Environmental response to climatic changes in the Pleistocene – selected evidence from Poland

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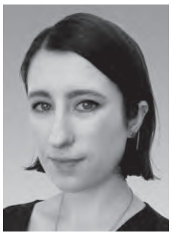
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A b s t r a c t. We review published data to explain climatic and environmental changes as recorded in the deposits and landforms of the Quaternary of Poland. A wide range of research methods have been used to reconstruct the environmental conditions at many sites and selected studies summarized here include those of interglacial palaeolake deposits at Ossówka and periglacial structures at Wierzchuca Nagórna (both in the Podlasie Region), a loess profile at Wąchock and sandy deposits in Korzecko (both in the Holy Cross Mountains), carbonate cementation forms at Reńsko (Wielkopolska Region), and well-preserved glacial landforms in the Dobrzyń Lakeland, Suwałki Lakeland and the Carpathians including the Tatra Mountains. The terrestrial record described is far from complete but it demonstrates that climate change in the Quaternary glacial and interglacial periods occurred with high frequency, varying intensity and cyclicity. Climate instability during cold phases of the Pleistocene is more evident, as expressed by terminal moraines in the Polish Lowland and in the mountains. In warmer periods, climatic instability was expressed mainly through high-resolution records. The examples provided from both cold and warm Quaternary phases clearly show climate changes as common and natural phenomena.

Keywords: *Quaternary, palaeoclimate, palaeonvironment, Poland*

In Quaternary research, the relationship between sedimentary records and climatic changes is a key focus, alongside stratigraphy. The ability to refer glacial till and loess to a cold climate, and lacustrine gyttja and palaeosols to a warm climate allows reconstruction of climate variations preserved in a geological record. The foundations of climatostratigraphy, that links sedimentary facies to climatic fluctuations, were established in seminal work by James Geikie (1839–1915), a professor at the University of Edinburgh (Geikie, 1874). He was the first researcher to postulate a significant role of continental glaciation in modelling the Earth surface and identifying sedimentary sequences formed under cold (glacial) and warm (interglacial) conditions. He was also a pioneer in recognizing the cyclicity of climatic conditions recorded in sedimentary strata and landforms in Great Britain.

Modern palaeoenvironmental reconstructions use a wide range of geological proxies and methods that enhance our understanding of the climatic and environmental conditions that governed sedimentary processes. Such approaches provide increasingly detailed insights into climatic regimes in the Quaternary.

The term ‘Quaternary’ appeared in the 18th century, but at that time it was not related to a climate change in Earth’s history reflected by extensive glaciation, especially in the Northern Hemisphere. It was since the mid-19th century that – in contrast to the rest of the Phanerozoic – the Quaternary sedimentary sequences were classified mostly on climatic changes, particularly as regards sequences of glacial deposits in central Europe and mid-latitude North America. Subdivision of the Quaternary was fundamentally lithological, because the stratigraphical sequences with glacial and nonglacial deposits were considered to represent glacial and interglacial periods respectively (cf. West, 1968, 1977; Bowen, 1978).

The key point is that both individual factors acting at the Earth’s surface, and the sum of them, are cyclical, these including climate, ocean and wind currents, and temperature. The repeated Pleistocene glaciations were caused by these same factors, and the climate oscillations between glaciations and interglacials dominated the environmental evolution of the Quaternary (Maslin, Ridgwell, 2005). They were principally generated by orbital forcing (Milanković cycles) acting on the interannual and latitudinal distribution of solar radiation at the Earth’s surface and consequently influencing its climate (Hays *et al.*, 1976).

The influence of climatic changes on sedimentation and erosion in the Quaternary, biological evolution, and the subdivision of the modern ocean sediment isotope stage sequences is based on the same basic concept. It enabled establishing the chronology of the climatic events, represented by the curves of oxygen isotope stages (OIS) in terrestrial, and marine isotope stages (MIS) in deep-sea, deposits, as well as estimation of the duration of the Qua-

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ternary itself (http://www.quaternary.stratigraphy.org.uk/). High-resolution analysis, e.g., of ice cores and lake deposits, showed that first-rank climatic units (glaciations and interglacials) were internally complex, with many shorter- and smaller-scale climatic episodes named events, oscillations, or phases (Gibbard, West, 2000; Lisiecki, Raymo, 2005; Hughes, Gibbard, 2018; Wieczorek *et al.*, 2021). In reality, the Quaternary is composed of glacial-interglacial cycles, in turn composed of different secondary minor cycles, e.g. of stadials and interstadials (por. Lindner *et al.*, 2002). This generally regular rhythm of climatic changes could be disrupted by extreme weather phenomena.

In Europe, the terms '*interglacial*' and '*interstadial*' were traditionally used to define characteristic types of non-glacial climatic conditions, indicated by vegetational changes (Jessen, Milthers, 1928; West, 1984). Several attempts were made to formalize the climate-based stratigraphy (e.g., American…, 1961; Mangerud *et al.*, 1974), referring to glacier advances and retreats, shifting of vegetation zones, migration of fauna including hominids. Although some of the climatic intervals were found globally synchronous, most of them were not expressed by a similar climate change everywhere or were identified locally and could not be detected at great distances, between different climatic provinces and across the terrestrial/marine facies boundary. Glacial-based terms were difficult to apply outside glaciated regions, and the interglacial-like events were found to be characteristic of cold rather than glacial climates and then the term '*interglacial*' had to be replaced by the term '*warm*' or '*temperate*' stage (Gibbard, West, 2000).

The evolution of the Earth is much easier to understand if based on reconstruction of its continuous climate change. This was expressed by warmings and coolings of varying magnitude, occasionally catastrophic for plants and animals, and causing remodelling of geological processes. Earth's climate history is reconstructed using different geological, climatological and archaeological tools, a selection of which depends on timescale, age, as well as desirable and possible accuracy (Table 1).

In this article we synthesize selected results of investigations of the climatic and environmental conditions in the Quaternary, as recorded in various types of deposits and landforms in Poland, emphasizing that the examples provided unequivocally demonstrate the natural climate changes that occurred during the Pleistocene. Most of the topics discussed are based on original research and reflect ongoing advances in the methodological framework of Quaternary geology, with a particular focus on the climate geology.

METHODS

In the study of landforms and Quaternary deposits, a wide range of research methods are employed for palaeoclimate reconstructions. These include both traditional fieldwork (geomorphology, drilling, and examination of exposures) and laboratory analyses (palynology, malacology and geochemistry), as well as advanced microscopic imaging (thin-section and scanning electron microscopy analyses), and anisotropy of magnetic susceptibility measurements.

Geomorphological analysis was carried out in the field, using maps and digital elevation models (DEM) in a study area located in the Carpathians including the Tatra Mountains, the Dobrzyń Lakeland, and the Suwałki Lakeland (Fig. 1). This enabled assessment of climate changes, based on the accurate identification, correlation of terminal moraines and other glacial landforms, and establishing their shape and size, spatial relationships and morphological lineaments (Dzierżek, 2009; Teodorski, 2023, 2024).

Analysis of periglacial structures at Wierzchuca Nagórna (Fig. 1) was based on geological fieldwork (Dzierżek, Stańczuk, 2006), electrical resistivity tomography, ground penetration radar (Mieszkowski *et al.*, 2014) and correlation with similar structures in western Poland (Ewertowski *et al.*, 2017; Marks *et al.*, 2019). Anisotropy of magnetic susceptibility (AMS) was applied in the Dobrzyń Lakeland (Teodorski, 2024) and Wąchock (Dzierżek *et al.*, 2020) to reconstruct transport directions during deposition.

