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Palaeoenvironmental investigation of the Warsaw Ice-Dammed Lake (Central Poland): 7-year cyclicity in the supply of terrigenous material

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ABSTRACT:

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The varved clays formed during the Saalian Glaciation (MIS 6) between Dębe and Izbica (northern Mazovia, Central Poland) were subjected to rock magnetic investigation. The studied varved clays represent a record of 110 years. In addition to annual cyclicity, there are other long-term cycles. One lasts 7 years on average and is related to changes in water level within the ice-dammed lake and/or changes in the supply of terrigenous material. This cyclicity is similar in duration to that observed in modern measurements of some parameters of the Earth's climate system and can be influenced by the internal dynamics of the Earth. Also, the investigated clays were deposited in two sedimentation zones of the lake, distal and proximal. During the first phase of clay sedimentation connected with the distal zone, the shoreline of the ice-dammed lake was in close proximity to the stagnant ice-sheet front, and the lake deepened. The ice-sheet front was to the north of Zakroczym and Dębe and to the north of the Bug valley (Zakroczym phase). Then, the ice-sheet front retreated towards Płońsk and Nasielsk (Nasielsk phase) and a higher amount of terrigenous material was delivered, leading to the deposition of clay in the shallower, proximal zone.

Key words: Quaternary; Saalian Glaciation (MIS 6); Varved clays; Magnetic susceptibility; Climate changes.

INTRODUCTION

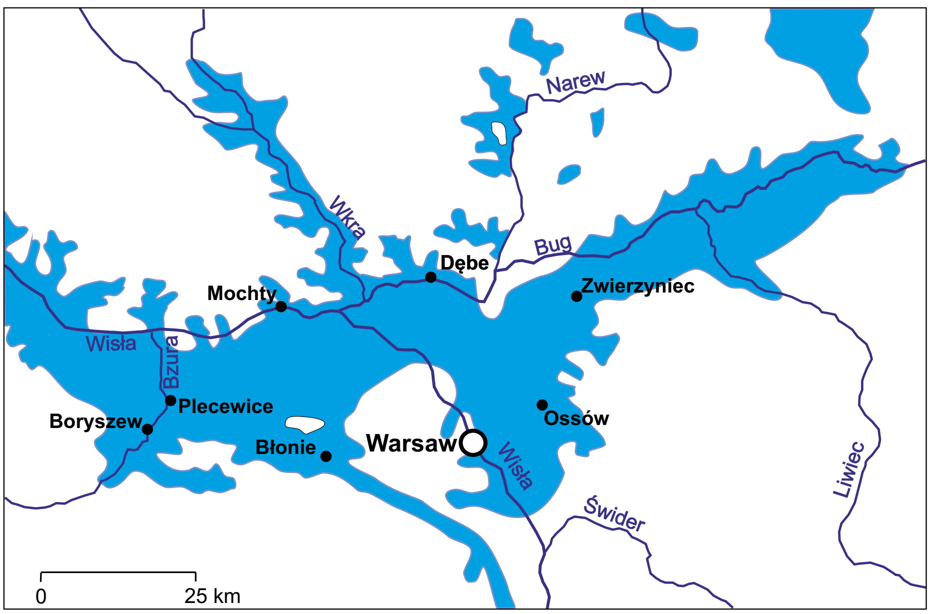
The varved clays which formed in ice-dammed lakes in the foreland of the ice-sheet are of great interest because of the seasonality of their sedimentation and the possibility of determining the time in which the lake was active (e.g., Ashley 1975; Ridge *et al.* 2012; Carrivick and Tweed 2013; Palmer *et al.* 2019). A single varve consists of a dark layer of clayey material and a light layer of silty material. The dark layer was formed by sedimentation of suspended material during winter periods, when the water surface of the lake was covered by ice. The light layer formed during summer periods from material delivered from beyond the reservoir (e.g., De Geer 1912; O'Sullivan 1983; Zolitschka *et al.* 2015). Therefore, varved clays can be used to date geological events and determine the seasonal variation of the sedimentary environment. The thickness of individual layers may depend on a variety of factors, such as climate, variability in the delivery of material from land, or the evolution of the lake (e.g., Merta 1986; Palmer *et al.* 2019).

In addition to the use of sedimentological methods for analyzing varved clays, rock magnetic methods, which are based on the magnetic properties of the studied sediments, began to be utilized in the first half of the 20th century. Ising (1942, 1943) stated that the sediments he studied possessed a natural remanent magnetization, which could be used to determine parameter variations in the Earth's magnetic field. Also, paleomagnetic issues concerning varved clays have been mainly focused on determining the age migration of the Earth's magnetic pole (e.g., Bakhmutov *et al.* 2006; Rogoziński 2017). Magnetic susceptibility has been used to reconstruct the environmental conditions in varved sediments (e.g., Björck *et al.* 1982, Haltia-Hovi *et al.* 2010). The susceptibility measurements (and other rock magnetism analysis) allow us to designate indirectly the content of magnetic minerals in tested sediments (Collinson 1983; Butler 1992; Dunlop and Özdemir 1997; Liu *et al.* 2012; Tauxe *et al.* 2018). The changing content of magnetic minerals (mainly magnetite sourced from eroded rocks) can be used to define the amount of terrigenous material supplied to lakes (Thompson and Oldfield 1986; Evans and Heller 2003; Liu *et al.* 2012).

This paper is aimed at determining the environmental changes that were recorded during sedimentation of the varved clays in the northern part of the Warsaw Ice-Dammed Lake based on magnetic susceptibility measurements and other magnetic parameters. In particular, there is an attempt herein to estimate the actual variability of the supply of terrigenous material to this part of the lake in the context of climatic changes during the recessional phase of the Saalian Glaciation (MIS 6) (Nowak 1967, 1978; Marks *et al.* 2016; Frankiewicz 2023). Varved clays, as annual-laminated sediments, in this case deposited in the Warsaw Ice-Dammed Lake, are a good and precise indicator of palaeoenvironmental changes in glacial environments. Magnetic susceptibility measurements, as a low-cost, easy and relatively speedy method, can be a support or an alternative to traditional methods used in sedimentology.

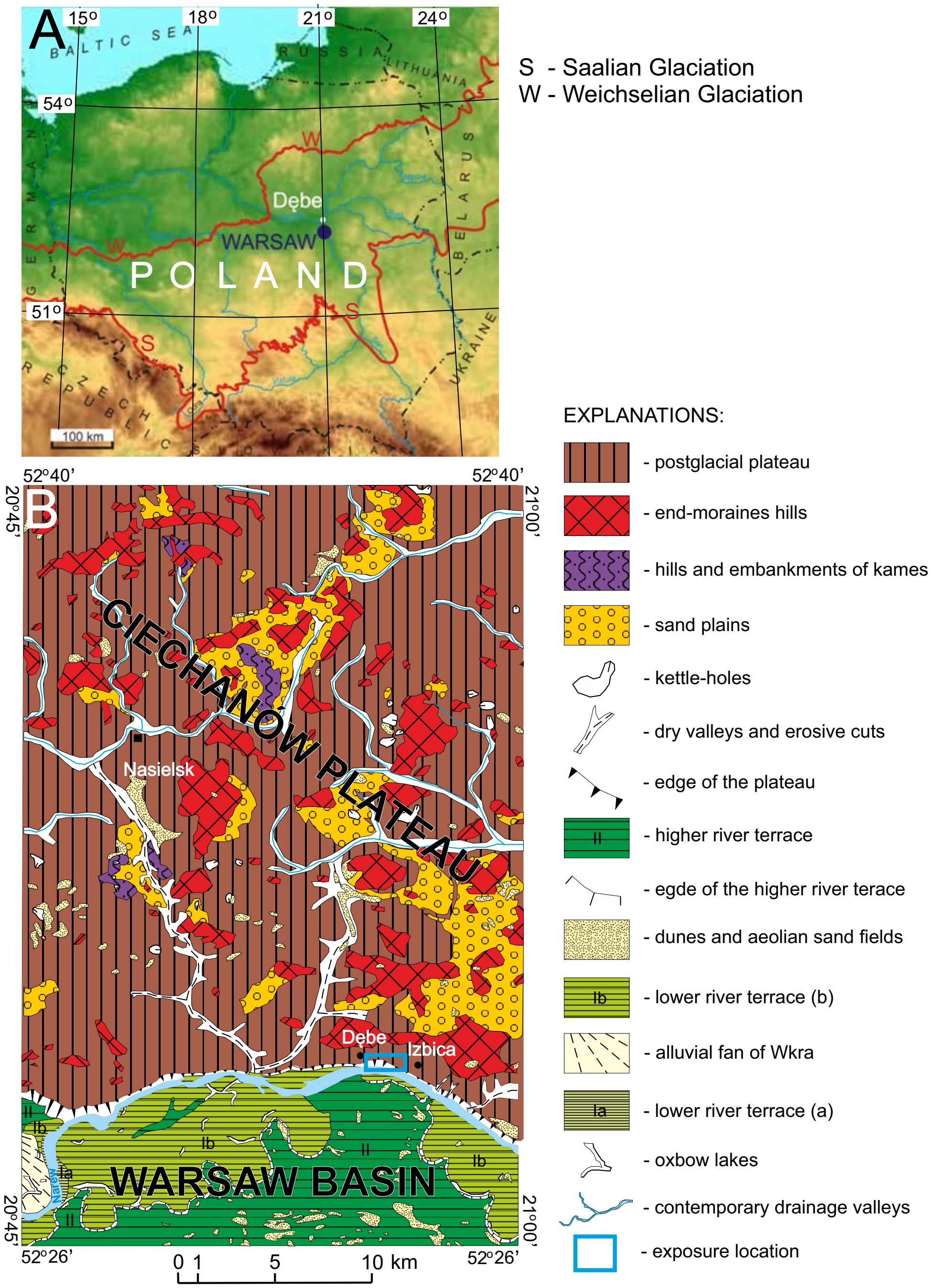
GEOMORPHOLOGY AND GEOLOGICAL SETTING

In the area of the Warsaw Basin, layers of varved clays have been identified in several sites and drill cores. Initially, their occurrence was connected with the extensive ice-dammed lake established during the Saalian Glaciation (Różycki 1967; Text-fig. 1). However, as a result of the discovery of sediments belonging to the Eemian Interglacial west of Warsaw (Janczyk-Kopikowa 1974; Karaszewski 1974), the varved clays have been assigned to the Weichselian Glaciation, similar to the other sites in the western part of the lake, e.g., in Plecewice or Boryszew. Furthermore, the ice-dammed sediments in the Zwierzyniec site (east of Warsaw) were included in the Weichselian Glaciation too (Kalińska-Nartiša *et al.* 2016). The TL age for varved clays near Radzymin is 51–55 ky BP and 53 ky BP for those near Błonie (Baraniecka and Konecka-Betley 1987). This could also suggest that the sediments were deposited during the last glaciation. On the other hand, Eemian Interglacial sediments separate two layers of varved clays in the Ossów profile (Sarnacka 1982). This ob-



