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A new stratigraphic position of some Early Pleistocene deposits in central Poland

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A new borehole in Rożce (SW Mazovian Lowland) drilled in 2012, combined with a wide variety of research methods (palaeomagnetism, palynological analysis, studies of plant macroremains and textural features of deposits) shed new light on the age and stratigraphic position of the Early Pleistocene deposits, formerly assigned as the Lower Pleistocene. The study focuses on the deposits from 50.7–104.0 m depth, between glacial till of the Nidanian Glaciation (ca. 0.9 Ma) and the Poznań Clays (ca. 5.322 Ma). The deposits situated directly underneath the till (50.7–60.2 m) are related to the Nidanian Glaciation and show a reversed polarity and correlate with the end of the Matuyama Epoch. The deposits from 60.2–104.0 m depth were accumulated during the Early Pliocene, i.e. approximately 5.332–4.6 million years ago. They appear to correlate with the middle part of the Gilbert Palaeomagnetic Epoch and thus they are considerably older than previously thought. The cored section indicates a stratigraphic gap of about 3.5 Ma from the Lower Pliocene to the first advance of the Scandinavian ice sheets into Poland, which are thought to have occurred in the early Middle Pleistocene. The analysed deposits accumulated under variable climatic conditions showing two periods with significant aridity alternated with two periods of increased humidity. Deposits of the arid periods contain no pollen, but aeolian sand quartz grains are found. During periods of more humid climate the area was covered by various types of mixed forest.

Key words: Late Miocene/Early Pliocene, Early Pleistocene, pollen analysis, palaeomagnetism, mineralogy, central Poland.

INTRODUCTION

The Early Pleistocene, corresponding to the Preglacial period (Mojski, 2006) in Poland, is one of the least researched periods of the Quaternary (Łanczont et al., 2003; Piwocki et al., 2004). In Western Europe, along the margins of the North Sea, the Early Pleistocene is typified mainly by the development of fluvial and deltaic deposits (Menke, 1975; Kasse, 1990; Boenigk and Frechen, 2006; Kemna, 2008; W esterhoff et al., 2008). In Poland, the Early Pleistocene was thought to have been represented by fluvial or lacustrine-fluvial facies. They form vast alluvial fans deposited in a relict lake, preserved since the Neogene (Różycki, 1972; Lindner, 1992; Mojski, 2006; Makowska, 2015). According to Lewiński (1928), their deposition started at the end of Poznań Clays accumulation during the Late Pliocene, and finished upon the encroachment of the first continental ice sheet. In later years, these boundaries were determined at 2.588 million years BP (Baraniecka, 1991; Stuchlik, 1994) and ca. 0.9 million years (Lindner et al., 2013).

The classification of Early Pleistocene deposits in Poland was based mainly on two drillings: Ponurzyca near Otwock (Baraniecka, 1975, 1976; Stuchlik, 1975) and Rożce near Grójec, Mazovian Lowland (Baraniecka, 1980, 1991; Stuchlik, 1987, 1994). Four climatic phases of Early Pleistocene accumulation have been distinguished in these drillings, namely two warm and two cold phases correlated with those defined for the Early Pleistocene in Western Europe: Praetiglian, Tiglian, Eburonian and Waalian. The following local names were used for the periods determined based on the drillings: Celestynovian which corresponds to the Waalian, Otwockian (Eburonian), Ponurzycian (Tiglian) and Różcian (Praetiglian; Table 1). How-

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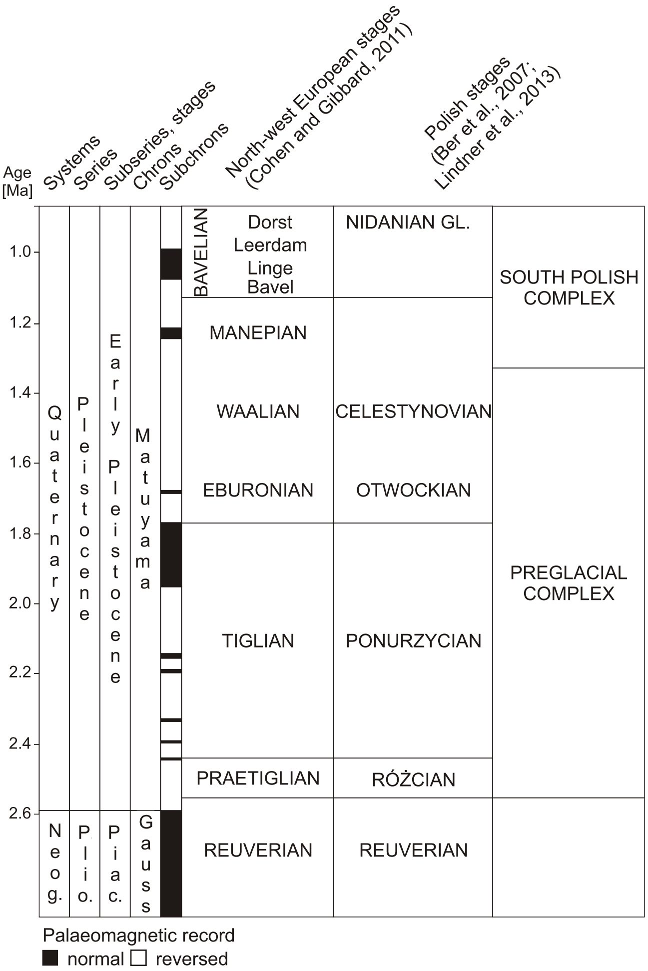
Table 1

Early Pleistocene stratigraphy of Poland (after Lindner et al., 2013) and correlation with global chronostratigraphy (Cohen and Gibbard, 2011)



ever, the results of the latest research show that the stratigraphic position of the Preglacial *sensu* Lewiński (1928) has begun to raise some doubts, because the Poznań Clays proved to be older (Piwocki et al., 2004). The end of their accumulation was moved from the Lower Pliocene to the Lower Miocene. This change meant that the Preglacial extended to the Early Pleistocene and the whole Pliocene, and currently it covers the period between ca. 5.322 and ca. 0.9 million years (Piwocki et al., 2004). The most common deposits are assigned to the Early Pleistocene. On the other hand, there are no deposits correlated with the Pliocene. An exception is the section from Wólka Ligęzowska, central Poland, with deposits representing almost the entire Pliocene (Skompski et al., 2006; Popescu et al., 2010; Makowska, 2015; Winter, 2015). Some researchers (Piwocki et al., 2004; Widera, 2007) assume, however, that this period coincides in the Polish Lowlands with a stratigraphic gap that covers the period between the end of the Miocene and the Early Pleistocene.

The main objective of this study is (1) to determine the age of the deposits dated so far at the Early Pleistocene, and (2) to reconstruct the environmental conditions under which the accumulation of the deposits occurred at the Rożce site (central Poland).

THE ROŻCE BOREHOLE DESCRIPTION

The research involved deposits of a borehole drilled at Rożce located SW of Grójec, SW Mazovian Lowland (51°50'7,29"N, 20°45'6,79"E, elevation 178 m a.s.l.; Fig. 1), at a distance of ca. 15 m from the historical drilling site of Rożce (Baraniecka, 1980), and finished at a depth of 116 m. The sequence of deposits and their lithology were compared with the section described by Baraniecka (1980; Fig. 2).

Six lithological units have been distinguished in the Rożce borehole that vary in terms of textural features (Fig. 2):

- Unit I (depth 104.0–116.0 m) – Poznań Clays;
- Unit II (depth 50.7–104.0 m) – sand and silt with scarce clay and gravel beds. In petrographic terms, the deposits are highly uniform and completely decalcified;
- Unit III (depth 49.55–50.7 m) – glacial till;
- Unit IV (depth 7.85–49.55 m) – considerably varied grain-size composition, ranging from gravel to clay;
- Unit V (depth 1.6–7.85 m) – glacial till;
- Unit VI (depth 0.0–1.6 m) – sand and gravel which grade into clayey silt with dispersed organic matter near the surface (Fig. 2).

METHODS

The study focuses on deposits from the depth interval of 50.7–104.0 m (Unit II; Fig. 2), which can be correlated with the Early Pleistocene deposits distinguished by Baraniecka (1980, 1991). Samples were taken and analysed by five different methods as listed below:

1. Palaeomagnetism – the results of this analysis were used to determine the age of deposits and their stratigraphic position:

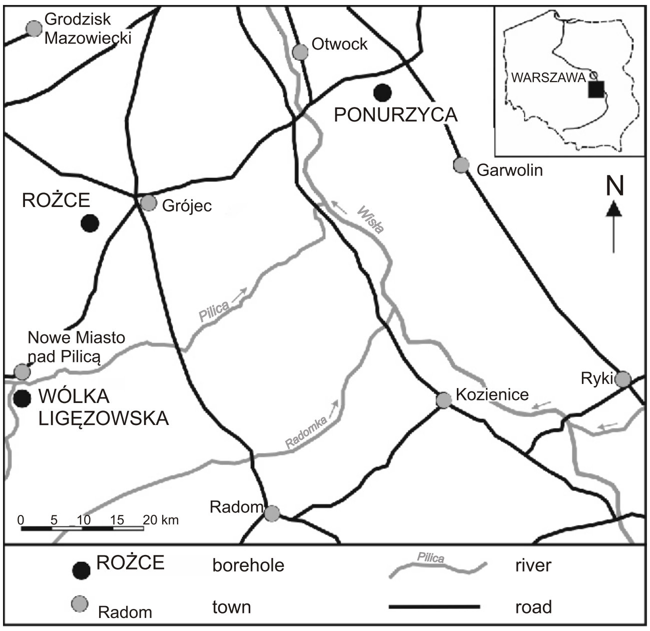


Fig. 1. Location of the Rożce borehole

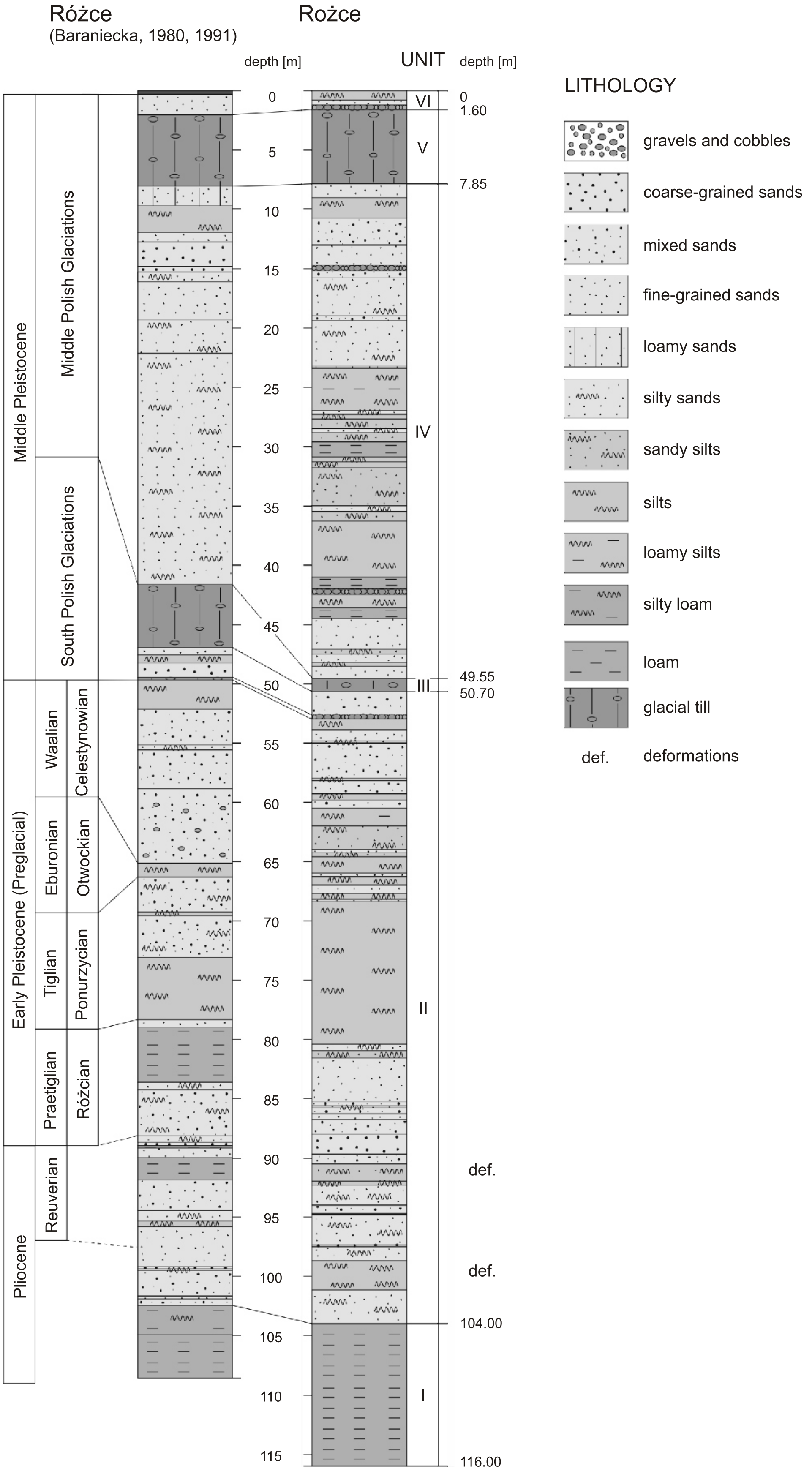


Fig. 2. Rożce lithological section

Correlation with the Różce historical section

– 78 cubic samples (65 from this core segment; 2 2 2 cm in size, oriented vertically) were subjected to remanent magnetisation analysis with the use of a cryogenic magnetometer *SQUID SRM 755* manufactured by 2G Enterprise (USA). The samples were step-wise demagnetised with an alternating field of up to 100 mT, which determined the components of the magnetic remanence in samples and their inclination. For the majority of samples, the relationship of laboratory-imposed saturation isothermal remanent magnetisation with temperature was studied to identify the ferrimagnetic minerals as a source of remanent magnetisation (STEPS 3 device);

2. Palaeobotany – the results were used to determine the climate conditions prevailing during the deposition, vegetation changes and the age of deposits:

a. pollen analysis

– palynological analysis (65 samples from a depth of 61.0–101.6 m). The palynological diagram included 54 pollen spectra with at least 200 pollen grains counted. The basic sum consists of tree and shrub pollen (AP) as well as dwarf shrubs and terrestrial herbaceous plants (NAP). The percentages of pollen of aquatic plants, spores and palynomorphs were calculated in relation to the basic sum;

b. analysis of plant macroremains

– after the volume of sediment was measured (150–200 ml), 211 samples were macerated according to a standard procedure (adopted by e.g., Stachowicz-Rybka, 2011). Macrofossils from 30 samples were identified on the basis of available publications and a reference collection provided by the Palaeobotanical Museum, Władysław Szafer Institute of Botany, Polish Academy of Sciences, Kraków.

3. Micromorphology – the results were used to determine the climate conditions, source of deposits and the conditions of transport and deposition:

– analysis of micromorphology of quartz grains in the fractions of 0.5–0.8 and 0.8–1.0 mm was carried out under an optical microscope (170 samples) using the Cailleux method (1942) as modified by Goździk (1980) and Mycielska-Dowgiałło and Woronko (1998);

4. Petrography and mineralogy – the analysis determined the sources of deposits and their age.

Petrographic and mineralogical analyses: the content of quartz in the fractions of 0.5–0.8 and 0.8–1.0 mm (193 samples), heavy minerals in the fraction of 0.1–0.2 mm, where the sum of transparent and non-transparent minerals was assumed to constitute 100% (71 samples), and the petrographic composition of glacial till in the fraction of 5–10 mm (1 sample). Based on the results of the latest analysis, petrographic coefficients O/K, K/W, A/B were calculated, where: O – total quantity of Paleozoic sedimentary rocks, K – total quantity of crystalline rocks and quartz coming from the disintegration of crystalline rocks, W – total quantity of Paleozoic limestone and dolomite, A – total quantity of rocks susceptible to destruction, B – total quantity of rocks resistant to destruction (Rzechowski, 1971). These coefficients help to determine the correlations with other clay layers in the region, and their age. The correlation is based on the fact that each continental glacier had a different sediment source area, and at the same time different rocks were exposed to exaration (Lisicki, 2003).

Furthermore, the total decalcification of deposits prevented the analysis of oxygen isotopes.

RESULTS

MINERALOGICAL COMPOSITION AND TEXTURAL FEATURES OF DEPOSITS

The grain roundness, degree of quartz grain surface frosting of the sandy fraction, and the composition of heavy minerals have allowed us to distinguish four major depositional subunits (A–D) in unit II (Figs. 2 and 3).

Subunit A (depth 82.45–104.0 m) is built of poorly sorted sand with a massive structure (Sm), interbedded with silt-clay deposits of massive structure (Fm), flaser lamination (FSf) and solid clay with a thickness of only 1 cm. Laminated clay (Fv) was found at a depth of 87.28–90.91 m. In addition, both ductile and brittle deformations of deposits were observed in the clay layers. Accumulation of subunit A occurred in a shallow littoral zone of a water body. The water level in the water body with laminated clay deposition was not stable and periodically increased. The mineral composition of the sandy fraction from subunit A (depth 82.45–104.0 m) is characterized by a very high percentage of quartz, mica and single feldspars. Quartz grains are very poorly rounded, representing the EM/EL type (>100%, including regeneration quartz grains) of a high-energy beach environment. Based on the composition of heavy minerals, two subunits can be distinguished: A1 and A2. Opaque minerals, amphiboles and garnets represent the major part of A1 (depth 86.8–104.0 m). The percentage of minerals resistant to chemical and physical weathering is low. There are also chlorites (up to 17.7%). In subunit A2 (depth 82.45–86.8 m), the content of garnets decreases towards the uppermost part of the subunit. They are replaced by more resistant minerals. The percentage of primary iron oxides also increases (up to 41.5% in the uppermost part of the subunit). The content of amphiboles remains very high (Fig. 3).

Subunit B (depth 80.3–82.45 m) is built of fine- and coarse-grained sand, horizontally stratified (Sh) at the bottom, and loamy sand of massive structure (SFm) in the uppermost layer. No deformation was observed in deposits of subunit B.

Quartz grains representing a high-energy aquatic environment (types EM/EL and EL), characterized by better rounding than in subunit A, are dominant in subunit B (depth 80.3–82.45 m). Grains developed in an aeolian environment (EM/RM; >43.1%) were also found there. In terms of heavy minerals composition, the subunit (B1, B2) was found to be bipartite. Primary iron oxides and very resistant minerals with the dominance of zircon play the key role in B1 (depth 81.4–82.45 m). The percentage of garnets decreases (<0.4% in the uppermost part). Siderites (approx. 98%) and ferruginous carbonates (51.4–78.5%) represent the majority of minerals in subunit B2 (depth 80.3–81.4 m; Fig. 3). It appears that the deposition of subunit B occurred in the subboreal conditions. Given the very high content of grains representing the aeolian environment in the deposits, and their structure, it can be assumed that they represent aeolian deposits aerated in the littoral zone of the drying lake.

