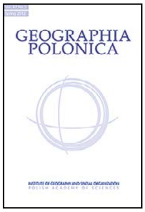

Geographia Polonica
2024, Volume 97, Issue 3, pp. 217-229
https://doi.org/10.7163/GPol.0277

INSTITUTE OF GEOGRAPHY AND SPATIAL ORGANIZATION
POLISH ACADEMY OF SCIENCES
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THE QUATERNARY OF POLAND AND ITS STRATIGRAPHIC CLASSIFICATION

Leszek Marks[1] • Zdzisław Jary[2]

[1] Faculty of Geology
University of Warsaw
Żwirki i Wigury 93, 02-089 Warsaw: Poland

[2] Department of Physical Geography, Institute of Geography and Regional Development
University of Wrocław
Cybulskiego 34, 50-205 Wrocław: Poland
e-mail: zdzislaw.jary@uwr.edu.pl (corresponding author)

Abstract

Quaternary studies in Poland require an improved integration of lithostratigraphy, biostratigraphy, chronostratigraphy, geochronology, magnetostratigraphy, climatostratigraphy and isotope stratigraphy. The former Polish loess stratigraphic schemes are of historical significance and should be verified using new research methods and implementation of the international unified loess labelling system. Arbitrary stratigraphic correlations should be avoided and a reliable stratigraphic subdivision of the Quaternary of Poland should be based on recognized international standards as well as stratotype sections and areas. This is essential both for the Quaternary sciences themselves and for the needs of the society.

Key words

Quaternary in Poland • stratigraphic classification • loess stratigraphy • stratigraphic chart

Introduction

The Quaternary with a duration of 2.6 million years is by far the shortest system of the Cenozoic Era. The stratigraphic categories most commonly used in Polish Quaternary studies are (Marks et al., 2014; Gibbard, 2015; Marks, 2023b): lithostratigraphy with pedostratigraphy and cryostratigraphy, morphostratigraphy, biostratigraphy including palynostratigraphy, malacostratigraphy, terio-stratigraphy and anthropostratigraphy, magnetostratigraphy and chronostratigraphy synchronized with geochronology and climatostratigraphy with isotope stratigraphy (Fig. 1).

A stratigraphical subdivision of the Quaternary has been based traditionally on premises that differ slightly from those of older geological periods. Quaternary studies have mostly focused on widely accessible terrestrial deposits, and a decisive role in their formation was played by climate change.

Main categories of stratigraphic classification	Stratigraphic units
Lithostratigraphy • pedostratigraphy	formation • palaeosol
Biostratigraphy • palynostratigraphy	zone • pollen succession
Magnetostratigraphy	magnetozone magnetosubzone
Chronostratigraphy	system • series • • subseries • • • stage
Climatostratigraphy	complex • glaciation – cooling • interglacial – warming

Figure 1. Main lithostratigraphic, biostratigraphic, magnetostratigraphic, chronostratigraphic and climatostratigraphic units, used in the Quaternary studies in Poland

Therefore, stratigraphic charts of the Quaternary in Poland mostly show the climatostratigraphic units.

Description of stratigraphic categories

Lithostratigraphy is commonly used in studies of the Quaternary in Poland, but all distinguished units are informal (Marks et al., 2014). In general, lithostratigraphic units should be defined using principal lithologic features, and their variability and superposition. They have been used occasionally for drilled cores (Kenig & Marks, 2001). Rare attempts to formalize these lithostratigraphic units have not been adopted (e.g. Makowska, 1986, 2009; Krzyszkowski, 1991; Krzyszkowski & Nita, 1995). Lithology is used to determine sedimentary environments and palaeoclimate, with limited applications for local stratigraphy. Lithostratigraphic units are defined by single or sets of features of the deposits (Mycielska-Dowgiałło & Rutkowski, 1995; Marks, 2001) and are given informal names, applicable usually within a limited geographic area. Deposits mainly represent local terrestrial environments, but similar deposits can occasionally reflect different environments (Marks, 2001). Lithostratigraphy is commonly used in loess stratigraphy in Poland.