Text-fig. 1. The extent of the Warsaw Ice-Dammed Lake (in blue) postulated by Różycki (1972) and based on the range of ice-dammed sediments; black dots – localizations of geological sites highlighted in the text.

servation confirms the occurrence of an ice-dammed lake during the Saalian Glaciation. A group of researchers postulated that the sediments of the older (Saalian) ice-dammed lake are exposed at Mochty and Dębe (Marks *et al.* 1996; Ruszczyńska-Szenajch *et al.* 2003). However, the obtained TL age of the sediments at Mochty is 115.6–120.8 ky for glacial tills, 126.5–131.3 ky for the supraglacial sands which cover the tills and >88.7 ky for varved clays on the top part of the profile and underlain mostly by the glacial till (Fedorowicz *et al.* 1993). The TL age for sediments at Dębe is 132.7–137.4 ky for glacial till, 108.8 ky for fluvioglacial sands and >71.7 ky for varved clays on the top part of the profile and underlain by the fluvioglacial sands (Fedorowicz *et al.* 1993). The obtained dates suggest deposition of varved clay at Mochty and Dębe

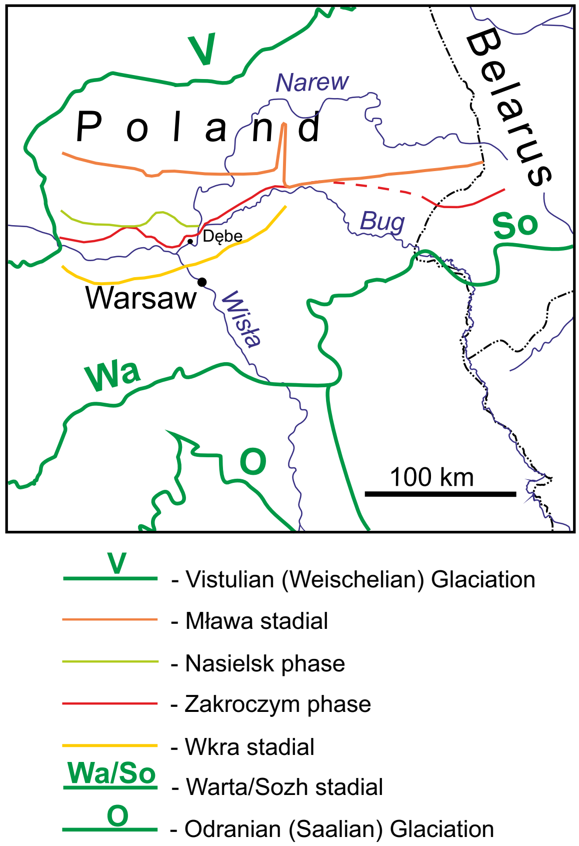


Text-fig. 2. Geomorphology and geological settings. A – location of the study area; B – geomorphological sketch-map of the study area (based on Nowak 1967).

during the Weichselian Glaciation, but the sediments are still older than those in the Radzymin and Błonie sites. It is worth noting that the profiles of the varved clays in the northern part of the paleolake are located at a lower altitude (clays begin from 77 m to 80 m a.s.l. at Mochty and 79–80 m to 81–83 m a.s.l. at Dębe) than other profiles with Weichselian varved clays (Błonie – 85–86 m a.s.l., Ossów – 88.5–90.5 m a.s.l., Zwierzyniec – 86.5–88 m a.s.l.; Marks *et al.* 2016). It is important to note that the dates should be interpreted with caution due to several errors in the TL dating method. In summary, despite long-term studies of the sediments within the Warsaw Ice-Dammed Lake, the stratigraphic position of the varved clays at Dębe and Mochty is not certain yet.

The study area is located on the southern border of the Ciechanów Plateau (Solon *et al.* 2018; Text-fig. 2B) and the studied profiles are located in the vicinity of Dębe and Izbica, ca. 20 km north of Warsaw (Text-fig. 2A). This border is expressed by an escarpment several meters high due to erosion by the Vistula River. The surface of the plateau is located at an altitude of 80–150 m a.s.l. and descends to the south. On the surface of the plateau, there are several moraine thrusts. According to Różycki (1972), the morainic hills were formed during the Zakroczym and Nasielsk recessional phases, which are part of the post-maximal Wkra Stadial of the Saalian Glaciation. The limit of the Zakroczym phase runs further west towards Płock (Text-fig. 3). To the east of Dębe, the limit of the Zakroczym phase runs toward Serock and next it runs parallel to the Bug valley (Różycki 1972). The extent of the Nasielsk phase is to the north of Płock and then to the south and east of Płońsk, and to the west and south of Nasielsk. The possibility of recreating the range of this phase ends in the Narew valley to the north of Serock.

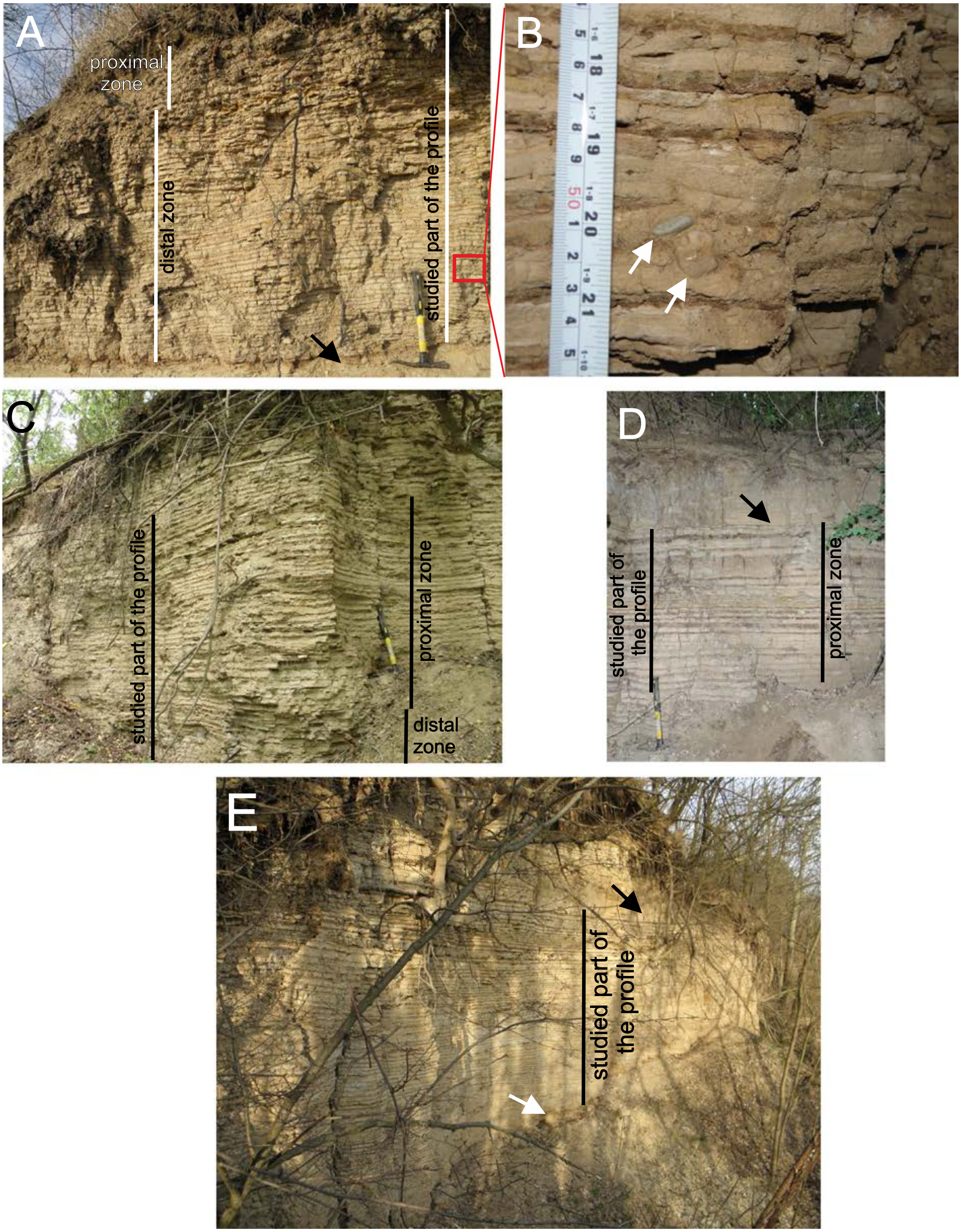
The oldest sediments exposed in the escarpment are glacial tills with a thickness of up to 7 m with boulder pavements on their top. Based on the study of these tills, it was concluded that the ice-sheet transgression took place from the northwest (Ruszczyńska-Szenajch *et al.* 2003; Teodorski *et al.* 2021). The till is covered by a layer of fluvioglacial sands deposited in the foreground of the ice-sheet. On top of the sands there are ice-dammed sediments represented mainly by varved clays. Based on the regional sediment position and the fact that the varved clays are covered in some places by glacial till from the Warta stadial of the Saalian Glaciation (Nowak 1967, 1978; Marks *et al.* 2016; Frankiewicz 2023), all the described sediments have been classified to the Saalian Glaciation.