Subunit C (depth 60.2–80.3 m) is built of massive clayey or clayey-silty deposits interbedded with fine-grained sands of ca. 2 m thickness and normal graded bedding (Sm), or sandy-clayey deposits with a thickness of merely 0.03 m. Accumulation of subunit B took place in a deep-water body where steady sedimentation of clayey deposits was interrupted by run-offs of sandy deposits. No deformation was observed in deposits of subunit C. In subunit C (depth 60.2–80.3 m), the sandy fraction is dominated by quartz EM/EL; the percentage of

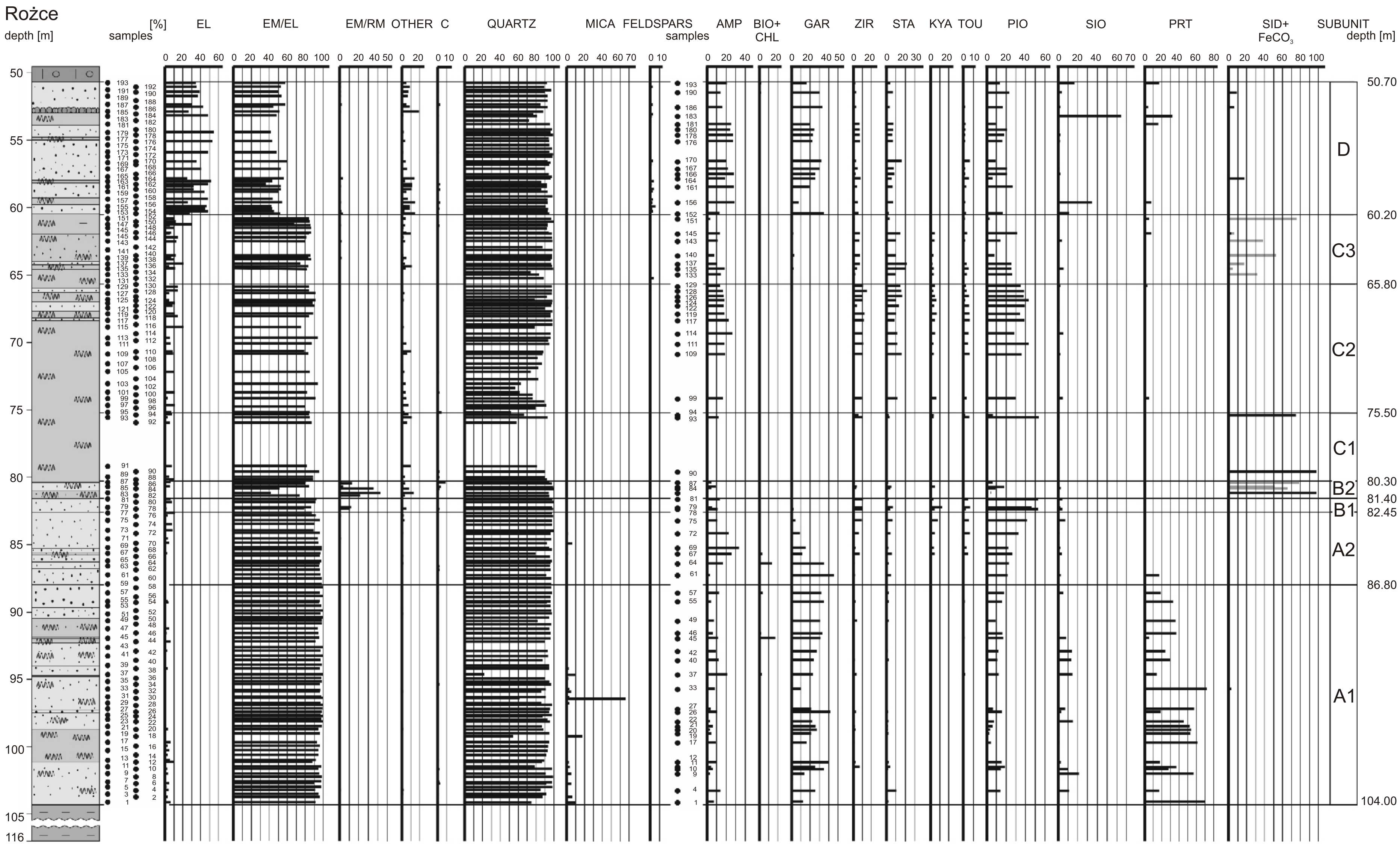


Fig. 3. Analysis of rounding and frosting of quartz sand grains according to Cailleux (1942) with the modification of Goździk (1980) and Mycielska-Dowgiałło and Woronko (1998)

Contents of minerals in the 0.5–0.8 and 0.8–1.0 mm fraction; contents of heavy minerals in the 0.1–0.2 mm fraction; EL – shiny, very well-rounded fluvial grains, EM/EL – shiny, moderately rounded fluvial grains, EM/RM – moderately rounded aeolian grains, C – broken grains; heavy minerals: AMP– amphiboles, BIO – biotite, CHL – chlorite, GAR – garnets, ZIR – zircon, STA – staurolite, KYA – kyanite, TOU – tourmalines, PIO – primary iron oxides, SIO – secondary iron oxides, PRT – pyrite, SID – siderite, $FeCO_3$ – iron carbonates; other explanation as in Figure 2 grains EL (>20.0%) increases towards the uppermost part. Grains EM/RM occur sporadically. In terms of heavy mineral content, the subunit (C1–C3) is tripartite. The composition of heavy minerals in subunit C1 (depth 75.5–80.3 m) is identical to that in subunit B2. In C2 (depth 65.8–75.5 m), siderite disappears and is replaced by resistant minerals, mainly zircon and staurolite, primary iron oxides and amphiboles. No garnets were found in the deposit. In subunit C3 (depth 60.2–65.8 m), there is a significant amount of iron carbonates and pyrite in the uppermost part. Garnets represent only a few percent of the content (Fig. 3).

Deposits of **subunit D** (depth 50.7–60.2 m) are represented by medium-grained sand with fine, horizontally stratified gravel (Sh). A characteristic feature of these deposits is the presence of feldspars in the fraction of sand and gravel. A small thrust fault with a gently inclined plane (ca. 45°) is observed in the deposits. Most likely, the accumulation of subunit D occurred in the conditions of intensive shallow flow.

Shiny grains of type EL (>40%) and EM/EL dominate in the deposits of subunit D (depth 50.7–60.2 m). The percentage of "OTHER" type of grains (that is, which is the result of weathering of chemical and mechanical operating *in situ*) increases (>19.7%). The deposits have a homogeneous mineralogical composition. Garnets, amphiboles, primary iron oxides, zircon and staurolite are dominant (Fig. 3).

The thus developed sediment is overlain by glacial till (depth 49.55–50.7 m) characterized by the petrographic indices of O/K = 1.02, K/W = 1.23 and A/B = 0.67. The comparison of these results with those obtained by Lisicki (2003) from the Vistula River Basin suggests that the till may come from the Narevian or Sanian I Glaciation. However, no straightforward interpretation is possible due to a small thickness of the deposits. It appears that the deformation of deposits in subunits A–D was caused by the continental ice sheet of this glaciation.

PALAEOMAGNETIC ANALYSIS

The analysis of remanent magnetisation provided results of variable quality due to the substantial variety of magnetic minerals as carriers of magnetic remanence in the sediment. Eventually, characteristic components of natural remanent magnetisation were determined in 67 samples. Some of the samples featured only a low-field component demagnetised with a field of up to 10–15 mT. The others contained two components featuring opposite polarity. This may suggest remagnetisation that may have occurred as a result of secondary magnetisation recorded in a secondary hematite or maghemite. The presence of greigite, being a late diagenic mineral (Sagnotti et al., 2005), does not significantly affect the magnetostratigraphic data, recording the magnetic field at most up to 100 ky later than deposition. The obtained results have allowed dividing the drill core into segments featuring the prevalence of normal or reversed polarity.

Deposits collected at a depth of 80.0–105.53 m have a dominant component with positive inclination. This fragment, however, is not uniform in terms of magnetic minerals (Fig. 4). The uppermost part of the Poznań Clay (depth 105.07–105.53 m) contains maghemite, while silt at a depth of 99.0–101.0 m – magnetite and hematite. Sandy samples from a depth of 80.0–92.0 m contain a very small amount of ferromagnetic fraction (mainly magnetite, likely secondary hematite). Apart from the normal component in magnetite or greigite found in deposits from below 85.0 m; samples rich in maghemite or hematite show traces of a secondary reversed component (Fig. 3).

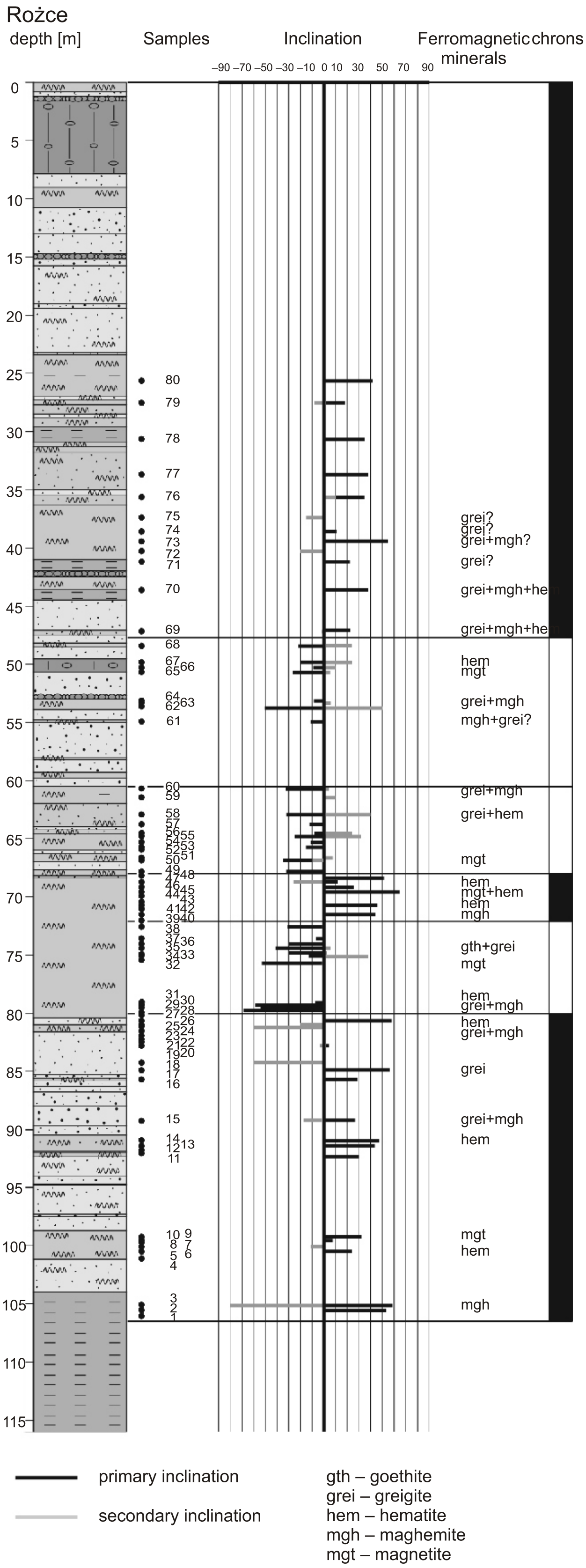


Fig 4. Magnetic polarity pattern

Explanations as in Figure 2

A fragment of the core characterized by reversed polarity of high inclination was found at a depth of 72.0–80.0 m in silt containing much siderite. Furthermore, greigite and hematite were found at a depth of 79.0–80.0 m, whereas between 74.0 and 75.0 m – greigite, maghemite and probably goethite (Fig. 3).