The stratigraphic correlation of sedimentary successions across different environments is challenging given that widespread key beds are rare (Marks, 1995; Marks & Pavlovskaya, 2003). In addition to classical lithostratigraphy (*sensu stricto*), pedostratigraphy and cryostratigraphy are also used in Poland (Marks et al., 2014). Pedostratigraphy deals with palaeosols and their complexes, defined by diagnostic biophysico-chemical and morphological features. Cryostratigraphy sets epigenetic periglacial features in a stratigraphic order.

Biostratigraphy may be based on the stratigraphic ranges of key taxa (index fossils) or the changes in assemblage composition in ecostratigraphic applications. The most popular in the Quaternary stratigraphy of Poland are: palynostratigraphy, malacostratigraphy, teriostratigraphy and anthropostratigraphy, each with different optimal time frames and precision (Marks et al., 2014; Marks, 2023b).

Chronostratigraphy, geochronology and magnetostratigraphy. Quaternary chronostratigraphy is established globally using age correlation of the palaeontologic, lithologic, magnetic, radiometric, morphologic and climatic features of the deposits.

Boundaries of the chronostratigraphic units are defined in type sections exhibiting continuous deposition (Walsh et al., 2004), and for the Quaternary formal chronostratigraphic units need not always represent marine environments (Walker et al., 2018; Head et al., 2021). Formally established units are defined by Global Stratotype Sections and Points (GSSPs) that utilize the isochronous nature of chronostratigraphic boundaries (Marks, 2023b). The chronostratigraphy of the Quaternary in Poland refers strictly to the global scheme and is based generally on rare palaeomagnetic investigations, but for the Upper Pleistocene and Holocene it also relies on evidence from radiocarbon, OSL and cosmogenic isotope dating, and U/Th dating in the case of cave sediments.

Climatostratigraphy. Most environmental changes occur in cycles forming the essence of cyclostratigraphy. Cyclic climate changes in the Quaternary drove both accumulation and erosion, making the stratigraphy climate-dependent. In spite of regional asynchrony and variable durations of individual climatic episodes, inter-regional correlation based on climatic premises is much more precise than reflected by other categories of stratigraphic classification. The weakness of climatostratigraphy are due to the complex varied and repeated record of climate change: since a lithology does not reflect these complexities univocally, then additional supporting evidence is also needed (e.g. fossils, palaeosols, geochemical content).

Quaternary climatostratigraphy is therefore an integrated stratigraphy (holostratigraphy) that combines results from other categories of stratigraphic classification, to achieve the most precise and reliable age resolution and best local-to-regional stratigraphic correlation (Marks et al., 2014). Cyclothems are treated as isochronic units, formed by various processes that generate cyclic sedimentation. Among these are cyclic climate changes reflected by glacial-interglacial and loess-palaeosol sequences (Kukla, 1977, 1978; Lindner et al., 2002; Marković et al., 2024). A theoretical justification of climatic cycles is supported by the Earth's orbital cycles (Milanković cycles), expressed by a periodical variation in the seasonal and latitudinal distribution of solar radiation influx to the Earth at frequencies of ~100, 41, and 23 kyr (Petrović & Marković, 2010). Milanković cycles do not alone account for the initiation and termination of the Pleistocene glaciations but, together with an understanding of climate feedbacks, explain why ice sheets developed quite regularly during the Pleistocene, following eccentricity, obliquity and precession cycles (Berger, 1988). Climatostratigraphic units of the Quaternary are principally of local or regional significance, because the rhythm of climate change in the Quaternary has been essentially modified in different areas (e.g. Kukla, 2005). During climate change, the advance or retreat of glaciers and migration of vegetation zones, animals and hominids, all occur progressively over time, so at fine scale represent diachronous surfaces.

Loess stratigraphy in Poland

The evolution of ideas on the stratigraphy of the Polish loess was presented by Maruszczak (1976, 1980, 1987, and others). The development of loess stratigraphy in Poland has been directly related to the progress of both research in Quaternary geology and the loess stratigraphy of other European countries. A decisive influence on this progress was stimulated by new research techniques, such as palaeopedological criteria, new methods in sedimentological, palaeomagnetic, geochemical research and an increasing use of various physical dating methods.

