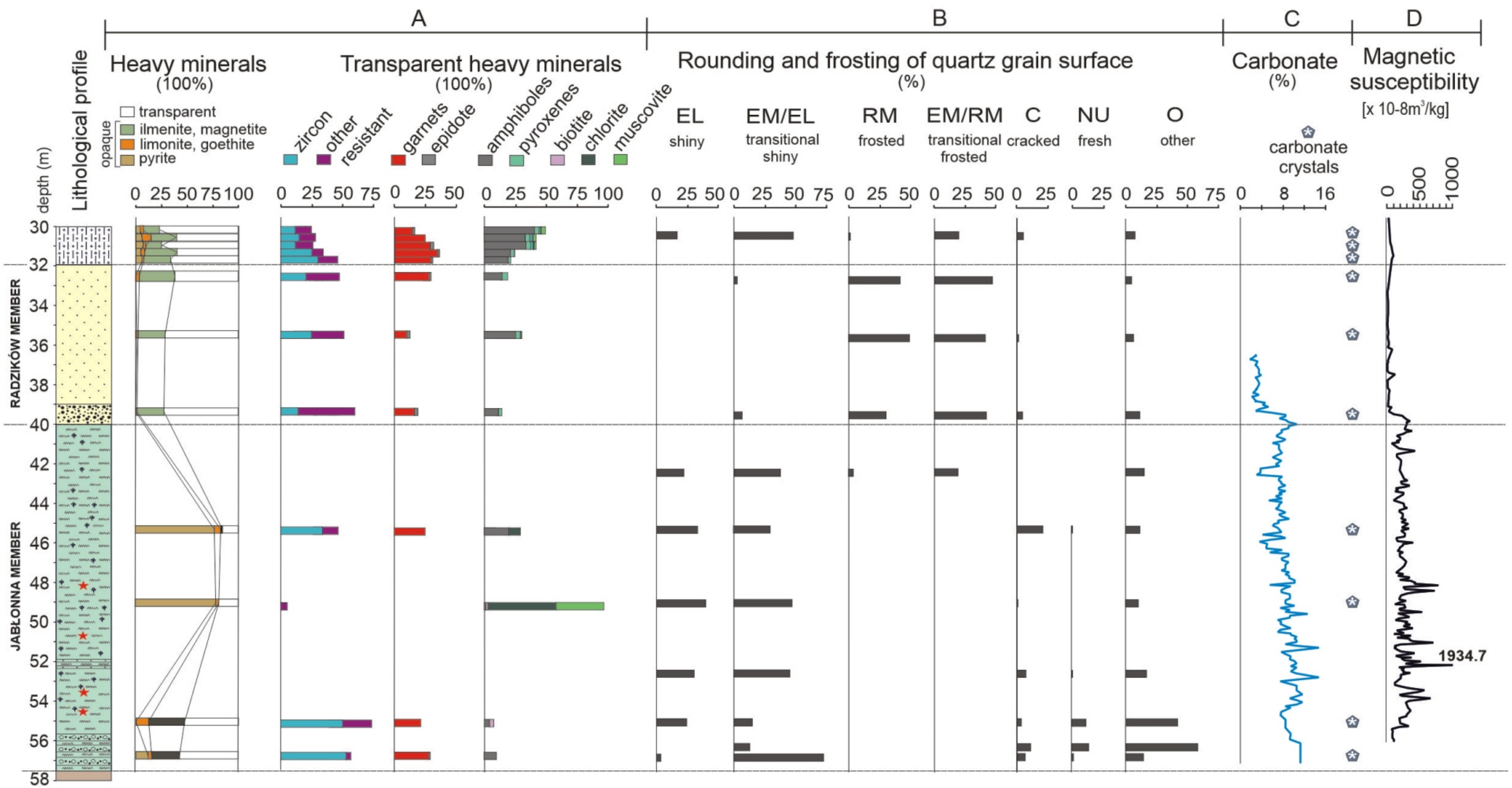

Fig. 5. Mineralogical, textural, geochemical and geophysical features of the Słopiec Formation deposits in the Jabłonna UJK-1 borehole profile

A – heavy mineral composition; **B** – carbonate content ($CaCO_3$); **C** – magnetic susceptibility; **D** – quartz grain morphology (rounding and frosting; based on Ludwikowska-Kędzia, 2018)

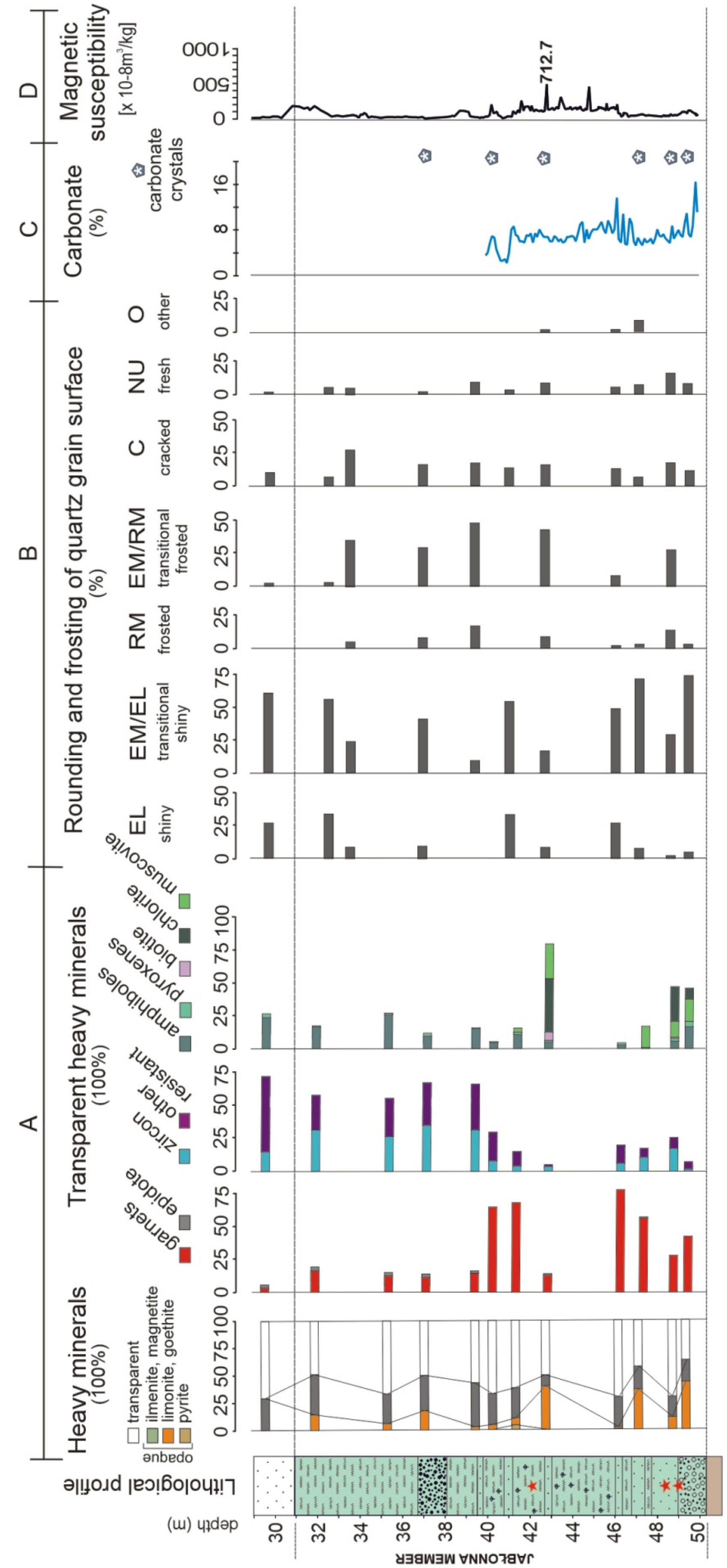

Fig. 6. Mineralogical, textural, geochemical and geophysical features of the Słopiec Formation deposits in the Słopiec UJK-2 borehole profile

A – heavy mineral composition; **B** – carbonate content (CaCO3); **C** – magnetic susceptibility; **D** – quartz grain morphology (rounding and frosting; based on Ludwikowska-Kędzia, 2018)

Table 2

Palynomorphs and palynoclasts identified from the Jabłonna Member (Słopiec Formation) in the Słopiec UJK-2 profile