Table 1. Main geological, archaeological, historical and meteorological methods used in climate reconstruction

Methods and palaeoclimatic indices or proxies			Examples or recorded intervals
Meteorological ('neoclimatology')		• regular instrumental measurements	• since 1659 CE (occasionally in the 16th century)
Historical and archaeological (historical climatology)		• diaries, chronicles • pedology • water gauge measurements • economic indices	• 127–151 CE: diary of Claudius Ptolemaeus from Alexandria • since 812 CE: beginning of cherry blossoms in Japan • since 3050 BCE: Nile • crop volume, prices of agricultural products, *etc.*
Geological (palaeoclimatology)	Quantitative and partly quantitative methods	• glacier advances • dendroclimatology • carottage measurements of temperature • lake water-level • oxygen isotopes in ice cores • sea water-level • palaeontological indices (e.g., pollen, molluscs) • deep-sea deposits	10 ka 100 ka 100 ka 800 ka 500 ka 1 Ma 10 Ma 200 Ma
	Qualitative methods	• fossils • lithology	4.2 Ga

Palynological analysis was used to reconstruct the environmental conditions and age of the buried lacustrine deposits at Ossówka (Fig. 1). Furthermore malacological, $\delta^{18}O$ and $\delta^{13}C$ analyses were applied (Nitychoruk *et al.*, 2005; Bińka *et al.*, 2023). Thin-section analysis was used to study micro- and macrostructures of carbonate-cemented deposits at Reńsko (Kulus, 2023). The examination of exposures at Wąchock involved reinterpretation of loess and palaeosol layers, integrating dating results and correlating with other reference loess sections in Poland (Dzierżek *et al.*, 2020).

Microtextural analysis using a scanning electron microscope was focused on surface textures of quartz sand grains from deposits at Korzecko and Miedzianka (8 km to the NW from Korzecko) in the Holy Cross Mountains (Fig. 1). This method is useful for determining the genesis of sandy deposits (in exposures and borehole cores) in visually similar alluvial, limnic or glaciofluvial deposits. It played a crucial role in reconstruction of sedimentary environments, climatic conditions, and transport and weathering processes (Woronko, 2012).

Dating of geological features was performed using the cosmogenic isotopes ^{36}Cl (Dzierżek, Zreda, 2007; Dzierżek, 2009) as well as thermoluminescence and optically stimulated luminescence methods (Lindner, Prószyński, 1979; Moska *et al.*, 2021).

RECORD OF CLIMATIC CHANGES IN SELECTED REGIONS

Here, selected records of climate changes preserved in different types of geological archives are described. They form together a unique compendium of knowledge about Earth's climatic history. The methods applied provide data on climate changes, with varying levels of accuracy (Table 1), but both large terminal moraines and the microrelief of quartz grain surfaces, as well as the presence of plant pollen in fossil lacustrine deposits, are equally significant in palaeoenvironmental reconstructions. Significant differences were noted in the regional development of vegetation in the Polish territory during interglacials, towards the north and east. The patterns reflect climate continentality, progressing eastwards as also indicated in the type and rate of many geomorphic processes (Marks *et al.*, 2016, 2019).

Lake deposits of the Mazovian Interglacial (Holsteinian) at Ossówka, eastern Poland

The Ossówka site (Fig. 1) with a 55-m sequence of lake deposits, is a unique example of almost uninterrupted lake deposition from the termination of the Elsterian Glaciation, through the Holsteinian Interglacial, to the beginning of the Saalian Glaciation (Nitychoruk *et al.*, 1999; Szymanek, 2017; Bińka, Marks, 2018; Bińka *et al.*, 2023). The beginning of sedimentation is dated at ~430 ka BP and lasted ~40 ka (Krupiński, 1995; Nitychoruk *et al.*, 2005; Szymanek, 2017).

The Ossówka pollen diagram shows the vegetation as it transformed from boreal, mixed and deciduous forest to open landscape, commonly with different transitional phases (Bińka *et al.*, 2023). The pollen spectrum indicates significant ecosystem dynamics and numerous climatic fluctuations. Two intra-interglacial cold episodes were noted at Ossówka: the Older Holsteinian Oscillation (OHO) and the Younger Holsteinian Oscillation (YHO) (Bińka, Marks, 2018; Fig. 2). The OHO was a cooling event with rising content of *Pinus*, *Betula*, and herbaceous plants, indicating a decline in temperate climate vegetation and gradual climate continentalization. The YHO was associated with the near-total withdrawal of *Abies* (Krupiński, 1995; Koutsodendris *et al.*, 2012; Nitychoruk *et al.*, 2018), but this environmental perturbation is rarely reflected in the European pollen records due to its short duration (roughly 800-years) and limited resolution (Bińka, Nitychoruk, 2013; Bińka *et al.*, 2023).

Stable oxygen isotope analysis of the mollusc shells of *Viviparus diluvianus* and *Valvata piscinalis* allowed reconstruction of the lake water mean temperature in July estimated at 20.0–21.4°C (Szymanek, 2017). The less favourable climatic conditions are reflected by decreased $\delta^{18}O$ values, reduced carbonate content in the deposits, and lake shallowing, likely associated with stronger influences of a continental climate (Nitychoruk *et al.*, 2005).

In the post-interglacial part, four distinct cold periods were identified with steppe-tundra vegetation and pronounced continental climate influences (L PAZ O-2, O-4, O-6, O-8). They were separated by three warm phases

Fig. 1. Location of selected sites and study areas, with extent of Scandinavian glaciations according to Marks *et al.* (2022): **S1** – Sanian 1 (Donian), **S2** – Sanian 2 (Elsterian), **O** – Odranian (Saalian), **V** – Vistulian (Weichselian); study regions and sites: **DL** – Dobrzyń Lakeland, **SL** – Suwałki Lakeland, **T** – Tatra Mountains, **Re** – Reńsko, **WN** – Wierzchuca Nagórna, **Os** – Ossówka, **W** – Wąchock, **Ko** – Korzecko

dominated by forest vegetation and oceanic climate influences (L-PAZes O-3, O-5 and O-7), separated by several lower-range oscillations (Bińka *et al*., 2023; Fig. 2).

Late Pleistocene to Early Holocene carbonate cementation of glaciofluvial deposits at Reńsko, western Poland

The site at Reńsko is located in the southwestern Wielkopolska Region and was occupied by an ice sheet of the Leszno Phase during the Vistulian Glaciation (Fig. 1). Glaciofluvial sand and gravel are overlain by a glacial till (Ewertowski, 2009) and carbonate cementation products form irregular lumps of conglomerate, from about 10 to about 30 cm in diameter (Fig. 3A; Kulus, 2023). Microscopic thin-section analyses of the conglomerate revealed two generations of carbonate cement. The first is a microsparite coating, ~10–20 μm thick (Fig. 3B). The second generation is a massive micrite cement with an admixture of iron compounds filling the intergranular pores (Fig. 3B). The pores without cement, have higher concentrations of iron compounds (Fig. 3C, D).

The environmental conditions determined by climate changes resulted presumably in different cemention patterns. Small, angular detrital grains resulting from the cracking of larger ones may have been formed by frost weathering in the periglacial climate of the late Vistulian. The first generation of cement – coatings around the grains – was associated with cementation in the vadose zone in a cold climate (Harwood, 1988). Micritic cement fills the intergranular space formed in the phreatic zone, i.e. at a higher groundwater level than the present one, probably in a milder climate at the beginning of the Holocene (Kulus, 2023). At that time, carbonate precipitation was manifested by the formation of lacustrine chalk in the depressions of the ice-marginal valley terrace around the Reńsko site (Szałajdewicz, 2000, 2004). Concentrations of iron compounds in the voids are related to precipitation of iron washed out from a soil developed later in the Holocene (Biernacka, 1993). Such interpretation of the thin-section in the context of climate-steered changes in the cementation environment (cf. Verhaert *et al*., 2002; Rattas *et al*., 2014; Woronko *et al*., 2022) requires further research.