In the Polish loess literature since the 1970s, there have been two independent stratigraphic schemes of loess-palaeosol sequences (LPS) in which fossil soils were adopted as the main criterion of the loess stratigraphy developed by Jersak (e.g. 1969, 1973a, 1975, 1976, 1991) and Maruszczak (e.g. 1972, 1976, 1987, 1991, 2001). Jersak relied mainly on palaeopedological criteria and the careful examination of periglacial structures (Jersak, 1973a, 1973b, 1975, 1976) and was a strong opponent of stratigraphy based on thermoluminescence (TL) age determination (Jersak, 1991; Jersak et al., 1992). He did not correlate LPS with the continuous marine isotope record of deep-sea sediments.

The scheme of Maruszczak is more modern and widely used in Poland. His most important achievements were attempts to correlate the Polish loess with magnetostratigraphy and the deep-sea isotope-oxygen record, and it elevated stratigraphic studies of the loess in Poland to modern standards (Maruszczak, 1987, 1991, 2001). The LPS chronology was established by TL dating performed in the Department of Physical Geography of the Maria Curie-Skłodowska University in Lublin, and it almost perfectly correlated with the marine isotope stages (e.g. Martinson et al., 1987). However, this apparent strength in Maruszczak's stratigraphic scheme has in recent years become a great controversy.

Enormous progress has recently taken place on research into LPS and their climatostratigraphic interpretation. In order to avoid confusion resulting from the use of numerous local and regional stratigraphic schemes, a unified chronostratigraphic model of loess derived from the classic work of Kukla & An (1989), and modified by Marković et al. (2015) has been increasingly used (Tab. 1). In this model, the loess units are indicated with the letter "L" and the soil units with the letter "S". Similar stratigraphic designation have been applied to the Dnister river basin by Bogucki & Łanczont (2002), and for the Polish loess by Jary & Ciszek (2013).

Middle Pleistocene loess stratigraphy in Poland

Research into Middle Pleistocene LPSs in Poland was undertaken mainly in the second half of the previous century. A stratigraphic scheme of loess and fossil soils was published by Maruszczak (1991). In addition to younger

Table 1. Unified loess stratigraphy (Marković et al., 2015) referred to marine isotope stages (Lisiecki & Raymo, 2005) and their correlation to the loess stratigraphy of Poland (Maruszczak, 1991, 2001) and northwestern Ukraine (Bogucki, 1986)

MIS	Unified loess stratigraphy Marković et al. (2015)	Poland Maruszczak (1991, 2001)	NW Ukraine Bogucki (1986)
1	S0	Holocene soil GH	Recent soil
2	L1LL1	LMg	Upper neo-Pleistocene loess
3	L1SS1	Gi/LMd + LMs + Gi/LMs	Dubno soil
4	L1LL2	LMd	Lower neo-Pleistocene loess
5	S1	GJ1 + Gi/GJ1 + LMn + Gi/LMn	Horohiv pedocomplex
6	L2	LSg (LSg3 + sg/LSg3 + LSg2 + g/LSg2 + LSg1)	Upper Mid-Pleistocene loess
7	S2	GJ2 + Gi/GJ2 + LSg4 + Gi/LSg4	Korshiv pedocomplex
8	L3	LSn + sg/LSn + LSd + Gi/LSd + LSs	Lower Mid-Pleistocene loess
9	S3	GJ3a	Luck pedocomplex
10	L4	LN1	Upper Old-Pleistocene loess
11	S4	GJ3b	Sokal pedocomplex
12	L5	LN2	Oka moraine (San 2)
13		GJ4a	
14	S5	???	
15		GJ4b	
16	L6	LN3	

loess and soil units related to the last interglacial-glacial cycle, which is discussed below, he distinguished several older loess units (Tab. 1):

- three subunits of the older upper loess (LSg1, LSg2 and LSg3), separated by the gleyey horizon g/LSg2 and soil sediments sg/LSg3, correlated with MIS 6,
- an interstadial soil developed on the fourth upper older loess Gi/LSg4, LSg4 unit and the soil pedocomplex consisting of the welded interstadial soil (Gi/GJ2) and the interglacial soil GJ2, correlated with MIS 7,
- middle (LSs), lower (LSd) and lowermost older loess units (LSn), separated by the interstadial soil Gi/LSd and soil sediments sg/LSn, correlated with MIS 8,
- the interglacial soil GJ3a, correlated with MIS 9,
- the first oldest loess LN1, correlated with MIS 10,
- the interglacial soil GJ3b, correlated with MIS 11 (?),
- the second oldest loess LN2, correlated with MIS 12 (?).

