*Acta Geologica Polonica*, Vol. 73 (2023), No. 3, pp. 289–306
DOI: 10.24425/agp.2023.145618

# Evolution of Professor Leszek Lindner's ideas on the Quaternary stratigraphy of Poland

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ABSTRACT:

Dzierżek, J. and Kulus, B. 2023. Evolution of Professor Leszek Lindner's ideas on the Quaternary stratigraphy of Poland. *Acta Geologica Polonica*, **73** (3), 289–306. Warszawa.

This contribution characterises the stratigraphic schemes of the Quaternary as constructed and published by Leszek Lindner in 1967–2019. The oldest schemes assume the subdivision of the Pleistocene into three glaciations (i.e., Cracow, Middle-Polish and Baltic) separated by two interglacials (Great and Eemian). The scheme published in 1992 comprises eight glacial and seven interglacial units. The most recent scheme for the Quaternary contains seven advances of the Scandinavian ice-sheet on the area of Poland during the Nidanian (MIS 22), Sanian 1 (MIS 16), Sanian 2 (MIS 12), Liviecian (MIS 10), Krznanian (MIS 8), Odranian (MIS 6), and Vistulian (MIS 2–5d) glaciations. They are separated by six interglacials: Podlasian, Ferdynandovian, Mazovian, Zbójnian, Lublinian and Eemian. The ranges of glacial transgressions, and key interglacial and preglacial sites are assembled in a cumulative scheme for the area of Poland. We review the main study methods on which the subsequent versions of the stratigraphic scheme were based. These include Prof. Lindner's own detailed field research in glaciated and extraglacial areas, and paleofloristic, paleontological and paleomagnetic studies of major interglacial sites carried out by numerous researchers, as well as thorough literature studies.

**Key words:** East-Central Europe; Pleistocene; Glaciations and interglacials; Climatostratigraphy; Quaternary deposits.

## INTRODUCTION

One of the key scopes in geology is establishing the age, mutual relationship and origin of rock units. In Quaternary geology this task is complicated due to the large lithological and genetical variability of terrestrial deposits, and the high resolution of the geological record. Analysis of sedimentary successions with the application of various research methods allows the reconstruction of climate cycles spanning the entire Quaternary. Such an approach to the subdivision of the youngest period in Earth's history is known as climatostratigraphy a term popularized in Polish literature by Stefan Zbigniew Różycki (1964) and later formalized by Marks *et al*. (2014). An important example of Quaternary climatostratigraphy is the subdivision of deep-sea core samples into 103 oxygen isotope stages (Shackleton and Opdyke 1973).

We characterise the evolution of Prof. Lindner's ideas on Quaternary stratigraphy and the causes of changes in the climatostratigraphic schemes. Possible directions of further studies on refining climate change in the Quaternary are indicated.

The Quaternary climatostratigraphy in Poland and neighbouring areas has been the most important focus of Leszek Lindner's research activities since the 1960s. During the many years of his employment at the University of Warsaw, he described numerous sequences of Quaternary sediments from exposures and boreholes from various parts of Poland, Ukraine, Belarus and Spitsbergen. The key points of his scientific carrier, i.e., doctorate and habilitation, were largely focused on the stratigraphy (lithostratigraphy) of Quaternary sediments. Detailed climatostratigraphic schemes for the studied sites and regions, supplemented with systematically published results obtained with the application of up-to-date research methods, were used to construct new stratigraphic schemes for Poland and their correlation with the neighbouring countries. On one hand, this resulted in frequently changing ideas on the exact number and extents of the Pleistocene ice-sheets, and on the other hand – developed Prof. Lindner's very strong position in the scientific community as an expert in the Quaternary stratigraphy.

This contribution is aimed at presenting the milestones leading to the current state of knowledge on the Quaternary stratigraphy in Poland. We will also make an attempt to analyse the causes and circumstances which resulted in these changing concepts. This paper is based largely on literature studies, mainly from the rich achievements of Prof. Lindner as evidenced by the expanded reference list.

## GEOLOGICAL SETTING

Leszek Lindner's study area was vast and diverse in terms of relief and origin and development of Pleistocene sediments. Subsequent versions of the elaborated stratigraphic scheme in this analysis were based on key sites/regions from lowland and highland areas with loess cover, and from middle mountains, located within the range of different ice sheets (Text-fig. 1). Among the key sites are those he has personally examined as well as those elaborated by other teams of researchers.

Leszek Lindner's first stratigraphic and palaeogeographic investigation was focused on the Pilica and Uniejówka valleys in the Miechów Upland, southern Poland (Lindner 1967). The Holy Cross Mountains area, particularly their Mesozoic Margin have always been extremely important in his investigation. In this area he gained experience and amassed a huge amount of data during the preparation of his doctoral and habilitation theses, and mapping surveys for the Detailed Geological Map of Poland in the scale 1:50,000 (Filonowicz and Lindner 1986; Cieśla and Lindner 1990). Moreover, he described the key interglacial sites in this area, i.e., Kozi Grzbiet (Głazek *et al.* 1976a, b) and Zakrucze near Małogoszcz (Lindner and Rzętkowska-Orowiecka 1998) (Text-fig. 1). Studies on loess in the Holy Cross Mountains and Małopolska regions were crucial for Quaternary stratigraphy (Chlebowski and Lindner 1975; Lindner 1976). Of large significance was the application on an ongoing basis of data on the sites from other parts of Poland, e.g., Suwałki region, Lower Vistula Valley, sub-Carpathian area, Podlasie, Sandomierz Basin, but also Belarus and Ukraine, successively documented by his students and associates.

Significant achievements in the fields of the stratigraphy and glacial history of the high mountain areas (Lindner 1994; Lindner *et al.* 2003) are out of the scope of this contribution and are not presented here.

## MATERIAL AND METHODS (A REVIEW)

In the initial stages of his research, Leszek Lindner relied on his own field data – detailed analyses of exposures and well-carried out cartographic studies. These were supplemented with analyses of archival cartographic data and drilling logs. As a result, 'local' stratigraphic schemes, based largely on lithostratigraphy, and connected with palaeogeography were correlated with existing regional and Polish stratigraphic schemes. Such an approach was fundamental in his activities; it became the standard of the so called "Warsaw School of Quaternary Studies", initiated by Prof. Stefan Zbigniew Różycki (Różycki 1961, 1967), and was developed by Prof. Lindner and his associates.

Progress in the recognition of Quaternary stratigraphy would not have been possible without fixing the results of the geological-geomorphological studies in correlation benchmarks, such as sites with a precise documentation on: mineralogy, petrography, palynology, malacology, diatomology geochemistry, palaeopedology, palaeomagnetism, dating, and others. Prof. Lindner diligently cooperated with specialists in particular research branches of the Quaternary, which resulted in reports on key sites for the Quaternary stratigraphy and palaeogeography of Poland. Petrographic studies of glacial tills were used to determine local directions of glacial ice movement in the Holy Cross Mountains, and to some degree also in age analyses (e.g., Lindner and Ruszczyńska-Szenajch 1977; Pożaryski *et al.* 2002; Dzierżek *et al.* 2021). Mineralogical investigations were commonly used to make conclusions on the sedimentary environment (Chlebowski and Lindner 1975, 1976, 1986; Dzierżek *et al.* 2022). Physical-chemical studies of palaeosols were the basis on which to subdivide loess successions (Lindner 1967, 1976), and were used in palaeogeographic reconstructions and the stratigraphy of extraglacial areas.