Taxon	Depth of samples			
	48.5 m	51.0 m	54.0 m	55.0m
Spores of cryptogams				
Baculatisporites (Osmunda)	+	+		
Baculatisporites primarius (Osmunda)		+		
Camarozonosporites heskemensis (Lycopodiaceae – *Lycopodiella)* more common in Paleogene	+			
cf. *Cicatricosisporites paradorogensis* (Schizeaceae) more common in Paleogene	+			
Concavisporites (Gleicheniaceae?)		+		
Concavissimisporites (Cretaceous)		+		
Laevigatosporites haardti (Polypodiaceae)		+		
Leiotriletes (Lygodiaceae)		+		
Neogenisporis crassicus (Gleicheniaceae)		+		
Neogenisporis neogenicus (Gleicheniaceae)	+	+		
Radialisporis radiatus (Lygodiaceae) more common in Paleogene	+ damaged			
Retitriletes (Lycopodium)	+ damaged			
Rudolphisporis major (Anthocerotaceae)		+		
Rugulatisporites (Oamundaceae)		+		
Stereisporites (Sphagnaceae)		+ damaged	+ damaged	
Stereisporites minor (Sphagnaceae)		+		
Pre-Cenozoic cryptogams		+		
Fungal spores and hyphae		+		
Pollen of gymnosperms				
Abiespollenites (Abies)	+		+	
Cathayapollis (Cathaya)	+			
Inaperturopollenites concedipites (Cupressaceae)		+		
Inaperturopollenites dubius (Cupressaceae)	+	+	+	
Piceapollis(Picea)		+	+	
Pinaceae pre-Cenozoic	+ damaged	+ damaged	+	
Pinuspollenites (Pinus)	+	+	+	+
Pinus diploxylon (Pinus sylvestris)		+		
Sciadopityspollenites (Sciadopitys)	+	+		
Sequoiapollenites (Sequoia)	+			
Zonalapollenites (Tsuga)	+	+ damaged	+	
Zonalapollenites spectabilis (Tsuga)	+			
Pollen of angiosperms				
Alnipollenites verus (Alnus)		+		
Araliaceoipollenites reticuloides (Hedera) highly thermophilous			+	
cf. *Boehlensipollis hohli* (Lythraceae) to Oligocene	+	+		
Carpinipites (Carpinus)	+			
Caryapollenites (Carya)		+ damaged		
Celtipollenites bobrowskae (Celtis)	+			+
Cichoraecidites gracilis (Asteraceae)		+		
cf.*Cupanieidites eucalyptoides* to Oligocene		+		
Cupuliferoipollenites pusillus (Castaneoideae) thermophilous	+ damaged		+	
cf. *Dicolporopollenites* Oligocene-Miocene, thermophilous		+		
Edmundipollis (Mastixiaceae, Cornaceae, Araliaceae) highly thermophilous	+			
Ericipites (Ericaceae)	+ damaged	+ damaged	+	
Faguspollenites (Fagus)		+ damaged		
Intratriporopollenites insculptus (Tilioideae)	+	+		
Juglanspollenites (Juglans)	+ damaged			
Liriodendroipollis (Liriodendron) thermophilous			+	
Magnolipollis (Magnoliaceae)		+		
Momipites (Engelhardtia)				
Momipites punctatus (Engelhardtia) thermophilous	+	+		

Tabl. 2 cont.

Monocolpopollenites						+
Myricipites (Myrica)			+ damaged		+	
Myricipites bituius			+			
Nyssapollenites (Nyssa)			+		+	
Orapollis (Alismataceae)				+		
cf. *Parthenopollenites marcodurensis*			+ damaged			
cf. *Periporopollenites (Liquidambar)*			+			
Pterocaryapollenites (Pterocarya)			+	+		
cf. *Quercopollenites (Quercus)*				+		
Quercopollenites asper (Quercus)			+			
Quercoidites henrici (Quercus) thermophilous			+			
Salixipollenites (Salix)			+			
Tricolporopollenites				+		
Tricolporopollenites fallax (Fabaceae) thermophilous			+ damaged			
Tricolporopollenites pseudocingulum (Styracaceae) thermophilous			+ damaged			
Triporopollenites						+
Trivestibulopollenites (Betula)				+		
Ulmipollenites undulosus (Ulmus)			+	+		
unidentified and damaged						+
Normapolles						
Trudopollis Cretaceous-Eocene				+		
Phytoplankton						
Achomosphaera alcicornu	Paleocene-Oligocene			+		
Botryococcus	to this day	brackish and freshwater facies	+	+	+	+
Caligodinium	Paleocene-Miocene			+		
Cordosphaeridium cf. *inodes*	Eocene-Oligocene			+		
Crassosphaera	Paleocene-Miocene	marine, brackish facies		+		
cf. *Cribroperidinium*	Jurassic-Eocene			+		
cf. *Distatodinium*	Eocene-Miocene					
cf. *Glaphyrocysta*	Paleocene-Miocene			+		
cf. *Homotryblium*	Paleocene-Miocene			+		
cf. *Isabelidinium*	Cretaceous-Paleocene			+		
Leiosphaeridia	to Oligocene	marine and brackish facies		+		
Operculodinium	Paleocene-Miocene			+		
cf. *Palambages*	Cretaceous-Paleocene			+		
Pediastrum	to this day	freshwater facies		+		
Sigmopollis	to this day	freshwater facies		+		
Spiniferites sp.	Jurasic to this day			+		
cf. *Spinidinium*	Paleocene			+		
cf. *Stoverocysta*	Eocene-Miocene			+		
cf. *Tanyosphaeridium*.	Cretaceous-Paleogene			+		
Veryhahchium	Paleozoic- to this day			+		
Zygnemataceae	to this day	freshwater facies		+		
dinocysts unidentified				+		
marine plankton unidentified				+ damaged		
Phytoclasts						
brown wood fragments			++	++	++	
black wood fragments			++	+++	+++	+++
cuticles			+++	++	+	+
Others						
traces of glauconite marine and brackish facies			+		+	+

Colour explanations:

Terrestrial environment
Marine environment, shelf

Table 3

Palynomorphs and palynoclasts identified from the Jabłonna Member (Słopiec Formation) in the Jabłonna UJK-1 profile

Taxon	42.2 m
Spores of cryptogams	
Baculatisporites (Osmunda)	+
Laevigatosporites haardti (Polypodiaceae)	+
Leiotriletes (Lygodiaceae)	+
Neogenisporis neogenicus (Gleicheniaceae)	+
Retitriletes (Lycopodium)	+ damaged
Stereisporites (Sphagnaceae)	+
cf. *Toroisporites* (Cyatheaceae, Lygodiaceae)	+ damaged
Fungal spores and hyphae	+
Pollen of gymnosperms	
Abiespollenites (Abies)	+
Inaperturopollenites dubius (Cupressaceae)	+
Pinaceae pre-Cenozoic	+ damaged
Pinuspollenites (Pinus)	+
Sequoiapollenites (Sequoia)	+
Zonalapollenites (Tsuga)	+
Pollen of angiosperms	
Alnipollenites verus (Alnus)	+
Celtipollenites bobrowskae (Celtis)	+
Cupuliferoipollenites pusillus (Castaneoideae)	+ damaged
Cyrillacaepollenites exactus (Cyrilla, Clethra)	+
Ilexpollenites propinqus (Ilex)	+
Intratriporopollenites insculptus (Tilioideae)	+
Momipites punctatus (Engelhardtia)	+
Nyssapollenites (Nyssa)	+
Polyatriopollenites (Pterocarya)	+
Quercopollenites (Quercus)	+
Tricolporopollenites dolium (Fagaceae?)	+
Trivestibulopollenites betuloides (Betula)	+
Ulmipollenites undulosus (Ulmus)	+
unidentified and damaged	+
Phytoplankton	
Botryococcus brackish and freshwater facies	+
Leiosphaeridia to Oligocene, marine and brackish facies	+
Pediastrum freshwater facies	+
unidentified freshwater	+
Phytoclasts	
brown wood fragments	+
black wood fragments	+++
cuticles	+

Colour explanations:

Terrestrial environment
Marine environment, shelf

Four samples were analysed in the Słopiec profile (Table 2; Figs. 2B, 7, 8). While the sporomorph frequency was generally satisfactory, the state of preservation of the specimens indicated the transport and redeposition of individual components of the palynomorph assemblage. They were damaged or fragmented, which was closely related to the origin of the deposits. This state of preservation often proved crucial in deciding to assign individual taxa to a specific genus or species. The morphology of pollen grain surfaces was often blurred, making diagnostic features difficult to observe. Many of the taxa listed in the table are preceded by 'cf.', (*conformis*) – meaning that they most resemble the genus/species named. Furthermore, some taxa are noted as damaged but identifiable.