Late Weichselian deglaciation of the Dobrzyń Lakeland, central Poland

Terminal moraines, which represent a striking morphological record of ice sheet extent, are well-documented on the Digital Elevation Model (DEM) of the Dobrzyń Lakeland (Fig. 4; Teodorski, 2023). In addition to prominent forms reaching heights of up to 15 m (e.g., the Chalin lobe), smaller moraine features with heights of 3–5 and 1–3 m were observed in the southern part of the area (Teodorski, 2023). These smaller forms represent short-term standstills of the ice margin (shorter than a subphase) and/or minor ice sheet advances (cf. Chandler *et al.,* 2020).

The terminal moraine sequences, reflecting the extent of ice lobes during deglaciation, define three main glacial substages in the Dobrzyń Lakeland (S1, S2, S3). These were recently described by Teodorski (2023, 2024), based on detailed DEM analysis and anisotropy of magnetic susceptibility methods applied to glacial tills. During a retreat from the S1 maximum extent in the southern part of the lakeland,

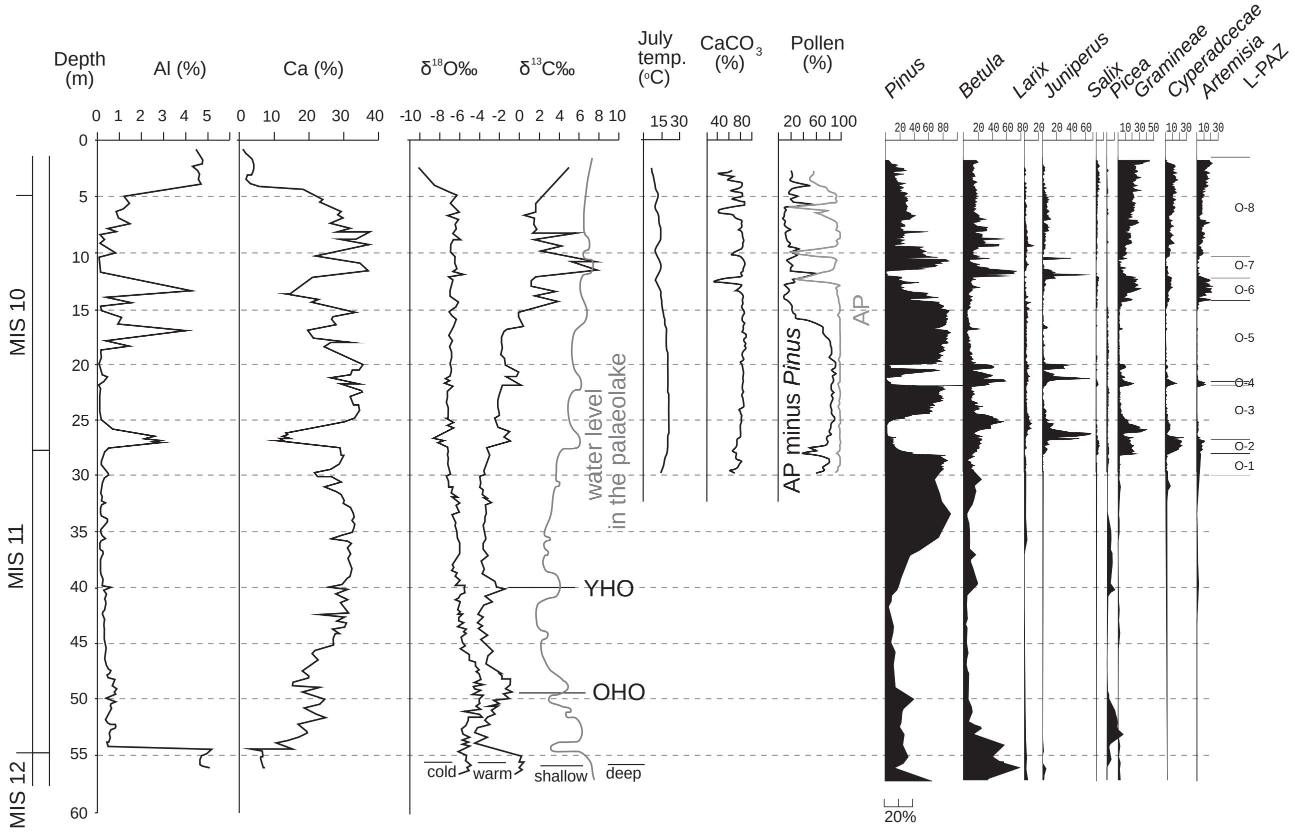

Fig. 2. A simplified pollen diagram from lake deposits at Ossówka in eastern Poland after Bińka *et al.* (2023). Depth distribution of Al, Ca, $CaCO_3$, and $\delta^{18}O$ and $\delta^{13}C$ isotope curves, AP minus *Pinus* – total tree pollen minus *Pinus* pollen, and July temperature – mean temperature of the warmest month after Nitychoruk *et al.* (1999, 2005)

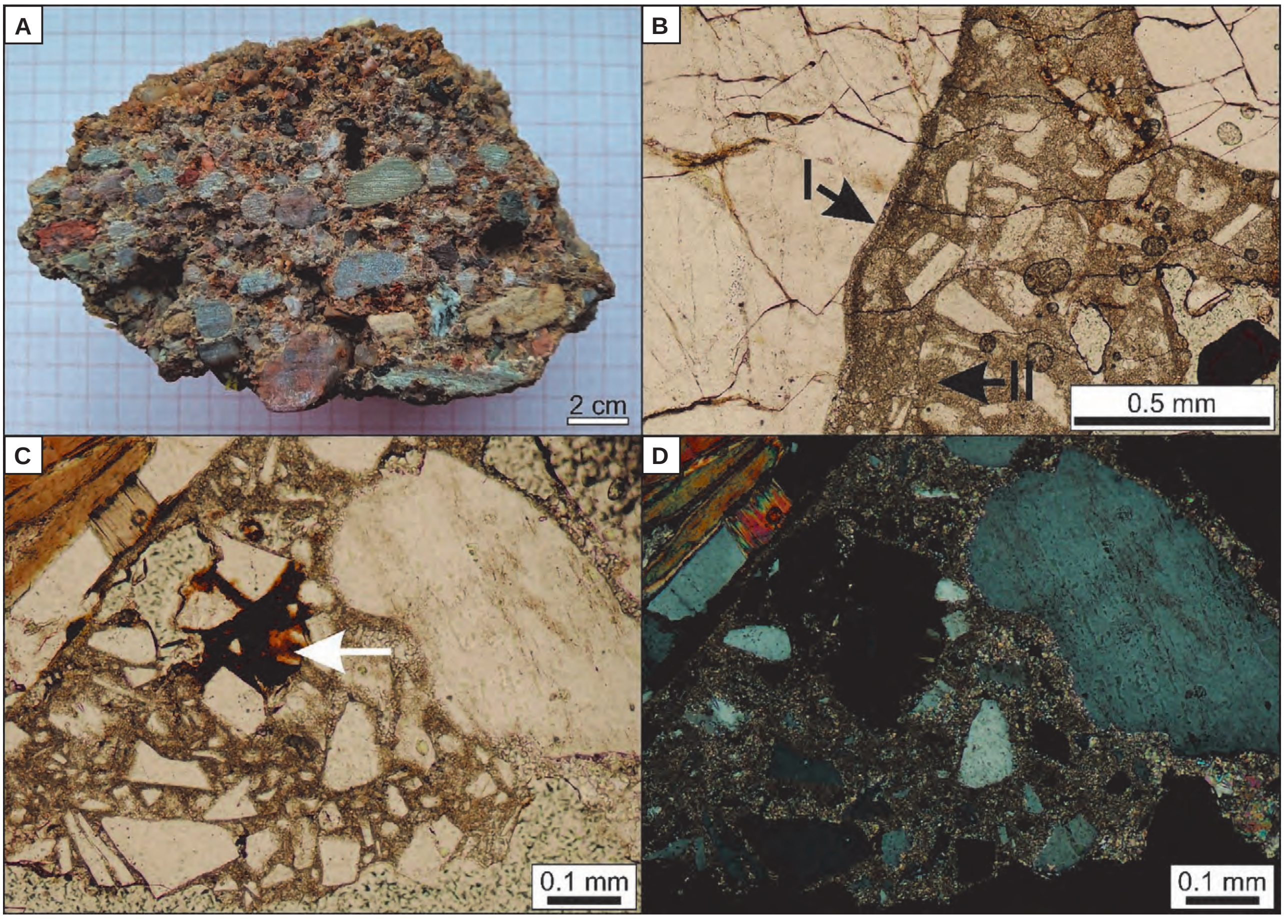

Fig. 3. Selected macro- and microstructures of cement in glaciofluvial deposits at Reńsko, SW Wielkopolska Region (Kulus, 2023). **A** – a carbonate conglomerate lump from the glaciofluvial succession; **B** – microstructure of conglomerate in a thin-section (plane polarized light), with 2 cement generations: microsparite coatings (I) and massive micrite cement with admixture of iron compounds (II); **C**, **D** – microbreccia in a thin-section (C – plane polarized light; D – crossed polars), see concentration of iron compounds in the void (white arrow on C)