Several key interglacial sites, e.g., Kozi Grzbiet (Głazek *et al.* 1976b, 1977), Zakrucze (Lindner and


Text-fig. 1. Location of selected research sites with regard to the main ice-sheet ranges. 1 – ice-sheet extent during the: Sanian 1 (S1), Sanian 2 (S2), Odranian (O), and Vistulian (V) glaciations; 2 – sites with preglacial deposits: WL – Wólka Ligęzowska, Ro – Rożce; 3 – interglacial sites: Podlasian (Ło – Łowisko, KG – Kozi Grzbiet, Do – Domuraty, Ka – Kalejty); Ferdynandovian (Bu – Bukowina, Po – Podgórze, Fa – Falęcice, Fe – Ferdynandów); Mazovian (Ad – Adamówka, Za – Zakrucze, Se – Sewerynów, Ja – Jamno); Zbójnian (Zb – Zbójno); Lublinian (Gr – Grabówka, Lo – Losy); Eemian (Sł – Sławno); 4 – sites with marine interglacial deposits: Holsteinian (Mazovian) (D – Domnovo), Eemian (Ty – Tychnowy); 5 – loess sites: Si – Siedliska, KZ – Kolonia Zadębce; 6 – site with submoraine palaeosol: Cz – Czernica.

Rzętkowska-Orowiecka 1998), and Zbójno (Lindner and Brykczyńska 1980) were elaborated in cooperation with palaeobotanists and palaeozoologists.

Dating using TL, OSL and C-14 methods – assumingly the main tools in determining the age of sediments and constructing chrono-stratigraphic schemes – were often, but not unhesitatingly, used by Prof. Lindner, particularly with regard to age determinations of glacial tills (Lindner *et al.* 1987; Fedorowicz *et al.* 1995). In turn, modern TL and OSL techniques were successfully applied in determining the absolute ages of loess successions (Lindner *et al.* 1999; Dzierżek and Lindner 2020; Dzierżek *et al.* 2020).

Palaeomagnetic analysis was used for identification of the of the very important Brunhes/Matuyama boundary position in the Kozi Grzbiet site, thus to date the Lower Pleistocene sediments (Głazek *et al.* 1977).

In the 1970s there appeared in Poland and Ukraine studies of long, continuous sequences of loess with fossil soils, covering several glaciations and interglaciations, being a record of paleoclimatic cycles and thus the succession of climatostratigraphic units (see Vieklich and Sirienko 1976; Pécsi 1986). They have become an aid in the chronological ordering of data from profiles representing short time segments. Changes in the ratio of oxygen isotopes in the shells of foraminifers preserved in deep-sea sediments allowed the distinguishing of the Marine Isotope Stages (Shackleton and Opdyke 1973). This soon become the basis for common correlations in climatostratigraphic studies.

## CHRONOLOGICAL REVIEW OF LESZEK LINDNER'S STRATIGRAPHIC SCHEMES OF THE QUATERNARY

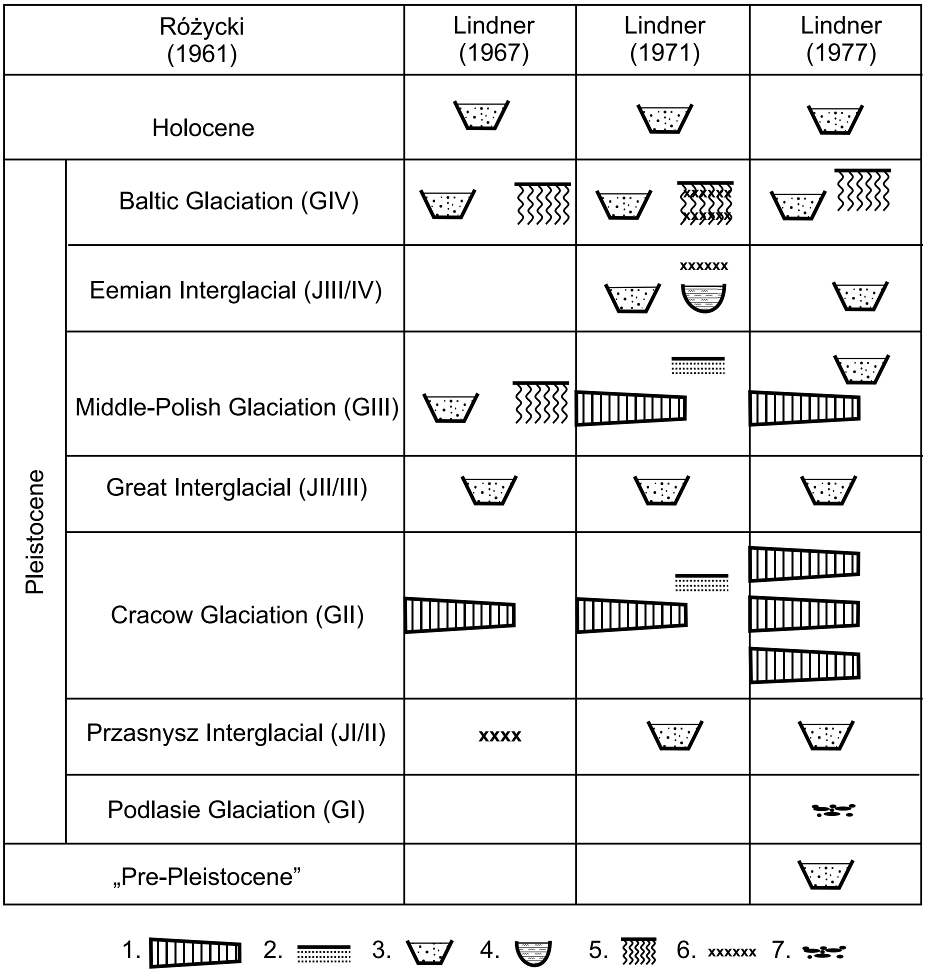
The first original recognition of Quaternary stratigraphy by Leszek Lindner was related to the upper Pilica and Uniejówka valleys in the northern part of the Miechów Upland (Lindner 1967). From that area he documented the fragmentarily preserved glacial deposits of the Cracow Glaciation (Mindel) and younger glaciofluvial series of the Middle-Polish Glaciation (Riss), adapting their stratigraphic position to the commonly used scheme of Różycki (1961) (Text-fig. 2). For the first time he had the opportunity to study loesses of the Baltic Glaciation (Würm).

His PhD thesis was on studying sediments occurring above the sandy-gravel series of the Great Interglacial the north-western Mesozoic Margin of the Holy Cross Mountains (Lindner 1971). Glacial tills recognised in the area were assigned to the Radomka glacistadial, with three phases of ice-sheet development: Końskie, Gowarczów, and Wieniawa. The first two phases were recorded as separate, widely distributed glacial till horizons – as far as to the catchment of the lower Wieprz and Krzna, where they were considered as evidence of the premaximal Krzna Stadial (Rühle 1970). Equally important was the detailed description of the gyttja and peat at the Bedlno site, assigned to the Eemian Interglacial (Środoń and Gołąbowa 1956). The youngest deposits, comprising mainly loesses with poorly developed palaeosols occurring near Przysucha, were assigned to the preglacial part of the Baltic Glaciation (Text-fig. 2), while the uppermost loess was attributed to the maximal phase of the Last Glaciation (Lindner 1971). Summing up, Leszek Lindner's doctoral thesis, particularly the amassed geological data and later elaborations of interglacial flora from Zbójno (Lindner and Brykczyńska 1980), became the foundation of the subdivision of the Middle-Polish Glaciation into three separate glacials.