The palynomorph spectrum of the sample from 55.0 m depth contains a few pollen grains in varying states of preservation. Some grains of the same taxon are dark, while others are light, which indicates different histories of their transport to the water body/lake. Older grains are usually darker because they were transported over a longer distance before being deposited. Their surfaces are often damaged, deformed, and broken, indicating that the palynomorphs were subjected to strong water currents and abrasion. However, the low taxonomic diversity composition (single damaged Pinaceae family pollen grains and *Tricolporopollenites pseudocingulum*, as well as *Celtipollenites* and *Monocolpopollenites*) prevents unambiguous dating of this part of the profile. Cretaceous forms and marine phytoplankton were not found. Numerous carbonized phytoclasts were found. These samples did not contain any clearly marine components (apart from individual weathered glauconite aggregates, which were probably redeposited).

The palynomorph assemblage in the sample from a depth of 54.0 m was slightly more numerous, though also mixed and without Cretaceous indicator taxa. The pre-Paleogene pollen included dark grains of the Pinaceae family with slightly blurred surface morphology. Furthermore, pollen grains of gymnosperms, representatives of coniferous forest (*Abies*, *Picea*, *Tsuga*) were quite numerous. Pollen grains of thermophilous angiosperms were also present, including: *Araliaceoipollenites*, *Cupuliferoipollenites pusillus*, *Liriodendroipollis*, and others. While the frequency of palynomorphs was satisfactory, the pollen material was poorly preserved. Marine phytoplankton was not found. Trace amounts of weathered glauconite aggregates were the only marine indicator, which suggests that they were also redeposited.

The sample taken at a depth of 51.0 m contained marine phytoplankton, as well as pollen and spores of various ages, including the Cretaceous, Paleogene and Neogene components (Table 2 and Fig. 7). This assemblage, coupled with the poor preservation of the specimens, prevented unambiguous dating and clearly indicated redeposition. The bisaccate pine family pollen grains occurred in three states of preservation: darker pollen with blurred surfaces and traces of corrosion interpreted as pre-Cenozoic, moderately numerous *Pinus* and *Picea* pollen (common in the Paleogene and Neogene), and pollen similar to modern *Pinus sylvestris*. This palynological spectrum indicates that pollen grains of different ages are mixed. Specimens of *Concavissimisporites,* unidentified pre-Cenozoic spores and representatives of the Pinaceae family were also found, as well as cf. *Isabelidinium* among the phytoplankton. These probably represent Cretaceous components of this assemblage. The following Paleogene genera and species were identified: cf. *Boehlensipollis hohli,* cf. *Cupanieidites eucalyptoides*, the Normapolles group with *Trudopollis* (Late Cretaceous-Early Paleogene). The remaining taxa are found in both the Paleogene and Neogene, although some taxa are more common in the Miocene (Cupressaceae, *Sciadopitys, Tsuga, Engelhardtia, Pterocarya, Carya,* Magnoliaceae), and some also in the Neogene and Quaternary (*Quercus, Fagus, Tilia, Betula, Alnus, Ulmus*, Ericaceae as well as herbs of the Asteraceae and Alismataceae). Therefore, redeposition of the Cretaceous, Paleogene, Neogene, and Quaternary taxa took place at this site. This may indicate that erosion and accumulation probably occurred during the Quaternary.

The sample from 48.5 m depth contained a moderately diverse spore-pollen spectrum but many specimens were damaged and showed traces of long transport, also indicating a long

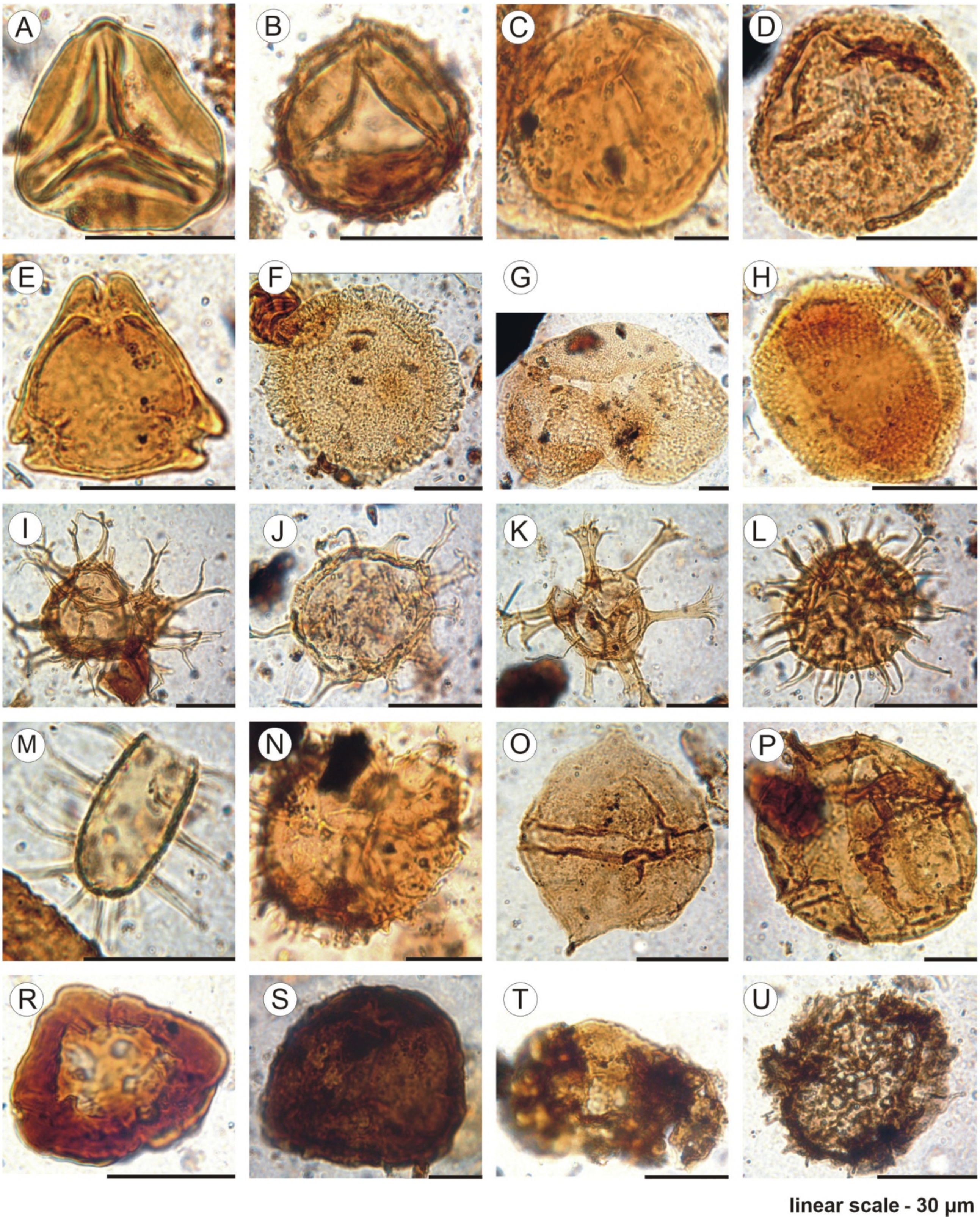

Fig. 7. Palynomorph specimens from the Jabłonna Member (Słopiec UJK-2 borehole), depth 51.0 m (photo: A. Mader)

A – *Neogenisporis crassicus* Krutzsch, **B** – *Rudolphisporis major* (Stuchlik) Stuchlik, **C** – cf. *Rugulatisporites,* **D** – *Baculatisporites primaries* (Wolf) Pflug & Thomson, **E** – *Trudopollis* sp., **F** – *Zonalapollenites* sp., **G** – *Pinuspollenites* sp., **H** – *Crassosphaera* sp., **I** – *Spiniferites* sp., **J** – *Achomosphaera alcicornu* (Eisenack) Davey & Williams, **K** – *Cordosphaeridium* cf. *inodes,* **L** – *Operculodinium* cf. *tiara,* **M** – *Tanyosphaeridium* sp., **N** – cf. *Glaphyrocysta,* **O** – cf. *Spinidinium,* **P** – cf. *Cribroperidinium,* **R**, **S** – Pre-Cenozoic cryptogams, **T** – Pre-Cenozoic Pinaceae, **U** – unidentified phytoplankton