This scheme was expanded by Dolecki (1995) who added the next oldest loess units LN3 and LN4. Maruszczak presented a brief characteristics of the new oldest loess and soil stratigraphic units in the final version of his stratigraphic scheme published in 2001. However, the soil and loess units older than MIS 11 (LN2, LN3, LN4) seem insufficiently documented as they were mainly based on drilling and require further research, both in the context of their age and origin (Maruszczak, 2001; Jary & Marks, 2024).

Poland is not a convenient place to study LPS of Middle Pleistocene age. They may occur only outside the area covered by the penultimate glaciation (Odranian=MIS 6) that being in the south-eastern part of Poland. However, the Middle Pleistocene LPS suitable for excavation and further research are extremely rare there. Synthetic stratigraphic sequences, represented in individual loess sites, were developed by combining several fragmentary sections that usually did not appear in a superposition. A unique stratotype section for this area is the Bojanice LPS, located on the Volhynian Upland in the Ukraine, just a few kilometres east of the Polish border (Tab. 1). This site exposes 4 loess units in superposition, corresponding to four glaciations and four interglacial pedocomplexes, the oldest of which is developed at the top of a glacial till of the San 2 (Oka) Glaciation (Bogucki, 1986; Bogucki et al., 1994; Kusiak et al., 2012).

In conclusion, it should be noted that the Middle Pleistocene interglacial soils in the loess-palaeosol complexes have been poorly examined in terms of palaeopedology. Both authors are of the opinion that for most loess researchers the palaeopedological interpretation of LPS was considered less important than the stratigraphic interpretation and the arbitrary correlation with the marine record mainly based on TL dating.

Upper Pleistocene loess stratigraphy in Poland

The more interesting and detailed part of the loess stratigraphy in Poland is the Upper Pleistocene (Fig. 2). In Jersak's scheme (1973a, 1991; Jersak et al., 1992), the sequence of loess and palaeosols from the last interglacial-glacial cycle begins with the Nietulisko I type pedocomplex. It consists of a forest soil covered with 1 to -3 humic horizons of chernozem type. Within the Nietulisko I type soil complex, there is the younger loess I which was completely transformed by pedogenetic processes related to the formation of the steppe humic horizons. The Nietulisko I type pedocomplex was correlated with the Eemian regional stage (last interglacial, broadly equivalent to MIS 5e) and early glacial of the Vistulan Glaciation (Jersak, 1973a). The Nietulisko I type soil complex is overlain by the younger loess IIa, deposited in the lower Plenivistulian. At the top of this loess unit is the Komorniki-type soil of the middle Plenivistulian. The younger loess IIb was deposited in the upper Plenivistulian (Jersak, 1973a; Jersak et al., 1992).

In the scheme of Maruszczak (1987, 1991, 2001), the last interglacial is represented by a forest soil developed on the older upper loess (GJ1/LSg) or on deposits of varied origin (Fig. 2). In the earliest Vistulian (MIS 5d-c according to Maruszczak, 1991, 2001), turfy soil horizons were superimposed on the Eemian soil, creating a soil complex that separates the older and younger loess. In some sections, this soil complex is overlain by the lowest younger loess (LMn), correlated with MIS 5b. At the top of LMn, the sg-Gi/LMn weathering-soil horizon developed, which was correlated with MIS 5a by Maruszczak (1991). Above, there is the younger lower loess (LMd), deposited in the lower Plenivistulian (MIS 4), with a weathering-soil horizon in its upper part (sg-Gi/LMd) and correlated with the middle Pleniglacial interstadials Glinde and/or Oerel (Behre, 1989). The younger middle loess (LMs) is correlated with part of the middle of MIS 3, and there is a poorly developed weathering and/or soil horizon at the top of LMs that Maruszczak (1991) correlated with the final part of MIS 3. The younger upper loess (LMg), correlated with MIS 2, is the most "typical" and thickest among the younger loess units and comprises usually 1 to -3 weak gley horizons (Fig. 2).