In his habilitation thesis, Lindner (1977) focused on the western part of the Holy Cross Mountains, where rich borehole material allowed him to refine the Quaternary stratigraphy. He discovered palaeoriver traces in the Lower Pleistocene, as well as products of physical weathering during the Podlasie Glaciation in the far ice-sheet foreland. He distinguished three horizons of glacial tills assigned to three stadials of the Cracow Glaciation (Text-fig. 2). This fact, coupled with the discovery of sites with interglacial flora in Kozi Grzbiet (Głazek *et al.* 1976b, 1977), allowed for the later subdivision of the South-Polish Glaciation into three separate glaciations: Nida, San 1 and San 2 (Lindner 1988a, b, 1992). In the western part of the area he distinguished glacial till and sands, gravel and muds from the maximal (Gowarczów-Łopuszno) and postmaximal phases of the Middle-Polish Glaciation. The Eemian Interglacial and the Baltic Glaciation were represented there by fluvial sediments. The loess horizon occurring in patches on the surface was correlated with the Baltic Glaciation (Lindner 1977).

The results of detailed studies in the Holy Cross Mountains were summarised in a climatostratigraphic scheme for the region (Lindner 1980). Data derived from field studies were supplemented with palaeontological documentation of interglacial sites (Środoń and Gołąbowa 1956; Jurkiewiczowa and Mamakowa 1960; Makowska 1976), including comprehensive analysis of the Kozi Grzbiet site (Głazek *et al.* 1976b; 1977).

A cooling, the 'Otwock Glaciation', followed by a warming, the 'Celestynów Interglacial' were distinguished within the Lower Pleistocene (Różycki 1980). The Lower Pleistocene sediments did not contain Scandinavian material. Younger colluvial and slopewash deposits were supposed to record the oldest Pleistocene processes in the extraglacial zone of the Narew ice-sheet. Of large significance was the recognition of a sand series (in some cases in several sedimentary cycles) and gyttja in the Ceteń site (Makowska 1976; Borówko-Dłużakowa 1977) as traces of the Podlasie Interglacial. Following high-resolution investigations in Kozi Grzbiet (Głazek *et al.* 1976b), the oldest glacial till recognised earlier in the Holy Cross Mountains was assigned to the Nida




Text-fig. 2. Correlation of lithostratigraphic horizons for the areas studied by Leszek Lindner in the 1960s and 1970s in reference to the stratigraphic scheme by Różycki (1961). 1 – glacial tills; 2 – glaciofluvial sediments; 3 – fluvial sediments; 4 – lake sediments; 5 – loess; 6 – palaeosol; 7 – erosional lag.

Glaciation, and the two younger glacial tills – as correlatives of two stadials within the San Glaciation. Fauna from Kozi Grzbiet, comprising fragments of mammals, amphibians, reptiles and land snails, indicated the interglacial character of the sediments, referred to the Małopolska Interglacial and correlated with Cromerian II. The variable content of collagen in the bone remains suggests a double climate optimum of this interglacial (Głazek *et al.* 1976b). The Brunhes/Matuyama palaeomagnetic boundary preserved in the older optimum (Głazek *et al.* 1977), presently dated at 780 ky, allowed for a precise age assignment of the sediments from this site.

Floral analysis of the Sewerynów (Jurkiewiczowa and Mamakowa 1960) and Podgórze (Jurkiewiczowa *et al.* 1973) sites, coupled with age determinations of fluvial sands in Wąchock (Lindner and Prószyński 1979) document the Great (Mazovian) Interglacial in the Holy Cross Mountains. The geological and palynological record of this interglacial suggest the heterogeneity of lake and fluvial conditions prevailing at that time. The subsequent Odra Glaciation is represented by several horizons of glacial tills from the pre-maximal (Krzna) and maximal (Radomka) stadials preserved only in the N and NW part of the Holy Cross Mountains area.

The Lublin Interglacial was documented by a TL dated (245±45 ka) sandy series in Wąchock and a 'Tomaszów-type' palaeosol (Jersak 1973). Therefore, the glacial till so far supposed to represent the post-maximal stadial of the Middle Polish Glaciation was assigned to a separate Warta Glaciation. Significantly, each of the mentioned glacial tills in the western part of the Holy Cross Mountains is underlain by loams with loess malacofauna (Poliński 1927; Czarnocki 1931) or the so-called submoraine loess from Kolonia Zadębce near Hrubieszów (Dolecki 1993).

The best documentation of the Eemian Interglacial in the area is based on the earlier studied sites in Bedlno (Środoń and Gołąbowa 1956) and Sławno (Tołpa 1961). The warming is also recorded as a palaeosol in the loess successions of southern Poland (Jersak 1973; Konecka-Betley and Straszewska 1977; Maruszczak 1986).

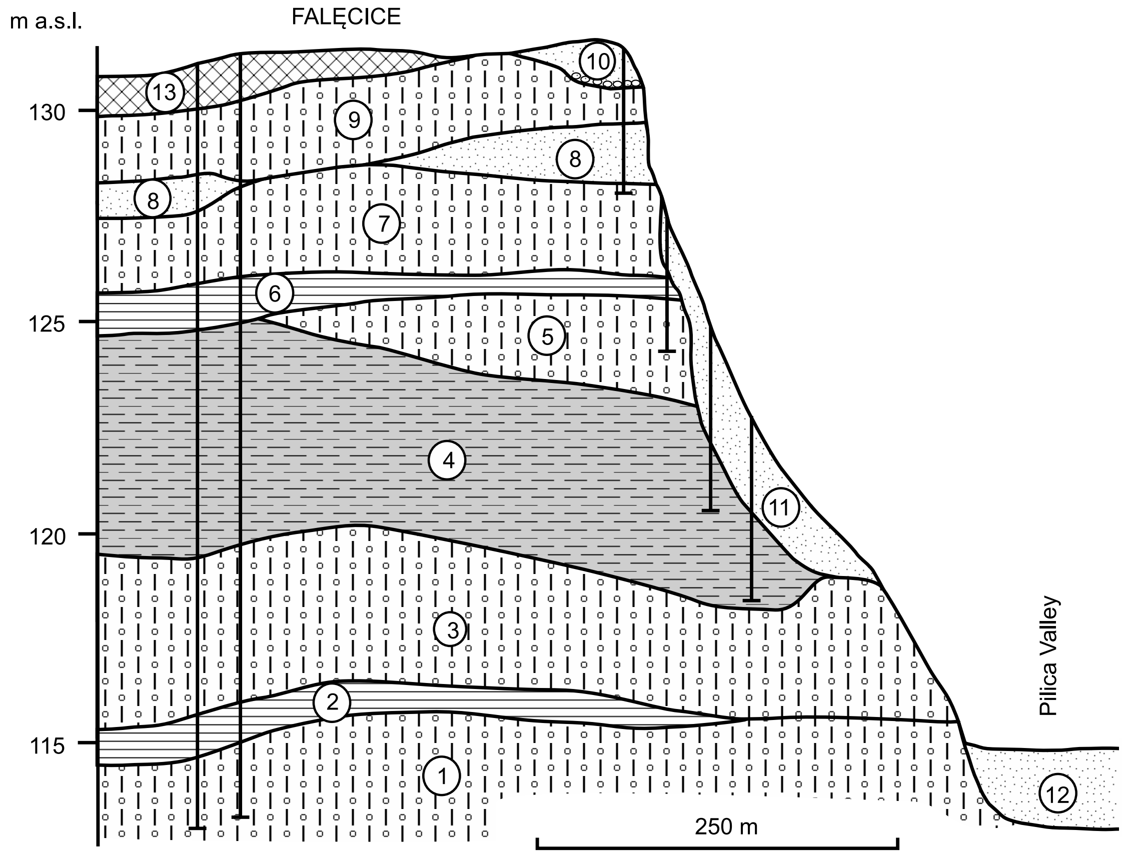
The North-Polish (Wisła, Vistulian) Glaciation was best documented by four loess horizons in the Opatów Upland and in Wąchock (Jersak 1973; Lindner and Prószyński 1979).