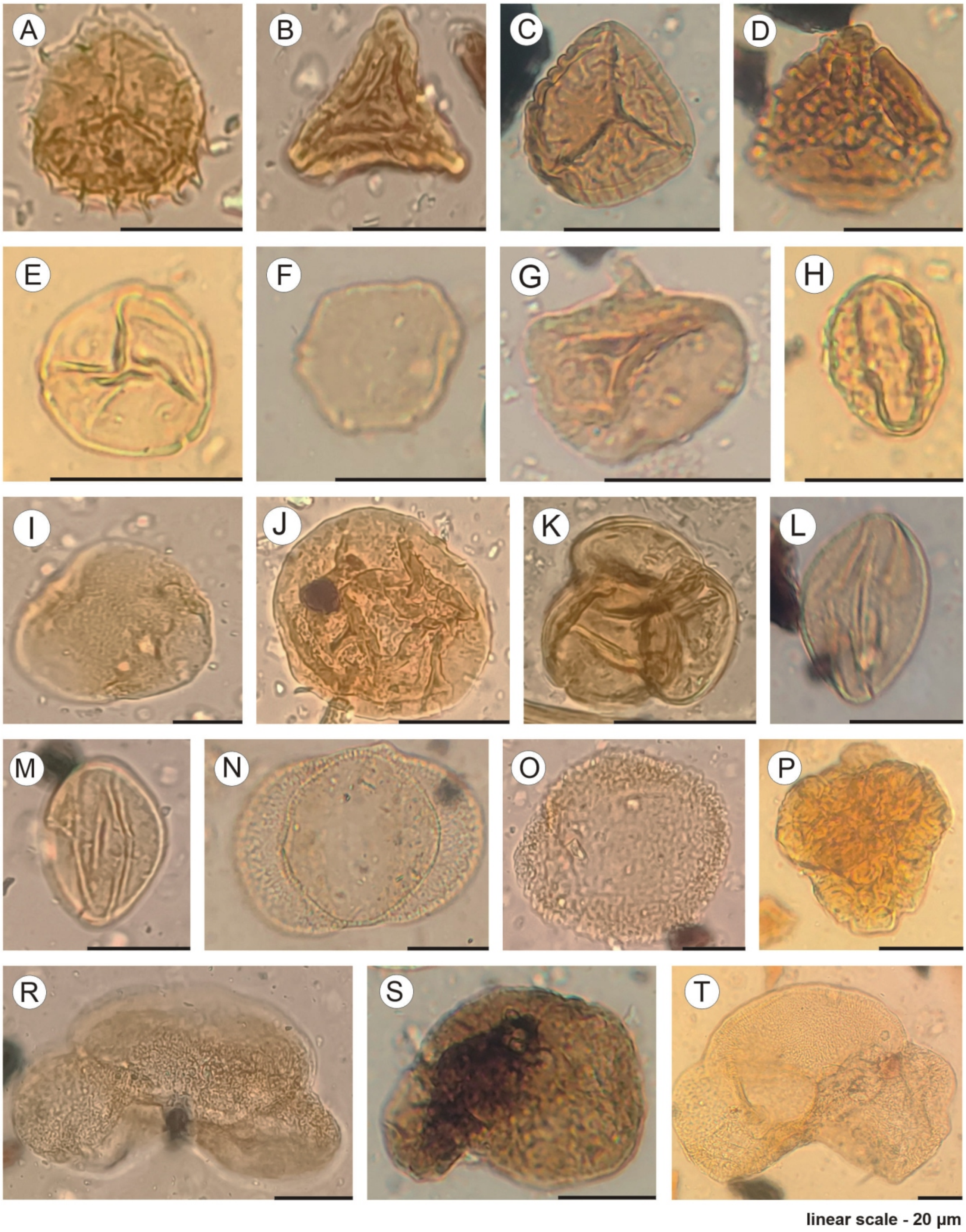

Fig. 8. Palynomorph specimens from the Jabłonna Member (Słopiec UJK–2 borehole), depth 48.5 m

A – *Retitriletes* sp., **B** – *Neogenisporis neogenicus* Krutzsch, **C** – *Camarozonosporites heskemensis* (Pflanzl) Krutzsch, **D** – *Cicatricosisporites paradorogensis* Krutzsch, **E** – *Myricipites bituitus* (Potonié) Nagy, **F** – *Pterocaryapollenites* sp., **G** – *Sequoiapollenites* sp., **H** – *Cupuliferoipollenites pusillus* (Potonié) Potonié, **I** – *Intratriporopollenites inculptus* Mai, **J** – *Leiosphaeridia* sp., **K** – *Ericipites*, **L** – *Tricolporopollenites pseudocingulum* (Potonié) Thomson & Pflug, **M** – *Quercoidited henrici* (Potonié) Potonié, Thomson & Thiergart, **N** – *Cathayapollis* sp., **O** – *Zonalapollenites* sp., **P** – *Botryococcus* sp., **R** – *Abiespollenites* sp., damaged, **S** – Pre–Cenozoic Pinaceae, **T** – *Abiespollenites* sp.

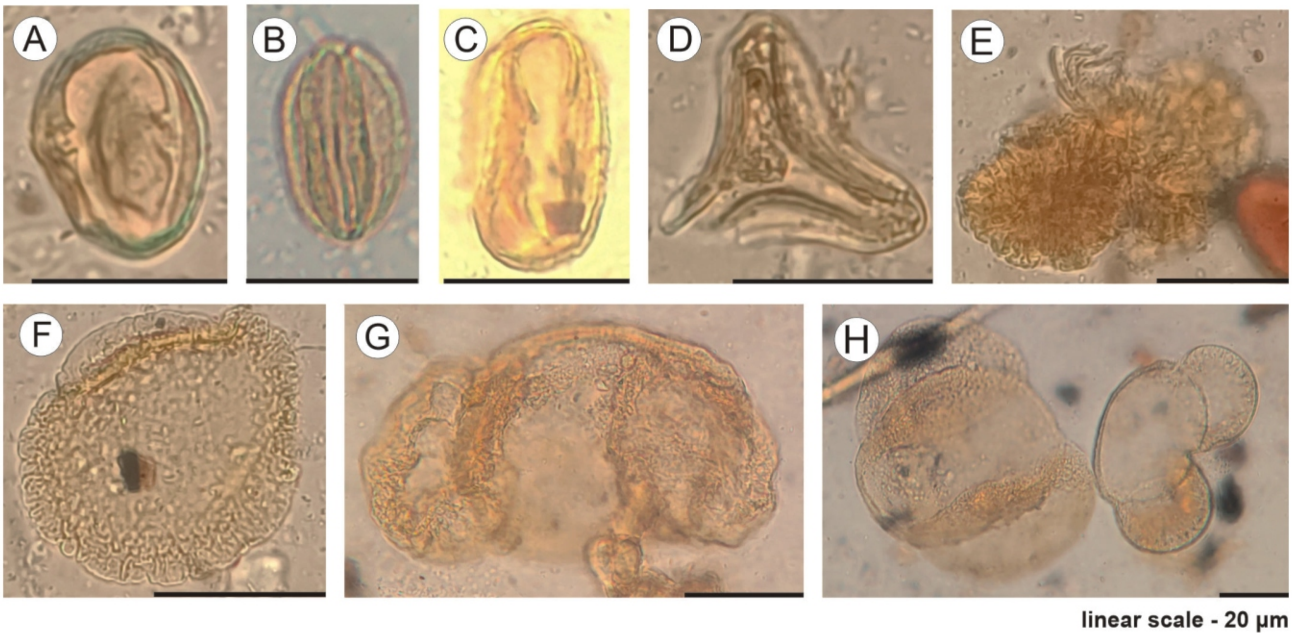

Fig. 9. Palynomorph specimens from the Jabłonna Member (Jabłonna UJK-1 borehole), depth 42.2 m

A – *Nyssapollenites* sp., **B** – *Quercopollenites* sp., **C** – *Tricolporopollenites dolium* (Potonié) Thomson & Pflug, **D** – *Neogenisporis neogenicus*, **E** – *Botryococcus* sp., **F** – *Zonalapollenites* sp., **G** – Pinaceae, damaged, **H** – left specimen – *Abiespollenites* sp.; right specimen – *Pinuspollenites*

history of their erosion and accumulation (Table 2 and Fig. 8). The presence of *Boehlensipollis hohli* pollen in this assemblage represents an Oligocene age, corroborated by the occurrence of pollen of the thermophilous plants *Edmundipollis, Inaperturopollenites insculptus, Cupuliferoipollenites pusillus, Tricolporopollenites fallax* and *Quercoidites henrici.* However, a Miocene age cannot be excluded. Cretaceous taxa do not occur in this assemblage. There is also no evidence of marine components in these deposits.

