

# Age position and palaeoenvironment of the main palaeosols in loess profiles of south-eastern Poland in the ranges of the Scandinavian ice sheets

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## ABSTRACT:

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This article attempts to reconstruct the climatic and environmental conditions of the development of the palaeosols found in loess profiles in south-eastern Poland. A comprehensive profile was developed by the authors, based on an extensive analysis of literature data, which elucidated the mutual relationships between the occurrence of loess and intra-loess palaeosols in south-eastern Poland in relation to recent Pleistocene stratigraphy. In south-eastern Poland, five interglacial palaeosols have been identified: *S5* – *Zadębcze* (Ferdynandovian, MIS 15–13), *S4* – *Sokal* (Mazovian, MIS 11), *S3* – *Załuźniczce* (Zbójnian, MIS 9), *S2* – *Tomaszów* (Lublinian, MIS 7) and *S1* – *Nietulisko* (Eemian–Early Vistulian, MIS 5e–a). Interglacial soils were developed in a warm and humid temperate climate. The two older soils, *S5* and *S4*, are most commonly represented as brown soils, developed in mixed forest environments. Palaeosols *S3*, *S2* and *S1* are most frequently represented as grey forest soil types that have developed in coniferous or mixed forest environments. The *Tomaszów* (*S2*) and *Nietulisko* (*S1*) soil types are pedocomplexes, which are defined by the presence of a layer of chernozem superimposed on a lessive soil. These pedocomplexes developed in varying environmental conditions during the early glacial period, dominated by steppes. Initial tundra soils which formed during interstadial periods were also recorded within the loess levels. The palaeosols documented in south-eastern Poland correlate well with the corresponding sections of long loess-soil sequences in Ukraine and other regions of Europe. Thus, they provide important supplementary data for reconstructing the rhythm of climate change in regions outside the range of the Scandinavian ice sheets.

**Key words:** Pleistocene, Stratigraphy, Palaeoenvironment, Soils, Loess.

## INTRODUCTION

Natural climate changes in the Quaternary period are most precisely recorded in deep-sea cores (Lisiecki and Raymo 2005; Jouzel *et al.* 2007). They illustrate on oxygen curves glacial-interglacial cycles with a frequency of 100 ky, as well as less regular cooling and warming cycles. However, comparing palaeoclimate data from deep-sea cores with

lake or glacial sediments is difficult due to the latter's discontinuous and/or incomplete record (Head and Gibbard 2015; Hughes *et al.* 2020). Among terrestrial environments, loess-soil sequences are relatively sensitive recorders of Quaternary climate change and are most often used for stratigraphic correlation (among others Kukla 1987; Maruszczak 2001; Marković *et al.* 2011, 2015; Jary and Ciszek 2013; Łanczont *et al.* 2019; Antoine *et al.* 2022).



The aim of this research is to reconstruct the palaeoenvironmental conditions influencing soil development, based on the analysis of available documentation of loess-paleosol sequences in south-eastern Poland, and to determine their trans-regional stratigraphic correlation. This will be achieved by analysing extensive literature data alongside our own research on sediments and Quaternary landforms, mainly from the Middle and Upper Pleistocene periods (Lindner *et al.* 2004, 2013; Dzierżek and Lindner 2024; Marks *et al.* 2016). This paper is based on the results of many years of research by numerous authors (Jersak 1976a, b, 1991; Jersak *et al.* 1992; Jary 1996, 2007; Jary and Ciszek 2013; Dolecki 1995, 2003; Maruszczak 1991, 2001; Łanczont and Bogucki 2007; Łanczont *et al.* 2019), concerning the determination of the number and age of the main loess levels and palaeosols preserved in south-eastern Poland and their relationship to the Scandinavian glaciations. The paper supplements the knowledge about geological profiles documenting the seven loess levels (L1–L7) in the Vistula River catchment (Dzierżek and Lindner 2024).