The modified scheme for the Quaternary was published in an academic text-book (Lindner 1992) and due to the educational aspect is of particular significance. Polish climatostratigraphic units were correlated with the Quaternary units of Europe and the rest of the world.

The Pre-Pleistocene – the non-glaciated part of the lower Quaternary, whose beginning at that time was set at c. 1.8 Ma – contains a cooling known as the 'Otwock Glaciation', and a warming known

| | Alps | Lindner (1980) | Lindner (1992) | Lindner *et al.* (2004) | Lindner *et al.* (2013) | Lindner and Dzierżek (2019) | MIS |
|---|---|---|---|---|---|---|---|
| Holocene | | Holocene | Holocene | Holocene | Holocene | Holocene | 1 |
| Pleistocene | Würm | Vistulian | North-Polish (Vistulian) | Vistulian | Vistulian | Vistulian | 2-5d |
| | Riss II/Würm | Eemian | Eemian | Eemian | Eemian | Eemian | 5e |
| | Riss II | Warta | Middle-Polish: Warta | Odranian+Wartanian | Odranian | Odranian | 6 |
| | Riss I/Riss II | Lublin | Middle-Polish: Lubawa | Lubavian | Lublinian | Lublinian | 7 |
| | Riss I | Odra | Middle-Polish: Odra | Krznanian | Krznanian | Krznanian | 8 |
| | Mindel II/Riss II | Great (Mazovian) | Zbójno | Zbójnian | Zbójnian | Zbójnian | 9 |
| | | | Liwiec | Liviecian | Liviecian | Liviecian | 10 |
| | | | Mazowsze | Mazovian | Mazovian | Mazovian | 11 |
| | Mindel II | San | South-Poland: San 2 | Sanian 2 | Sanian 2 | Sanian 2 | 12 |
| | | | South-Poland: Ferdynandów | Ferdynandovian | Ferdynandovian | Ferdynandovian | 13-15 |
| | | | South-Poland: San 1 | Sanian 1 | Sanian 1 | Sanian 1 | 16 |
| | Mindel I/Mindel II | B/M Małopolska | South-Poland: Małopolska B/M | Małopolanian | B/M Domuratovian | B/M | 17-19 |
| | Mindel I | Nida | South-Poland: Nida | Nidanian | Podlasian | Podlasian | 20 ⋮ |
| | Günz/Mindel I | Podlasie | Podlasie | Augustovian | Augustovian | | 21 |
| | Günz | Narew | Narew | Narevian | Nidanian | Nidanian | 22 |
| | Donau/Günz | Protopleistocene: "Celestynów" | Prepleistocene: "Celestynów" | Celestynovian Otwockian Ponurzycian | Preglacial | Preglacial: Krasnystaw serie | 23 ⋮ 103 |
| | Donau | Protopleistocene: "Otwock" | Prepleistocene: "Otwock" | Różzcian | | | |

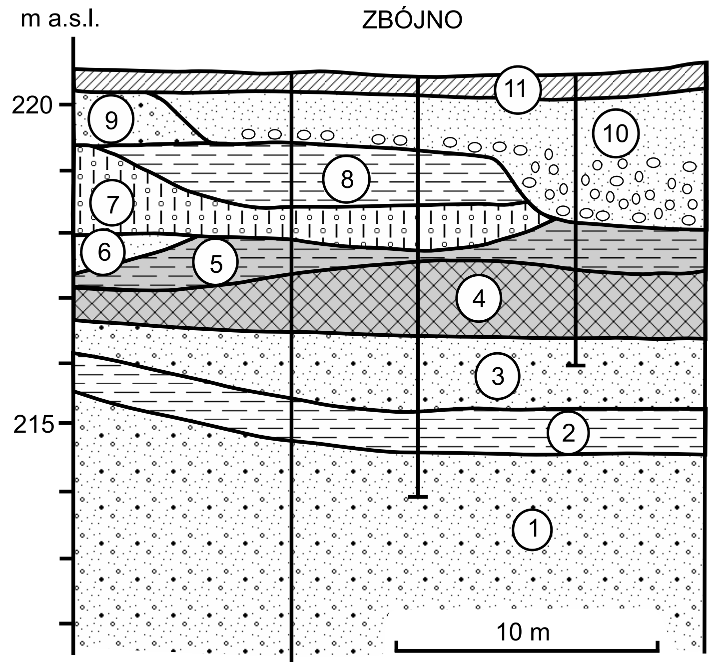
Text-fig. 3. Compilation of Leszek Lindner's Quaternary stratigraphic schemes of Poland from 1980–2019. Glacial units are highlighted in grey; MIS – marine isotope stages; $\frac{B}{M}$ – Brunhes/Matuyama palaeomagnetic boundary.




Text-fig. 4. Geological position of deposits representing the Ferdynandovian Interglacial in Falęcice (after Lindner *et al.* 1991a and unpublished data). Nidanian Glaciation: 1 – glacial till; 2 – ice-dammed lake silt; Sanian 1 Glaciation: 3 – glacial till; Ferdynandovian Interglacial: 4 – lake clay with peat intercalations and shaly clay; Sanian 2 Glaciation: 5 – glacial till; Krznanian (?) Glaciation: 6 – ice-dammed lake silt; 7 – glacial till; Lubavian Interglacial: 8 – fluvial sand and gravel; Odranian Glaciation: 9 – glacial till; 10 – glaciofluvial sand and gravel; Vistulian glaciation: 11 – slopewash deposits; 12 – fluvial sand; Holocene: 13 – anthropogenic material.

as the 'Celestynów Interglacial' (Text-fig. 3). In this scheme, the Pleistocene comprised four main cold units: the oldest glaciation (Narew), the South-Polish Glaciations, the Middle-Polish Glaciations, and the North-Polish (Vistulian) Glaciation. The South-Polish Glaciations (South-Polish Megaglacial) comprises the following glaciations: Nida, San1 and San 2 (Wilga after Mojski 1985). Between the Nida and San1 glaciations occurs the Małopolska (Kozi Grzbiet) Interglacial with well-documented fauna, flora and palaeomagnetic data from the Kozi Grzbiet site (cited above). In turn, between the San 1 and San 2 glaciations occurs the Ferdynandów Interglacial (Janczyk-Kopikowa *et al.* 1981; Lindner 1988b; Lindner *et al*. 1991a; Text-fig. 4).