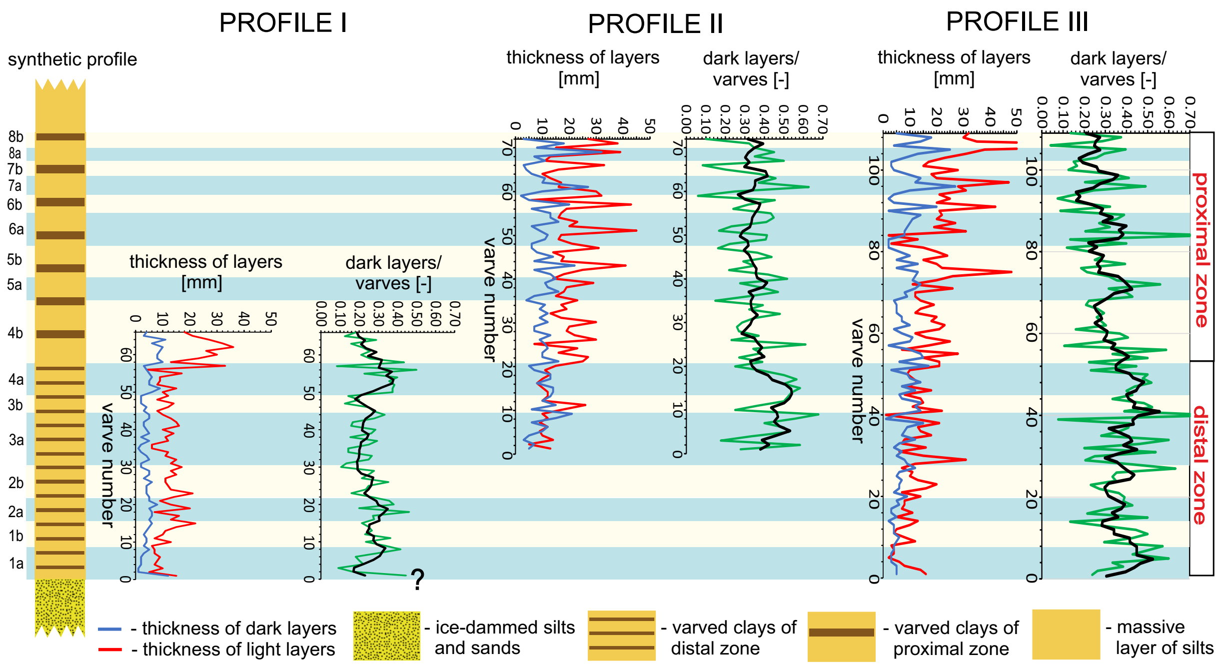
Text-fig. 3. The extent of selected Odranian (Saalian) Glaciation stadials and phases (Różycki 1972; Marks *et al.* 1996; Mojski 2005; Marks *et al.* 2016; Marks *et al.* 2017; Marks *et al.* 2019).

Three profiles of varved clays were studied in accessible exposures. Profile I is the westernmost (52°29’28”N; 20°55’50”E). The profile begins at an elevation of 79.3 m a.s.l. and the varved clays reach a thickness of 1.45 m. Here, the clays are underlain by sands with flow structures preserved (Text-fig. 4A; the boundary between sands and clays is marked by a black arrow) and a thin layer of probably washed-out varved clay. The bottom part of the varved clays is partially disturbed. In the lower part of the profile, varves of low thickness were observed. In the middle part, the thickness generally increases and reaches the greatest thickness in the top part.

Profile II (52°29’28”N; 20°55’53”E) begins at an elevation of 80.2 m a.s.l. The length of the entire profile is 2.62 m, of which 2.12 m was analyzed (up to a thick, massive layer of silts; Text-fig. 4D, black arrow). In the lower part of the profile no sands underlying the clays were encountered. Here the lower part of the investigated profile is characterized by varves



Text-fig. 4. Characteristics of the varved clays studied. A – exposition of varved clays in profile I, black arrow shows the boundary between ice-dammed sands and clays; B – dropstones (white arrows) in profile I; C – exposition of varved clays in the lower part of profile II; D – exposition of varved clays in the upper part of profile II, black arrow shows the bottom part of the thick, massive layer of silts; E – exposition of varved clays in profile III, white arrow – boundary between ice-dammed sands and clays, black arrow – bottom part of the thick, massive layer of silts.



Text-fig. 5. The thickness of layers and thickness ratio of dark layers and varves in profiles I–III; 1a–9b – intervals of long-term cyclicity.

with a smaller thickness compared to the rest of the profile (Text-fig. 4C, D). However, the thickness of the varves is greater than in profile I.

The longest and easternmost profile III (52° 29'28"N; 20°55'55"E) begins at 78.9 m a.s.l. Its total length is about 4 m, 2.75 m of which were analyzed (up to a thick, massive layer of silts; Text-fig. 4E, black arrow). In this profile, a sand layer was also identified under the clay (Text-fig. 4E; white arrow). Generally, the varve thickness increases again towards the top of the profile.

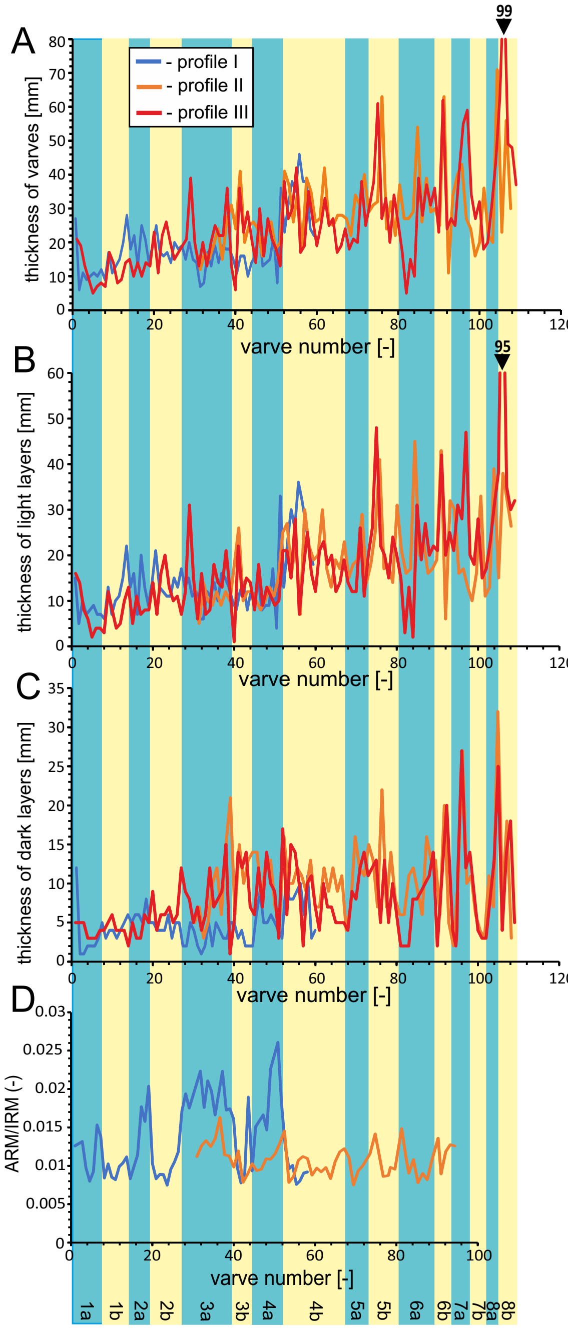
METHODS

Varve thickness analysis

This method is based on measuring the thickness of the varves, as well as the thickness of individual light and dark layers (Petterson *et al.* 1999; Lamoureux 2001). The thickness of varves was measured in terrain by ruler and scaled photos. The measurements were made along the vertical profiles. A single varve was defined as the distance between one upper boundary of the winter layer (the most visible within following varves) and the upper boundary of the winter layer of the next varve. Changes in varve thickness were related to changes in conditions during sedimentation of the varved clays. In addition, the ratio of the thickness of the dark layers to the thickness of the varve was calculated. This ratio may indicate climatic changes during the existence of the ice-dammed lake (Paluszkiewicz 2005) or changes in the water level in the lake and, consequently, changes in the depth of sediment deposition (Merta 1978, 1986). Based on the varve thickness graphs created, the studied profiles of varved-clay exposure sites were correlated (Text-figs 5 and 6).

MAGNETIC SUSCEPTIBILITY MEASUREMENTS AND ROCK MAGNETIC ANALYSIS

Measurements of magnetic susceptibility were made for 118 crushed rock samples, about 6.5 g, inserted in plastic boxes (v = 8 cm^3). The samples were taken from successive light-colored layers of varved clays in profiles I (61 samples) and II (57 samples). This sampling methodology was adopted due to the fact that the well oxidized summer layers better record changes in the supply of mineral material to the lake. The dark layers, due to sedimentation under anaerobic conditions, may be subjected to post-depositional processes such as the formation of iron sulphides like greigite and subsequent late diagenetic oxidation (e.g.,



Text-fig. 6. Correlation of profiles (I–III) based on the thickness of varves (A), thickness of light (B) and dark (C) layers and ARM/IRM – ratio between anhysteretic remanent magnetization and isothermal remanent magnetization in 1T (D).

Roberts *et al.* 1996; Snowball 1996). Furthermore, in many places their small thickness makes it very difficult to take a suitable sample. For magnetic susceptibility (χ) measurements, a Kappabridge KLY-2 (Geofyzika Brno) was used.

To identify the type of magnetic minerals responsible for the χ recording, the anhysteretic remanent magnetization (ARM), isothermal remanent magnetization (IRM), and S-ratio were measured in the samples. ARM acquisition was performed using an alternating field of 100 mT along with a steady bias field of 0.1 mT generated in a MOLSPIN Shielded Demagnetiser with the P.A.R.M. attachment. For IRM analysis, the samples were magnetized along the z-axis with a field of 1 T followed by an antiparallel field of 100 mT using a MMPM 10 pulse magnetizer. The remanent magnetization was measured using a JR-6A spinner magnetometer. From the IRM results obtained, the S-ratio was calculated, which is expressed by the formula -(IRM_{-100mT}/IRM_{1T}) (Grabowski *et al.* 2016) and indicates the ratio of low coercivity (e.g., magnetite) to high coercivity (e.g., hematite, goethite) minerals in the studied samples (e.g., Opdyke and Channell 1996). In addition, the ARM/IRM_{1T} ratio was calculated, which can be useful as a grain size indicator of the magnetic minerals (e.g., Özdemir and Banerjee 1982; Jovane *et al.* 2007; Grabowski *et al.* 2016). Additionally, stepwise acquisition of IRM up to 1.4 T was performed on the selected samples. The magnetic measurements were carried out at the Polish Geological Institute – National Research Institute in Warsaw.

RESULTS

Varve thickness

The studied profiles represent a record of 110 varves of annual sedimentation in an ice-dammed lake. The varve thickness increases from less than 10 mm in the lower part of the section (e.g., in the lower part of profile I) to over 90 mm in the upper part of the section (e.g., in the uppermost part of profile III), see Text-fig. 6a.