Sediment at a depth of 68.0–72.0 m shows normal polarity with the main media represented by iron oxides (magnetite, hematite, maghemite). Inclusions of pyrite/greigite weathered to hematite were found only in a magnetically anomalous sample from a depth of 61.2–68.0 m (Fig. 3).

Deposits collected at a depth of 61.2–68.0 m were characterised by mixed polarity with the dominant component of reversed polarity. Normal components are likely to be secondary, recorded in the hematite phase.

Part of the core from a depth of 25.0–61.2 m was characterized by mixed polarity. Both reversed polarity (dominant down to 48.0 m) and normal polarity (dominant in the upper part) components were found. These deposits contained mainly greigite with maghemite, with the exception of clay that included hematite and magnetite (Fig. 3).

THE PALYNOLOGICAL ANALYSIS

The alternation of sand and clay deposits from 61.00–101.80 m depth indicates a changing depositional environment of lacustrine-fluvial character. It affected deposition of the pollen and its preservation. The presence of heavily damaged, often amorphous pollen, in particular Pinaceae (at a depth of 89.00–98.3 m; >47%) indicates multiple redeposition. The pollen was also destroyed by corrosion caused by oxidation and post-depositional weathering. Furthermore, the pollen sequence from Rożce shows large gaps affecting the reconstruction of vegetation and climate changes.

Based on the changes in the pollen spectra, six phases of vegetation development can be distinguished in the pollen sequence from a depth of 61.0–101.8 m (Fig. 5), which indicate transformations of plant communities and climate changes.

Although pollen assemblages of the oldest phase, i.e. phase I (depth 101.8–98.3m), are dominated by AP pollen, the values of NAP are above 30%. Mixed forests with *Pinus, Betula* and *Quercus* and an admixture of *Carpinus, Tsuga, Sequoia, Sciadopitrys* and Cupressaceae occurred across arid areas. More humid regions were overgrown with swamp forests of *Alnus* and *Nyssa.* High percentage of NAP, in particular Poaceae (17.9%) and Cyperaceae (6.2%), as well as considerable taxonomic diversity, indicates the presence of open vegetation adapted to varying moisture conditions. The nature of vegetation indicates temperate climate with clear seasonality.

Pollen assemblages from phase II (depth 95.1–98.10 m) are characterized by varying AP values and high proportion of redeposited sporomorphs. Pollen of trees is represented by *Pinus sylvestris* type, *P. haploxylon* type*/Cathaya, Quercus*, *Carpinus, Alnus* and *Betula*. The percentages of *Picea* (maximum values of 24.5%), *Sciadopitys, Tsuga, Abies* and Cupressaceae are varied. The percentage of NAP is also variable, but relatively high – up to 30% (Poaceae dominate). At the beginning of the phase, mixed forest developed with *Picea* and *Pinus sylvestris* type, *P. hoploxylon* type/*Cathaya, Tsuga, Sciadopitys* and *Abies,* where broad-leaved trees were represented mostly by *Quercus, Betula* and *Carpinus.* Riparian forests with *Carya, Pterocarya, Salix* and *Ulmus* spread, but swamp forests with *Alnus* continued to occur*.* Development of open vegetation is evidenced by the increasing values of Poaceae and other herbaceous plants. Based on the vegetation changes, it can be concluded that there was a change in climate conditions. The growing importance of such trees as *Picea, Tsuga, Sciadopitys* and *Abies* may reflect increased precipitation and a slight air temperature drop, which indicates climate cooling.

The percentage of *Ulmus*, *Carya*, *Carpinus*, *Fagus*, *Pterocarya*, *Zelkova*, Taxodiaceae and *Salix* increases in phase III (89.0–94.6 m). Pollen of other trees, except for *Parrotia* (6.5%), accounts for up to 2% of the total taxonomic richness, while shrubs are represented mostly by *Corylus* (above 25%). At the same time, the values of redeposited sporomorphs were still high. Riparian forests with *Ulmus, Carya, Pterocarya, Salix* and *Liquidambar* were spreading, enriched with a new taxon – *Vitis.* Swamp forests with *Alnus* and increased proportion of Taxodiaceae were still present. New taxa appeared in deciduous forest, including *Fagus, Juglans, Parrotia, Aesculus,* various species of *Tilia, Eucommia* and *Castanea/Castanopsis.* Shrubs represented by *Corylus, Sambucus* and *Viburnum* became a significant component of forests*.* The changes in vegetation reflect climate warming, increased amount of precipitation, and reduced seasonality of climate that resembled a warm temperate climate.

Significant changes in the pollen spectra of phase IV (samples from depths of 84.60–85.65 m and 82.9 m) are reflected in the increased percentage of NAP (>70%), with the dominance of Ericaceae (max. 18.8%) and Poaceae (26.3%) pollen. In addition to Poaceae, pollen of *Artemisia*, Asteraceae, Chenopodiaceae and Cichorioideae dominates in the sample from a depth of 85.65 m. Brassicaceae, Caryophyllaceae and *Anthemis* type are present in large quantities. The pollen assemblage in samples from a depth of 85.65 indicates the development of steppe-like communities with the dominance of Poaceae and *Artemisia* as well as communities of Ericaceae low shrubs. However, the presence of arboreal pollen, e.g. *Quercus, Betula, Alnus* and *Ulmus* and *Nyssa* should be linked with the occurrence of more humid places, located for instance along rivers. With respect to steppe-like communities, it can be assumed that the climate was generally dry with continental conditions, strong seasonality and relatively cold winters. Changes in plant communities in phase IV are reflected in the increased quantity of the pollen of trees, including *Pinus, Quercus, Ulmus, Carpinus, Fagus* and others, correlated with the decreased proportion of NAP. Such changes suggest a reduction in diverse plant communities of open habitats. Mixed forests with *Pinus* and *Quercus* as well as riparian forests with *Ulmus* developed*.* Open plant communities were still widespread, but with a much smaller proportion of *Artemisia* and Ericaceae. Considering the vegetation changes, it can be assumed that the amount of precipitation increased and the climate became less continental.

Phase V (depth 68.5–68.9m) is characterised by the dominance of arboreal pollen, mainly *Pinus sylvestris* type, *P. haploxylon* type, *Betula* (>28%), *Quercus, Fagus, Ulmus Nyssa* and other conifers (*Sequoia, Picea, Sciadopitys,* Taxodiaceae). The content of NAP is low and represented mainly by Poaceae and Ericaceae. Pollen assemblages indicate the development of mixed deciduous forest. Riparian forests with *Alnus, Ulmus, Nyssa* and Taxodiaceae occurred along the rivers. Forest plant communities provide evidence for temperate, mild and rather humid climate.

In phase VI (depth 61.0–68.3 m), the percentage of NAP is high (>50%; mainly Poaceae). Taxonomic diversity of herbaceous plant pollen is high and dominated by *Artemisia*, Chenopodiaceae, *Rumex*, different species of *Ranunculus* (*R. acris* type and *R. flammula* type), Cichorioideae, *Plantago* and Cyperaceae. The values of Ericaceae significantly dropped. AP