The Great Interglacial as a mega unit between the South-Polish and Middle-Polish glaciations was narrowed to the Mazowsze Interglacial (*sensu stricto*), documented e.g., by the Adamówka site in the Sandomierz Basin (Bińka *et al.* 1987) and in Podlasie (Krupiński *et al*. 1986). During the Mazowsze Interglacial, global sea-level rise resulted in the formation of a bay of the Holstein Sea, documented in Domnovo (Loginova 1979) close to the northern Polish border (Text-fig. 1). The Middle-Polish Megaglacial was subdivided into three separate glacial units: Liwiec, Odra and Warta glaciations. The Liwiec Glaciation was primarily identified by Różycki (1967) as the older, pre-maximal stadial of the Middle-Polish Glaciation. The lowermost loess (Maruszczak 1986) accumulated at that time in the upland areas of southern Poland. The Zbójno Interglacial (Lindner and Brykczyńska 1980; Text-fig. 5) separated the Liwiec Glaciation from the Odra Glaciation, and the Lubawa Interglacial – the Odra Glaciation from the Warta Glaciation (Text-fig. 3). The Lubawa (Lublin, Rügen) Interglacial, earlier known as the Grabówka Interglacial (Makowska




Text-fig. 5. Geological setting of the Zbójnian Interglacial lake sediments (after Lindner and Brykczyńska 1980, modified). Mazovian Interglacial: 1 – fluvial sand with gravel; Liviecian (?) Glaciation: 2 – ice-dammed lake silt; Zbójnian Interglacial: 3 – fluvial sand with gravel; 4 – peat; 5 – peaty silt; Odranian Glaciation: 6 – glacifluvial sand; 7 – glacial till; 8 – ice-dammed silt; 9 – glacifluvial sand with gravel; Holocene: 10 – sand with gravel and lag deposits in its lowermost part (fluvial); 11 – recent soil.

1977) was documented in Losy near Lubawa (Text-fig. 1). The palynological succession of this interglacial differed from the Eemian record in the succession of the appearance of linden (*Tilia*) and hazel (*Corylus*) (Krupiński and Marks 1986).

Owing to the studies of Makowska (1986), the documentation of the Eemian Interglacial was enriched by information from subsequent sites with marine deposits in the Lower Vistula Valley, and the North-Polish Glaciation is represented by glacial tills corresponding to three stadials: Toruń, Świecie and Main, separated by the Gniew and Grudziądz interstadials (Lindner 1992). Accumulation of five horizons of younger loesses (LM in the nomenclature of Maruszczak 1986), separated by four palaeosol horizons (see Dzierżek and Lindner 2020) took place at that time in central and southern Poland.

The climatostratigraphic scheme for East-Central Europe was revised by a group of international researchers under the leadership of Leszek Lindner (Lindner *et al.* 2004). Subdivision of the Quaternary was based on earlier stratigraphic correlations and extensive studies in sites with glacial deposits, loesses, palaeosols and organogenic sediments. The recognised climatostratigraphic units were correlated with oxygen isotope stages (Gibbard *et al.* 1998) and the palaeomagnetic record. The age of the base of the Quaternary was placed at 2.6 Ma, which was in accordance with contemporary chronostratigraphic concepts. Significant changes in this scheme referred to the lower Quaternary, in which the following units were distinguished: the oldest Różcian cooling, the interglacial-type Ponurzycian warming, the Otwockian cooling, and the Celestynovian warming. The oldest glacial period was named Narevian Glaciation. The succeeding warm period – the Augustovian Interglacial – was subdivided into three smaller warm units separated by cold units. This was a consequence of a new interpretation of sites in NE Poland (Janczyk-Kopikowa 1996), and many sites in Ukraine and Belarus (Gozhik *et al.* 2000). This long interglacial was characterized by a variable climate. Above was placed the Nidanian Glaciation, Małopolanian Interglacial and the Sanian 1 Glaciation. The palynologic documentation of the subsequent interglacial – the Ferdynandovian Interglacial – allowed the distinguishing of units characterised by significant cooling and two warm units (Pidek 2000; Marciniak and Lindner 2003). The interglacial is followed by the Sanian 2 Glaciation, the Mazovian Interglacial, the Liviecian Glaciation, and the Zbójnian Interglacial. Another novel issue of this scheme was the distinguishing of the Krznanian Glaciation, so far understood as a pre-maximal stadial of the Odranian Glaciation (see Lindner and Marks 1999). This glacial interval corresponds to the Dnieper 1 Glaciation in Ukraine; at that time its correlatives in Belarus and Western Europe were not known in the geological record (Lindner *et al.* 2004). Later this unit was correlated with the Saale II Glaciation (Lindner *et al.* 2013). The next unit – the Lubavian Interglacial – besides at the key site in Losy (Krupiński and Marks 1986) was also documented in Belarus (Yelovicheva 2001) and Ukraine (Bogutsky *et al.* 2000). In consequence of earlier changes in the rank of Middle Pleistocene glacial episodes, the Odra and Warta glaciations were combined into one unit known as the Odranian+Wartanian Glaciation. The upper part of the scheme included the Eemian Interglacial, the Vistulian Glaciation, and the Holocene.

Another important input in the debate on Quaternary climatostratigraphy was the publication of Lindner *et al.* (2013). Based on the reinterpretation of data from interglacial sites, e.g., Kozi Grzbiet (Głazek *et al.* 1976b, 1977), Ferdynandów (Janczyk-Kopikowa 1991), Kalejty (Winter 2001; Lisicki and Winter 2004), Domuraty (Winter *et al.* 2008), and Kończyce (Wójcik *et al.* 2004), the position of the main interglacials was verified. The distinguished climatostratigraphic units were correlated with oxygen curves (Lisiecki and Raymo 2005; Cohen and Gibbard 2010). The Quaternary was subdivided into the following climatostratigraphic complexes: Preglacial, South-Polish, Middle-Polish and North-Polish, following previous proposals (Lindner and Marks 2011). These complexes include a series of sediments formed in both warm and cold climates.

Subdivision of the Preglacial Complex (MIS 23–103) remained unchanged compared to the previous schemes. Simple interglacials with one optimum were distinguished within the Middle-Polish and North-Polish Complexes. In turn, in the composite South-Polish Complex, two warm phases separated by a cool phase were noted. An important factor with impact on the stratigraphic scheme was the determining the Brunhes/Matuyama palaeomagnetic boundary in Kalejty (NE Poland) and Kończyce (SW Poland), analogous to its earlier detection in Kozi Grzbiet. In consequence, the glacial till occurring below that boundary in these sites documents the oldest, Nidanian Glaciation (MIS 22). The name of this glacial period was changed due to the fact that Różycki (1978) considered the Narew Glaciation to have an ice-sheet range restricted only to NW Poland.

A younger unit in this scheme is the Podlasian Interglacial, whose older part is represented by the Augustovian-type, and the younger part – by the Domuratovian-type floral successions. The climate variability of this diverse interglacial is registered in the deep-sea core samples of MIS 17-21.