## MATERIAL AND METHODS

This work is a synthesis of archival literature data. We selected previously studied profiles in south-eastern Poland to be compared with loess-palaeosol profiles in central-eastern and western Europe. We have proposed names for interglacial soils, taking into account the names of the sites in south-eastern Poland, where they are best documented or were firstly recorded. However, for the soil from the Mazovian interglacial period we used the name Sokal soil which is established in the literature, and which is well recognized in the profiles of Ukraine. The descriptions and identification of the soils are based on original works and include the most important physical characteristics of the fossil soils, their thickness, sand and clay content, as well as some geochemical characteristics and context in the geological profile. The compilation of information on the conditions for the development of the described types of palaeosols made it possible to determine the general characteristics of the environment and climate prevailing in south-eastern Poland during the Pleistocene pedogenesis periods. The specific temperature values cited for of individual palaeosols, based mainly on palaeobotanical analysis, are indicative.

The basis for stratigraphic considerations is a re-analysis of the geological situation of individual sites and their regional correlation linked to the new

division of the Quaternary stratigraphy of Poland. The TL dating results are cited in their original form and serve as an aid in determining the age of loess-soil levels. Despite occasional doubts about the quality of TL dating techniques from the end of the last century, no studies have yet appeared in Poland that deny their accuracy. We also used the available palaeomagnetic data collected at some sites.

Based on an analysis of short profiles from selected SE positions in Poland, we created a synthetic profile, which we compared with long profiles in other European regions. We realize that, in the absence of reliable methods for correlating palaeosols and dating them, this correlation is preliminary in nature and requires verification in the future.

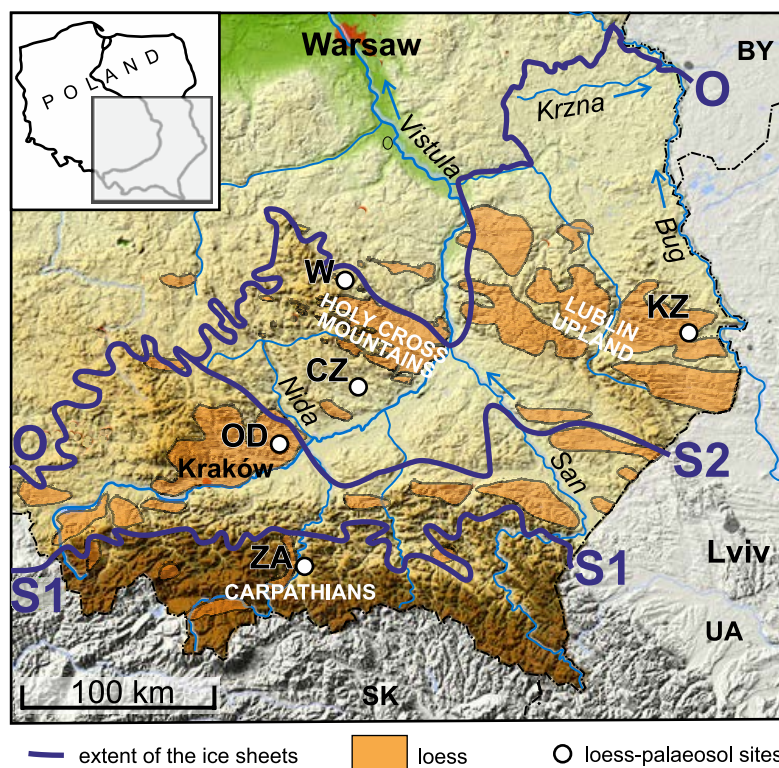
## CHARACTERISTICS OF PALAEOSOLS IN SOUTH-EASTERN POLAND

The loess-palaeosol sequences in south-eastern Poland represent both warming (or interglacial) and cooling (glacial) conditions of pedogenesis. Interglacial soils are most often represented by soil complexes, defined as superimposed soil or its constituent parts, reflecting the protracted and intricate process of pedogenesis under shifting climatic conditions. Also lower-rank (interstadial) palaeosols have been documented in loess, manifesting as one or two genetic levels.