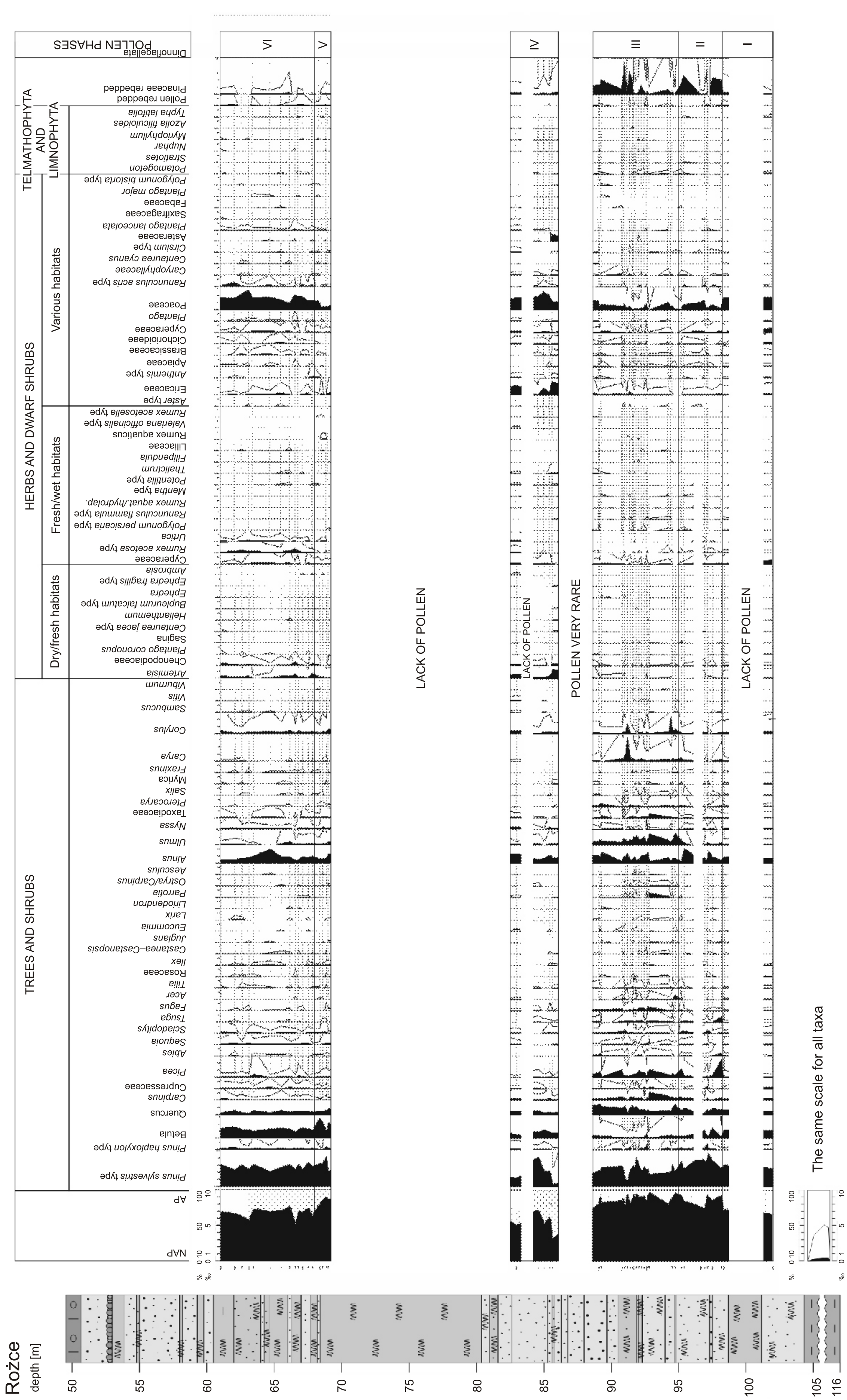


Fig. 5. Pollen diagram

Explanations as in Figure 2

is represented mainly by pollen of *Pinus sylvestris* type, *Alnus*, *Betula* and *Quercus*. The values of *Nyssa*, *Sequoia*, *Carpinus, Ulmus,* Taxodiaceae, *Picea*, *Tilia* vary but do not exceed 4%. Rich pollen flora of the trees reflects the presence of open, mixed deciduous forest and riparian forest. Open environments with vegetation rich in herbs, mainly Poaceae, *Artemisia,* Chenopodiaceae, Cichorioideae, *Rumex acetosa* type, *Plantago, Urtica* and *Ranunculus*, show fluctuations that reflect expansion of open vegetation.

The climate of phase VI resembled a temperate climate with a strong continental influence. It follows from the oscillating AP/NAP ratio related to the spread and withdrawal of open communities correlated with the disappearance of alluvial (riparian) communities and cyclic increases and decreases in the climate humidity/aridity.

VARIATION IN PLANT MACROREMAINS

Plant remains were found only at a depth of 79.35–98.60 m. Macroflora is very poor. Only several taxa (usually small quantities) were identified, including: a single megaspore of *Selaginella pliocenica* Dorof., high frequencies of megaspores of *Azolla glabra* Nikit. and *Salvinia* cf. *intermedia* Nikit., as well as single fruits and seeds of *Actinidia faveolata* Reid and Reid, *Sambucus lucida* Dorof., *Vitis parasylvestris* Kirchheimer, and *Hypericum tertiaerum* Nikit. They were accompanied by less abundant *Carpinus betuloides* Unger., *Betula* cf. *cholmechensis* Dorof., *Dulichium marginatum* (Reid and Reid) Dorof., *Urtica pliocenica* Dorof., *Najas* cf. *marina* L., *N.* cf. *minor* All., *Nymphaea* sp., and less diagnostic *Lycopus europaeus* L. and *Potamogeton* sp.

DISCUSSION

THE AGE OF SEDIMENT

The results of studies of deposits from Rożce have allowed determining the age of deposits correlated by Baraniecka (1991) with the Early Pleistocene, to follow the changing environmental conditions prevailing during their accumulation and the variability of sources of material supplied to the then existing system.

Despite relatively large differences in the feature of quartz grain surface, composition of heavy minerals and presence of amphiboles, the deposits from the 60.2–104.0 m depth interval in Rożce (subunits A–C) can be classified as the pre-Quaternary substratum (Woronko and Bujak, 2010). On the other hand, the changes in development of the deposits may be attributed to different sources of material supply (Kosmowska-Ceranowicz, 1979; Badura and Przybylski, 2004; Piwocki et al., 2004) and climate changes during their accumulation.

In terms of mineralogy, deposits at a depth of 50.7–60.2 m (D subunit) have similar characteristics to fluvioglacial deposits with a varying flow regime. A large amount of EL grains may indicate the supply of material from the north. This type of grains were found in deposits in the Płock Basin (Roman and Woronko, 2014), as well as in the glacial till from the Wartanian stadial of the Odranian Glaciation (Saalian) in northern Poland (Woronko et al., 2013) and in the deposits of the Toruń–Eberswalde proglacial stream valley (Woronko and Pisarska-Jamroży, 2015). In addition, a similar composition of heavy minerals, i.e. predominance of garnets and amphiboles, was found in glacial till of the Saalian Glaciation in the Netherlands (Rappol and Stoltenberg, 1985) and in Lithuania (Vareikienë et al., 2007). In each case, the source of deposits was sought in the Fennoscandian Shield, including Archaean–Proterozoic crystalline rocks and younger recycled sedimentary rocks ranging in age from Cambrian to Paleogene. It is likely that deposits associated with the glacial Pleistocene in the Rożce section had the same source as well. The fact is further confirmed by a large amount of feldspars found in the deposits.

Most of the palynologically identified taxa (particularly forest taxa) are associated with the broadly defined zone of temperate climate (Table 2; Figs. 5 and 6). In addition, open field vegetation becomes increasingly common. Elements of the subtropical flora are least frequent in the whole profile, while the proportion of warm-temperate flora is significant (Fig. 5).

Phases I, II, III are characterized by a distinct proportion of NAP and high taxonomic diversity (Fig. 5). Based on the palynoflora, the Middle Miocene age of the deposits should be ruled out due to the absence of taxa typical of this period: *Sterculiaceae*, *Tricoloporopollenites pseudocingulum, T. fallax* and *Tricolporopollentes liblarensis,* and a significant proportion of vegetation likely associated with plant communities of open areas. On the other hand, plant communities composed mainly of temperate-zone species (primarily associated with forest communities), with only minor proportion of subtropical species, dominated in Poland in the Upper Miocene (Ziembińska-Tworzydło, 1998). A characteristic feature of the Upper Miocene were large quantities of *Betula* pollen (climate phase XI, *Betulaepollenites–Cyperaceaepollis* spore-pollen zone; Piwocki and Ziembińska-Tworzydło, 1997), which indicates significant cooling of the climate. There is a high similarity between the composition and the variety of plant communities from the Upper Miocene and the communities from Rożce, which may suggest the Late Miocene age of phase I. Phase II, and in particular phase III, is distinguished by a significant percentage of Juglandaceae pollen, represented by *Carya, Pterocarya* and *Juglans.* It is possible that this phase should be correlated with climate phase XII, the *Carpinipites–Juglandaceae* spore-pollen zone distinguished for the uppermost Upper Miocene (Piwocki and Ziembińska-Tworzydło, 1997).

Significant changes in the pollen flora occurred in phase IV, documented by the decreasing proportion of arboreal pollen, especially trees of warm-temperate climate correlated with the growing proportion of NAP, mainly Ericaceae, Poaceae and *Artemisia.* The major transformation of plant communities was expressed in the decreasing amount of mesothermal vegetation combined with the increased proportion of herbaceous plants, in particular Poaceae and, to a lesser extent, steppe elements. This drastic change in plant communities indicates a climate change that could be associated with a strong regional climate fluctuation. The likely cause of this change is the late Messinian Salinity Crisis (5.96–5.322 Ma), during which the temperature at moderate and higher latitudes probably dropped by even a few degrees (Ivanovic et al., 2014).

The age of deposits from depths of 82.90 m and 84.6–85.65 m (IV phase) is more difficult to determine. This is due to the lack of pollen record in some layers of the sand unit – frequent in this part of the profile. There are, however, significant changes in the natural environment, which led to deforestation and expansion of herbaceous vegetation and Ericaceae with the occurrence of *Quercus, Nyssa* and *Ilex* (Fig. 5; Table 2). A question arises whether such a significant change in plant communities may be associated with a very strong climate cooling leading to the development of steppe-tundra, or rather with a strong reduction in the amount of precipitation, or perhaps it reflects local vegetation encroachment on dry and

Table 2

Description of local pollen assemblages and climate changes in deposits of the Rożce borehole

	Depth [m]	Plant communities	Climate
VI	61.0–67.9	Mixed pine-birch forest on infertile substratum with *Quercus*, *Picea, Sciadopitys, Sequoia* and *Carpinus* as well as *Fagus, Ilex* and *Abies.* Riparian forests with *Alnus* and Taxodiaceae*, Nyssa* and *Ulmus* along river banks. Herbaceous communities of various species composition depending on the type of soil, distance from a water body and rivers, soil moisture and topography.	Temperate climate with continental influence and periodic increases and decreases in moisture content/aridity.
V	68.3–68.9	Mixed forests with *Betula*, *Pinus*, *Quercus*, *Carpinus*, and a small proportion of *Sequoia*, *Picea* and *Ilex*. Riparian forests with *Alnus*, *Ulmus* and *Nyssa*.	Temperate climate with higher humidity.
IV	82.9–85.65	Steppe-like vegetation with Poaceae, *Artemisia,* Asteraceae, Chenopodiaceae, Caryophyllaceae, *Anthemis* type, Brassicaceae, *Centaurea* on dry habitats (various species), *Helianthemum* and *Ephedra fragilis* type. Wet habitats overgrown with plant communities of Ericaceae, Cyperaceae, *Plantago* and *Ranunculus*. Reduced and species-poor dry pine-oak forest. Riparian forests with *Alnus*, *Nyssa* and *Ulmus* along rivers and at water bodies.	Temperate dry climate. Probably a strong temperature drop in winter months, even below 0°C. Precipitation in winter. Significant impact of continentality and strong seasonality of climate.
III	89.0–94.6	Broad-leaved forest with constant occurrence of *Pinus, Quercus*, *Picea*, a significant admixture of *Carpinus* and *Fagus,* and varying proportions of *Parrotia, Aesculus, Juglans, Tilia, Castanea, Castanopsis* and conifers *Sciadopitys, Tsuga, Abies,* Cupressaceae, *Sequoia* and *Larix.* Understory: *Corylus*, *Sambucus, Viburnum*, *Ligustrum*, and Ericaceae in the groundcover. *Riparian forests: Alnus, Ulmus, Carya, Pterocarya, Liquidambar* and *Salix.* Swamp forest with Taxodiaceae, *Nyssa* and *Alnus.* Open vegetation: herbaceous plants up to 30%, in particular Poaceae, Cyperaceae, *Artemisia*, Cichoriodeae, Chenopodiaceae, Apiaceae, *Ranunculus* and others.	Temperate climate, warm and humid with precipitation in winter and clear seasonality.
II	95.1–98.1	Open mixed forests dominated by *Picea, Abies, Tsuga* and *Quercus*, *Betula* and a small admixture of other deciduous trees. Riparian forests with *Alnus* and *Ulmus* and *Carya*. Reduced importance of open vegetation.	Increase in humidity of climate accompanied by slight weather cooling.
I	98.3–101.8	Open mixed forests with *Pinus, Quercus, Betula, Carpinus*, Cupressaceae and *Picea.* Riparian forests with *Alnus*. Open vegetation dominated by Poaceae, Cyperaceae and Ericaceae.	Temperate climate with continental conditions and clear seasonality.