In the Jabłonna profile, three samples from the depths of 42.2, 48.8 and 49.3 m were analysed (Fig. 2B). Only the sample from a depth of 42.2 m yielded a pollen spectrum (Table 3 and Fig. 9). The remaining samples contained only a few black wood fragments and traces of amorphous organic matter, and no palynomorphs were found.

The pollen spectrum of the sample from 42.2 m depth in the Jabłonna profile is similar to that of the two samples taken from depths of 48.5 m and 54.0 m in the Słopiec profile. The pollen frequency was low and the state of preservation poor. This assemblage also contains pre-Cenozoic pollen grains belonging to the Pinaceae family, and marine phytoplankton is absent. The pollen is dominated by Miocene taxa, including *Sequoiapollenites*, *Cupuliferoipollenites pusillus*, *Momipites punctatus*, *Nyssapollenites* and others. There are also no indicators of marine facies. Therefore, as in the Słopiec profile, an important component of this assemblage are pollen taxa more commonly found in the Miocene.

INTERPRETATION

DEPOSITIONAL ENVIRONMENT

The Słopiec Formation comprises lacustrine-fluvial deposits including two members – the Jabłonna Member represents a lacustrine environment, whereas the Radzików Member represents a fluvial (delta) environment.

The deposits of the Jabłonna Member of the Słopiec Formation accumulated in a lake, or lakes, that formed in a karst depression, which was initially supplied with gravels with an admixture of silty-sandy material (Figs. 2A, B, 3, 4A, B1–10, C and Table 1). Inflow of clastic material primarily occurred through gravitational processes such as subaqueous flows, and indirectly as subaqueous landslides (through secondary flows; remobilisation; e.g., Sammartini et al., 2021; Sabatier et al., 2022). This is indicated by the typical grain size change in the sequence, from gravels (clast-supported gravel with a silty-clayey matrix) at the bottom to sands/muds in the upper part (Fig. 3). These gravels are composed of weathered local rocks, both siliciclastic and carbonate. Their poor rounding and low degree of smoothing suggest that they were transported over a short distance by a relatively energetic process.

The textural features and suite of sedimentary structures in the overlying thick muds are an indicative record of repeated deposition from traction and suspension resulting from the changes in the velocity of turbidity currents and in the concentration of material supplied to the lake (Fig. 4A, B1–10, C). In places, these deposits correspond to a part or all of the turbidite sequence of Bouma (1962), and/or form heterolithic deposits, characterized by variable lamina and bed thicknesses (Fig. 4B1–5, 9, 10).

The predominant horizontal lamination of muds is a record of undisturbed settling from suspension in a stagnant water body (Fig. 4B1–5, C). Flaser lamination, on the other hand, indicates alternating deposition of coarser material transported by flow, and finer material settled from suspension during periods of still water. The recurrence of these very different depositional conditions took place in closed water bodies and floodplain basins (Gradziński et al., 1986; Zieliński, 2014). The massive structure and lack of lamination of the muds are interpreted as a record of rapid deposition from suspension or as a result of destruction of primary sedimentary structures due to sediment liquefaction or material supply from the slopes to the lake by high-density flows (e.g., flows from the slopes or from river mouths), resulting in the formation of turbidity currents (Gradziński et al., 1986; Zieliński, 2014; Sabatier et al., 2022). The convoluted stratification found in the deposits indicates deformation during deposition, probably under the influence of subaqueous currents or landslides (Gradziński et al., 1986; Zieliński, 2014; Gladstone et al., 2018), and possibly also seismic shocks (e.g., van Loon and Pisarska-Jamroży, 2014; Bronikowska et al., 2021; Müller et al., 2021; Sabatier et al., 2022). The disrupted fragments of mud laminae are a record of water escaping from the deposit (Lowe, 1975) or vertical movements in the deposits with unstable density stratification (Anketell et al., 1970; Cegła and Dżułyński, 1970). The occurrence of angular sand lumps, which are found in massive muds of the profile studied in places, suggests that they were detached by erosion and transported as frozen and/or dried material (Fig. 4B6, 7). The presence of black coatings and manganese-iron dendrites around these sand lumps indicates variable oxidation-reduction conditions.

The occurrence of thick, laminated bottom deposits in the water body/lake suggests that the limited depth of water mixing may have been a permanent feature (meromictic lake?). The location of the lake in a karst depression (situated in a basin) prevented wind-driven mixing of the water, providing natural shelter for the lake. The absence of mixing to the very bottom prevented oxygen inflow and favoured the maintenance of anaerobic conditions.

The high proportion of micas (muscovite, biotite) and/or chlorites (which are minerals with low aero- and hydrodynamic equivalents) also suggests that the muds were deposited in the lake (Figs. 4A1, 5A, 6A). On the other hand, the intermittent disappearance of mica minerals from the deposits may indicate a change in the source area and/or periodic increases in current velocity resulting in the removal of fine-grained material. This could imply that the water body was periodically a flow-through lake, with seasonal water level fluctuations.

Pyrite framboids, greigite, and authigenic carbonates were found in the muds (Figs. 4A3, 5A, C, 6A, C). Framboidal pyrite is most often of biogenic origin (Wolicka, 2010a) and is related to the activity of microorganisms, i.e. magnetotactic bacteria (MTB; e.g., Mann et al., 1990; Bazylinski et al., 1995; Luptáková et al., 2012; Sawłowicz, 2016). Its formation is favoured by reducing (anoxic) conditions in the lake (cf. Zatoń et al., 2008), coupled with the presence of large amounts of organic matter (Fig. 4A2). A greater input of organic matter into the water body/lake enhances the redox gradient in the deposits, which, together with sufficient iron availability (e.g. from iron-rich limestones), promotes the metabolism of MTB. Greigite (Fe_3S_4) carries a magnetic signal and is an intermediate stage in the formation of framboidal pyrite. Its presence indicates the existence of a redox boundary that separates oxygenated water from water containing hydrogen sulphide (Wilkin and Barnes, 1997; Zatoń et al., 2008). The precipitation of greigite requires reducing conditions at the sediment-water interface or within the interstitial water, which are related to the presence of sulphur and iron oxides. Such reducing conditions are typical of stratified lakes and other stratified water bodies (Ron et al., 2007). The authigenic carbonates, which occur as aggregates of micrite formed in the deposit during early diagenesis after being overlain by younger deposits, are also most likely of biogenic origin. Their precipitation is related to the activity of a mixed community of sulphate-reducing bacteria, which are able to bioprecipitate carbonates such as calcite, dolomite, and siderite (Wolicka, 2010b). The presence of these minerals indicates conditions favourable for the dissolution of carbonate bedrock, transport in solution to the lake, and the subsequent chemical or biochemical precipitation of carbonates.

The heavy mineral assemblage in the sand fraction of the muds is characterized by a significant content of opaque minerals, including primary and secondary iron oxides (Figs. 5A and 6A). This may indicate advanced weathering processes and supports depositional conditions typical of a lacustrine environment (Barczuk and Nejbert, 2007). The gradual increase in the proportion of fine-grained aeolian sands in the upper part of the Jabłonna Member is a record of the transition from basin/lacustrine to fluvial depositional environment.

The palynomorphs and palynoclasts identified in the muds of the Jabłonna Member indicate a similar, dynamic history of syn- and post-depositional processes. The composition and state of preservation of the palynomorph assemblages suggest mixing and redeposition, possibly multiple times, as well as several episodes of material supply to the water body. A notable feature of all samples is the poor state of preservation of sporomorphs, and, in the sample from a depth of 51.0 m (Słopiec UJK-2 borehole; Table 2 and Fig. 7), phytoplankton. The different states of preservation of the same genus of palynomorphs indicate multiple cycles of their supply to and deposition in the basin. This palynological pattern, which records the destruction and mixing of palynological material, is typical of karst depressions (dolines and uvalas), and indicates their energetic history (e.g., Szulc and Worobiec, 2012; Worobiec and Szulc, 2020).

The occurrence of gravels in the sands of the overlying Radzików Member, and particularly of well-rounded silty-clayey and sandy intraclasts, suggests that the muds of the Jabłonna Member were affected by erosion (Figs. 3 and 4C). Increase in river energy is also recorded in the grain-size changes in the Radzików Member profile. An initial upwards-fining trend shifts to an opposite, upwards-coarsening trend, and ultimately ends with the deposition of massive sands with an admixture of fine gravels. The grain-size characteristics and sedimentary structures indicate a deltaic depositional environment (subaerial and/or subaqueous river-sediment accumulations near the mouth of a stream or river; cf. Miall, 2014; Zieliński, 2014). The occurrence of magnetite (a magnetization carrier) in the deposits of the Radzików Member is a record of fluvial transport and depositional conditions in the river mouth zone (deltaic environmental; (e.g., Bazylinski et al., 1995). At the same time, it indicates a freshwater environment, in which freshwater MTB produce almost exclusively magnetite (Fe_3O_4; Sawłowicz, 2016).