### **Palaeosol (S5) from the Ferdynandovian interglacial (MIS 15–13)**

In the lower part of the Kolonia Zadębce loess profile, at a depth of approximately 13.8–14.2 m, probably the oldest palaeosol in south-eastern Poland has been documented (Dolecki 1995). The soil has reduced upper genetic levels and a well-developed illuvial level, described as grey-brown or olive-grey loam, strongly gleyed. The soil's development is presumed to have occurred under humid conditions, as substantiated by the presence of clay fractions (up to 34%) and iron oxides (up to 4.1%) that have penetrated deeper into the soil profile. The position of the soil between L6 and L5 loess horizons (Dzierżek and Lindner 2024), as well as the TL age indicators (Dolecki 1995) for loess (547 ka $\pm$ 82 ka), allow us to link its formation to the Ferdynandovian interglacial.

The palaeosol in the Czernica profile (Lindner 1988), located in the southern part of the Holy Cross Mts. (HCM) region, developed in the upper part of glacial till and covered with 5-meter thick loess and



Text-fig. 1. Location of selected loess-palaeosol sequences in south-eastern Poland. Blue lines – extent of the Sanian 1 (S1), Sanian 2 (S2) and Odranian (O) ice sheets. Loess-palaeosol sites: ZA – Załubińcze; OD – Odonów; CZ – Czernica; W – Wąchock; KZ – Kolonia Zadębce.

glacial deposits, likely dates from the same period. This soil has been classified by us as *Zadębce soil* (S5).

### Interstadial palaeosol from the Sanian 2 glaciation (MIS 12)

In the Załubińcze profile in the vicinity of Nowy Sącz, at a depth of 17–18.2 m, the poorly developed gley soil has been identified within lowest loess (Text-figs. 1, 2) (Nawrocki and Wójcik 1995). This is a layer of brownish-yellow clay with grey spots and rusty edges, with a thickness in excess of 1 m. TL age indicators in the range of 411–476 ka place the pedogenesis of this soil in the interstadial conditions within the San 2 glaciation (Text-fig. 2).