The stratigraphic correlation of particular litho- and pedostratigraphic units defined by Jersak (1973a) and Maruszczak (1987, 1991, 2001) is not obvious. It should also be taken into account that Maruszczak subsequently changed his primary interpretation and description of characteristics for some lithostratigraphic units. The first loess stratigraphic scheme and chronostratigraphic interpretation made by Maruszczak in the 1970s were similar to the Ukrainian scheme of Veklich (1968). The pedostratigraphic units in the loess record were correlated with successive biostratigraphical units known in Europe in the 1960s.

Two important changes in Maruszczak's scheme for the Upper Pleistocene loess stratigraphy should be pointed out (Fig. 2). In the 1970s, the basal palaeosol was interpreted by Maruszczak as the Eemian soil. Since 1987, the same unit has been described as a palaeosol

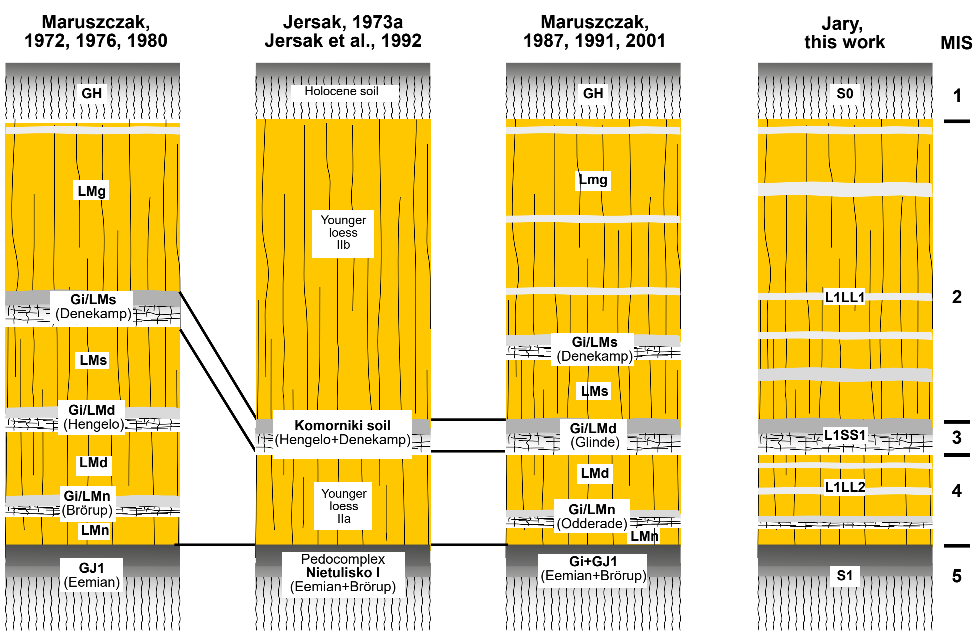

Figure 2. Correlation of the Upper Pleistocene loess-palaeosol stratigraphic units in Poland by Maruszczak (from the 1970s and since 1987) with the Jersak scheme (according to Jary, 2007, modified) and chronostratigraphic interpretation of the Upper Pleistocene loess in Poland using a unified labelling system

complex, consisting of interglacial forest soil and the welded humus horizon of the earliest Vistulian age. The second correction is even more important. In the 1970s, the interstadial soil in the upper part of middle younger loess Gi/LMs was the best developed palaeosol within the younger loess and this unit was correlated with the Komorniki soil. In the 1980s, Maruszczak verified his own stratigraphic interpretation of the main loess sections in Poland. In two major loess sections he established that the formerly interpreted palaeosol Gi/LMs in fact consisted of the truncated B horizon of the interglacial forest soil GJ1. Since 1987, the soil developed in the upper part of the lower younger loess Gi/LMd became the main palaeosol within the younger loess according to Maruszczak and this unit was correlated with the Komorniki soil (Fig. 2).

However, the age of the Gi/LMd soil was estimated by Maruszczak based on TL dating performed in the Lublin laboratory and correlated with the Glinde Interstadial. This was in contrast to ^{14}C datings of this soil which proved a correlation with the Hengelo and Denekamp interstadials of the younger Vistulian (Vandenberghe & van der Plicht, 2016).