two brief advances occurred, highlighted by push moraines near Dobrzyń. The second substage (S2) is associated with the advance of a small ice lobe in the central part of the lakeland (Fig. 4), correlated probably to a regional climatic shift, but the influence of local factors, such as thermal conditions at the ice sheet base and the meltwater volume, cannot be excluded. The final substage (S3) during the ice sheet retreat in the Dobrzyń Lakeland is delineated by terminal moraines of the Kujawy-Dobrzyń advance (dated to 17.7 ka BP, after Kozarski, 1995). The arrangement of terminal moraines, ice sheet lobes, ice movement directions during each substage, and their chronological correlations are shown (Fig. 4).

Late Pleistocene ice wedges at Wierzchuca Nagórna, eastern Poland

Each advance of the Scandinavian ice sheet during the Pleistocene was accompanied by permafrost aggradation in the extraglacial area. This is inferred from numerous examples of fossil periglacial forms and structures preserved in deposits of the Polish Lowland (e.g., Kozarski, 1995; Dzierżek, Stańczuk, 2006; Dzierżek, 2009; Ewertowski

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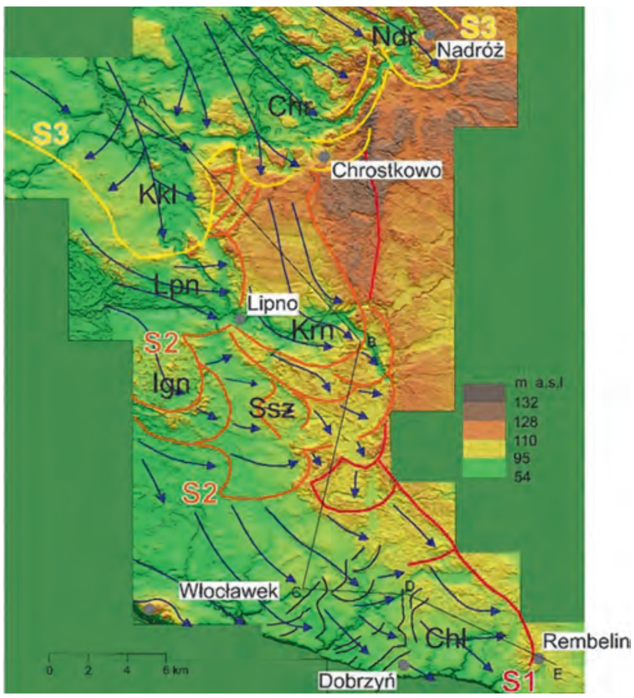

Fig. 4. Ice sheet retreat during the Vistulian Glaciation in the Dobrzyń Lakeland on a DEM: **A** – coloured lines: terminal moraines of three substages during ice sheet retreat (S1, S2, S3), dark blue arrows – directions of ice movement during each substage: ice lobes: **Ndr** – Nadróż, **Chr** – Chrostkowo, **Kkl** – Kikół, **Lpn** – Lipno, **Ign** – Ignackowo, **Krn** – Karnkowo, **Ssz** – Suszewo, **Chl** – Chalin, based on Teodorski (2024), modified; **A**–**E** –morphological profile (Fig. 9)

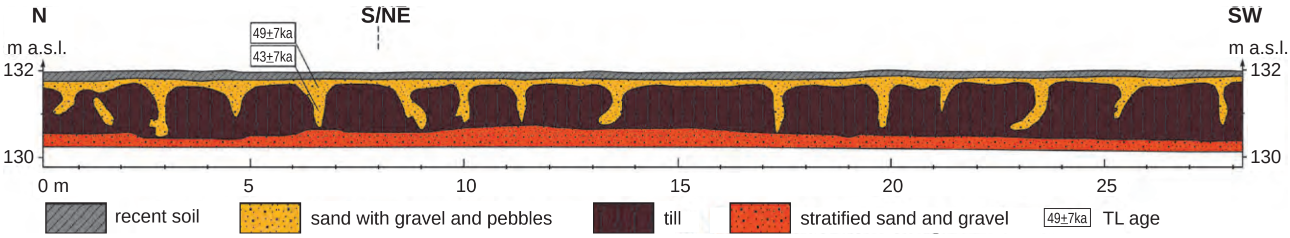

Fig. 5. Ice wedges at Wierzchuca Nagórna (after Dzierżek, Stańczuk, 2006, modified)

et al., 2017). Pseudomorphs of ice wedges and polygonal crack networks serve as direct evidence of harsh climatic conditions during the Pleistocene.

The Wierzchuca Nagórna site (Fig. 1), in which the pseudomorphs of ice wedges occur approximately at 1.7 m intervals in the exposure wall, provides evidence of a climate favourable for the development of a dense network of ice wedges in an extraglacial area (Fig. 5). The exceptionally dense occurrence of ice wedges reflects the lithology of the near-surface layer (Dzierżek, Stańczuk, 2006; Dzierżek, 2009), though primarily the harsh climate at that time (cf. Marks *et al.*, 2019). Currently, similar densely-arranged features are noted in northern Finland and the Canadian Arctic (Maizels, 1986). By comparing the climatic conditions in these regions, the formation of the polygonal crack network in eastern Poland seems to have required a mean air temperature of ~–10°C. The harsh climatic conditions in eastern Poland during this period are also indicated by the minimum summer thaw depth recorded at Wierzchuca Nagórna of just 0.7 m (Dzierżek, 2009). Thickness variations of the summer active layer are a sensitive indicator of climate change, as observed in the modern polar environments. For instance, at Bellsund in Spitsbergen, the thickness of the active layer of permafrost increased from 0.8 to 1.2 m in 1986–2013 (Mędrek *et al.*, 2014).

A record of climate change in quartz grains

The glaciofluvial sandy deposits at Korzecko and Miedzianka in the Holy Cross Mountains (Fig. 1) build a distinct morphological terrace on mountain slopes at ~300 m a.s.l. On Miedzianka Mt. they were interpreted as kame terrace deposits of the Sanian 2 Glaciation (Lindner, Dzierżek, 2019). Micromorphological analysis of quartz grains (Cabalski *et al.*, 2021; Dzierżek *et al.*, 2023) reveals that these deposits are dominated by intermediate-matt (EM/RM) and rounded-matt (RM) grains (83–90%). This indicates that they underwent intense aeolian reworking under cold and arid climatic conditions. A similar grain composition is typical for deposits at Korzecko, located on the Korzecko Ridges (Dzierżek *et al.*, 2023). For EM/RM grains, aeolian reworking is noted only on the most convex parts of their surfaces, whereas RM grains show entirely matt surfaces (Fig. 6). A higher content of fractured grains (C), indicative of weathering processes, was also observed. A high degree of aeolian reworking of quartz grains in the samples studied is likely linked to the prolonged periglacial conditions that have repeatedly occurred in this region. No structures typical of chemical weathering were identified in the deposits analysed (Fig. 6).