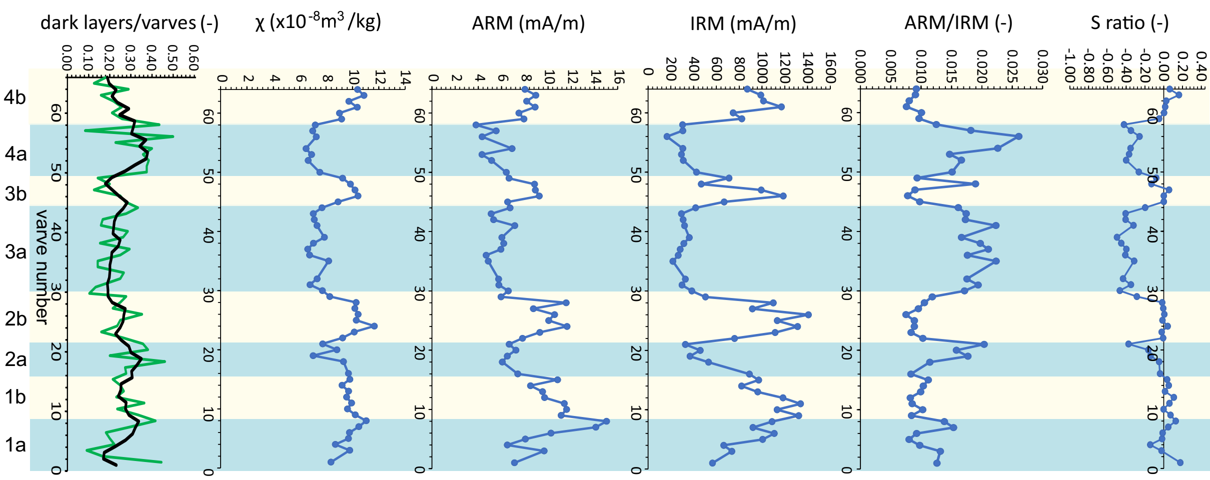
Based on the changes in the thickness of dark layers relative to the thickness of the entire varve, several year-cycles (1a–8b) may be indicated. These are best preserved in profile III. In intervals marked by the letter 'a', this ratio generally gradually increases within single intervals, even reaching over 0.5 in interval 4a in profile II. The exception is cycle 1a in profile I, where this ratio is high (0.45) at the beginning of the cycle. This may be part of another cycle. On the other hand, it is the initial varve of clay sedimentation (Text-fig. 4a). Such varves may be characterized by a greater thickness of dark layers than the varves above, which may be due to the washing out of early deposited sediments (Marks *et al.* 1996). A different trend can be observed in the intervals marked with the letter 'b'. In these parts of the profiles, the thickness of light layers is higher within the layers (up to 95 mm thick in interval 8b in profile III), which analogically causes a decrease in the ratio of the dark layer thickness to the thickness of the varve. In the upper part of the section, this ratio drops below 0.2. These intervals last 7 years on average.

Generally, in the lower part of the section (1a–4a), the varves are thinner (6–40 mm thick) and the average accumulation rate is 18 mm/year. In the studied section, the length of this interval is 58 years. In contrast, the upper part of the section (4b–8b) is characterized by thicker varves (12–99 mm thick) and an average accumulation rate of 32 mm/year, with an interval length of at least 52 years. Furthermore, varve thicknesses are more variable here, e.g., varves 40–60 in profile II.

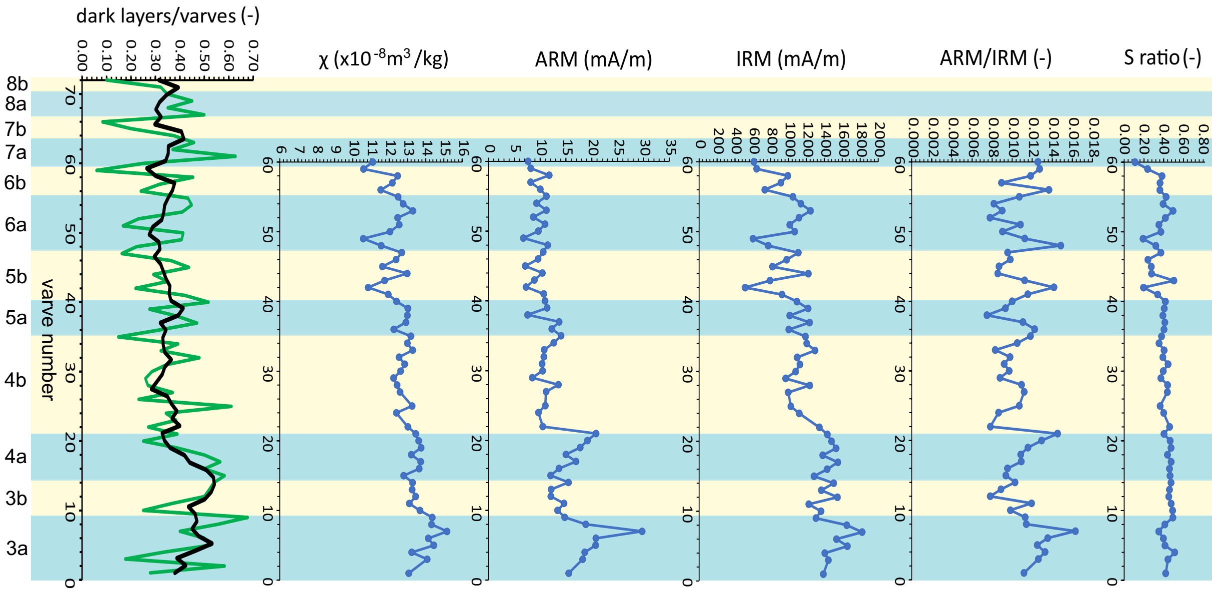
Magnetic susceptibility and magnetization carriers

In profile I, the magnetic susceptibility (χ) is in the range of 6–12 × 10^{-8} m^3/kg (Text-fig. 7). On the basis of χ values, one can conclude the bipartite nature of the described profile. The lower part of the profile (1a–2b) is characterized by the mean χ of 9.59 ± 0.96 × 10^{-8} m^3/kg and the variation in values producing the average is relatively small. In the upper part of the profile (3a–4b), the average magnetic susceptibility is 8.15 ± 1.38 × 10^{-8} m^3/kg and the variations are more pronounced. The changes in susceptibility relate directly to the other long-term cycles determined from the varve thickness graph analysis. Susceptibility takes higher values in intervals marked 'b' (mean 9.87 ± 0.68 × 10^{-8} m^3/kg) and lower values in intervals marked 'a' (7.96 ± 1.25 × 10^{-8} m^3/kg). The differences between the intervals are more pronounced in the values of measured remanent magnetization. For intervals with a higher χ, the average ARM value is 9.14 ± 1.59 mA/m and the average IRM_{1T} value is 984.79 ± 245.82 mA/m, while for the intervals with lower susceptibility, the remanent values are also lower, taking 6.80 ± 2.46 mA/m and 469.16 ± 263.92 mA/m, respectively. The variation is also evident based on other parameters. For the 'b' intervals, the average ARM/IRM_{1T} ratio is 0.010 ± 0.002 and the S-ratio averages 0.00 ± 0.08. The 'a' intervals take values equal to 0.020 ± 0.004 and -0.25 ± 0.19, respectively. The ARM/IRM_{1T} ratio seems to be the best correlating ratio with changing intervals 1a–4b.

The results obtained for profile II are more ambiguous (Text-fig. 8). The χ values range between 10.58 and 15.17 × 10^{-8} m^3/kg. The most noticeable differences in magnetic parameters occur between clays representing intervals 3a–4a and intervals 4b–7a. The susceptibility takes the average values of 13.69 ± 0.57 × 10^{-8} m^3/kg and 12.35 ± 0.72 × 10^{-8} m^3/kg, respectively. On the other hand, the average remanent magnetization values are 17.01 ± 4.08 and 10.24 ± 1.80 mA/m for ARM and 1464.46 ± 137.75 and 1012.68 ± 203.58 mA/m for IRM. A clear decrease in the remanent values near the boundary between intervals 4a and 4b is also evident. The other parameters do not show much regularity. The magnetic parameters in profile II take higher values than in profile I, within intervals 3a–4a. Despite this, the changes in the ARM/IRM_{1T} ratio are similar – the



Text-fig. 7. Results of magnetic measurements in profile I; χ – magnetic susceptibility, ARM – anhysteretic remanent magnetization; IRM – isothermal remanent magnetization in 1T; ARM/IRM – ratio between anhysteretic remanent magnetization and isothermal remanent magnetization in 1T; S ratio – ratio between isothermal remanent magnetization in -100 mT and isothermal remanent magnetization in 1T.



Text-fig. 8. Results of magnetic measurements in profile II; χ – magnetic susceptibility, ARM – anhysteretic remanent magnetization; IRM – isothermal remanent magnetization in 1T; ARM/IRM – ratio between anhysteretic remanent magnetization and isothermal remanent magnetization in 1T; S-ratio – ratio between isothermal remanent magnetization in -100 mT and isothermal remanent magnetization in 1T.