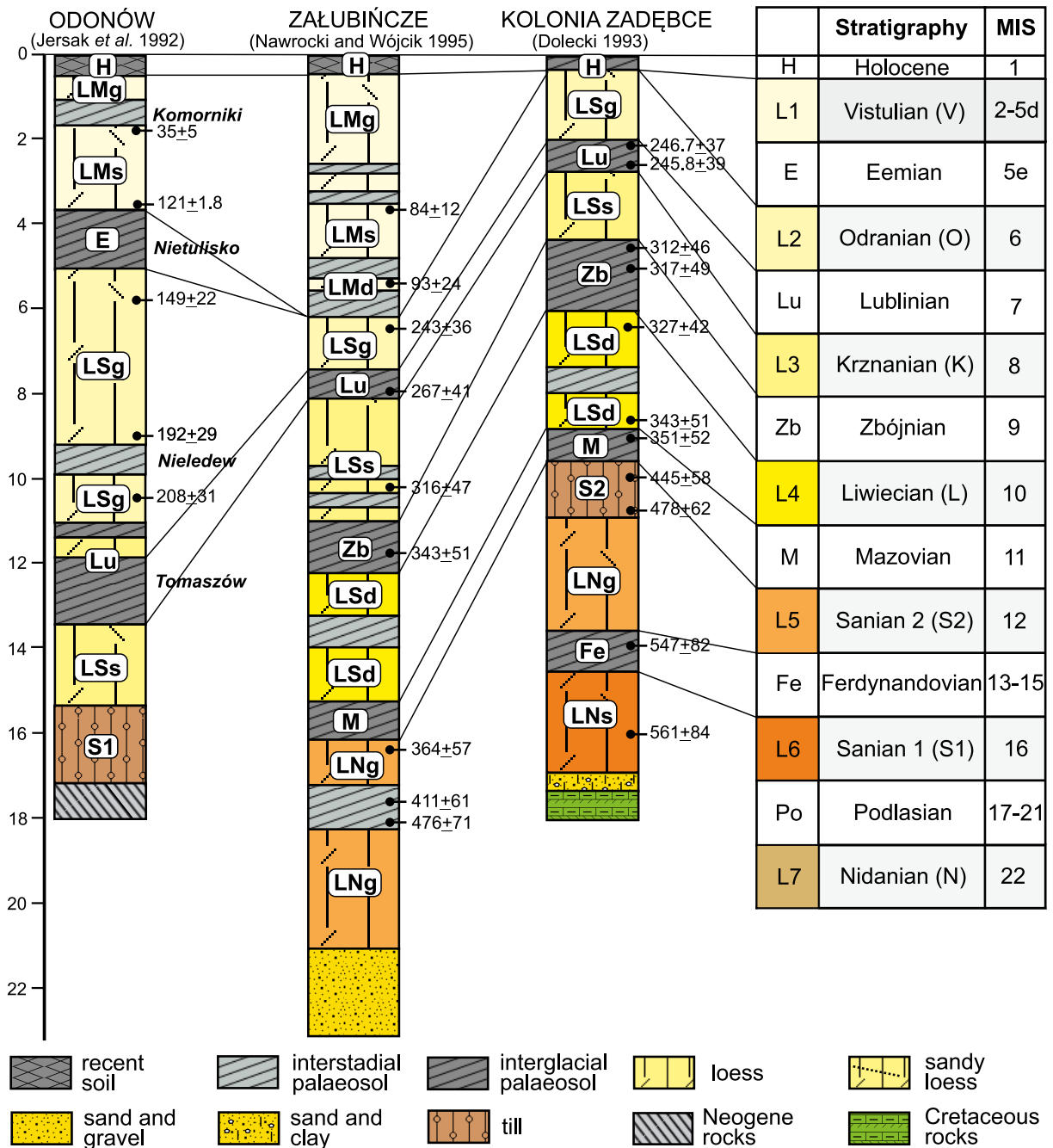
### Palaeosol (S4) from the Mazovian interglacial (MIS 11)

Also in the Załubińcze profile, at the depth of 15.2–16 m, there is a palaeosol with a poorly preserved humus layer. This layer is characterized by the presence of ash-black and grey-brown layers and patches, along with higher levels of gleying. In

turn, in the Kolonia Zadębce site, Dolecki (1995) described the genetic levels A1g-A3g-Bt-C of the well preserved palaeosol, developed on the top of glacial till at the depth of 8.5–9 m. At the Bt level, which shows signs of weathering and gleying, the proportion of iron oxides reach 2.64%, while the clay content is between 22% and 25%. Carbonates occur in cracks crossing the soil. These palaeosols, probably of the brown soil type, were formed in a temperate boreal climate dominated by coniferous and mixed forests or steppes.

The characteristics of the soil level, its position in loess profiles, the TL age indices, and the Emperor palaeomagnetic episode documented in the Załubińcze profile (Nawrocki and Wójcik 1995), allow us to link its formation to the Mazovian interglacial (Text-fig. 2).

Due to its proximity to the Boyanice profile in the western part of Ukraine and its similarity in soil formation to the Sokal Ridge (Bogucki *et al.* 1995, 1998, 2021; Lindner and Marciniak 1998; Kusiak *et al.* 2012; Łanczont *et al.* 2019), we propose to call this soil the *Sokal soil* (S4).



Text-fig. 2. Selected loess-palaeosols sequences in south-eastern Poland (based on Dzierżek and Lindner 2024). Names of loess levels according to Maruszczak 1991: LNs – oldest middle loess; LNg – oldest upper loess; LSd – older lower loess; LSs – older middle loess; LSg – older upper loess; LMd – younger lower loess; LMs – younger middle loess; LMg – younger upper loess. 547±82 – TL age indicators.