Loess-palaeosol succession at Wąchock, central Poland

Loess, along with glacial deposits, is among the main types of Pleistocene deposits that, together with palaeosols formed during interglacial periods, constitute the foundation of the Pleistocene climatostratigraphic subdivision (Lindner, 1991; Maruszczak, 2001). In central-eastern Europe, loess is among the most sensitive indicators of a cold climate. Its accumulation occurred in the extraglacial

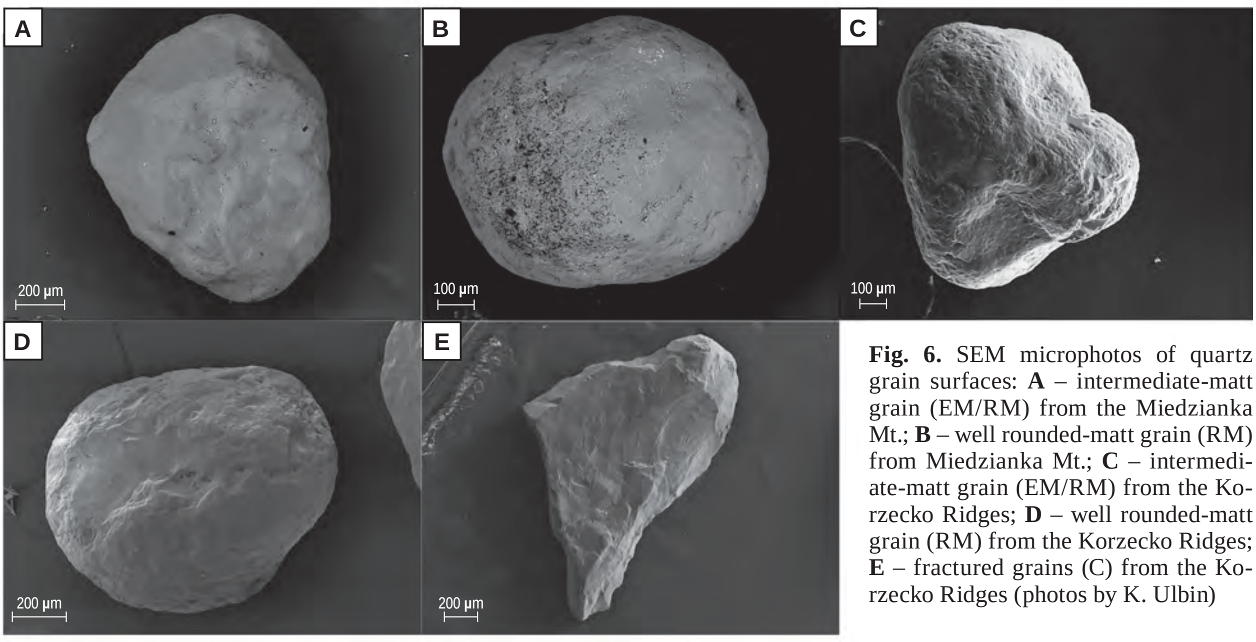

Fig. 6. SEM microphotos of quartz grain surfaces: **A** – intermediate-matt grain (EM/RM) from the Miedzianka Mt.; **B** – well rounded-matt grain (RM) from Miedzianka Mt.; **C** – intermediate-matt grain (EM/RM) from the Korzecko Ridges; **D** – well rounded-matt grain (RM) from the Korzecko Ridges; **E** – fractured grains (C) from the Korzecko Ridges (photos by K. Ulbin)

area of each Scandinavian ice sheet. Analysis of loess sections, in which loess layers and palaeosols occur in superposition, allows for a reconstruction of the continuous rhythm of climatic changes over the past 900,000 years (Lindner *et al.*, 2002, 2004). In Poland, the so-called younger loess of the Vistulian Glaciation is the most widespread (Jary, 2007; Dzierżek *et al.*, 2020).

In the Wąchock section, northern part of the Holy Cross Mountains (Fig. 1), the younger loess occurs very close to the maximum extent of the Vistulian ice sheet. This loess records the entire succession of stadial and interstadial climatic changes during the last glaciation (Fig. 7; Dzierżek *et al.*, 2022). Noteworthy is a several centimetre-thick loess layer above the B horizon of the Eemian forest soil, likely representing the Herning cooling noted in Western Europe (MIS 5d; cf. Dzierżek *et al.*, 2020). Above this loess layer, a succession of two interstadial soils (Brørup and Odderade) is separated by the lowermost younger loess (LMn). The subsequent layer, the lower younger loess (LMd), may correspond to the Świecie stadial (MIS 4). Above this loess, two younger tundra palaeosols (Orel and Glinde) and a tundra soil succession (Moershoofd, Hengelo and Denekamp) are separated by the middle younger loess (LMs). This part of the section corresponds probably to the Grudziądz Interstadial formation in the Lower Vistula Valley (Makowska, 1986), attributed to MIS 3. The upper younger loess, with a preserved ice wedge pseudomorph, can be correlated with the initial and maximum phases of the main Vistulian stadial, attributed to MIS 2, during which the ice sheet reached its maximum in Poland (Marks *et al.*, 2016).

Climate modelling of the mountainous relief in the Carpathians

In mountainous areas, Quaternary climate changes are reflected by a specific record, expressed by spectacular glacial landforms and slope deposits. In the Tatra Mts. a distribution of end moraines, glacially polished surfaces and striations, combined with cosmogenic isotope ^{36}Cl dating, allowed identification of three stadials (Sucha Woda, Bystra and Białka) during the last glaciation (Fig. 1; e.g., Lindner *et al.*, 1990; Lindner, 1994; Dzierżek, 2009; Makos, Nitychoruk, 2011; Makos *et al.*, 2014; Zasadni, Kłapyta, 2014). Glacier retreat, corresponding with a general trend of climatic change, was also recorded in lake deposits of the Czarny Staw Gąsienicowy Lake (Baumgart-Kotarba, Kotarba, 1993, 2001). Residual cirque glaciers persisted in the Late Glacial and the Early Holocene (Makos *et al.*, 2013; Makos, 2015).

The rate of slope processes, especially in a periglacial zone, was strongly dependent on climate change that promoted intense physical weathering of the rock walls and production of debris, subsequently transported downslope. Freeze-thaw cycles played a significant role in rock disintegration (French, 2007). The availability of water from precipitation, or melting of snow and ground ice, acted as a triggering factor for mass movements. In the Polish Carpathians, 115,000 landslides have been identified, associated with both older and contemporary landslide activity, primarily triggered by catastrophic rainfall events (Rączkowski, Mrozek, 2002; Gorczyca, 2004).

Climate changes during the Late Glacial and the Holocene in the Carpathians are also recorded in peat bogs of landslide depressions, indicated by intercalations of slopewash mineral material in sections with organic deposits (Gil *et al.*, 1974; Starkel, 1990, 1995; Baumgart-Kotarba, Kotarba, 1993, 1996; Margielewski, 2006, 2014). The most recent intense slopewash and related processes occurred during the Little Ice Age (Margielewski, 2006; Margielewski *et al.*, 2022).