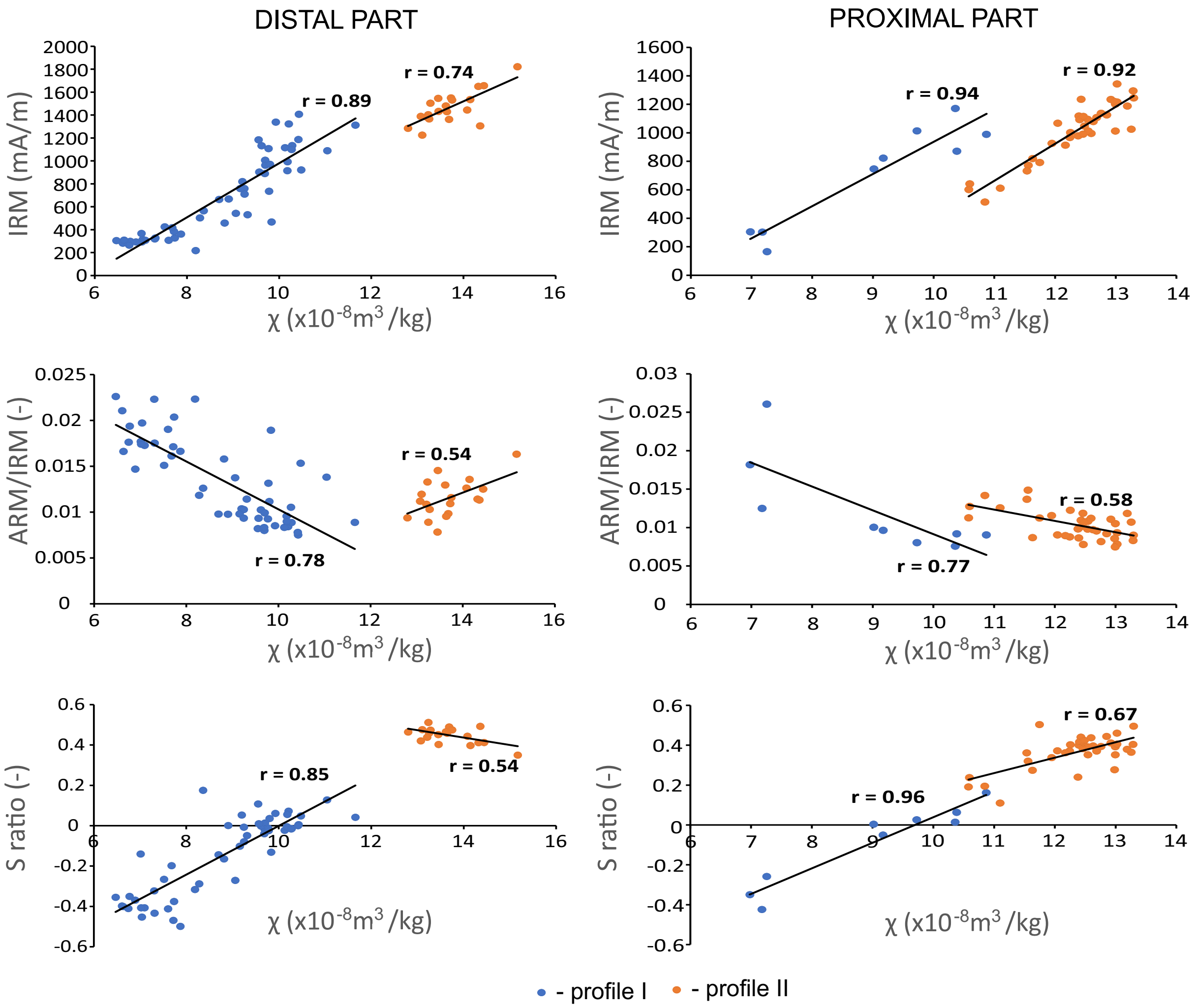
ratio has higher values in intervals marked ‘a’ (up to 0.016), and lower values in intervals marked ‘b’ (below 0.012).

DISCUSSION

Rock magnetism

The received results of petromagnetic research indicate that ferromagnetic minerals are responsible for magnetic susceptibility (χ). This is evidenced by a good correlation between susceptibility values and isothermal remanent magnetization (IRM) values, both in samples from the distal and proximal sedimentary zones of the ice-dammed lake in both studied profiles (Text-fig. 9).

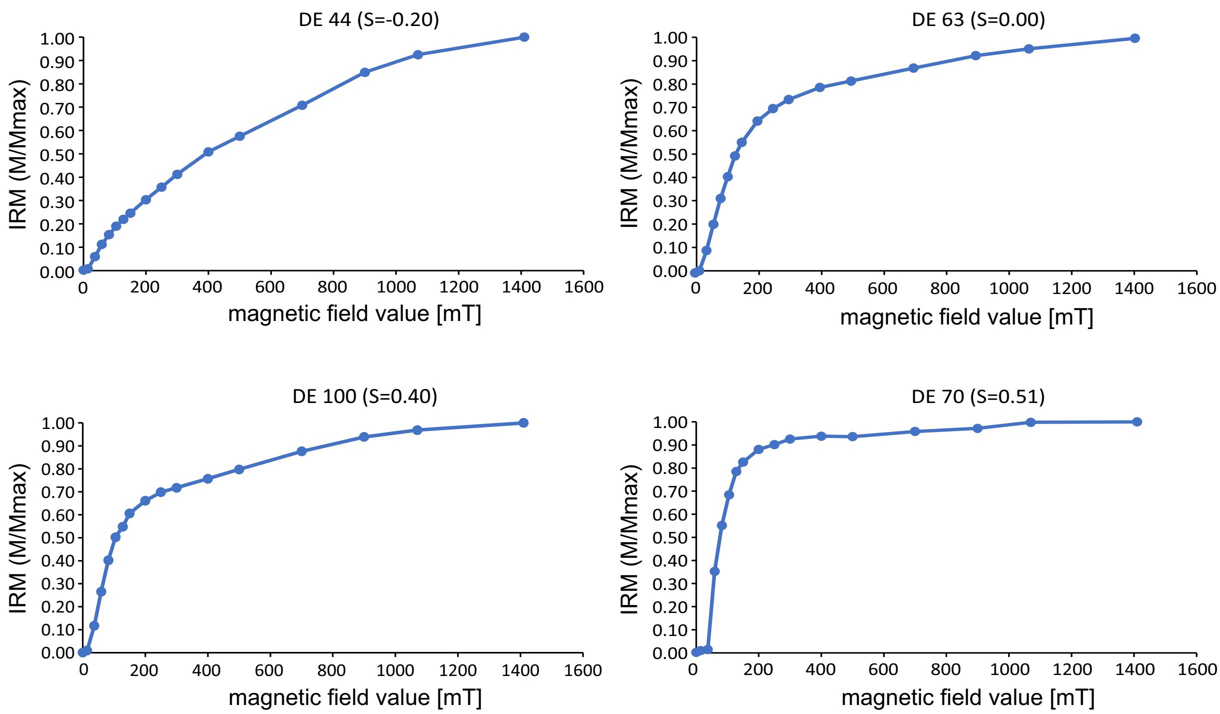
Profile I is characterized by variable magnetic mineralogy. High-coercivity magnetic minerals predominate in samples from sediments representing intervals marked ‘a’, as indicated by negative values of the S-ratio (Text-fig. 9). Most likely, this mineral is hematite, which causes sample DE 44 from an interval marked ‘a’ to not reach full saturation even in a magnetic field of 1.4 T (Text-fig. 10). However, based on the conducted research, it cannot be ruled out that there is some goethite content in the tested samples. The IRM saturation curve of this sample also indicates a relatively low content of low-coercivity minerals. On the other hand, samples from intervals marked ‘b’ are characterized by a relatively higher content of low-coercivity magnetic minerals such as magnetite, which causes the S-ratio to take values above 0.0 (Text-fig. 9). In addition to magnetite, there is also a smaller amount of hematite, as indicated by the IRM saturation curve for sample DE 63 (Text-fig. 10). The changing magnetite content affects the χ values, which is also confirmed by a good positive correlation between χ and the S-ratio in sediments from both sedimentary zones. An inverse correlation between ARM/IRM$_{1T}$ and χ was also observed (Text-fig. 9). A decreasing ARM/IRM$_{1T}$ ratio may indicate an increase in magnetite diameter (e.g., Grabowski *et al.* 2016). Low values of the ratio are characteristic of periods marked ‘b’ (Text-fig. 7), whereas, for periods marked ‘a’, high values of the ratio indicate the presence of smaller magnetite grains. According to the correlation between ARM/IRM$_{1T}$ and χ, it can be concluded that the presence of larger diameter magnetite grains in the tested clays causes the susceptibility values to increase. Such a relationship can be observed between SD magnetite grains and MD magnetite grains, which are characterized by a larger diameter than the previous type (Hatfield and Stoner 2013). However, based on the available results, it is not possible to exclude the occurrence of fine-grained SP magnetite in the tested samples, which also has a high magnetic susceptibility.



Text-fig. 9. Correlation diagrams of magnetic measurements; χ – magnetic susceptibility, ARM – anhysteretic remanent magnetization; IRM – isothermal remanent magnetization in 1T; ARM/IRM – ratio between anhysteretic remanent magnetization and isothermal remanent magnetization in 1T; S-ratio – ratio between isothermal remanent magnetization in -100 mT and isothermal remanent magnetization in 1T.

Profile II is characterized by a different magnetic mineralogy. Generally, changes in the magnetic mineralogy of the sediments are weakly correlated with cycles determined by changes in the thickness of light and dark layers (Text-fig. 8). Most likely, the tested samples contain relatively more magnetite than the clay samples from Profile I. This is evidenced by higher χ and S-ratio values in the common stratigraphic part of both profiles (periods 3a–4b; Text-figs 7, 8 and 9). In samples from the distal part of the lake of Profile II, no significant correlations were observed between χ *versus* ARM/IRM_{1T} and χ *versus* S-ratio (Text-fig. 9). The reason may be the occurrence of two types of magnetic minerals and/or minerals with different grain sizes. Generally, it can be concluded that in this part of Profile II, the content of hematite may have a greater influence on susceptibility changes compared to the results obtained in Profile I. The presence of hematite in the tested samples is confirmed by the IRM saturation curves for samples DE 70 and DE 100 (Text-fig. 10). A lower ARM/IRM_{1T} ratio than in Profile I and higher S-ratio values may indicate magnetite with a larger diameter. In the proximal sedimentary zone, correlations between basic magnetic parameters are stronger.

Despite some differences in magnetic mineralogy in the common stratigraphic part of both profiles, a certain relationship can be observed. The ARM/IRM_{1T} ratio is different but high for intervals marked ‘a’ in the distal sedimentary zone of both profiles.



Text-fig. 10. IRM saturation curves from the selected samples.

However, for periods marked ‘b’, the value of this ratio decreases in both profiles and assumes similar values (Text-fig. 6), which may indicate similar processes affecting the content and type of magnetic minerals in the tested samples.

Palaeoenvironmental reconstruction

The examined profiles of varved clays represent sedimentation between the distal and proximal sedimentation zone of the lake (based on the types of varves mentioned in Merta 1978). The changes in magnetic parameter values of clays accumulated in the distal sedimentary zone indicate a certain cyclicity, similar to the changes in the dark and light layer thickness. In the intervals marked ‘a’, the values of χ, ARM, and IRM_{IT} are lower than in the intervals marked ‘b’. However, a different situation is observed in the clays accumulated in the distal zone in profile II, where the values of the above-mentioned magnetic parameters behave oppositely, i.e., are higher in the intervals marked ‘a’ than in the intervals marked ‘b’. A common feature of these two studied profiles is the similarly changing values of the ARM/IRM_{IT} ratio in the distal sedimentary zone (see Rock magnetism subsection). According to the author, changes in the values of this ratio confirm the correlation between the studied profiles resulting from the analysis of the varve thickness or changes in the thickness of individual light and dark layers interpreted in the studied clays. This allows for the determination of environmental changes occurring during the sedimentation of the studied clays.