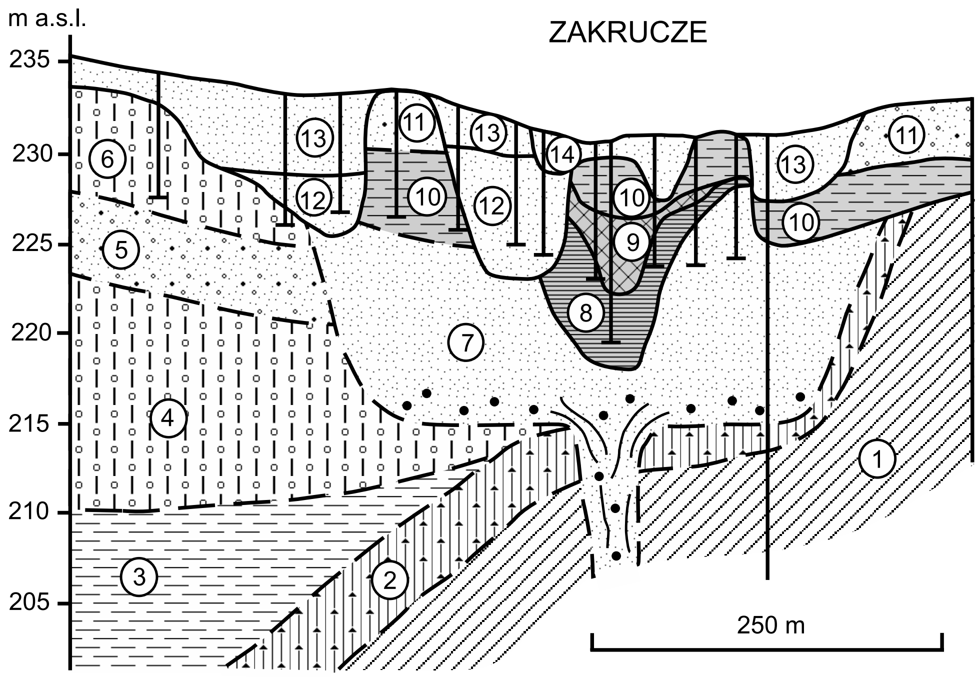
The Podlasian Interglacial is followed by the Sanian 1 Glaciation (MIS 16). Higher occurs the Ferdynandovian Interglacial (MIS 13–15), followed by the Sanian 2 Glaciation (MIS 12; Text-fig. 3). This glaciation tops the South-Polish Complex. During the Late Pleistocene there were four interglacials: Mazovian (MIS 11), Zbójnian (MIS 9), Lublinian (previously referred to the Lubavian – MIS 7) and Eemian (MIS 5e), separated by glacial units: Liviecian (MIS 10), Krznanian (MIS 8) and Odranian (MIS 6), and the Vistulian Glaciation (MIS 2–5d). The European lithostratigraphic correlation of the Liviecian and Krznanian glaciations is difficult and dubious, as is the correlation of the floral documentation for the Zbójnian and Lublinian interglacials. It is worth noting, however, that these units correlate with the record of climate changes preserved in the loess sequences of Ukraine (Łanczont and Bogucky 2007) and Poland (see Dolecki 1993).

The most recent viewpoint on Quaternary stratigraphy was presented by Lindner and Dzierżek (2019). This paper contains a revision of the existing ideas on the distribution and age of Quaternary sediments in the Holy Cross Mountains taking into account new geological data from Poland (Dzierżek and Szymanek 2013; Bujak *et al.* 2016; Kalińska-Nartiša *et al.* 2016; Dzierżek *et al.* 2019) and new stratigraphic schemes (e.g., Marks *et al.* 2016, 2019). In general, the scheme recalls the previous version (Lindner *et al.* 2013) with regard to the names of climatostratigraphic units and their correlation with isotope stages. Glacial tills from the area were assigned to the Nidanian, Sanian 1, Sanian 2 and Odranian glaciations. In later studies, a new palaeogeographic reconstruction of the area was prepared for the maximum of the Sanian 2 Glaciation (Dzierżek *et al.* 2021) and the maximum of the Odranian Glaciation (Dzierżek *et al.* 2019; Cabalski *et al.* 2021). The presence of ice-sheets of the remaining glaciations (Liviecian, Krznanian and Vistulian) was indirectly confirmed by periglacial, slope and cave structures. The Upper Pleistocene, mainly the Vistulian Glaciation, is registered in the recently restudied loess successions from the area (Dzierżek and Lindner 2020; Dzierżek *et al.* 2020, 2022). Characteristic of interglacial units in this scheme is based on the key sites Kozi Grzbiet (Podlasian Interglacial) and Zakrucze (Mazovian Interglacial) (Text-fig. 6).

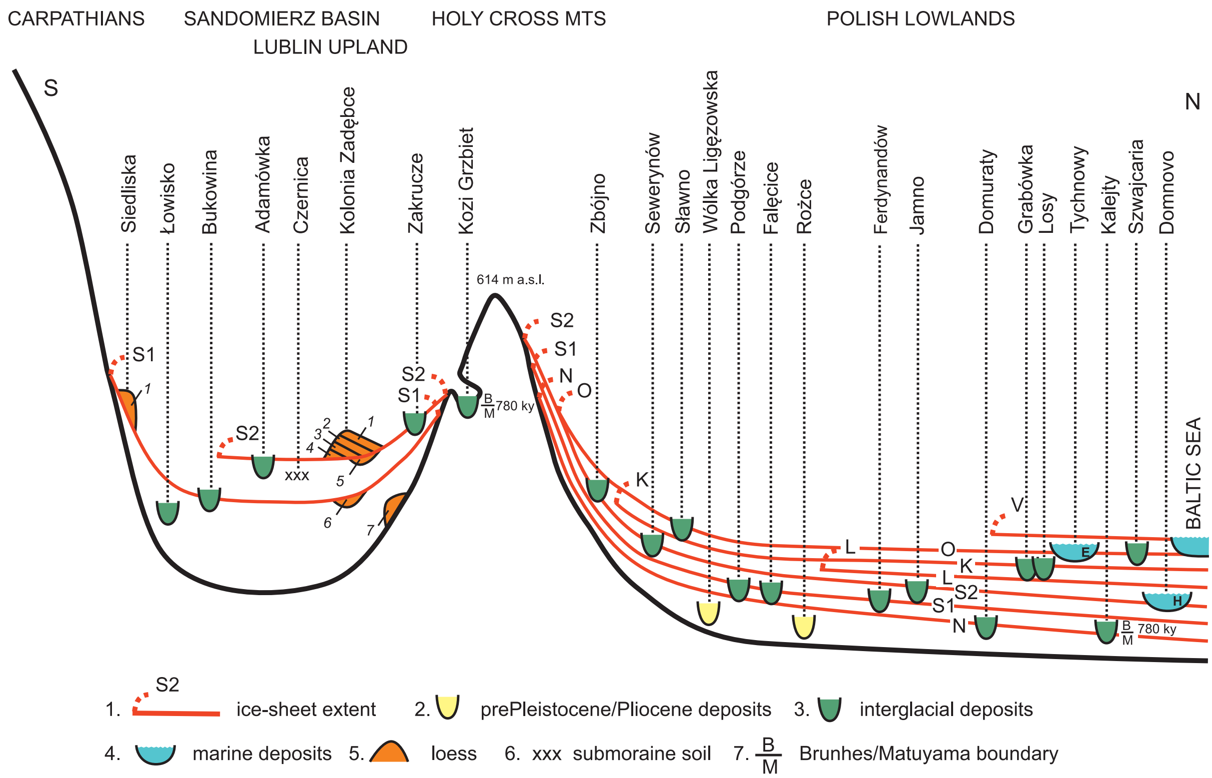
DISCUSSION AND COMMENTS

The current stratigraphic scheme for the Quaternary in the Vistula catchment has been condensed in Text-fig. 7, which shows the location of selected key sites with regard to the ice-sheet extent during particular glaciations. For the Preglacial Complex, the key sites are: Wólka Ligęzowska (Makowska 2015) and Rożce (Baraniecka 1991; Bujak *et al*. 2016); for the Podlasian Interglacial: Łowisko (Stuchlik and Wójcik 2001), Domuraty (Winter and Lisicki 2005; Winter *et al*. 2008), Kalejty (Janczyk-Kopikowa 1996), and Kozi Grzbiet (Głazek *et al.* 1976b, 1977); for the Ferdynandovian Interglacial: Ferdynandów (Janczyk-Kopikowa 1991), Bukowina (Granoszewski 1999; Wieczorek 1999), Falęcice (Lindner *et al*. 1991a; Text-fig. 4) and Podgórze (Jurkiewiczowa *et al.* 1973); for the Mazovian Interglacial: Adamówka (Bińka *et al.* 1987), Jamno (Brzeziński and Janczyk-Kopikowa 1991), Sewerynów (Jurkiewiczowa and Mamakowa 1960), Zakrucze (Lindner and Rzętkowska-Orowiecka 1998; Text-fig. 6) and Domnovo (Loginova 1979); for the Zbójnian Interglacial: Zbójno (Lindner and Brykczyńska 1980; Text-fig. 5); for the Lublinian Interglacial: Grabówka (Makowska 1977, 1986) and Losy (Krupiński and Marks 1986); and for the Eemian Interglacial: Sławno (Tołpa 1961), Szwajcaria (Borówko-Dłużakowa and Halicki 1957) and Tychnowy (Makowska 1986). Although most of the schemes described above include also the correlation of glacial and interglacial units with their equivalents in loess successions, these issues are not discussed further, and only some of them are marked as symbols in the scheme: Siedliska (Łanczont and Alexandrowicz 1997), Kolonia Zadębce (Dolecki 1993) and Czernica (Lindner 1988b).