### Interstadial soil from the Liwecian cooling (MIS 10)

In the Załubińcze loess profile, at a depth of 13.2–13.95 m, a distinct gley horizon occurs, which

is manifested as light grey patches (Nawrocki and Wójcik 1995). In the Kolonia Zadębcze profile, in the analogous geological context, there is a poorly preserved soil horizon with a thickness of 0.9 m (Dolecki 1995). In the same stratigraphic position

other palaeosols were identified in other profiles in the Lublin Upland (LU), e.g., in the Stefankowice profile (Dolecki 1995). In this profile a fairly rich set of plant pollen has been identified, suggesting a boreal climate and open spaces during its development (Table 1). These conditions correspond to pedogenesis during the interstadial period within the Liwecian cooling (MIS 10).

### Palaeosol (S3) from the Zbójnian warming period (MIS 9)

In Kolonia Zadębce the full profile (A1g-A3g-Btg-C) of the next palaeosol is documented, at the depth of 4.2–6.1 m (Dolecki 1993). This soil is of grey forest type. The alluvial layer is characterized by an increased content of coarser fractions and a lower content of dust (11%) and iron oxide. The presence of charcoal in this layer is indicative of the occurrence of forest during the layer's evolution (Dolecki 1995). The illuvial horizon, with its characteristic mesh-like structure following the ground ice, exhibits an enrichment in  $\text{Fe}_2\text{O}_3$  (3.75%) and a clay fraction (up to 23%), indicative of illuviation processes. The soil is leached of carbonates, which occur in secondary form in the accumulation horizon.

In the middle part of the Załubińcze profile, at the depth of 11–12.2 m, a similar palaeosol is documented (Nawrocki and Wójcik 1995). The TL age indicators obtained for soil levels from both described profiles place them in the Zbójnian warming (interglacial) period. We define this palaeosol as *Załubińcze soil (S3)*.

### Palaeosol (S2) from the Lublinian warming (interglacial) period (MIS 7)

The younger palaeosol is recorded in several profiles in south-eastern Poland. In the Odonów profile, a well-preserved pedocomplex composed of interglacial grey forest soil overlaid by a marshy layer with chernozem is documented (Jersak 1973; Jersak *et al.* 1992). A complex system of cryogenic fissures (associated with permafrost) filled with chernozem from the upper part of the complex has developed on this soil (Jersak 1988). The fissures, which have been measured at up to 2 m deep, do not extend to the topsoil layer. It therefore follows that they must have formed earlier, probably under seasonal permafrost conditions.

In the Kolonia Zadębce profile, Dolecki (1993) describes a forest-steppe chernozem developed on loess, at a depth of 2–2.3 m. As the profile descends,

Plant species	Content (%)
<i>Pinus</i>	31.8
<i>Betula</i>	18.4
<i>Alnus</i>	4
<i>Picea</i>	3.6
<i>Corylus</i>	2.6
<i>Carpinus</i>	1.3
<i>Salix</i>	1.3
Cyperaceae	21.7
Graminae	7
<i>Artemisia</i>	4.86

Table 1. Pollen content of selected taxa in interstadial soil within loess L4, according to Bałaga (1993).

there is a marked enrichment of the sediment in  $\text{Fe}_2\text{O}_3$  (up to 3.29%) and in the colloidal fraction (up to 25%). The profile displays unambiguous indications of illuviation in the soil profile, along with evidence of chernozem degradation (Dolecki 1995).

In the Załubińcze profile within loess layer, at the depth of 6.2–9.5 m several gley horizons in the form of ashen spots in yellow silts occurred (Nawrocki and Wójcik 1995). Above the gley horizon, at 7.5 m depth, the Biwa I palaeomagnetic event was documented. This fact, combined with the contemporary interpretation of the TL data at 267.41 ka of the subject soil (Nawrocki and Wójcik 1995) allows its correlation with the Lublinian warming period (cf. Marks *et al.* 2016; Dzierżek and Lindner 2024).