The cycles observed based on the changes of the dark layers/varves ratio and changes of the values of rock magnetism parameters (mainly in the distal accumulation zone) last 7 years on average. However, it is worth emphasizing that the cyclicity is best visible in the intervals 1a–6a and the cycles last 6–8 years. The exceptions are intervals 3a and 4b, where the cycles persist 14 and 15 years, respectively. It is possible that the cyclicity in these intervals is disturbed by additional, undefined factors or the boundaries of the cycles are blurred. In the upper part of the profile of the studied clays (intervals 6b–8b), the length of the cycles decreases to 3–4 years, i.e., they are twice as short.

The cycles that last on average 7 years are similar to those described based on the contemporary measurement data. Pfeffer *et al.* (2023b) illustrated a cyclicity in the Earth system, which lasts around 6 ± 1 years. This has been observed, e.g., in changes in the length of day, Earth’s magnetic field and position of magnetic poles of Earth as well as Earth’s gravity field (Abarca del Rio *et al.* 2000; Mound and Buffet 2006; Silva *et al.* 2012; Ding and Chao 2018; Pfeffer *et al.* 2023b). Cycles with similar periods have been recorded also in the climate system of Earth – in the changes of global mean sea level, mass balances of the Greenland ice sheet and glaciers, terrestrial water storage, or global mean surface temperature (Moreira *et al.* 2021; Pfeffer *et al.* 2023a; Pfeffer *et al.* 2023b). Although the cause of the above-described cyclicity in the elements of the Earth's climate system is not yet well understood, it has been suggested that its formation may be potentially influenced by processes occurring in the Earth's interior and interactions between its internal structural elements (Pfeffer *et al.* 2023b).

It cannot be clearly stated whether the cyclicity recorded in the varved clay profile at Dębe is similar to that described by Pfeffer *et al.* (2023b) and the proposed reason for its occurrence may be only one of many probable causes. This is due to the fact that modern measurements of the described parameters last for a relatively short time – in most cases, a maximum of several dozen years.

Furthermore, instrumental and geological data have different accuracy, which can make comparisons between them difficult. Nevertheless, it is worthwhile extending the study of the described short-term cyclicity to geological profiles with longer time records, such as lake sediments from the Holocene.

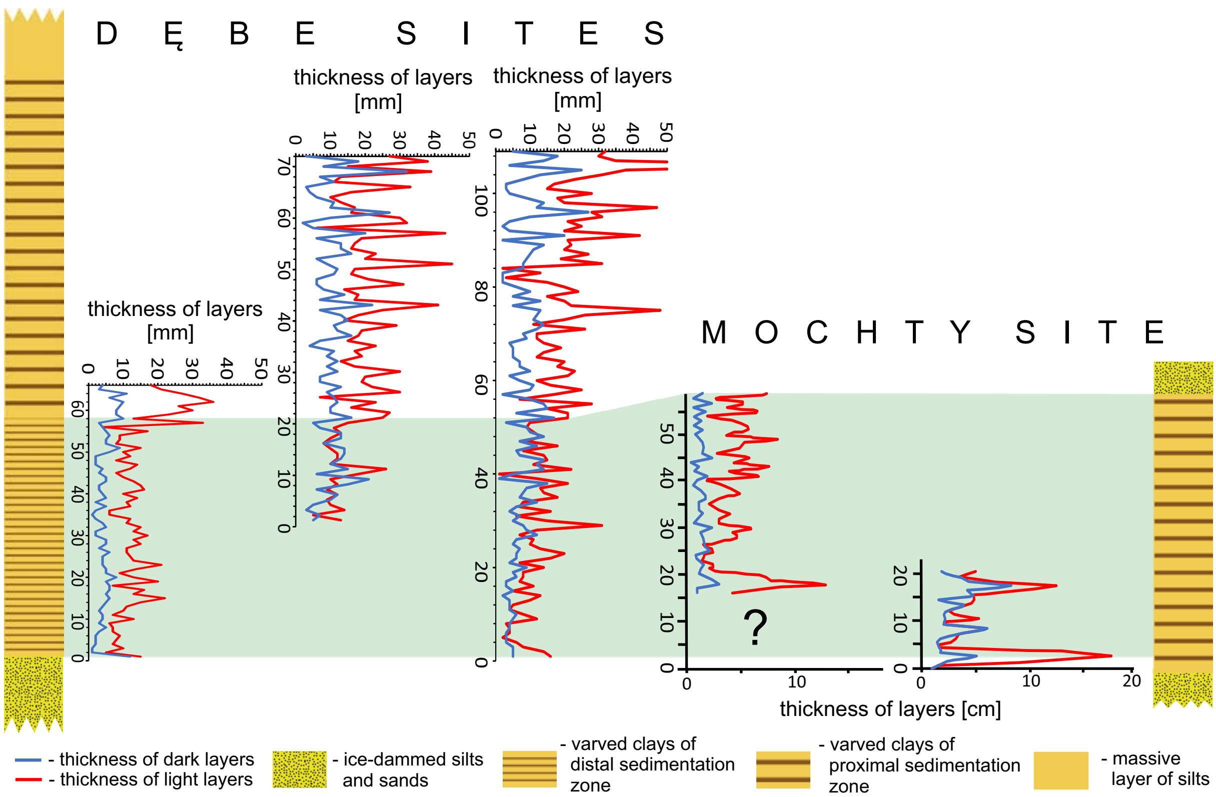
For the studied sediments, deposition took place in the area close to the distal sedimentary zone at first (intervals 1a–4a), and then there was a transition to sedimentation in the area close to the proximal part (intervals 4b–9b). In the lower part of the section (intervals 1a–4a), the varves are considerably thinner than in the upper part of the studied clays, and the annual increase in sediment is small (18 mm/year). The low average sedimentation rate in the lower part of the profile of the tested varved clays may result from the profile being located in the deeper (distal) sector of the lake. The greater distance from sediment source inflow (from the mouths of rivers, shores of the lake) could result in lower sediment supply for the reservoir and consequently, varves of relatively small thickness could be deposited (Ashley 1975; Merta 1978; Ridge *et al.* 2012; Heideman *et al.* 2015; Palmer *et al.* 2019). Because of the calmer sedimentation environment in the distal sedimentation zone, the record of changes in magnetic susceptibility reflects well the intervals and cyclicity of sedimentation interpreted from changes in the thickness of dark and light layers. In the lower part of profile I (1a–2b), the supply of terrigenous material was relatively high. This statement is supported by higher values of the χ, ARM and IRM_{1T} in profile I and an inversely proportional correlation of the ARM/IRM_{1T} ratio with χ values (Text-fig. 9). Increased delivery of terrigenous material is also suggested by an increase in the thickness of the dark layers, with a maximum at interval 2a. The increase in thickness suggests a greater amount of suspended material that may have been deposited during winter. The interval 2a also represents a temporal deepening of the lake within the lower part of the profile I, expressed by a decrease in χ, ARM and IRM values and a predominance of fine-grained magnetite (higher ARM/IRM_{1T} ratio). The negative S-ratio value indicates the predominance of high coercivity minerals such as goethite and hematite. However, the author suggests that throughout the profile, high coercivity minerals may be at similar levels, and the variation in S-ratio values may be predominantly dependent on the amount of magnetite supplied to the lake. Furthermore, the increase in depth in interval 2a is indirectly indicated by dropstones found in the clays (Text-fig. 4B; white arrows), which suggest close proximity of the lake banks to the ice-sheet front and the occurrence of the ice blocks. The deepening ends with the onset of interval 2b. The upper part of profile I (intervals 3a–4a) is predominantly sedimentation in the part of the lake as it is becoming deeper. The maximum depth of the reservoir is represented by sediments belonging to interval 4a. The lowest values of χ, ARM, IRM_{1T} and the highest ARM/IRM_{1T} ratio in the entire profile, as well as a thicker dark layer, compared to the light layer confirms this statement.

The upper part of the section (intervals 4b–8b) is characterized by varves of greater thickness (sedimentation rate is 32 mm/year) and represents a more proximal sedimentation zone. The varves in the proximal zone have a more complex structure, probably similar to the Bouma sequence (Bouma 1962; Bakhmutov *et al.* 2009), but this statement needs a broader investigation. Several erosional horizons are observed within selected light layers. The horizons are often underlain by thin layers of sands with ripple marks. Merta (1978) observed ripple marks on the top surfaces of the light layers of varved clays deposited in different localizations of the Warsaw Ice-Dammed Lake area. The forms were interpreted as a result of wave activity during summer periods. It means that sedimentation of the varved clays took place at a relatively shallow depth, probably in a proximal sedimentation zone. A similar situation might have occurred at the Dębe site, but this statement requires broader investigation. It is also noteworthy that in the upper part of the section, the clay is characterized by a greater variability in varve thicknesses, which may be caused by greater environmental dynamics related to the shallowing of the lake and/or a greater supply of material transported from land. Interval 4b–8b is also characterized by a greater thickness of light layers relative to dark layers. The above-described characteristic of this zone in profile II causes the obtained record of changes in magnetic parameters not to be characterized by clear cyclicity as observed in the distal sedimentation zone of the lake.

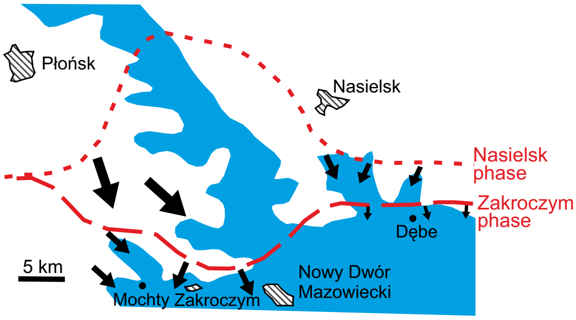
As these intervals (1a–4a and 4b–8b) are characterized by a long duration (at least 58 years for the distal sedimentation zone and at least 52 years for the proximal zone), they can have an ability to record climate changes (Merta 1978; Paluszkiewicz 2005). The cause of the changes in the sedimentological record may be the retreat of the ice-sheet front located in the north. Melting of the ice sheet may have led to an increased supply of mineral material to the sediment reservoir compared to that of clays deposited in the distal sedimentation zone. Subsequently, decreasing values of χ, ARM and IRM within the proximal zone recorded in profile II suggest a smaller supply of magnetic minerals to the reservoir. This may be due to the longer transport path of glacial material associated with the retreating ice-sheet front. The second explanation of the smaller supply may be associated with the closure of one source of drift of terrigenous material and/or the opening of another source of terrigenous material.