Several characteristic features can be observed when analysing the evolution of Prof. Lindner's concepts on Quaternary climatostratigraphy. The main feature of subsequent schemes was at first their emergence from the results of detailed analyses (often his own field studies; Text-fig. 2) and the working out a climatostratigraphic scheme for a small area followed by the construction of a regional scheme, and finally the assembly of a panregional scheme. The correlation of the schemes presented in Text-fig. 3 does not include the 'transitional', local stratigraphic schemes published regularly with increasing data inflow (e.g., Lindner 1972, 1984, 1988a; Lindner *et al*. 1995).




Text-fig. 6. Geological position of the Mazovian Interglacial sediments in Zakrucze near Małogoszcz (after Lindner and Rzętkowska-Orowiecka 1998, modified). Upper Jurassic: 1 – limestones; South-Polish Complex: 2 – limestone weathering waste; 3 – ice-dammed silt; 4 – glacial till, 5 – fluvial (?) sand with gravel; 6 – glacial till; 7 – fluvial sand and gravel deformed by karst phenomena; Mazovian Interglacial: 8 – lake silt with bituminous shale; 9 – peat with pieces of wood; 10 – lake silt; the remaining part of the Middle-Polish Complex and the North-Polish Complex: 11 – glacifluvial sand and gravel; 12 – fluvial sand; 13 – fluvial sand with limestone debris; Holocene: 14 – fluvial and slopewash sand with gravel admixture.




Text-fig. 7. The main units of the Quaternary climatostratigraphic scheme of Poland (after Lindner 2015, supplemented). 1 – ice-sheet extent during particular glaciations: N – Nidanian, S1 – Sanian 1, S2 – Sanian 2, L – Liviecian, K – Krznianian, O – Odranian, V – Vistulian; 2 – preglacial sites: Wólka Ligęzowska, Rożce; 3 – interglacial sites: Podlasian – Łowisko, Kozi Grzbiet, Domuraty, Kalejty; Ferdynandovian – Bukowina, Podgórze, Falęcice, Ferdynandów; Mazovian – Adamówka, Zakrucze, Sewerynów, Jamno, Domnovo; Zbójnian – Zbójno; Lublinian – Grabówka, Losy; Eemian – Sławno, Tychnowy; 4 – sites with interglacial marine deposits: H – Holsteinian (Mazovian), E – Eemian; 5 – main loess horizons in Siedlce and Kolonia Zadębce: 1 – younger loess, 2 – upper older loess, 3 – lower older loess, 4–7 – oldest loesses; 6 – site with submoraine palaeosol in Cz – Czernica site; 7 – Brunhes/Matuyama palaeomagnetic boundary documented in Kozi Grzbiet and Kalejty. Correlation of climatostratigraphic units for the Quaternary of Poland with units in Western Europe and Ukraine after Linder *et al*. 2004, 2013 and Marks *et al*. 2016 is presented in Text-fig. 8.

The next feature evident in the stratigraphic schemes presented by Prof. Lindner is elaboration of the subdivision and then withdrawal from the existing (Różycki 1961, 1967; Text-fig. 2) scheme comprising the subdivision of the Polish Pleistocene into three large glacial units: Cracow (South-Polish), Middle-Polish and Baltic (North-Polish). At maximum nine glaciations were distinguished (Lindner 1984), excluding the preglacial “glaciations” (those were always treated as coolings and the term glaciation in that case was written in quotation marks). At present, seven glaciations are distinguished by the University of Warsaw team (Lindner *et al*. 2013; Marks *et al*. 2016; Lindner and Dzierżek 2019). The largest changes in this evolution were with regard to the subdivision of the megaglacials into smaller units (Text-fig. 3).

Since the 1980s, glaciations have been named after the rivers whose catchments had the best documentation of glacial tills at a given moment. Interglacials were called after the names of regions or sites with a documented floral succession in Poland, with only the exception of the Eemian Interglacial named after the Eem river in the Netherlands. Sometimes the unit names are presented in their original spelling with a Polish declension (Lindner 1992). Since 2004, the names of climatostratigraphic units have been given an English spelling. In the case of a few names, e.g., ‘Różcian’ or ‘Krznanian’, which are impossible to pronounce for the English-speaking community, this could not be useful. The need to correlate climatostratigraphic units with Alpine units deeply rooted in the literature (Günz, Mindel, Riss, Würm) was evident in the first schemes (Lindner 1971, 1977, 1980).

The position of the Holocene remains unchanged in all schemes. This results from the relatively stable position of the Pleistocene/Holocene boundary.

There are also several factors which had an impact on the evolution of the discussed concepts over several decades:

1. The stratigraphic schemes were based on Prof. Lindner's own field studies (geological mapping, lithological analysis of profiles, geomorphological analysis) and analysis of core data during preparation of master (Lindner 1967), doctoral (Lindner 1971), and habilitation (Lindner 1977) theses, as well as other projects.

2. Of large importance was Leszek Lindner's cooperation in research teams working on 4 key sites with strata of the: Podlasian (Głazek *et al.* 1976b), Ferdynandovian (Lindner *et al.* 1991a), Mazovian (Lindner and Rzętkowska-Orowiecka 1998), and Zbójnian (Lindner and Brykczyńska 1980) interglacials. The palaeoenvironmental and age interpretations of many archival sites have changed over the years, which has resulted in new concepts of the Quaternary stratigraphic scheme. As presented above, the relatively recent discovery of interglacial sites in Kalejty and Domuraty located in NE Poland (Janczyk-Kopikowa 1996; Winter 2001; Winter and Lisicki 2005; Winter *et al.* 2008), and studies at the Kończyce site in the western part of the Oświęcim Basin in southern Poland (Wójcik *et al.* 2004) became the basis of new concepts on the stratigraphic position of the oldest glacial and interglacial sediments in Poland (Lindner *et al.* 2013; Marks *et al.* 2016). The climatostratigraphic scheme for Poland worked out by Leszek Lindner by the end of the last century (Lindner 1992) was later subsequently supplemented and correlated with Quaternary strata in Belarus (Lindner and Yelovichova 1998; Lindner and Astapova 2000), Ukraine (Lindner *et al.* 2004, 2013), and Moldova (Gozhik and Lindner 2007).

4. Another reason for improved versions of the Quaternary scheme was the successive development of research methods, including age determinations. These have always been treated with great caution in dating glacial deposits, particularly glacial tills (Lindner *et al.* 1987; Fedorowicz *et al.* 1995; Lindner and Fedorowicz 1996). More commonly, TL and OSL methods have been applied for dating loesses (Lindner and Prószyński 1979; Lindner *et al.* 1999; Dzierżek and Lindner 2020; Dzierżek *et al.* 2020).