heavily eroded areas. If the pollen of *Quercus, Nyssa* and *Ilex* occurs *in situ*, one should assume that the communities are of regional distribution. Similar climate changes were recorded in profiles of Central Europe (Utescher et al., 2000), although with less clear continentalization of climate. However, based on the occurrence of arboreal elements of the warm-temperate flora, with a significant proportion of elements of the moderate-cold flora, it can be concluded that the deposits of this phase represent the oldest Lower Pliocene. In this context, sedimentation of deposits from a depth of 61.0–68.3 m (phase V and VI) took place in the Early Pliocene.

Vegetation and climate changes in the Late Pliocene and late Early Pliocene were reconstructed based on palynological data from Wólka Ligęzowska (Popescu et al., 2010; Winter, 2015). As regards the pollen spectra reflecting the vegetation and climate at the end of Pliocene, there is a difference between data from Wólka Ligęzowska and Rożce (Fig. 6). Subtropical taxa are rare in both profiles derived from cores, while warm-temperate taxa are significantly represented. The percentage of warm-temperate elements is higher, in particular in the lower part of the Wólka Ligęzowska profile. The values of pollen of herbaceous plants and Ericaceae are very high in both profiles, but there are also differences expressed by lower values of *Artemisia* in Rożce. Based on the pollen data, the Pliocene/Pleistocene boundary was established in the Wólka Ligęzowska profile (Popescu et al., 2010; Winter, 2015). The end of the Pliocene in the Wólka Ligęzowska profile is documented by a high percentage of pollen of *Pinus sylvestris* type, i.e. up to 75%. (Fig. 5). No such high values have been determined in Rożce. The transition to the Quaternary in the core of Wólka Ligęzowska is expressed in a high percentage of NAP, including *Artemisia* and Ericaceae, and by the absence of pollen of *Quercus, Corylus, Nyssa, Ulmus* and other plants with higher thermal requirements, which occur in the sequence from Rożce. Taking into account the differences in the pollen floras, it has been suggested that phase IV from Rożce may represent the broadly defined boundary between the Miocene and the Pliocene.

There are no palynological data for the Early Pleistocene in Wólka Ligęzowska, Simultaneously in other profiles from central Poland with a palynological record representing the Early Pleistocene, no pollen of warm-temperate trees were found, e.g. *Sequoia, Nyssa,* Taxodiaceae, *Aesculus, Liriodendron* and *Liquidambar* (Winter, 2015). And thus, pollen flora from phases V and VI in Rożce, absent in deposits from Wólka Ligęzowska, may be correlated with the lowest Early Pliocene. The differences in the pollen floras between both profiles may confirm the Miocene/Pliocene age of deposits from a depth of 61.2–101.8 m in Rożce.

Plant remains from a depth of 79.35–98.60 m (I–IV pollen phase) suggest that the deposits date back to the Neogene. Nonetheless, a number of taxa found in the Rożce section occur in deposits dated from the Early Miocene to the Early Pleistocene (e.g., *Salvinia* cf. *intermedia* Nikit., *Selaginella pliocenica* Dorof., *Sambucus lucida* Dorofeev*, Hypericum tertiaerum* Nikit., *Actinidia faveolata* Reid and Reid*,* and *Vitis parasylvestris* Kirchheimer). Taking into account the results of palynological studies, one should remember, however, that deposition of macroremains occurred at most in the latest Late Miocene. When considering climatic and environmental conditions, the identified taxa correspond to the first vegetation phase distinguished in pollen analysis (depth of 89.0–101.6 m) and indicate that the plant remains originate from a shallow basin with warm eutrophic waters.

Narrowing down the age of the studied deposits on the basis of palaeobotanical data and taking into consideration the changes in polarity, allows attributing the individual parts of the core to specific subchrons identified in the middle part of the Gilbert Palaeomagnetic Epoch (approx. 5.23–4.62 Ma; Fig. 7). The strata at a depth of 80.0–104.0 m may be correlated with normal polarity subchron C3n.4n (Thvera), at 72.0–80.0 m – with reversed polarity subchron C3n.3r, at 68.0–72.0 m – with normal polarity subchron C3n.3n (Sidufjall), and at 61.2–68.0 m – with reversed polarity subchron C3n.2r (Fig. 7). On the other hand, the overlying sediment related to the ice sheet advance, which shows reversed polarity, can be correlated with the end of the Matuyama Epoch and the Narevian Glaciation. Petrographic analyses indicated a similar age of this till, albeit it cannot be ruled out that it actually originates from the Elstera Glaciation.

Bearing in mind the above palaeomagnetic and palynological data, it may be concluded that the sediment from a depth of 61.0–104.0 m was deposited at the beginning of the Early Pliocene. However, the end of deposition proves to be more difficult to determine. It can be assumed that the deposits are not younger than ca. 4.6 Ma, as this period correlates with the beginning of the Early Pliocene warm period (4.6–3.1 Ma, Dekens et al., 2007).

The study results place the so-called Preglacial sediment of Rożce in a different stratigraphic situation than it was originally suggested by Baraniecka (1991) who estimated its accumulation at 2.56–1.0 Ma years. The deposits drilled in Rożce at a depth of 60.2–104.0 m probably accumulated in a period of 5.23–4.62 Ma. A question arises what happened in this area over approx. 3.5 million years, i.e. between the accumulation of the analysed Lower Pliocene deposits and the advance of the first Scandinavian ice sheet in Poland. Deposits of that period are rarely found in central Poland (Piwocki et al., 2004; Widera, 2007). There might be several interpretations of this phenomenon. It is likely that deposits of this time interval were removed as a result of fluvial erosion, which could be more intensive at the time when the first Scandinavian continental glaciers developed. The first of them could be either the late Pliocene continental ice sheet at ca. 3.312–3.264 Ma (MIS M2; e.g., Lisiecki and Raymo, 2005; Khélifi et al., 2009; McKay et al., 2012) or the Early Pleistocene one at ca. 2.5 Ma (MIS 95–100; Groeneveld et al., 2014). At that time, the water level of the world's ocean decreased by even 65 m (Dwyer and Chandler, 2009; Miller et