PROVENANCE AND TRANSPORT OF SŁOPIEC FORMATION DEPOSITS

The source materials for the Słopiec Formation deposits (primarily the Jabłonna Member) were weathering mantles of various ages, derived from local Paleozoic rocks of the HCM massif, which were reworked in terrestrial environments (karst, fluvial, slope, and aeolian), and in a brackish environment (of a Miocene sea).

The numerous monocrystalline carbonate grains (including dolomite) in the Jabłonna Member indicates the availability of local weathered material derived from the mechanical destruction of carbonate bedrock, e.g. detrital dolomites (cf. Ludwikowska-Kędzia, 2018; Ludwikowska-Kędzia and Kubala-Kukuś, 2023; Figs. 5C and 6C), and/or favourable conditions for the removal of the karst channel infills (Urban, 2013). The presence of these carbonate grains also indicates that the weathered material was transported over a short distance.

The autochthonous origin of the muds (Jabłonna Member) is further corroborated and documented by the presence of aggregates of massive, fine-crystalline pyrite (co-occurring with angular quartz grains, probably derived from rock disintegration) as well as by a high content of micas (muscovite and biotite; Figs. 5A and 6A). The occurrence of pyrite in the Paleozoic bedrock and the availability of weathered bedrock material are well documented in the HCM (Rubinowski, 1962; Fijałkowska and Fijałkowski, 1963). Similarly, the presence of muscovite has been documented. It may originate from a) weathered Cambrian sandstones of the southern and central parts of the HCM (e.g., Kowalczewski et al., 2006), b) Triassic sandstones of the Permian-Mesozoic margin of the HCM (e.g., Rembiś, 2010), and also c) karst cave deposits (e.g., Urban, 2013). Biotite, as well as pyroxenes, may be derived from weathered lamprophyres in the Daleszyce area (e.g., Rubinowski, 1962; Kardymowicz, 1962; Krzemińska and Krzemiński, 2019).

The sequence of the main components of the heavy mineral spectrum of the Jabłonna Member deposits (mainly in their lower and middle parts; Fig. 5A) is similar to that observed in marine deposits (Racinowski, 2010) as well as in the Paleogene-Neogene fluvial units of various ages found in the neighbouring Sandomierz Basin (Mycielska-Dowgiałło, 1978). In these deposits, amphiboles constitute a small percentage, while pyroxenes are absent. This source of deposits is also indicated by the predominance of EL (very well-rounded with a smooth, shiny the entire surface; Cailleux, 1942) and EM/EL (moderately rounded, with a smooth, shiny surface; Cailleux, 1942) quartz grains in the muds, due to the repeated, intensive, and persistent reworking of deposits in high-energy aqueous environments (beach and/or fluvial; Figs. 5B and 6B). Consequently, the quartz grains became rounded and shiny (Linde and Mycielska-Dowgiałło, 1980). This interpretation is supported by the location of the study area and the boreholes within the brackish zone of the Miocene sea. The heavy mineral spectrum of the Jabłonna Member deposits is also similar to that found in the Neogene deposits filling karst sinkholes. These deposits are characterized by a narrow heavy mineral spectrum, which is composed almost exclusively of minerals resistant to chemical and physical weathering (tourmalines, zircons, rutiles, disthenes) (Barcicki et al., 1991; Mycielska-Dowgiałło, 1995; Marcinkowski and Mycielska-Dowgiałło, 2013; Ludwikowska-Kędzia, 2013; Urban, 2013). Therefore, the source materials for the Jabłonna Member deposits were the Neogene deposits formed both in aqueous (marine and/or fluvial) and in terrestrial (karst) environments.

Generally, the low content of heavy minerals in the Jabłonna Member deposits and the low-diversity spectrum suggest that the source area was poor in heavy minerals rather than that the deposits of the source area were subjected to persistent weathering (Ludwikowska-Kędzia, 2013). The subangular and subrounded heavy mineral grains in the deposits indicate short transport and/or a lack of favourable conditions for their transport. Qualitative and quantitative changes in the proportions of the main minerals in the Jabłonna Member deposits demonstrate the periodicity of material supply to the lake, as well as the repeated changes of source areas (and thus the directions of transport) of the deposits.

The differences in the taxonomic composition of the palynomorph assemblages described, including Cretaceous, Paleogene and Miocene material, demonstrate the different source areas and the supply of detrital material from various directions: Cretaceous, Paleocene, Eocene, Oligocene and Miocene deposits were eroded, and then the resulting deposits were subjected to further reworking.

The higher diversity of the heavy mineral spectrum recorded in the middle and/or upper parts of the Jabłonna Member and in the Radzików Member, the increased content of garnets and amphiboles (minerals moderately to non-resistant to chemical weathering), as well as the high content of pyroxenes accompanied by a decrease in zircon content, indicate the supply of relatively “fresh”, allochthonous weathered material (Ludwikowska-Kędzia, 2013). This supply of allochthonous material to the bottom of the Słopiec Basin can be related to the direct inflow of glaciofluvial water or to the erosion of older glacial deposit covers (Czarnocki, 1931).

Thus, the deposits of the Słopiec Formation represent autochthonous weathering products of the local bedrock, inherited from the Paleogene–Neogene stage of morphogenesis of the Holy Cross Mountains, which were subsequently enriched with allochthonous material during the final stage of their sedimentation.

Although the depositional model provides information about flow conditions based on deposit characteristics, it is difficult to determine the initial factors that triggered gravity flows into the lake (as turbidity currents can have various triggers, the lithological records of which are similar). The material was initially transported to the bottom of the karst polje in the Słopiec Basin, into the karst lake, by denudation processes acting on the slopes of the surrounding hills. These processes most likely involved slope wash, landslides and mud/debris flows, generating turbidity currents of varying densities into the lake. Material was also transported under water, in the marginal zone of the lake, by subaqueous flows and landslides, as well as by ephemeral streams flowing down from higher areas of the basin and forming alluvial fans. At a later stage of lake infilling, the sediments were probably supplied by fluvial transport (floods?) and accumulated as fans (deltas) where rivers flowed into the lake. The entire lithological and depositional record of the Słopiec Formation recalls processes functioning within a karst polje of diverse relief (cf. Ford and Williams, 2007). Comprehensive information on the depositional conditions and sedimentary environment of the Słopiec Formation can be obtained only after investigating the spatial variability of deposit characteristics in other palaeodepressions of the Słopiec Basin, in the neighbouring Marzysz area, as well as in other morphostructural units of the Holy Cross Mountains.

The lakes in the Słopiec Basin analysed were probably initially deep. However, the thick and laterally extensive deposits of the Jabłonna Member gradually filled the karst depressions (Fig. 2A). These deposits not only sealed the depressions, but also levelled the topographically varied surface of the karstified basin floor, up to an elevation of at least 225 m (230 m) a.s.l. This altered the conditions for the transfer of water and deposits within the bottom of the polje (depression), and may have facilitated, or even determined, the development of a permanent river network. The course of these events in the Słopiec Basin was undoubtedly influenced by climatic and/or tectonic changes that affected the dynamics of morphogenetic and lithogenetic processes in the Holy Cross Mountains.

CLIMATE CONDITIONS DURING THE DEPOSITION OF THE SŁOPIEC FORMATION

The supply of clastic and organic material to the bottom of the karst depression, and consequently into the ephemeral water bodies (karst lakes), occurred under cold climate conditions.

These cold climate conditions are indicated by the high content of C (cracked) and O (other) quartz grains as well as by the occurrence of spherical iron concretions found in the bottom and middle parts of the Jabłonna Member (Figs. 5B and 6B). These grain types form in dry and cold periglacial environments (Mycielska-Dowgiałło and Woronko, 1998, 2001, 2004), are a record of frost weathering, and reflect the existence of an active layer (e.g., Hoch and Woronko, 2007; Woronko and Bujak, 2010, 2018; Woronko and Hoch, 2011; Woronko and Pisarska-Jamroży, 2016; Vandenberghe et al., 2016; Górska and Woronko, 2022), as well as shaping of grains by intense chemical and mechanical weathering (Mycielska-Dowgiałło and Woronko, 1998). Under such climatic conditions – typical of the subarctic climates that prevailed at the beginning of the Pleistocene glaciations – vegetation cover decreased and disappearing forest communities were replaced by forest-steppe-tundra and steppe-tundra vegetation (Winter, 2015). Extensive, exposed, mostly sandy weathering covers appeared, favouring the development of aeolian processes (e.g., Mycielska-Dowgiałło, 1995; Bujak, 2007; Woronko, 2012; Woronko and Bujak, 2018). Mycielska-Dowgiałło and Woronko (1998) demonstrated that a high proportion of matt surface quartz grains found in Polish deposits accumulated before the Middle Polish Glaciations and at the end of the Last Glaciation (Woronko and Bujak, 2018). Mojski (2005) related the rounding of quartz grains in preglacial deposits to the activity of aeolian processes, which occurred in areas without vegetation and covered by sandy deposits at the end of the pre-glacial period. Woronko and Bujak (2018) identified seven periods of intensification of aeolian processes in Poland during the Quaternary, that can be correlated with the advance and/or retreat of ice sheets.