Profile I is characterized by lower thickness of dark layers and similar thickness of light layers within varves 34–52 (intervals 3a–4a) in comparison with the other profiles (see Text-fig. 6). The differences in this part of the profiles are also visible in the ARM/IRM$_{1T}$ ratio and other magnetic parameters. In profile I, the ratio is higher than in the other profile. This may be related to the smaller diameter of the magnetic mineral grains. It is worth saying that the ARM/IRM$_{1T}$ ratio is similar in varves 40–46 (interval 3b) and 55–64 (interval 4b) (see Text-fig. 6) in both profile I and profile II, i.e., in the periods with higher supply of the material. The collected results show that the sedimentation in profile I might have occurred temporarily in a relatively shallower part of the reservoir than in profile II (lower dark layers/varves ratio in profile I) but still in the more distal accumulation zone. Additionally, the results probably indicate a lower supply and/or a smaller diameter of terrigenous material (higher ARM/IRM$_{1T}$ ratio in intervals 3a and 4a, lower values of χ, ARM and IRM as well as a lower thickness of dark layers).

The site near Mochty is the second site where sediments belonging to the Saalian Glaciation were



Text-fig. 11. Varve correlation between the Dębe and Mochty sites.



Text-fig. 12. Paleogeographic reconstruction with the limits of the Zakroczym and Nasielsk phases, Saalian Glaciation (MIS 6); black arrows – the magnitude of the terrigenous material input – bigger arrows show a higher amount of the sediment supply.

exposed. It is located c.a. 26 km to the west of Dębe. The glacial till, 2–8 m thick, is exposed in the escarpment of the postglacial plateau (Marks *et al.* 1996). The till is covered by a 2 m thick layer of supraglacial sands. Above the till or sands is a 0.1–0.3 m thick pavement. It is covered by a 7 m thick layer of fine sands, which accumulated in an ice-dammed lake. The sands pass up in to a 3–4 m thick layer of varved clays. At the back of the escarpment, 3 m thick, ice-dammed sands and silts lie on the varved clays. These ice-dammed sands and silts indicate the next stage of ice-dammed lake sedimentation. Within the varved clays, 59 varves were distinguished and are shown in the profile in Text-fig. 11. The varve thickness is differential and is 2–23 cm, 1.5–20 cm for light layers and 0.4–9 cm for dark layers.

This research reveals that varved clays at the Mochty site were deposited in the first stage of the development of an ice-dammed lake, after the accumulation of the fine sands. The clays may be correlated with the part of the varved clays from Dębe which accumulated in the distal sedimentation zone (Text-fig. 11). The sedimentation rate in the Mochty profile is 65 mm/year, whereas it is only 18 mm/year in Dębe. The first stage of lake sedimentation is related to the stagnation of the ice-sheet front to the north of Zakroczym (Zakroczym phase; Różycki 1972; Marks *et al.* 1996). The ice-sheet front in the vicinity of Dębe was also in close proximity to the north of Dębe (Text-fig. 12; Nowak 1967; Różycki 1972). The second stage of the accumulation at Mochty, connected with the accumulation of the upper ice-dammed sands and silts, may be correlated with the part of the varved clays from Dębe which were deposited in the proximal zone. The increased supply of the terrigenous material in both profiles may be related to the retreat of the Saalian ice-sheet front to the north towards Płońsk and Nasielsk (Nasielsk phase). The higher sedimentation rate at Mochty may correspond to its location closer to the lake shoreline (Text-fig. 12) and to the faster melting of ice in the western part, or it could have been located closer to the source of supply of material (Carrivick and Tweed 2013).

CONCLUSIONS

The studied profiles of varved clays formed during the recessional phase of the Saalian Glaciation (MIS 6) contain a total of 110 varves of annual deposition and represent a transitional environment between the distal and proximal sedimentation zones of the ice-dammed lake. Their transition is climatic in nature or may be associated with the closure of one source of the drift of terrigenous material and/or the opening of another source of terrigenous material. The sedimentation in distal and proximal sedimentation zones lasted at least 58 and 52 years, respectively.

In addition to the cyclicality associated with annual sedimentation in summer and winter, another type of cyclicality was observed. The long-term cyclicity (1a–8b) refers to changes in the water surface level in the lake and/or changes in the supply of terrigenous material. These intervals last 7 years on average. The cyclicity is similar in duration to that observed in modern measurements of some parameters of the Earth's climate system and can be influenced by the internal dynamics of the Earth.

Based on the sedimentological record and magnetic properties of the studied varved clays, it can be concluded that in the first phase of clay sedimentation (interval 1a–4a) the shoreline of the ice-dammed lake was relatively close to the stagnant front of the ice-sheet and the lake was generally becoming deeper. Relatively rapid climate warming led to increased melting of the ice-sheet and its regression. This was recorded in the transition from sedimentation in the more distal sedimentation zone to deposition in the more proximal zone.

The comparative analysis between sediments examined from the Dębe and Mochty sites shows two phases of sedimentation in the ice-dammed lake. The first stage is recorded by sedimentation of the varved clays. The second stage is characterized by the higher supply of terrigenous material. The sedimentation of the varved clays at Dębe was changed from the distal to the proximal sedimentation zone. At the same time, the ice-dammed silts and sands accumulated at the Mochty site. The increasing input of material is caused by the ice-sheet front retreating from the area near Zakroczym, and from the area to the north of Dębe and furthermore to the north of the Bug valley (Zakroczym phase) towards Płońsk and Nasielsk (Nasielsk phase).

The analysis of varved clays on the basis of magnetic susceptibility and other indices yielded the best results for clays deposited in the more distal sedimentation zone due to a calmer depositional environment. Clays from the more proximal zone, due to a more dynamic deposition environment, were characterized by frequent erosion and most likely redeposition of some material, and provided less information on environmental changes. This is also influenced by the more complex magnetic mineralogy.

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REFERENCES

Abarca del Rio, R., Gambis, D. and Salstein, D.A. 2000. Interannual signals in length of day and atmospheric angular momentum. *Annales Geophysicae*, **18**, 347–364.

Ashley, G.M. 1975. Rhythmic sedimentation in glacial lake Hitchcock, Massachusetts, Connecticut. In: Jopling, A.V., McDonald, B.C. (Eds), Glaciofluvial and Glaciolacustrine Sedimentation. *Society of Economic Palaeontologists and Mineralogists. Special Publication*, **23**, 304–320.

Bakhmutov, V., Kolka, V. and Yevzerov, V. 2006. Lithology and paleomagnetic record of Late Weichselian varved clays from NW Russia. *Geological Quarterly*, **50**, 353–368.

Bakhmutov, V.G., Yevzerov, V.Y. and Kolka, V.V. 2009. Varved clay paleomagnetism: Sedimentogenesis and secular variation record. *Izvestiya, Physics of the Solid Earth*, **45**, 567–582.

Baraniecka, M.D. and Konecka-Betley, K. 1987. Fluvial sediments of the Vistulian and Holocene in the Warsaw Basin. In: Starkel, L. (Ed.), Evolution of the Vistula river valley during the last 15 000 years, part II. *Geographical Studies IGiPZ PAN Special Issue*, **4**, 151–170.

Björck, A., Dearing, J.A. and Jonsson, A. 1982. Magnetic susceptibility of Late Weichselian deposits in southeastern Sweden. *Boreas*, **11**, 99–111.

Bouma, A.N. 1962. Sedimentology of some flysch deposits, 168 pp. Elsevier; Amsterdam/New York.

Butler, R.F. 1992. Paleomagnetism: Magnetic Domains to Geologic Terranes, 238 pp. Blackwell Scientific Publications; Boston.

Carrivick, J.L. and Tweed, F.S. 2013. Proglacial lakes: character, behaviour and geological importance. *Quaternary Science Reviews*, **78**, 34–52.

Collinson, D.W. 1983. Methods in Rock Magnetism and Palaeomagnetism, 503 pp. Springer; Dordrecht.

De Geer, G. 1912. A geochronology of the last 12000 years. In: Compte Rendu 11 Congress Geologique International, 11th International Geological Congress (1910), Stockholm, Sweden, **1**, 241–253.

Ding, H. and Chao, B.F. 2018. A 6-year westward rotary motion in the Earth: Detection and possible MICG coupling mechanism. *Earth and Planetary Science Letters*, **495**, 50–55.

Dunlop, D.J. and Özdemir Ö., 1997. Rock Magnetism. Fundamentals and Frontiers, 573 pp. Cambridge University Press; Cambridge.

Evans, M.E. and Heller, F. 2003. Environmental Magnetism: Principles and Applications of Enviromagnetics, 299 pp. Academic Press; Cambridge.

Fedorowicz, S., Grzybowski, K. and Marks, L. 1993. Warta Glaciation in the Warsaw Region based on recent thermoluminescence datings. *Geological Quarterly*, **37**, 67–80.

Frankiewicz, A. 2023. Objaśnienia do Szczegółowej Mapy Geologicznej Polski, arkusz Legionowo (aktualizacja), 45 pp. Wydawnictwa Geologiczne, PIG-PIB; Warszawa.

Grabowski, J., Lakova, I., Petrova, S., Stoykova, K., Ivanova, D., Wójcik-Tabol, P., Sobień, K. and Schnabl, P. 2016. Paleomagnetism and integrated stratigraphy of the Upper Berriasian hemipelagic succession in the Barlya section Western Balkan, Bulgaria: Implication for lithogenic input and paleoredox variations. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **461**, 156–177.

Haltia-Hovi, E., Nowaczyk, N., Saarinen, T. and Plessen B. 2010**.** Magnetic properties and environmental changes recorded in Lake Lehmilampi (Finland) during the Holocene. *Journal of Paleolimnology*, **43**, 1–13.

Hatfield, R.G. and Stoner, J.S. 2013. Magnetic Proxies and Susceptibility. In: Elias, S.A. (Ed.), The Encyclopedia of Quaternary Science, vol. 2, 884–898. Amsterdam: Elsevier.

Heideman, M., Menounos, B. and Clague, J.J. 2015. An 825-year long varve record from Lillooet Lake, British Columbia, and its potential as a flood proxy. *Quaternary Science Reviews*, **126**, 158–174.

Ising, G. 1942. Den varfiga lerans egeskaper. *Geologiska Föreningen i Stockholm Förhandlingar*, **64**, 126–142.

Ising, G. 1943. On the magnetic properties of varved clay. *Arkiv för matematik, astronomi och fysik*, **29**, 1–37.