In this stratigraphic position, the palaeosol in the Tomaszów profile in the eastern part of the HCM is well documented (Jersak 1973). It is named as *Tomaszów soil (S2)* and should be correlated with MIS 7 (Maruszczak 1991).

In the Odonów profile, as in several other loess profiles in south-eastern Poland, above the Tomaszów soil within the L2 loess level there is an interstadial paleosol referred to as *Nieledew soil* (Jersak 1973, Maruszczak 1991).

### Palaeosol complex (S1) from the Eemian – Early Vistulian period (MIS 5e–a)

In the upper part of the profile in Odonów (Jersak 1973, 1976b; Jersak *et al.* 1992), as in other sites in southern Poland (Jersak 1965, 1991; Maruszczak 1991; Jary 2007), there is the youngest, well-developed pedocomplex, which separates two loess levels (Text-fig. 2). It usually consists of a thick (up to 0.7 m) dark grey layer of organic accumulation A of the chernozem type, often separated by an erosive surface, and a lower layer of enrichment B or Bt of grey-forest

soil, over 1 m thick, brown in colour, clayey, with traces of iron oxides (Jary and Ciszek 2013). In the upper part of the profile, two generations of fissures with primary filling, including chernozem, are developed (Jersak 1991; Jary 2007).

The formation of the complex is attributed to the period from the Eemian interglacial to the Early Vistulian (Jersak 1977). In an analysis of multiple loess-soil profiles from this period in southern Poland and Ukraine, Jary (2007) correlated the formation of brown soil with a long-term process of pedogenesis during the Eemian interglacial (MIS 5e) under moderately warm climatic conditions. In contrast, the formation of chernozem soil types was associated with periods of warming during the Early Vistulian (Brørup MIS 5c) and Odderade (MIS 5a) stages, when the climate was moderately cool. During brief intervals of cooling in the Early Vistulian (Herning – MIS 5d, and Rederstall – MIS 5b), frost cracks formed and the lower layers of the pedocomplex were partially destroyed. The soils of this complex are readily identifiable in a multitude of profiles across southern Poland (Jary 2007; Dzierżek *et al.* 2020).

This is very important soil level in pedostratigraphy named as the *Nietulisko soil complex* (Jersak 1965, 1973; Maruszczak 1991) (S1), separated L2 and L1 level of loess.

### Interstadial palaeosol from the Vistulian glacial period (MIS 3)

Within the younger loess deposits (L1), many profiles in southern Poland describe a tundra gley and marsh soil, referred to as *Komorniki soil* (Jersak 1991; Maruszczak 1991). In the Odonów profile (Text-fig. 2), the soil is reported to have a thickness of several centimetres and is described as a grey pseudogley soil, characterized by the presence of rusty spots and ferruginous precipitates. Most probably, the formation of this soil has occurred during a period of Pleniglacial warmer conditions (cf. Dzierżek *et al.* 2020). The pedogenesis process took place in conditions of excessive moisture associated with the summer thawing of ground ice (Jersak 1991, 1993).

## DISCUSSION

The reconstruction of palaeoenvironment based on the analysis of soils is not always easy and complete. There are at least three reasons for this. Firstly, botanical material (i.e. pollen and plant remains) is typically scarce and destroyed by soil processes in