Jary (2007) assumed that the representative, Upper Pleistocene interfluve LPS in Poland consists of four units: two polygenetic palaeosol complexes and two usually calcareous loess units. In the uppermost loess unit Holocene soil has developed. Jary & Ciszek (2013) correlated the Upper Pleistocene loess and soil units with MIS and assigned them appropriate labels within the unified loess stratigraphic nomenclature (Fig. 2). The results of new high-resolution OSL and ^{14}C dating of several LPS in Poland presently confirm this chronostratigraphic interpretation (Moska et al., 2011, 2012, 2015, 2017, 2018, 2019a, 2019b; Zöller et al., 2022; Jary et al., 2023).

Discussion

A reliable chronology in Quaternary climatostratigraphy while important, is limited by available dating methods. The boundaries of climatostratigraphic units are usually synchronous only within a limited area, complicating direct correlation with chronostratigraphic units. Deep-sea sediments typically have continuous sedimentation and are most suitable to define the boundaries of climatostratigraphic units if leads and lags relative to climate change are taken into account (Parrenin et al., 2007). Marine isotope stages (MIS) based on benthic foraminiferal oxygen isotope ratios in deep-sea sediments are widely used in Quaternary stratigraphic correlation (Cohen & Gibbard, 2019) as they reflect global ice volume changes and hence indirectly global temperature changes.

The stratigraphic chart of the Quaternary of Poland presented here (Fig. 3) includes only those units that broadly comply with accepted requirements (http://quaternary.stratigraphy.org/stratigraphic-guide). A stratigraphic subdivision of interglacials and stratigraphic units in the extraglacial area is established based on the examination of loess-palaeosol sequences as well as fluvial and lake deposits.

Traditional stratigraphic subdivisions of the Quaternary are applicable regionally, but not globally (http://quaternary.stratigraphy.org/regional-divisions). The chronostratigraphic subdivision of the Quaternary, mostly developed since 2009 (Head, 2019) and based on magneto- and climatostratigraphic units (Pillans & Head, 2024), has provided a formal framework within the international chronostratigraphic chart. The European standard stratigraphic subdivision comprises the climatostratigraphic units distinguished in the Netherlands, Germany and UK (Zagwijn, 1985; Gibbard et al., 2005; Litt, 2007), to which the Polish stratigraphic chart is linked (Fig. 3).

The need for a reliable stratigraphic subdivision of the Quaternary results firstly from the inestimable significance of its deposits in geological investigations (geological mapping included), but also in the everyday life of society. In Europe where the Quaternary was originally defined, its sediments and processes have played a decisive role in modelling of the landscape and subsurface geology. A considerable differentiation in time and space as well as recognition of the Quaternary deposits and their cartographic projection,