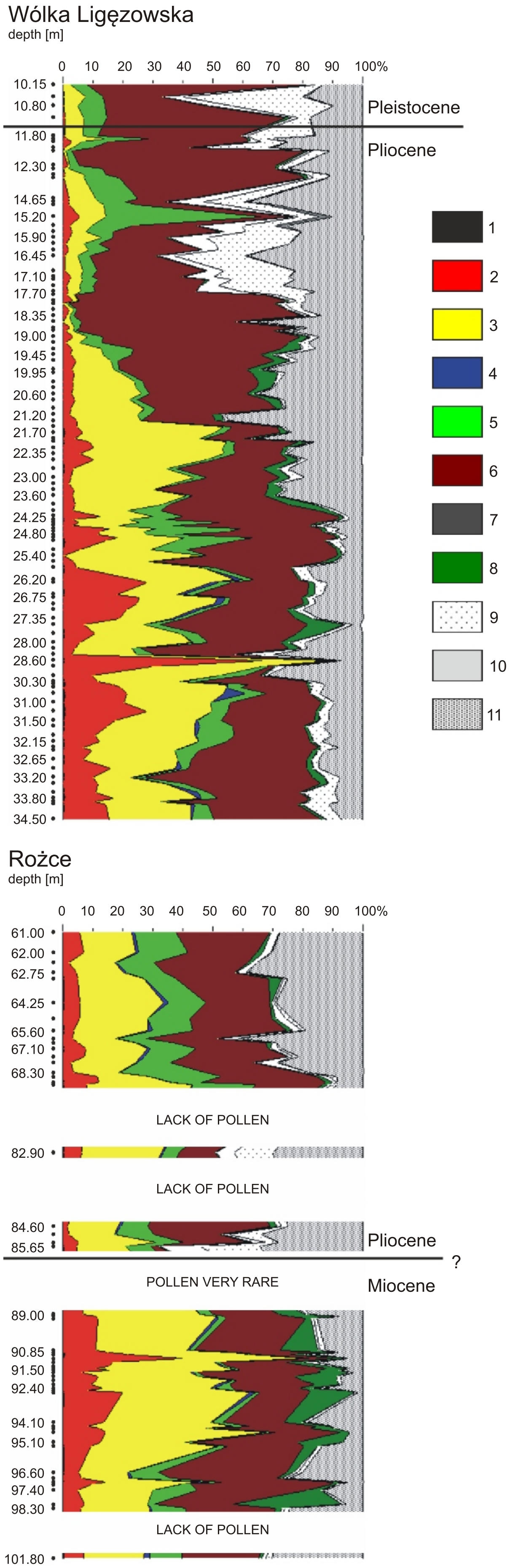


Fig. 6. Synthetic pollen diagrams of the Wólka Ligęzowska and Rożce sites

Pollen groups (thermic classification: Piwocki and Ziembińska, 1997, modified); 1 – subtropical elements (Araliaceae, *Engelhardtia, Ilex margaritatus, Itea, Platycaria, Symplocos, Reevesia*); 2 – warm-temperate elements (*Aesculus, Acer, Apocynum, Buxus, Carya, Castanea/Castanopsis, Cedrus, Celtis, Cistus, Cunninghamia, Diervilla, Eucommia, Ilex, Juglans, Liquidambar, Liriodendron, Magnolia, Nyssa, Ostrya/Carpinus, Parrotia, Parthenocissus, Pinus haploxylon* type/*Cathaya, Pterocarya, Rhus, Sciadopitys, Sequoia,* Taxodiaceae, *Taxodium/Glyptostrobus, Theligonum, Zelkova*); 3 – cool-temperate elements (*Alnus,* Caprifoliaceae, *Carpinus, Cornus, Corylus, Daphne, Fagus, Frangula, Fraxinus, Hedera, Hippophaë, Juniperus , Ligustrum, Lonicera, Myrica, Quercus, Rosa,* Rosaceae, *Salix, Sambucus, Tilia, Ulmus, Viburnum, Viscum, Vitis*); 4 – Cupressaceae; 5 – *Betula*; 6 – *Pinus sylvestris* type; 7 – conifers (*Abies, Larix, Picea, Taxus, Tsuga*); 8 – steppe elements (*Artemisia, Ephedra*); 9 – Ericaceae; 10 – *Betula nana* type; 11 – herbs (*Anthemis* type, *Ambrosia,* Apiaceae, *Aster* type, Asteraceae, Brassicaceae, Caryophyllaceae, *Centaurea,* Chenopodiaceae, *Cerastium* type, Cichorioideae, *Cirsium* type, Cyperaceae, Euphorbia, Fabaceae, *Helianthemum, Helianthus* type, *Geranium, Gentiana, Humulus,* Lamiaceae, Liliaceae, *Lythrum, Menyanthes,* Oenotheraceae, Plantago, Poaceae, *Polygonum, Potentilla* typ, *Ranunculus, Rumex,* Rutaceae, *Saussurea* typ, *Saxifraga, Succisa, Thalictrum, Urtica, Valeriana, Xantium* type and others)

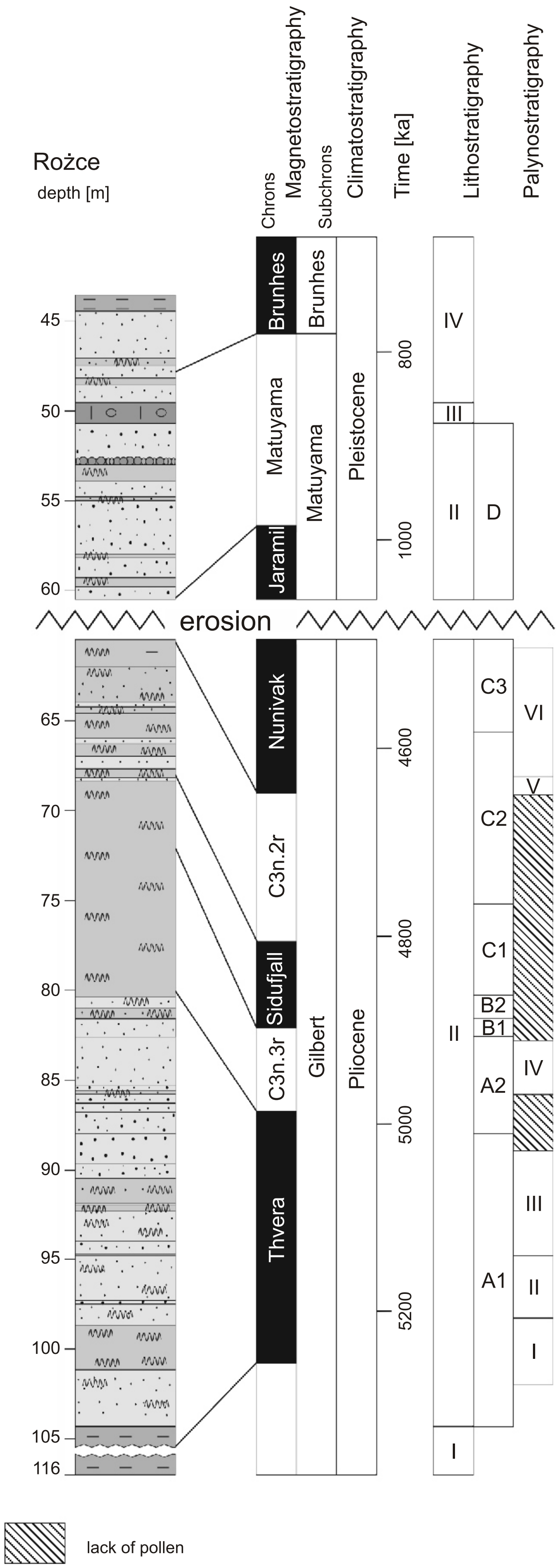


Fig. 7. Age of deposits

Explanations as in Figure 2

al., 2012; Dolan et al., 2015), which resulted in a significant reduction of the base level of erosion. The stratigraphic gap could also be caused by plate tectonic movements occurring in one of the last phases of the Alpine orogeny: the Rhodanic or Wallachian phases. In the eastern part of the Wielkopolska Region (W Poland), these movements resulted in subsidence of some grabens by approximately 50 m, while others were uplifted by over 100 m (Widera, 2007). It is also possible that both these causes contributed to the removal of the deposits. The study results show that the Lower Pleistocene deposits of Poland require further detailed studies and the current stratigraphic divisions may need correction (e.g., Ber et al., 2007).

CONCLUSIONS

The results of comprehensive analyses of deposits from the Rożce site (depth 50.7–104.9 m) enabled the authors to estimate the age of deposits referred to as Preglacial, as well as to reconstruct changes in polarity, climate and vegetation. The following was determined:

– bipartite character of Preglacial series: deposits at 60.2–104.0 m are to be correlated with the Lower Pliocene (approx. 5.23–4.62 Ma), the middle part of the Gilbert Palaeomagnetic Epoch, i.e. normal polarity subchron C3n.4n (Thvera), reverse C3n.3r, normal C3n.3n (Sidufjall) and reverse polarity subchron C3n.2r;
– accumulation of deposits at 50.7–60.2 m was related to the first occurrence of the Scandinavian ice sheet in the region (0.9 million years; likely the Nidanian Glaciation);
– there is a stratigraphic gap spanning approx. 3.5 million years (60.2 m depth) from the end of the Early Pliocene to the end of the Early Pleistocene;
– the Lower Pliocene deposits reveal indications of climatic changes by showing increased aridity and cooling, resulting in replacement of forests by grasslands typical of open landscapes;
– climatic changes recorded in pollen spectra are reflected in changes in the sediment mineral composition and surface features of quartz grains;
– high percentage of minerals characterized by low resistance to weathering (including amphiboles), in the heavy mineral composition of deposits, dates back to the Early Pliocene;
– the Rożce site is the first North European Late Neogene and Early Pliocene locality studied by means of pollen and palaeomagnetism analyses for age determination in a long-cored section.

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REFERENCES

Badura, J., Przybylski, B., 2004. Evolution of the late Neogene and Eopleistocene fluvial system in the foreland of the Sudetes Mountains, SW Poland. Annales Societatis Geologorum Poloniae, **74**: 43–61.

Baraniecka, M.D., 1975. The Ponurzyca sequence and implications for the origin and age of the Mazovia Preglacial (in Polish with English summary). Kwartalnik Geologiczny, **19** (3): 651–665.

Baraniecka, M.D., 1976. Explanations to Detailed Geological Map of Poland, scale 1:50,000 Otwock Sheet (561) (in Polish). Wyd. Geol., Warszawa.

Baraniecka, M.D., 1980. Explanations to Detailed Geological Map of Poland, scale 1:50,000 Grójec Sheet (596) (in Polish). Wyd. Geol., Warszawa.

Baraniecka, M.D., 1991. Section Różce against main sections of preglacial deposits in southern Mazowsze (in Polish with English summary). Przegląd Geologiczny, **39**: 254–257.

Ber, A., Lindner, L., Marks, L., 2007. Proposal of a stratigraphic subdivision of the Quaternary of Poland (in Polish). Przegląd Geologiczny, **55**: 115–118.

Boenigk, W., Frechen, M., 2006. The Pliocene and Quaternary Fluvial Archives of the Rhine System. Quaternary Science Reviews, **25**: 550–574.

Cailleux, A., 1942. Les actions eoliennes periglaciaires en Europe. Mémoires de la Société géologique de France, **41**: 1–176.

Cohen, K.M., Gibbard, P.L., 2011. Global chronostratigraphical correlation table for the last 2.7 million years. www.quaternary.stratigraphy.org.uk

Dekens, P.S., Ravelo, A.C., McCarthy, M.D., 2007. Warm upwelling regions in the Pliocene warm period. Paleoceanography, **22**, PA3211, doi:10.1029/2006PA001394

Dolan, A.M., Haywood, A.M., Hunter, S.J., Tindall, J.C., Dowsett, H.J., Hill, D.J., Pickering, S.J., 2015. Modelling the enigmatic Late Pliocene Glacial Event – Marine Isotope Stage M2. Global and Planetary Change, **128**: 47–60.

Dwyer, G.S., Chandler, M.A., 2009. Mid-Pliocene sea level and continental ice volume based on coupled benthic Mg/Ca palaeotemperatures and oxygen isotopes. Philosophical Transactions of the Royal Society A, **367**: 157–168.

Goździk, J., 1980. The role of micromorphologic analyses in investigations of the deposits in the Bełchatów open-cast mine (in Polish with English summary). Studia Regionalne, **4**: 101–114.