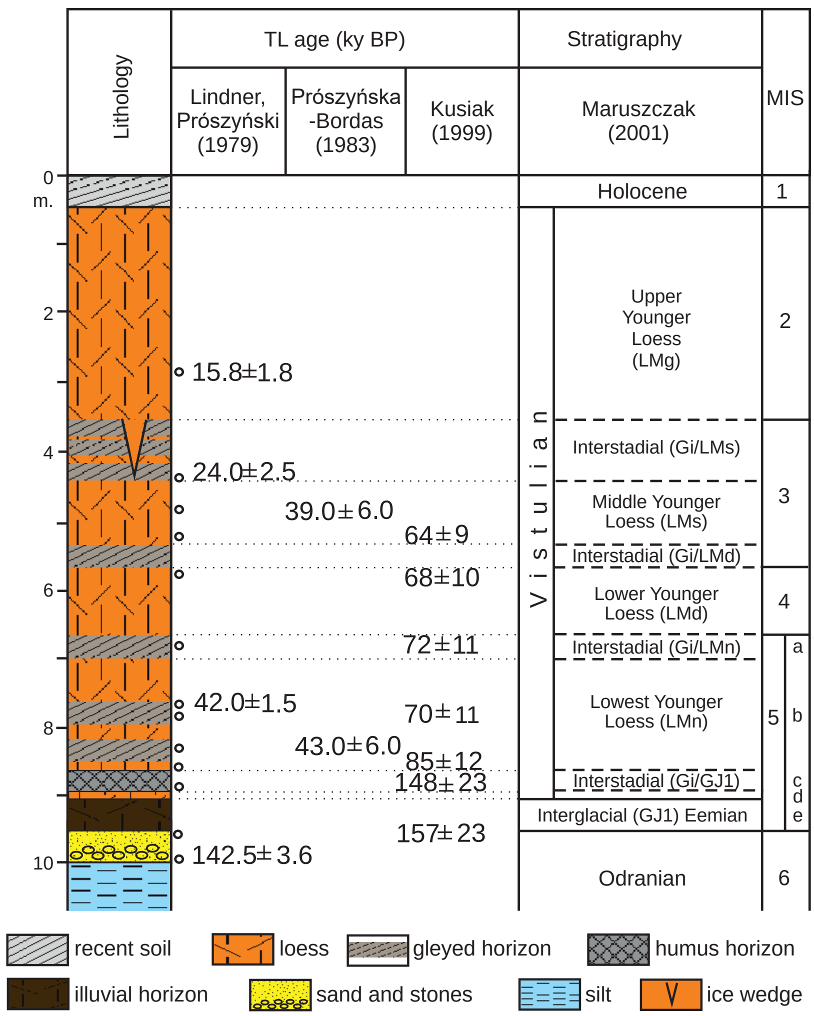

Fig. 7. Stratigraphy of the younger loess succession at Wąchock (Dzierżek *et al.*, 2020, modified); **MIS** – Marine Isotope Stages

DISCUSSION

The sites described are a small part of detailed, site- or region-specific palaeoenvironmental studies, that illustrate how climate changed in Poland during the Quaternary. The application of particular research methodologies is dependent on the lithology of the deposits studied, the research objectives, and the accuracy of palaeoenvironmental reconstruction required. Due to the variety of the deposits examined, it is impossible to use a single tool for all carriers of palaeocli-

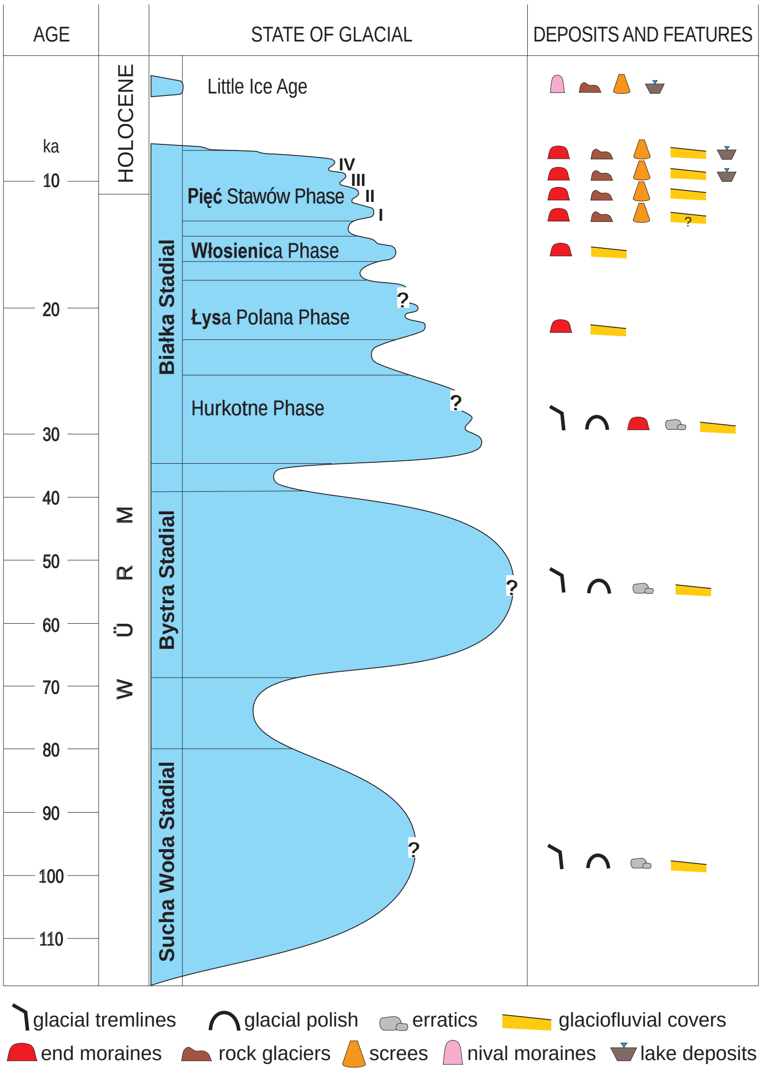

Fig. 8. A record of climate change during the last Pleistocene glaciation in the Tatra Mts. (after Lindner *et al.*, 2003; Dzierżek, 2009)

matic information. This, in turn, creates challenges in comparing the results obtained. However, this unique informational patchwork contributes to an increasingly comprehensive understanding of past climate.

Reconstruction of climate changes in micro- and macro-scale

Microscale climate variations are most effectively reflected in the chemical and palaeontological records of lake deposits. Such records, as at Ossówka, allow climate changes to be identified with high precision, down to an annual or even seasonal resolution in the case of varved deposits (e.g., Goslar, 1995).

In the palaeolake deposits of Ossówka, the climatic changes reconstructed span the entire Holsteinian Interglacial (MIS 11), along with the initial phase of the subsequent cooling period (Nitychoruk *et al.*, 2005). Moreover, two brief cooling events within the interglacial, the OHO and YHO, were identified (Bińka, Marks, 2018; Nitychoruk *et al.*, 2018), demonstrating the instability of Holsteinian climate and suggesting parallels with the current interglacial, the Holocene (Koutsodendris *et al.*, 2012). Isotopic and geochemical analyses further corroborate these findings, including estimates of temperatures during specific sediment accumulation phases.

Cold climatic conditions can be deduced from analysis of quartz grain surfaces. Size, shape and microstructures reflect transport and erosion intensity that are strongly dependent on climatic conditions. These studies inform our understanding of the cyclicity of climate changes and their impact on the landscape.

Preliminary interpretations of cement microstructures at Reńsko suggest that variations in their morphology and composition may reflect climatic and, indirectly, humidity changes within the sediment. However, reconstructing the impact of climate on cementation processes is significantly more challenging compared to other palaeoclimatic reconstructions.

In macroforms (e.g., terminal moraines and loess–palaeosol successions), climate changes are somewhat easier but are less precisely reconstructed. For example, while the DEM (Digital Elevation Model) of the Dobrzyń Lakeland shows traces of short-term ice sheet oscillations, their rank (annual or multi-annual?) is uncertain. Despite the well-preserved morphology of landforms from the last glaciation, both in mountainous and continental regions, the resolution of macro-scale reconstructions is inherently lower than that of micro-scale records. However, detailed terrain analyses allow for identification of ice sheet activity through small-scale oscillations, which provide clear evidence of climatic instability during ice sheet and mountain glacier retreat phases. Harsh climatic conditions are also recorded in macrostructures formed under periglacial climates. Their preservation state, size and density, and the thickness of the active layer in surficial sediments have been used to estimate palaeotemperatures (Dzierżek, 2009) and to identify regional climatic differences on the forefield of the last glaciation (Marks *et al.*, 2019).