Successfully evolving palaeomagnetic studies have supplied strong arguments for the precise placement of climatostratigraphic units in the schemes. This began with the Kozi Grzbiet site (Głazek *et al.* 1976a, 1977), and now is developed e.g., in the analysis of the anisotropy of magnetic susceptibility, which supplies rich data on the transportation directions of dust particles (Nawrocki *et al.* 2018, 2019; Dzierżek *et al.* 2020).

With the emergence of data on the continuous record of climate change in deep-sea core samples (Shackleton and Opdyke 1973), stratigraphic schemes for the Quaternary began to refer to these data (Lindner 1984). The most recent correlation of continental glacial units with climate changes recorded in deep-sea core samples (Lisiecki and Raymo 2005) are presented in Text-figs 3 and 8. In the present stage of research, these correlations are still loaded with some dose of subjectivity.

5. An extremely important factor when constructing stratigraphic schemes was the correlation of continental glacial sediments with the loess successions of Poland and Ukraine. The possibility of recognising a continuous documentation of climate changes during the last 900,000 years in thick loess successions greatly enhances these correlations (Maruszczak 1986, 2001; Lindner *et al.* 1991b; Łanczont 1995; Gozhik *et al.* 2000, 2014; Łanczont and Bogutsky 2007; Text-fig. 8).

6. Another impulse to verify existing climatostratigraphic schemes was the systematic inflow of literature data on Quaternary stratigraphy and palaeogeography, including the documentation of new interglacial sites and the results of age determinations. One of such turning points in Quaternary chronostratigraphy was the establishment of the stratotype for the base of the Quaternary at 2.588 Ma based on data from the Monte San Nicola section in Sicily by the International Commission on Stratigraphy (Gibbard *et al.* 2010). Another motivation for meticulous tracking of the most recent research results was Leszek Lindner's long-term work as a university teacher, being obliged to transfer knowledge to his students and associates. Presently, some of them are independent researchers and followers of the Warsaw School of Quaternary Stratigraphy created by Stefan Zbigniew Różycki, and immensely developed by Leszek Lindner.

Summing up the retrospective analysis of Prof. Lindner's concepts on Quaternary climatostratigraphy, his accomplishments should be treated with respect and appreciation. His research has had profound impact on the scientific community in Poland and East-Central Europe. However, his schemes are not always readily applied. Over the years there have been various different concepts on Quaternary stratigraphy, e.g., by Mojski (1985, 2005), Baraniecka (1990), and Ber (2005). Some of them are still being used in various research centres despite the fact that

| Ma | Stratigraphy | Western Europe | | Poland | Ukraine | MIS |
|---|---|---|---|---|---|---|
| | Holocene | Holocene | | Holocene | Holocene | 1 |
| | Late Pleistocene | Weichselian | | Vistulian | Valdai | 2-5d |
| | | Eemian | | Eemian | Pryluky | 5e |
| 0.13 | Middle Pleistocene | Saale III (Drenthe) | | Odranian | Tyasmin | 6 |
| | | Schöningen | | Lublinian | Kaydaky | 7 |
| | | Saale II | | Krznanian | Dnieper | 8 |
| | | Dömnitz | | Zbójnian | Patogoylivka | 9 |
| | | Saale I (Fuhne) | | Liviecian | Orel | 10 |
| | | Holsteinian | | Mazovian | Zavadivka | 11 |
| 0.42 | | Elsterian | | Sanian 2 | Oka (Tilihul) | 12 |
| | | Cromerian Complex | Cromerian IV | Ferdynandovian | Lubny | 13-15 |
| | | | Glacial C | Sanian 1 | Don (Sula) | 16 |
| | | | Cromerian III | Podlasian | Martonosha | 17 |
| | | | Glacial B | | | 18 |
| 0.78 | Early Pleistocene | | Cromerian II | B/M | B/M | 19 |
| | | | Glacial A | | | 20 |
| | | | Cromerian I | | | 21 |
| | | Dorst | | Nidanian | Pryazovsk | 22 |

Text-fig. 8. Pleistocene stratigraphy of Western Europe, Poland and Ukraine, and its correlation with marine isotope stages (MIS; after Lindner *et al*. 2004, 2013; Lisiecki and Raymo 2005; Marks *et al*. 2016); $\frac{B}{M}$ – Brunhes/Matuyama palaeomagnetic boundary.

the scheme presented by Lindner *et al.* (2013), further established by Marks *et al.* (2016), remains valid and is consequently being taught at the Faculty of Geology, University of Warsaw.

On the other hand, further possibilities and directions of climatostratigraphic research should be discussed. The relative stability of the isotope curves in oceanic cores does not guarantee the stability of the stratigraphic scheme for the continental record. Further development of age determinations using physical, chemical and isotopical technics is a chance to tie the distinguished climatostratigraphic units to the temporal scale. It seems that the most urgent task includes better recognition of climate changes in the Early Quaternary, which encompasses almost 1.6 my, i.e., twice as long as its glacial part. So far, the subdivision of this part of the stratigraphic scheme is incomplete, although the documentation in central and southern Poland within clastic sediments is rich (see Bujak *et al.* 2016). Another important challenge in future studies on Quaternary stratigraphy is the better correlation of the climate changes recorded in glacial deposits on continents with those of mountain glaciers.

## CONCLUSIONS

1. Prof. Lindner’s achievements with regard to climatostratigraphy are immense and their impact on the Quaternary community is undeniable. The achievements described above form the foundations of the Warsaw School of Quaternary Stratigraphy.

2. The development of a good stratigraphic scheme required (and still requires) taking into account a vast number of elements systematically appearing with the inflow of new data from: mapping surveys, palaeogeomorphology, lithostratigraphic analysis, palaeofloral and palaeozoological documentation, age determinations using physical and isotopic methods, palaeomagnetic analyses, as well as the comparison of these data with the record of climate change in deep-sea core samples.

3. Leszek Lindner’s climatostratigraphic schemes have been based not only on the key sites with documented floral successions recorded in lake, cave and marine deposits, but also on the analysis of thick loess with fossil soil sequences from Poland and Ukraine.

4. The current stratigraphic scheme of L. Lindner and his team for the Quaternary assumes the pres-

ence of seven glaciations: Nidanian, Sanian 1, Sanian 2, Liviecian, Krznanian, Odranian and Vistulian, and six interglacials: Podlasian, Ferdynandovian, Mazovian, Zbójnian, Lublinian and Eemian. The long Preglacial probably encompasses two coolings and two warmings.

5. Despite the relative stability of the current scheme (see Marks *et al*. 2016, 2019) it can be assumed that with inflow of new data it will be appropriately modified, particularly in its lowermost part.

6. Projection of climate changes in the Quaternary should be enhanced with development of physico-chemical techniques for the age determination of sediments, palaeomagnetic analysis including dating, and a more detailed recognition of the environmental features recorded in mineral and organogenic sediments as well as in fossil soils present in loess deposited over a lengthy period and containing fossil soil sequences.

## Acknowledgements

We are grateful to Prof. Teresa Madeyska and Prof. Leszek Marks for their insightful reviews and valuable comments on the manuscript. Our sincere gratitude goes to Prof. Leszek Lindner for his great help in the preparation of the text and illustrations for this manuscript, and his continuous inspiration to undertake subsequent research challenges. We also would like to thank Robert Janiszewski for help in preparing the graphics.

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*Manuscript submitted: 23rd January 2023*
*Revised version accepted: 19th June 2023*