Groeneveld, J., Hathorne, E.C., Steinke, S., DeBey, H., Mackensen, A., Tiedemann, R., 2014. Glacial induced closure of the Panamanian Gateway during Marine Isotope Stages (MIS) 95–100 (~2.5 Ma). Earth and Planetary Science Letters, **404**: 296–306.

Ivanovic, R. F., Valdez P.J., Flecker R., Gutjahr, M., 2014. Modelling global-scale climate impacts of the late Miocene Messinian Salinity Crisis. Climat of the Past, **10**: 607–622.

Kasse, C., 1990. Lithostratigraphy and provenance of the Early-Pleistocene deposits in the southern Netherlands and northern Belgium. Geologie en Mijnbouw, **69**: 327–340.

Khélifi, N., Sarnthein, M., Andersen, N., Blanz, T., Frank, M., Garbe-Schönberg, D., Haley, B.A., Stumpf, R., Weinelt, M., 2009. A major and long-term Pliocene intensification of the Mediterranean outflow, 3.5–3.3 Ma ago. Geology, **37**: 811–814.

Kemna, H., 2008. Pliocene and Lower Pleistocene fluvial history of the Lower Rhine Embayment, Germany: Examples of the tectonic forcing of river courses Quaternary International, **189**: 106–114.

Kosmowska-Ceranowicz, B., 1979. Lithological variability and origin of the Tertiary clastic sediments in some regions of northern and central Poland in the context of the analysis of the transparent heavy minerals (in Polish with English summary). Prace Muzeum Ziemi, **30**, 3–73.

Lewiński, J., 1928. Preglacjał w dolinie Bystrzycy pod Lublinem (in Polish). Sprawozdanie z posiedzeń Towarzystwa Naukowego Warszawskiego, Wydział III Nauk Matematycznych i Przyrodniczych, **21**: 111–118.

Lindner, L., ed., 1992. Czwartorzęd. Osady, metody badań, stratygrafia (in Polish). Wydawnictwo PAE, Warszawa.

Lindner, L., Marks, L., Nita, M., 2013. Climatostratigraphy of interglacials in Poland: Middle and Upper Pleistocene lower boundaries from a Polish perspective. Quaternary International, **292**: 113–123.

Lisicki, S., 2003. Lithotypes and lithostratigraphy of tills of the Pleistocene in the Vistula drainage basin area, Poland (in Polish with English summary). Prace Państwowego Instytutu Geologicznego, **177**: 1–105.

Lisiecki, L.E., Raymo, M.E., 2005. A Pliocene-Pleistocene stack of 57 globally distributed benthic ^{18}O records. Paleoceanography, **20**, PA1003, doi:10.1029/2004PA001071

Łanczont, M., Bogutsky, A., Racinowski R., Seul, C., Wojtanowicz, J., 2003. Eopleistocene and lower Mesopleistocene paleosols in the Zahvizdja profile in the East Carpathian Foreland (W Ukraine) Quaternary International, **106–107**: 119–130.

Makowska, A., 2015. The geological structure and stratigraphy of the preglacial formation in the southern Mazovia region, lower Pilica River area (in Polish with English summary). Prace Państwowego Instytutu Geologicznego, **202**: 7–52.

McKay, R., Naish, T., Carter, L., Riesselman, C., Dunbar, R., Sjunneskog, C., Winter, D., Sangiorgi, F., Warren, C., Pagani, M., Schouten, S., Willmott, V., Levy, R., DeConto, R., Powell, R.D., 2012. Antarctic and Southern Ocean influences on Late Pliocene global cooling. Proceedings of the National Academy of Sciences, **109**: 6423–6428.

Menke, B., 1975. Vegetationsgeschichte und Florenstratigraphie Nordwestdeutschlands im Pliozän und Frühquartär. Mit ein Beitrag zur Biostratigraphie des Weichsel-Frühglazials. Geologisches Jahrbuch Reihe A, **26**: 3–151.

Miller, K.G., Wright, J.D., Browning, J.V., Kulpecz, A., Kominz, M., Naish, T.R., Cramer, B.S., Rosenthal, Y., Peltier, W.R., Sosdian, S., 2012. High tide of the warm Pliocene: implications of global sea level for Antarctic deglaciation. Geology, **40**: 407–410.

Mojski, J.E., 2006. Ziemie polskie w czwartorzędzie. Zarys morfogenezy (in Polish). Państwowy Instytut Geologiczny, Warszawa.

Mycielska-Dowiałło, E., Woronko, B., 1998. Rounding and frosting analysis of quartz grains of sand fraction, and its interpretative value (in Polish with English summary). Przegląd Geologiczny, **46**: 1275–1281.

Piwocki, M., Ziembińska-Tworzydło, M., 1997. Neogene of the Polish Lowlands – lithostratigraphy and pollen-zones. Geological Quarterly, **41** (1): 21–40.

Piwocki, M., Badura, J., Przybylski, B., 2004. Niż Polski i jego południowe obrzeżenie. Neogen (in Polish). In: Budowa geologiczna Polski. Tom I, Stratygrafia, cz. 3a Kenozoik, Paleogen i neogen (eds. T.M. Peryt and M. Piwocki). Państwowy Instytut Geologiczny, Warszawa.

Popescu, S.-M., Biltekin, D., Winter, H., Suc, J-P., Melinte-Dobrinescu, M.C., Klotz, S., Rabineau, M., Combourieu-Nebout, N., Clauzon, G., Deaconu, F., 2010. Pliocene and Lower Pleistocene vegetation and climate changes at the European scale: Long pollen records and climatostratigraphy. Quaternary International, **219**: 152–167.

Rappol, M., Stoltenberg H.M.P., 1985. Compositional variability of Saalian till in The Netherlands and its origin. Boreas, **14**: 33–50.

Roman, M., Woronko, B., 2014. Osady fluwialne z przełomu neogenu i czwartorzędu w stanowisku Baruchowo (Kotlina Płocka) (in Polish). In: III Sedymentologiczne Spotkanie Dyskusyjne “Znaczenie mikromorfologii ziarn kwarcu i płytek cienkich w badaniach środowisk sedymentacyjnych” 19 marca

2014 (ed. B. Woronko). Streszczenia referatów. Faculty of Geography and Regional Studies University of Warsaw.

Różycki, S.Z., 1972. Pleistocene of central Poland in regard with the past of upper Tertiary (in Polish). PWN, Warszawa.

Rzechowski J., 1971. Granulometric-petrographic properties of the till in the drainage basin of the middle Widawka (in Polish with English summary). Biuletyn Instytutu Geologicznego, **254**: 111–155.

Sagnotti, L., Roberts, A.P., Weaver, R., Verosub, K.L., Florindo, F., Pike, C.R., Clayton, T., Wilson, G.S., 2005. Apparent magnetic polarity reversals due to remagnetization resulting from late diagenetic growth of greigite from siderite. Geophysical Journal International, **160**: 89–100.

Skompski, S., Makowska, A., Jakubicz, B., 2006. Detailed Geological Map of Poland, scale 1:50,000 Nowe Miasto nad Pilicą Sheet (669) (in Polish). Państwowy Instytut Geologiczny, Warszawa.

Stachowicz-Rybka, R., 2011. Flora and vegetation changes on the basis of plant macroremains analysis from an early Pleistocene lake of the Augustów Plain, NE Poland. Acta Palaeobotanica, **51**: 39–104.

Stuchlik, L., 1975. Palynological characteristics of the preglacial sediments of Ponurzyca (Otwock area) (in Polish with English summary). Kwartalnik Geologiczny, **19** (3): 667–678.

Stuchlik, L., 1987. Przegląd badań paleobotanicznych osadów plioceńskich wczesnoplejstoceńskich Polski środkowej i południowej (in Polish). In: Problemy młodszego neogenu i eoplejstocenu w Polsce (eds. A. Jahn and S. Dyjor): 53–63. Ossolineum, Wrocław.

Stuchlik, L., 1994. Some late Pliocene and early Pleistocene pollen profiles from Poland. NATO-ASI Series I, **27**: 371–382.

Utescher, T., **Mosbrugger, V., Ashraf, A.R., 2000**. Terrestrial climate evolution in Northwest Germany over the last 25 million years. Palaios, **15**: 430–449.

Vareikienë, O., Marmo, J., Chernet, T., Laukkanen, J., 2007. Results of heavy mineral pre-concentration by the Knelson for the geochemical study of soil: a case study in Lithuania. Geologija, **60**: 1–9.

Westerhoff, W.E., Kemna, H.A., Boenigk, W., 2008. The confluence area of Rhine, Meuse, and Belgian rivers: Late Pliocene and Early Pleistocene fluvial history of the northern Lower Rhine Embayment. Netherlands Journal of Geosciences — Geologie en Mijnbouw, **87**: 107–125.

Widera, M., 2007. Lithostratigraphy and palaeotectonics of the sub-Pleistocene Cenozoic of Wielkopolska (in Polish with English summary). Seria Geologia, **18**. Wydawnictwo Naukowe UAM, Poznań.

Winter H., 2015. Climatic changes dynamics in the Pliocene and lower Pleistocene, and Neogene/Quaternary transition in sediments from south Mazovia (Central Poland) on the basis of palynological data (in Polish with English summary). Prace Państwowego Instytutu Geologicznego, **202**: 53–106.

Woronko, B., Bujak, Ł., 2010. Micromorfology of sand quartz grains from the preglacial Kozienice series as an indicator of transportation and deposition processes in the southern Mazovian Lowland (in Polish with English summary). Biuletyn Państwowego Instytutu Geologicznego, **438**: 137–154.

Woronko, B., Pisarska-Jamroży, M., 2015. Micro-scale frost weathering of sand-sized quartz grains. Permafrost and Periglacial Processes, doi: 10.1002/ppp.1855

Woronko, B., Rychel, J., Karasiewicz, M.K., Ber, A., Krzywicki, T., Marks, L., Pochocka-Szwarc, K., 2013. Heavy and light minerals as a tool for reconstructing depositional environments: an example from the Jałówka site (northern Podlasie region, NE Poland). Geologos, **19**: 47–66.

Ziembińska-Tworzydło, M., 1998. Climatic phases and spore-pollen zones. Prace Państwowego Instytutu Geologicznego, **160**: 12–16.