The observations provided highlight only a limited interpretative potential of geological records at both micro- and macro-scales in reconstructing Quaternary climate change.

Rate of climatic changes in geological and geomorphological records

The dynamics of individual ice lobes depends on several factors, including the migration of the glaciation centre, topography, tectonics and the presence/absence of permafrost. Under stable environmental conditions (Weckwerth *et al.*, 2019), climate is the primary factor that controls ice sheet advance and retreat. This topic is particularly prominent in the current discussions of the modern warming.

In the Dobrzyń Lakeland, the Weichselian ice sheet margin retreated a distance of ~62 km in 1.3 ka, from the maximum extent of the Poznań Phase south of Płock to the Kujawy-Dobrzyń (Chodzież) subphase moraines. Assuming a uniform process, the average retreat rate can be estimated at about 47 m/year. The retreat of the last ice sheet from the Dobrzyń Lakeland was relatively rapid and irregular, involving at least one oscillation (Fig. 9). In contrast, in the Suwałki Lakeland, the cosmogenic ^{36}Cl dating of glacial erratics suggests that the average retreat rate of the last ice sheet was ~9 m/year (Dzierżek, 2009), significantly less than in the Dobrzyń Lakeland and western Poland (~90 m/year according to Wysota, 2002) at the same time. This slower rate likely reflects mostly an increased climatic continentality towards the east. In general, these rates are higher than those calculated for some of the modern glaciers in Spitsbergen (cf. Reder, Zagórski, 2007).

Geological processes generally follow a climate change and consequently, the estimated rate of processes induced by climate change is inherently prone to error from the outset. This was clearly demonstrated in the case of mass movement rates in the vicinity of glaciers in southern Bellsund, Spitsbergen, during a 30-year period (1986–2016). It emerged that due to degradation of permafrost driven by contemporary climate warming, the near-surface layer in tundra becomes significantly drier and it results in less intense solifluction. Some benchmarks on the debris-weathered slopes have not changed their position for 30 years, while others moved at a maximum rate of 0.5 cm/year (Dzierżek *et al.*, 2019). These results are often an order of magnitude smaller than those reported in the literature (e.g., Rączkowska, 2007) and suggest caution when calculating the average rate of geological processes. Solifluction is commonly active in brief periods, dependent on the specific environmental conditions in each area.

When estimating the rate of geological processes, brief periods of intensified processes caused by abrupt climate or anomalous atmospheric events are commonly neglected. A geological record of such processes is usually subtle and difficult to detect. In the Dobrzyń Lakeland, a brief advance of the ice sheet was recorded, expressed by moraines from the S2 stage in the central part of the region. At the current stage of research, this oscillation cannot be precisely correlated with any selected part of the climatic curve (Fig. 9).

A variability of climatic conditions is also evident in the loess sections. At Wąchock, individual beds of the younger

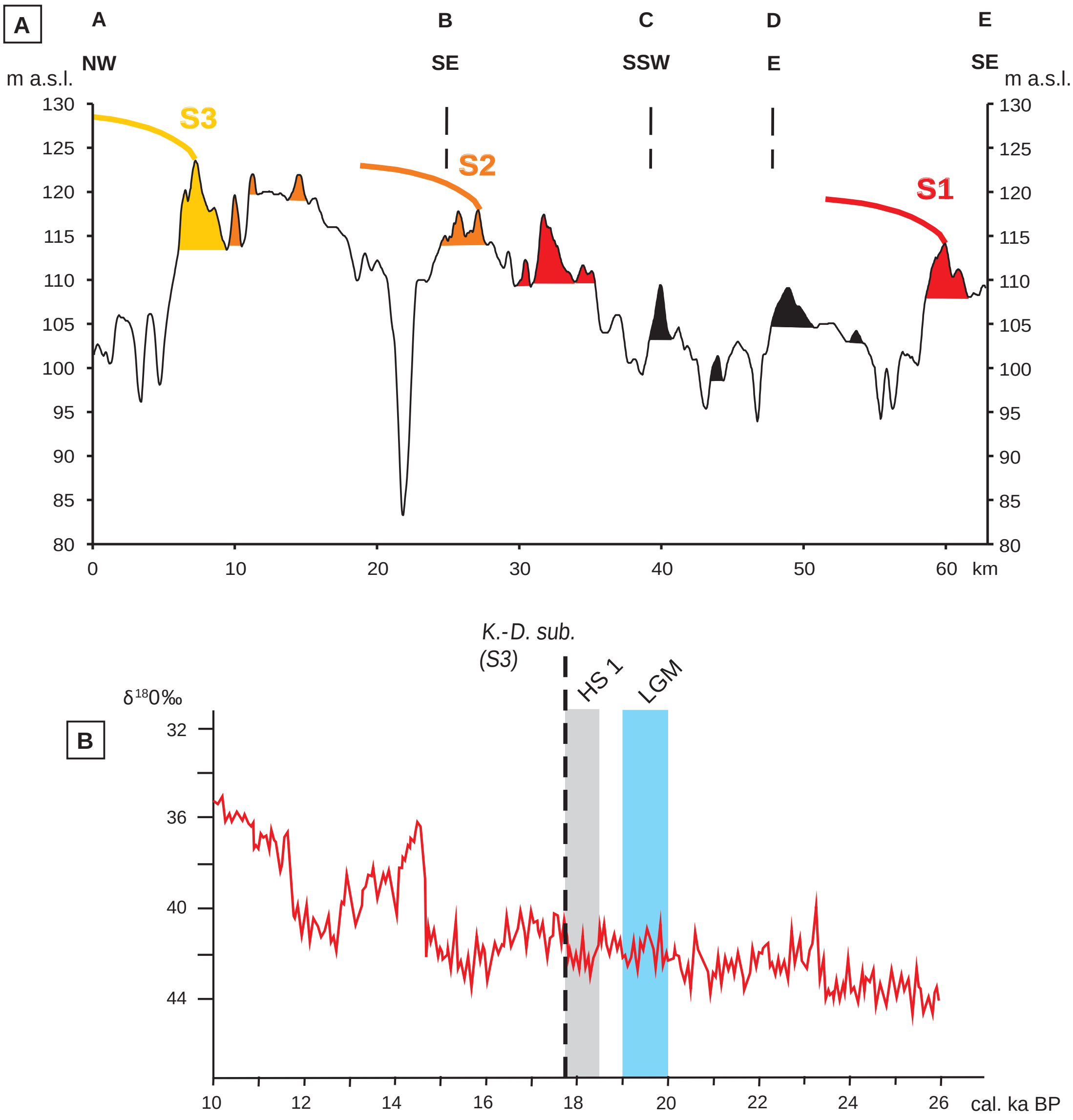

Fig. 9. Stages of deglaciation in the Dobrzyń Lakeland. **A** – morphological profile on the A–E line (location on Fig. 4) showing end moraines formed in successive retreat stages (red – stage S1, orange – stage S2, yellow – stage S3) and intermediate recessional moraines (black); **B** – maximum extent of the Vistula Glaciation (LGM) ice sheet in central Poland; the youngest Heinrich event – HS 1 (after Heinrich, 1988), the Kujawy-Dobrzyń subphase – K.-D. sub. (S3) (after Kozarski, 1995); the NGRIP oxygen curve (after Svensson *et al.*, 2006)