Janczyk-Kopikowa, Z. 1974. The Eemian Interglacial Sediments at Błonie near Warsaw. *Bulletin of the Polish Academy of Sciences. Earth Sciences*, **22**, 147–150.

Jovane, L., Sprovieri, M., Florindo, F., Acton, G., Coccioni, R., Dall'Antonia, B. and Dinarés-Turell, J. 2007**.** Eocene–Oligocene paleoceanographic changes in the stratotype section, Massignano, Italy: Clues from rock magnetism and stable isotopes. *Journal Geophysics Resesearch*, **112**, 1–16.

Kalińska-Nartiša, E. , Dzierżek, J. ,Bińka, K., Borkowski, A., Rydelek, P. and Zawrzykraj, P. 2016. Upper Pleistocene palaeoenvironmental changes at the Zwierzyniec site, central Poland. *Geological Quarterly*, **60**, 610–623.

Karaszewski, W. 1974. Age of the Warsaw Ice Dammed Lake Sediments. *Bulletin of the Polish Academy of Sciences. Earth Sciences*, **22**, 151–155.

Lamoureux, S. 2001. Varve chronology techniques. In: Last, W.M and Smol. J.P (Eds), Tracking Environmental Change Using Lake Sediments. Volume 1: Basin Analysis, Coring, and Chronological Techniques, 247–260. Kluwer Academic Publishers; Dordrecht.

Liu, Q., Roberts, A.P., Larrasoaña, J.C., Banerjee, S.K., Guyodo, Y., Tauxe, L. and Oldfield, F. 2012. Environmental magnetism: Principles and applications. *Reviews of Geophysics*, **50**, 1–50.

Marks, L., Bińka, K., Woronko, B., Majecka, A. and Teodorski, A. 2019. Revision of the late Middle Pleistocene stratigraphy and palaeoclimate in Poland. *Quaternary International*, **534**, 5–17.

Marks, L., Dzierżek, J., Gadomski, M., Gałązka, D. and Pochocka, K. 1996. Stanowisko stratotypowe plejstoceńskich osadów lodowcowych w Mochtach na NW od Warszawy. In: Marks, L., Mycielska-Dowgiałło, E., Pękalska, A., Roszczynko, W. and Woronko, B. (Eds), Stratygrafia plejstocenu Polski: materiały II konferencji, Grabanów, 18–20 września 1995. Komisja Stratygrafii i Paleogeografii Plejstocenu. Komitet Badań Czwartorzędu Polskiej Akademii Nauk; Warszawa.

Marks, L., Dzierżek, J., Janiszewski, R., Kaczorowski, J., Lindner, L., Majecka, A., Makos, M., Szymanek, M., Tołoczko-Pasek, A. and Woronko, B. 2016. Quaternary stratigraphy and palaeogeography of Poland. *Acta Geologica Polonica*, **66**, 403–427.

Marks, L., Karabanov, A.K., Nitychoruk, J., Bahdasarau, M., Krzywicki, T., Majecka, A., Pochocka-Szwarc, K., Rychel, J., Zbucki, Ł., Hradunova, A., Hrachanik, M., Mamchyk, S., Rylova, T., Nowacki, Ł. and Pielach, M. 2017. Paleogeografia południowej części obszaru przygranicznego Polski i Białorusi w czwartorzędzie. In: Marks, M., Karabanov, A. K. (Eds). Mapa geologiczna południowej części obszaru przygranicznego Polski i Białorusi: rejon Białej Podlaskiej i Brestu 1:250 000. Państwowy Instytut Geologiczny; Warszawa

Merta, T. 1978. Extraglacial varved deposits of the Warsaw Ice-Dammed Lake (younger Pleistocene), Mazovia Lowland, Central Poland. *Acta Geologica Polonica*, **28**, 241–271.

Merta, T. 1986. Varve sedimentation in extraglacial ice-dammed lakes. *Acta Geologica Polonica*, **36**, 325–336.

Mojski, J.E. 2005. Ziemie polskie w czwartorzędzie. Zarys morfologii, 404 pp. Państwowy Instytut Geologiczny; Warszawa.

Moreira, L., Cazenave, A. and Palanisamy, H. 2021. Influence of interannual variability in estimating the rate and acceleration of present-day global mean sea level. *Global and Planetary Change*, **199**, 1–16.

Mound, J.E. and Buffett, B.A. 2006. Detection of a gravitational oscillation in length-of-day. *Earth and Planetary Science Letters*, **243**, 383–389.

Nowak, J. 1967. Objaśnienia do Szczegółowej Mapy Geologicznej Polski, arkusz Nasielsk, 38 pp. Wydawnictwa Geologiczne, PIG-PIB; Warszawa.

Nowak, J. 1978. Objaśnienia do Szczegółowej Mapy Geologicznej Polski, arkusz Legionowo, 55 pp. Wydawnictwa Geologiczne, PIG-PIB; Warszawa.

Opdyke, N.D. and Channel, J.E.T. 1996. Magnetic Stratigraphy, 346 pp. Academic Press, San Diego.

O'Sullivan, P.E. 1983. Annually-laminated lake sediments and the study of Quaternary environmental changes – a review. *Quaternary Science Review*, **1**, 245–313.

Özdemir, Ö. and Banerjee, S.K. 1982. A preliminary magnetic study of soil samples from west-central Minnesota. *Earth and Planetary Science Letters*, **59**, 393–403.

Palmer, A.P., Bendle, J.M., MacLeod, A., Rose, J. and Thorndycraft, V.R. 2019. The micromorphology of glaciolacustrine varve sediments and their use for reconstructing palaeoglaciological and palaeoenvironmental change. *Quaternary Science Reviews*, **226**, 1–21.

Paluszkiewicz, R. 2005. Wykształcenie i ilość warw jako podstawa określenia czasu trwania sedymentacji w obrębie zbiornika zastoiskowego (zastoisko złocienieckie – Pomorze Zachodnie). In: Kotarba, A., Krzemień, K. and Święchowicz, J. (Eds), Współczesna rzeźba ewolucji Polski, VII Zjazd Geomorfologów Polskich, Kraków, 19–22 września 2005. Instytut Geografii i Gospodarki Przestrzennej Uniwersytetu Jagiellońskiego; Kraków.

Petterson, G., Odgaard, B.V. and Renberg, I. 1999. Image analysis as a method to quantify sediment components. *Journal of Paleolimnology*, **22**, 443–455.

Pfeffer, J., Cazenave, A., Blazquez, A., Decharme,, B., Munier, S. and Barnoud, A. 2023a. Assessment of pluri-annual and decadal changes in terrestrial water storage predicted by global hydrological models in comparison with the GRACE satellite gravity mission. *Global and Planetary Change*, **27**, 3743–3768.

Pfeffer, J., Cazenave, A., Rosat, S., Moreira, L., Mandea, M., Dehant, V. and Coupry, B. 2023b. A 6-year cycle in the Earth system. *Global and Planetary Change*, **229**, 1–28.

Ridge, J.C., Balco, G., Bayless, R.L., Beck, C.C., Carter, L.B., Dean, J.L., Voytek, E.B. and Wei, J.H. 2012. The new North American Varve Chronology: a precise record of southeastern Laurentide Ice Sheet deglaciation and climate, 18.2–12.5 kyr BP, and correlations with Greenland ice core records. *American Journal of Science*, **312**, 685–722.

Roberts, A.P., Reynolds, R.L., Verosub, K.L. and Adam, D.P. 1996. Environmental magnetic implications of Greigite (Fe_3S_4) Formation in a 3 m.y. lake sediment record from Butte Valley, northern California. *Geophysical Research Letter*, **23**, 2859–2862.

Rogoziński, R. 2017. Analiza zmian położenia wirtualnego bieguna geomagnetycznego Ziemi na podstawie badań paleomagnetycznych złoża Lębork, 169 pp. Praca Doktorska, Wydział Geodezji i Kartografii, Politechnika Warszawska.

Różycki, S.Z. 1967. Plejstocen Polski Środkowej, 251 pp. Wydawnictwo Naukowe PWN; Warszawa.

Różycki, S.Z. 1972. Nizina Północnomazowiecka. In: Kondracki, J. (Ed.) Geografia fizyczna Polski, 463 pp. Wydawnictwo Naukowe PWN; Warszawa.

Ruszczyńska-Szenajch, H., Trzciński, J. and Jarosińska, U. 2003. Lodgement till deposition and deformation investigated by macroscopic observation, thin-section analysis and electron microscope study at side Dębe, central Poland. *Boreas*, **32**, 399–415.

Sarnacka, Z. 1982. Stratygrafia i charakterystyka litologiczna osadów czwartorzędowych rejonu dolnej Wisły na południe od Warszawy. *Biuletyn Instytutu Geologicznego*, **337**, 143–192.

Silva, L., Jackson, L. and Mound, J. 2012. Assessing the importance and expression of the 6- year geomagnetic oscillation. *Journal of Geophysical* Research, **117**, 1–9.

Snowball, I.F. 1997. Gyroremanent magnetization and the magnetic properties of greigite-bearing clays in southern Sweden. *Geophysical Journal International*, **129**, 624–636.

Solon, J., Borzyszkowski, J., Bidłasik, M., Richling, A., Badora, K., Balon, J., Brzezińska-Wójcik, T., Chabudziński, Ł., Dobrowolski, R., Grzegorczyk, I., Jodłowski, M., Kistowski, M., Kot, R., Krąż, P., Lechnio, J., Macias, A., Majchrowska, A., Malinowska, E., Migoń, P., Myga-Piątek, U., Nita, J., Papińska, E., Rodzik, J., Strzyż, M., Terpiłowski, S. and Ziaja, W. 2018. Physico-geographical mesoregions of Poland: verification and adjustment of boundaries on the basis of contemporary spatial data. *Geographia Polonica*, **91**, 143–170.

Tauxe, L., Banerjee, S.K., Butler, R.F. and van der Voo, R. 2018. Essentials of Paleomagnetism, 5th Web Edition.

Teodorski, A., Dzierżek, J. and Ziółkowski, P. 2021. Reconstruction of subglacial depositional conditions based on the anisotropy of magnetic susceptibility: an example from Dębe (Central Poland). *Journal of Quaternary Science*, **36**, 391–402.

Thompson, R. and Oldfield, F. 1986. Environmental Magnetism, 227 pp. Springer; Dordrecht.

Zolitschka, B., Francus, P., Ojala, A.E.K. and Schimmelmann, A. 2015. Varves in lake sediments – a review. *Quaternary Science Reviews*, **117**, 1–41.

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