A record of environmental conditions favouring the development of aeolian processes in the Słopiec Basin is clearly visible in the upper part of the Słopiec Formation, i.e. in the Radzików Member deposits. This is evident from the high proportion of quartz grains of RM (very well-rounded with matt surfaces) and EM/RM (moderately rounded, with a matt surface only on convex parts of grains) type (Fig. 6B), which are characteristic of an aeolian environment (Mycielska-Dowgiałło and Woronko, 1998). This feature suggested that aeolian grains supplied the alluvium of rivers functioning in cold climate conditions that favoured the intensive and long-term development of aeolian processes in a periglacial environment (e.g., Kozarski et al., 1988; Goździk, 2001; Woronko, 2012; Zieliński, 2014). These deposits are classified as fluvioperiglacial (Goździk, 1995, 2001) or fluvio-aeolian (Woronko, 2012; Zieliński et al., 2015; Ballantyne, 2018).

The fluvio-aeolian deposits of the Radzików Member are very similar to those of the FA unit, documented in the Czaplów UJK-3 borehole profile, located in the adjacent Kielce-Łagów Valley in the HCM (Ludwikowska-Kędzia, 2018). Similar features characterize the deposits of the so-called Radzików series, which accumulated at the foot of the Szydłów Foothills (Makowska et al., 1976). The Radzików series deposits contain a high proportion of aeolian quartz grains; it overlies Miocene marine deposits and is overlain by till, which documents its stratigraphic position and indicates a periglacial environment.

The persistently high proportion of aeolian quartz grains in the Radzików Member profile can be interpreted as the result of the redeposition of older aeolian deposits (Goździk, 1980; Mycielska-Dowgiałło, 1995, 2007; Mycielska-Dowgiałło and Woronko, 2001; Woronko, 2012), or as the result of the simultaneous activity of aeolian and fluvial processes during sedimentation. A modern equivalent of such an environment could be a polar desert, e.g. McMurdo Valley in Antarctica, where sand is transported mainly in the form of dunes moving in shallow, gravel-bed braided channels of the Onyx River (Mosley, 1988).

The increased proportion of sand in the profile of the Jabłonna Member, together with the increased content of aeolian grains, indicates an increase in the energy and dynamics of aeolian and/or fluvial erosion processes in the HCM that were responsible for transporting the deposits. The periodic disappearance of permafrost probably played a significant role in the "mobilization" of these deposits (cf. Zieliński et al., 2015). This disappearance resulted in a change in the availability of weathered material and its grain size, from silty to sandy. This phenomenon also contributed to changes in the dynamics of the fluvial system (e.g., by modifying the hydrological river regime, and consequently altering the conditions and possibilities of sediment supply and transport).

The magnetic susceptibility fluctuations observed in the Jabłonna Member reflect cyclical climate changes and/or episodic environmental changes (cf. Nawrocki, 2009; Figs. 5D and 6D). Cool climate conditions prevailed during the initial stages of formation of the Jabłonna Member. Later periods of organic matter being supplied to the lake, its decomposition, and the formation of iron and sulphur compounds, can be correlated with episodes of climate warming and/or periodic increases in erosion. The process of sulphate reduction in the lake deposits in the presence of organic matter can be explained by the periodic freezing of the lake surface, which limited gas exchange and oxygen availability. As indicated by studies of the meromictic, ice-covered Lake Vanda in the Southern Victoria Dry Valley in Antarctica (Canfield and Green, 1985), sulphate reduction is by far the most important anoxic process here, occurring in the presence of organic matter.

Well-preserved pollen grains of Quaternary plants, including thermophilous species, are absent from the palynomorph assemblages of the Jabłonna Member. Therefore, the final deposition probably occurred in the Quaternary but during the colder periods of the pre-glacial Pleistocene when erosion was more intense.

Favourable conditions for the development of aeolian processes could have been intensified in a karst environment (Ford and Williams, 2007; Ludwikowska-Kędzia, 2018). A large proportion of well-rounded and matt quartz grains is noted in the Quaternary deposits filling the karst forms in the Holy Cruss region (Urban, 2013), including at the Neogene–Quaternary boundary (Barcicki et al., 1991, 1996).

DISCUSSION

The diagnostic features compiled of the Słopiec Formation, supplemented with palynological data from the Jabłonna Member in the Jabłonna UJK-1 and Słopiec UJK-2 boreholes in the Słopiec Basin, enable comparison with existing views on the provenance of the pre-glacial deposits in the HCM and reconstruction of the palaeoenvironmental conditions.

As regards the pre-glacial muds in the Quaternary lithostratigraphic profile of the Holy Cross Mountains, a genetic link has been suggested with loess deposited in fluvial and/or lacustrine environments, either directly through aeolian transport or by surface wash processes (Filonowicz, 1972).

Analysis of the muds from the Jabłonna UJK-1 and Słopiec UJK-2 boreholes revealed that deposition of the Jabłonna Member took place in a lacustrine environment, although it was clearly influenced by the bedrock palaeorelief and its structural-karst determinants. These conditions, little discussed in previous literature, undoubtedly influenced the mode and rate of sediment deposition, the spatial variability of lithofacies, and the extent of individual facies within the lake. This explains the variability in deposit characteristics of the Jabłonna Member observed in the two borehole profiles examined, despite their close spatial proximity.

We exercise caution in using the term "loess" when referring to the provenance of the Jabłonna Member deposits (muds), as the term directly implies a genetic link with aeolian transport under periglacial conditions on the foreland of an ice sheet. A more accurate description would be: autochthonous silty, clayey, and sandy weathered material inherited from the Paleogene-Neogene stage of litho- and morphogenesis of the HCM.

This designation reflects the actual provenance of the material composing the Jabłonna Member, particularly given that no molluscan fauna that could determine a connection with loess was found in these deposits. However, determining the exact factors that triggered its transport requires further investigation, including documenting the genetic relationship between the loess covers and the local weathered bedrock in the HCM. The uncertainties do not relate to the aeolian activity in the HCM area under study, which is well-documented in the Słopiec Formation (e.g., in the Radzików Member), nor to the co-occurrence of cold climate conditions favouring aeolian processes during the pre-glacial period. The principal research challenge concerns the timing and duration of these aeolian processes: whether they occurred prior to the onset of sedimentation of the Słopiec Formation, or operated concurrently with its deposition.

Deposits such as those that were the source of material for the pre-glacial Słopiec Formation (with inherited, specific "environmental" lithogenetic features) have survived to the present day due to the specific structural relief of the HCM, particularly within the bottoms of structural depressions, such as the Kielce-Łagów Depression. These are usually the infills of karst sinkholes, consisting of mineral deposits such as clays, silts and sands (Fijałkowska and Fijałkowski, 1965, 1971, 1984; Filonowicz, 1976; Ludwikowska-Kędzia, 2013; Urban, 2013), as well as organic deposits such as peat, organic silts and lignite (Ludwikowska-Kędzia, unpublished materials). Such deposits are accessible and recognizable in various morphogenetic environments in the HCM, such as fluvial or slope environments. For example, there are younger muds and sands, such as Pleistocene (Vistulian, Late Glacial) and Holocene muds in the FSA deposits of the Słopiec UJK-2 borehole. These, despite having similarities in terms of lithogenesis, lithofacies and grain size to their pre-glacial equivalents, differ in several important respects. These differences include: a high proportion of non-resistant minerals in the heavy mineral spectrum (originating from the glaciogenic deposits); low magnetic susceptibility values; and above all a different palynological spectrum, in terms of both stratigraphy and environment (Ludwikowska-Kędzia, 2000, 2018).