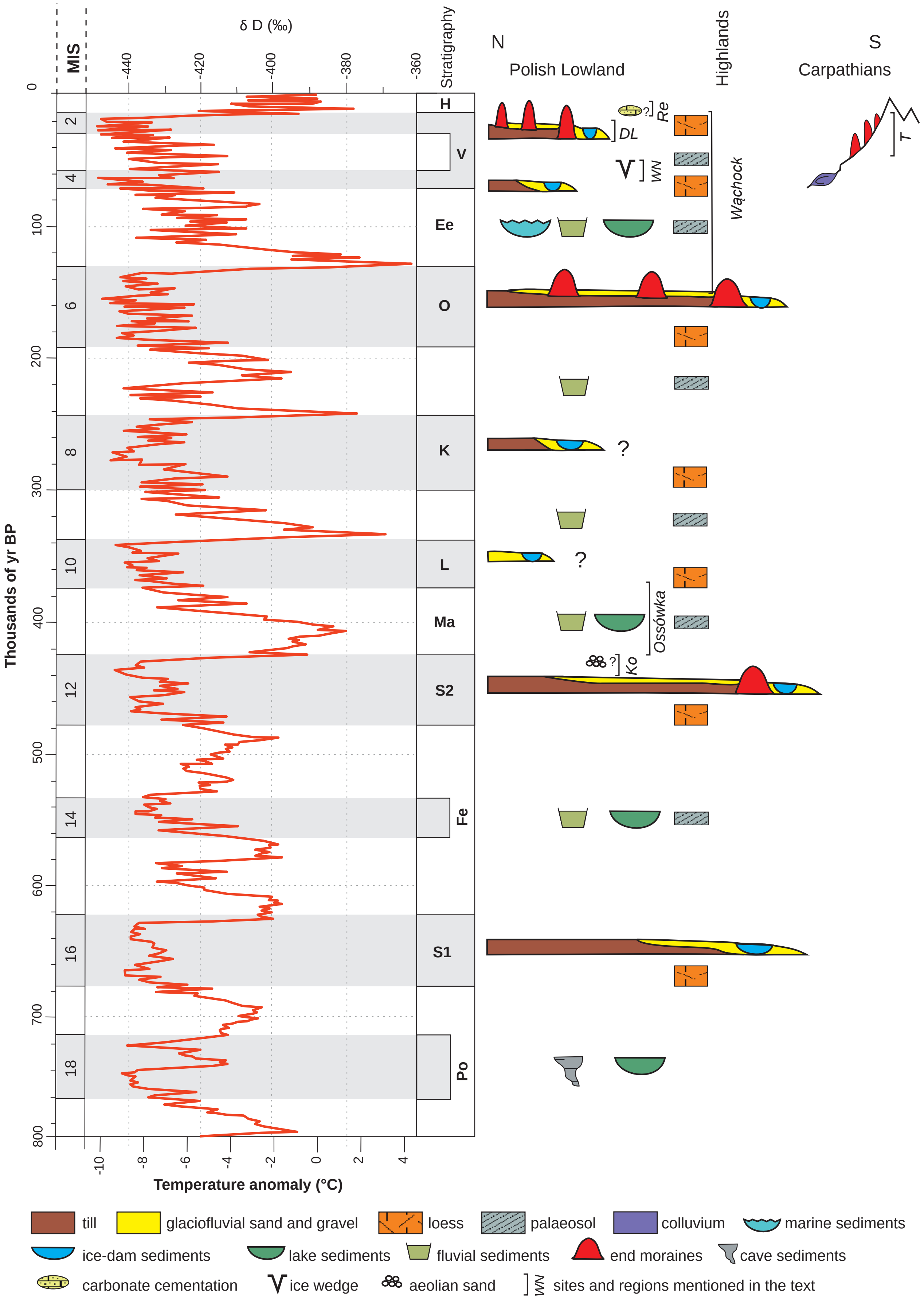

Fig. 10. Climatic changes in the Pleistocene (Palacios *et al.*, 2022) and their geological and geomorphological record in Poland (based on Dzierżek, Lindner, 2024). **Ko** – Korzecko; **DL** – Dobrzyń Lakeland; **WN** – Wierzchuca Nagórna; **Re** – Reńsko; **T** – Tatra Mts.; stratigraphy: **Po** – Podlasian Integlacial; **S1** – Sanian 1 Glaciation; **Fe** – Fedynandovian Interglacial; **S2** – Sanian 2 Glaciation; **Ma** – Mazovian Interglacial; **L** – Liwiecian Glaciation (?); **K** – Krznanian Glaciation (?); **O** – Odranian Glaciation; **Ee** – Eemian Interglacial; **V** – Vistulian (Weichselian) Glaciation.

loess correspond well to global climatic changes in the Late Pleistocene. A climatostratigraphic correlation based on loess-palaeosol successions and glacial tills (Dzierżek, Lindner, 2024), complemented with data from studies of interglacial lake deposits, provide a consistent picture of climate change in the Pleistocene of Poland (Fig. 10).

Cyclicity of climate change in the Quaternary

Cyclicity is the predominant characteristic feature of climate change in the Quaternary. The developmental pattern of the glaciations was similar, regardless of the regional extents of the ice sheets (cf. Wieczorek *et al.*, 2021): the maximum phase of ice sheet development is indicated by the terminal (or end) moraine, accompanied by the accumulation of outwash plains in the forefield, and followed during deglaciation involving stagnation areas (Fig. 10). The ice sheet retreat was interrupted by periodic, irregular pauses or advances, recorded by successive terminal or end moraines, documented both in areas occupied by the Scandinavian ice sheet and the mountain glaciers. Each glaciation is recorded by a till bed. Ice sheet advances were accompanied or preceded by loess accumulation in the extraglacial area (Dzierżek, Lindner, 2024). Under periglacial conditions, the forefield of an ice sheet was subject to intensive physical weathering processes and aeolian activity, accompanied by the development of periglacial structures, common in areas with permafrost as documented at Wierzchuca Nagórna and Wąchock.

Interglacial periods are recorded in geological documentation through buried lake, fluvial and more rarely, marine deposits (Fig. 10). The example from Ossówka demonstrates that the climate varied during interglacials (Nitychoruk *et al.*, 2018). This is corroborated by temperature changes recorded in deep-sea cores (Lisiecki, Raymo, 2005). During the Pleistocene, soils developed on the loess substrate, reflecting changes in climatic and environmental conditions. A record of fluctuating climatic conditions during interglacials is less frequently reconstructed from cave deposits (Głazek *et al.*, 1977; Krajcarz, 2023). A relationship between the geological and geomorphological record and climatic changes during the Pleistocene, is shown (Fig. 10).

CONCLUSIONS

A correlation of global, regional and local research results is crucial for interpretation of climate changes in Earth's history. The climatic events in the past were usually time-transgressive, even between adjacent regions, especially if reflected in a terrestrial record. Knowing the principles and mechanisms of climate processes in the past is an essential procedure to understand the driving forces of the current climate system and to propose future scenarios.

A detailed continuous record of climatic changes from deep-sea cores (Lisiecki, Raymo, 2005) and its correlation with the incomplete and varied terrestrial record in different sedimentary environments and at different scales is not comprehensive. However, it highlights many features typical of Quaternary climate, particularly its cyclicity expressed through glacial-interglacial megacycles that comprise short-term, smaller-scale and regular changes.

At the current stage of research, a correlation of the minor climatic changes reconstructed from deep-sea deposits to specific terrestrial records (landform features, segments of palynological diagrams, periods of ice sheet activity) is limited and may pertain to brief intervals. This remains a challenge for future Quaternary researchers.

The examples and interpretations described demonstrate climate changes recorded in the Quaternary deposits and landforms, and show that both past climate changes and environmental transformations form the foundations of this scientific inquiry.

Based on various increasingly well-developed research methods, these changes can be observed and interpreted, but resolution of the climatic signals recognized in geological, geomorphological, and palaeobotanical records depends on the carrier of a signal and the method selected.

The rate of retreat of the Vistulian ice sheet in northern Poland, driven by global climate changes, varied, and was faster in the west than in the east. It was linked to local climatic conditions and perhaps also to geological factors.

The examples provided from both cold and warm Quaternary periods clearly show that climate changes are common and natural phenomena.

Climate changes in the Quaternary were characterized by high frequency, varying intensity, and regular cyclicity and this applies both to glacial and interglacial periods.

Climate instability during cold phases of the Pleistocene is more evident, as expressed for instance by the terminal moraine systems in the Polish Lowland and in the mountains. In warmer periods, climate instability can be mainly detected in micro-records.

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