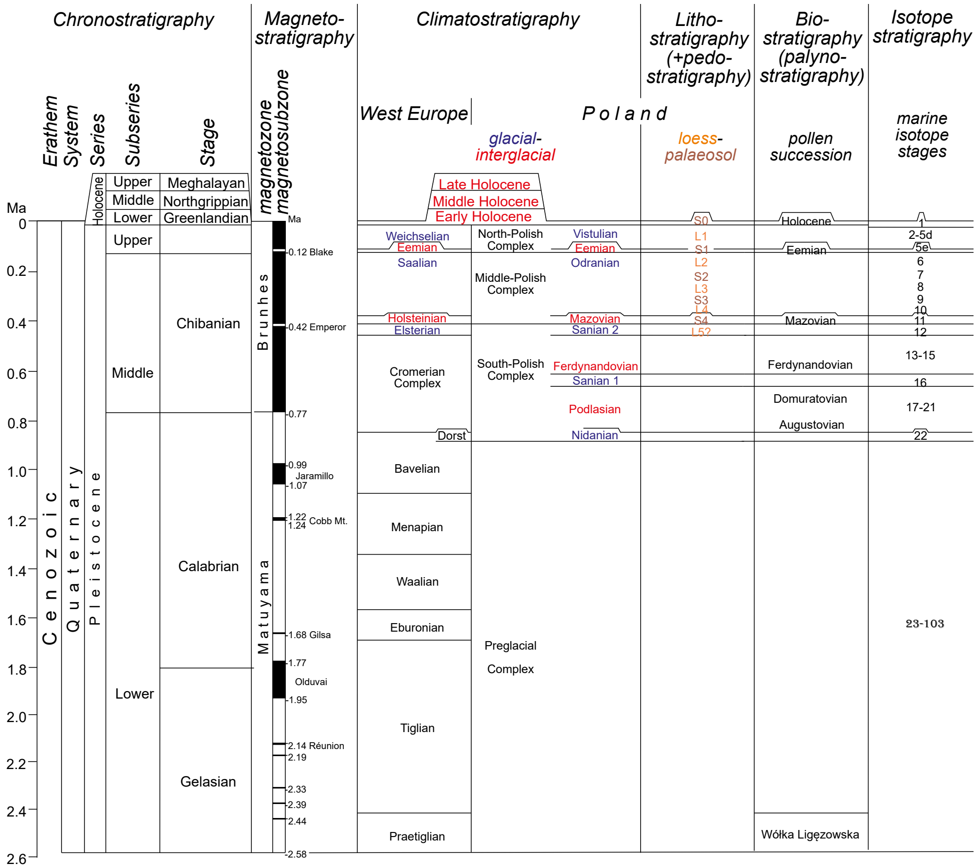

Figure 3. Stratigraphic chart of the Quaternary of Poland based on Marks (2023ab), Marks & Jary (2023) and Jary & Marks (2024), and modified here; blue – glaciations, red – interglacials, orange – loess, brown – palaeosol

support the general and historical subdivision of the Quaternary into the Pleistocene and the Holocene. At the same time, the tempestuous scientific and international discussions over the past 20 years has resulted in the almost complete formal stratigraphic subdivision of the Quaternary in a global scale (Gibbard & Head, 2009; Gibbard et al., 2010; Cita et al., 2012; Walker et al., 2018; Head, 2021; Head et al., 2021; Suganuma et al., 2021) and these stratigraphic standards can also be applied in Poland (Marks et al., 2014).

Chrono- and climatostratigraphic terminologies are often treated as if they are interchangeable, but doing so compromises precision in inter-regional correlation. Quaternary climatostratigraphic units are usually correlated with chronostratigraphic units such that cold and warm stages follow one another. This simplistic approach confuses the distinction between climato- and chronostratigraphic subdivisions, a confusion compounded by the absence of stratotype sections for most climatostratigraphic units.

Modern climatostratigraphic correlation is based in essence on synchronized local terrestrial and shallow-marine records (usually fragmentary, but of a high resolution) with potentially continuous deep-sea sequences (but of considerably lower resolution) and ice cores.

The application of the Milanković orbital cycles to estimate the age of individual MISs (Imbrie et al., 1984) and dating of ice cores (Orombelli et al., 2010) has enabled correlation of climato- and chronostratigraphic units, despite diachronic climate changes caused by leads and lags in planetary feedback systems. Climatostratigraphic units understood in this way can usefully approximate chronostratigraphic units.

Conclusions

A compilation of stratigraphic subdivisions of glacial and extraglacial areas is among the most important challenges for Quaternary stratigraphy in Poland, because key sections record only a limited time frame. The most complete so far is the stratigraphic subdivision of the Upper Pleistocene and Holocene, much less of the Middle Pleistocene and the least of the Lower Pleistocene.

Although the stratigraphic problems of loess in Poland appeared to have been almost completely explained in the 1990s, the results of those studies are mainly of historical importance and should be verified based on new research methods and techniques. The application of a unified loess stratigraphic model will enable more efficient development of international cooperation which will provide the framework for the evaluation of a European model of loess stratigraphy.

The main focus of stratigraphic studies in Poland should be to select regional stratotypes, starting with the main chronostratigraphic units (Neogene/Quaternary, Lower/Middle Pleistocene, Middle/Upper Pleistocene and Pleistocene/Holocene boundaries). The Lake Gościąż site in central Poland has the best potential to serve as a regional stratotype for the Pleistocene/Holocene boundary. The next stratotypes should be the key sections of bio-, litho- and climatostratigraphic units (Fig. 3).

A reliable stratigraphic subdivision for the Quaternary of Poland should be based on recognized international standards. This is essential, not only due to the significance of Quaternary deposits in geological investigations, but also the needs of modern society.

Acknowledgements

We are deeply grateful to the anonymous reviewer for helpful comments and Prof. Martin J. Head who also corrected the English.

Editors' note:
Unless otherwise stated, the sources of tables and figures are the author's, on the basis of their own research.

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Article first received • 24 January 2024
Article accepted • 6 May 2024