The sedimentary palaeoenvironment of the Słopiec Formation, and primarily the Jabłonna Member, does not necessarily have to be directly related to the formation of lakes by the blocking of valleys by ice masses (Lindner, 1984). The structural relief of the HCM is characterized by the alternating occurrence of structural depressions (with basin-like widenings of river valley bottoms) and parallel ridges. This relief itself predisposes the area to the formation of deposit accumulation zones, which are controlled by changes in climatic and environmental conditions. The present-day fluvial environment in the Słopiec Basin provides favourable conditions for the formation of overbank facies (in ephemeral floodplain lakes). The same was true during the Vistulian and earlier Holocene intervals in the river valleys of the Świętokrzyskie region (Ludwikowska-Kędzia, 2000). These conditions include: the occurrence of extensive, flat bottoms of basins and structural depressions with a shallow gradient, additionally with local erosional bases in the form of bedrock outcrops, the availability of abundant fine-grained material, and transport in suspension in most rivers. The Słopiec Formation deposits (primarily the Jabłonna Member) did not accumulate in deeply eroded river valleys (Filonowicz, 1972, Lindner, 1984, 2004), but rather in zones of structural-karst palaeodepressions with polje features. This zones were typically controlled by a system of tectonic faults and grabens. Consequently, these deposits can rather be interpreted as examples of preserved lacustrine sediments and alluvium than as evidence of the existence of river palaeovalleys cut deep into the bedrock (e.g., Falkowski and Kowalski, 1987).

Our research suggests that the search for the sources of deposits such as the Jabłonna Member muds among outcrops of the Krakowiec clays (Filonowicz, 1972; Machów Formation, Miocene; outer zone of the Carpathian Foredeep, surroundings of HCM; Czapowski, 2004) does not seem justified. The variation in age and degree of preservation of the palynomorphs does not suggest that erosion has affected exclusively Miocene marine deposits. The relationship between the muds of the Jabłonna Member in the Słopiec Formation and the Miocene marine deposits may have resulted from them having the same source area, i.e. local weathered material of the Paleozoic and Mesozoic bedrock as well as Paleogene-Neogene deposits (terrestrial facies) in the HCM. The only differences between the muds and the Miocene marine deposits are the timing and the mode of sediment transport, as well as the type of final sedimentary environment that gave the deposits their specific features (controlled by the local relief, climatic changes and tectonic factors in the HCM). The differences in grain size between the muds of the Jabłonna Member and the Miocene marine deposits may be due to the fact that the Jabłonna Member deposits came from the covers that accumulated at the foot of the southern slope of the HCM, probably in the brackish zone of a sea with a Dalmatian-type coastline (Radwański, 1969, 1973), which favoured the deposition of coarser grain fractions. However, the finer material could have been transported by turbidity currents towards the deeper and/or more southerly parts of the Miocene sea.

The pre-glacial Słopiec Formation accumulated under cool climate conditions, which can be related to the variable climate conditions of the pre-glacial Pleistocene corresponding to Marine Isotope Stages (MIS) 103-23 (Granoszewski and Winter, 2016), mainly to a) an interval of cyclical coolings, initially shorter than warm periods (MIS 104-31; ~2.56–1.2 Ma), and/or b) large-scale climate cooling, i.e. the "900 ka cooling event" (MIS 24–22; ~940–860 ka), when three cooling fluctuations occurred at ~930 ka, 900 ka, and 880 ka, representing a key phase of the early Mid-Pleistocene Transition (MIS 36–17; ~1.25–0.7 Ma; Clark et al., 2006). In the context of INTIMATE stratigraphy (INTegration Ice core, MArine, and TErrestrial records; Rasmussen et al., 2014), it can be inferred that deposition took place during intervals of climatic change similar to those that determined the activation of fluvial and slope environments in the HCM region during the Late Pleistocene (Michczyńska et al., 2022, 2024). This would mean that the Słopiec Formation deposits could have formed during cold (stadial) phases, during transitional phases (from long-term stadials to interstadials), and/or during short-term, alternating stadial and interstadial phases, with a tendency towards cooling.

It seems reasonable to relate the Jabłonna Member deposits to the conditions prevailing during the South Polish Glaciations (Lindner, 1984, 2004; Dzierżek et al., 2021; Fig. 1A). However, the lack of a comprehensive and well-documented model of glacial evolution in the HCM, particularly in its southern and central parts, as well as criticism of previous concepts (e.g., Liszkowski, 1976; Ludwikowska-Kędzia, 2018) hinder any unambiguous conclusions. Such doubts are further reinforced by the results of litho- and chronostratigraphic studies of Quaternary deposits (from fluvial, glacial, and slope environments) conducted in this part of the HCM (e.g., Ludwikowska-Kędzia and Pawelec, 2014; Ludwikowska-Kędzia et al., 2015; Pawelec and Ludwikowska-Kędzia, 2016; Ludwikowska-Kędzia, 2018, 2021). These results suggested that the glaciogenic deposits should be related to the Middle Polish Glaciations (MIS 9-6).Therefore, the age of accumulation of the pre-glacial Słopiec Formation in the Holy Cross Mts requires further investigation. The pre-glacial period remains poorly understood in the Quaternary history of Poland (Bujak et al., 2016; Marks, 2023a), with numerous unresolved and challenging issues.

An alternative hypothesis proposed by Ludwikowska-Kędzia (2018) – that the FR unit (i.e. the Jabłonna Member) deposits accumulated in the coastal zone (lagoon) of the Miocene sea – is not confirmed, as these deposits lack well-preserved, untransported marine phytoplankton. Therefore, it is difficult to agree with Kowalski (2001) who assigned a Paleogene-Neogene age to the deposits in the Białe Ługi Valley, as they can be considered equivalent to the Słopiec Formation, and particularly as they occur in an adjacent part of the karst-structural depression system in the Słopiec Basin. As there is no clear stratigraphic evidence to support such an interpretation, it can only be assumed that the source materials for these deposits were weathering covers inherited from the Paleogene-Neogene stage of litho- and morphogenesis in the HCM.

CONCLUSIONS

Studies of the pre-glacial deposits (*sensu* Lewiński, 1928, 1929) conducted in two new boreholes (Jabłonna UJK-1 and Słopiec UJK-2) in the Słopiec Basin in the Holy Cross Mountains, enabled the identification and compilation of their diagnostic features. The degree of recognition and specific character of this autochthonous succession in the lithostratigraphic profile of Quaternary sediments of the HCM (cf. Czarnocki, 1927, 1931; Łyczewska, 1971; Filonowicz, 1972; Lindner, 1984; Ludwikowska-Kędzia, 2018) justifies the formal adoption of the name Słopiec Formation (named after the village near the boreholes) as a lithostratigraphic unit of the Quaternary in the southern part of the HCM. The boundaries of the Słopiec Formation are clear. It lies on Paleozoic bedrock and is overlain by glacigenic deposits of an uncertain stratigraphic position. The Słopiec Formation comprises lacustrine–fluvial deposits: a) the Jabłonna Member, which is represented by lacustrine deposits, and b) the Radzików Member (fluvio-aeolian), which is represented by fluvial (deltaic) deposits with evidence of the aeolian influence. The accumulation of the Słopiec Formation deposits took place in a karst lake environment under cooler intervals of the pre-glacial Pleistocene, at times of intensified erosion. These lakes were probably meromictic and ephemeral, formed in karst-structural depressions of the Paleozoic bedrock. Over time, the lacustrine depositional conditions clearly evolved towards a fluvial (deltaic) environment. The source material came from the weathering covers of the Paleozoic and Mesozoic local bedrock, as well as from Paleogene-Neogene cover deposits. The material was transported over short distances from multiple directions, and its supply to the lakes followed a cyclical pattern. The cyclical nature of material supply to the lake was triggered by changes in climatic and/or tectonic conditions.

Palynological analysis of the Jabłonna Member deposits identified 23 cryptogam taxa, 20 gymnosperm taxa, 51 angiosperm taxa, and 24 phytoplankton taxa. Significant mixing of palynomorphs of various ages (Cretaceous, Paleogene, Miocene, Quaternary) was observed, and their state of preservation suggests repeated redeposition. Scarce marine phytoplankton represented the Paleogene. The final phase of deposition of the Jabłonna Member in the Słopiec Formation occurred during the Quaternary Period. However, the exact stratigraphic position of the pre-glacial Słopiec Formation is uncertain.

The identification of Quaternary lithostratigraphic units in the HCM (e.g., the Słopiec Formation), the determination of their diagnostic sedimentological features, and their classification within depositional systems (glacial and non-glacial) across individual morphostructural units of this Paleozoic massif – conducted independently and at a local spatial scale (Ludwikowska-Kędzia, 2018) – constitutes a first and essential step toward broader regional (and even supra-regional) lithostratigraphic correlations.

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