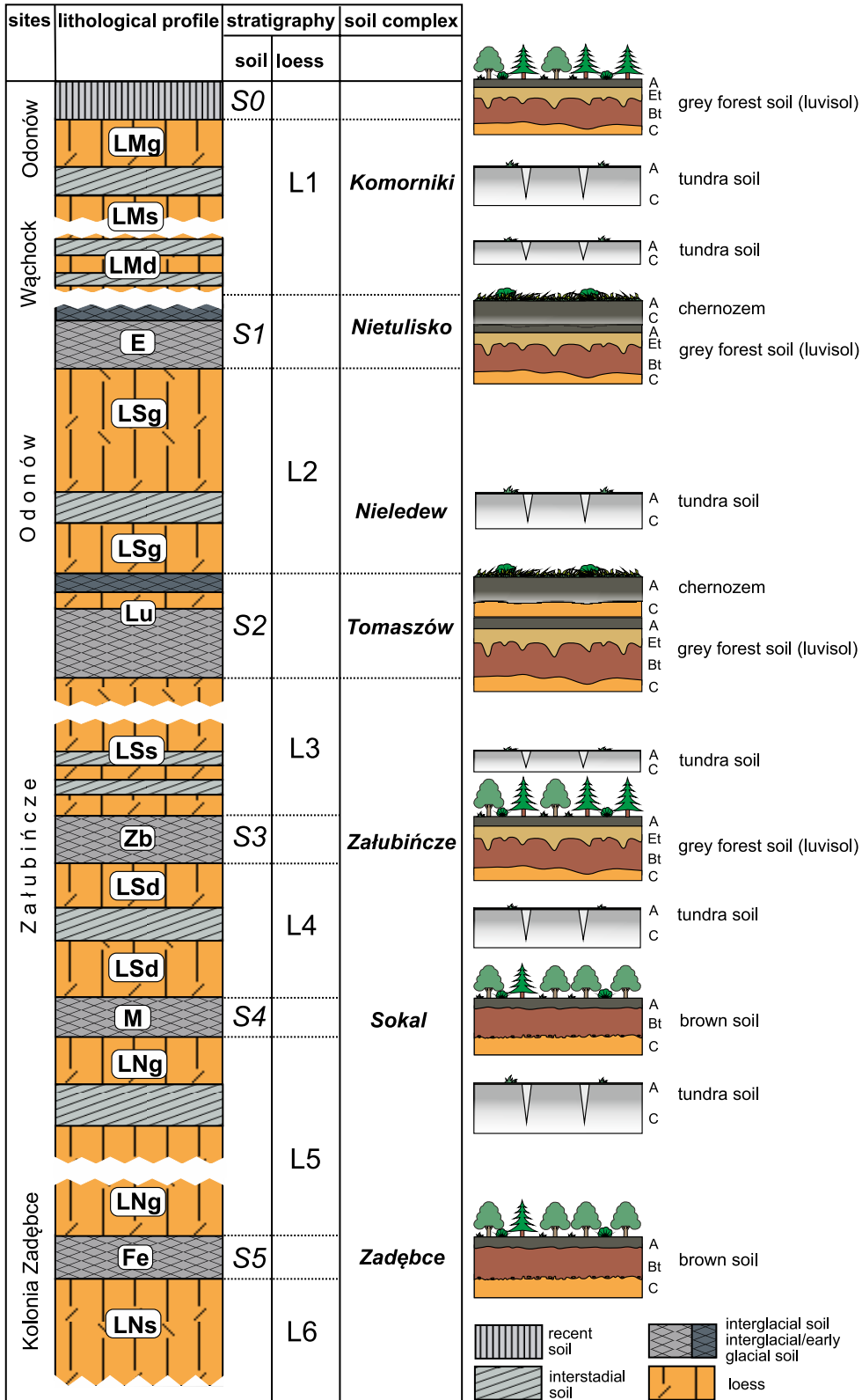
palaeosols. Secondly, profiles located on plateaus or slopes are often discontinuous due to erosion or washing out. Thirdly, in palaeosols, there is a possibility of overlapping paleoenvironmental signals from several periods with different characteristics. Nevertheless, a collective analysis of data preserved in soils provides interesting information not only about the conditions for the development of individual soils, but also about the variability of these conditions in time and space (cf. Komar *et al.* 2009).

In the region of south-eastern Poland, five Pleistocene soils or pedocomplexes (S1–S5) has been documented, in accordance with the current stratigraphic division of the Pleistocene (Marks 2023; Dzierżek and Lindner 2024).

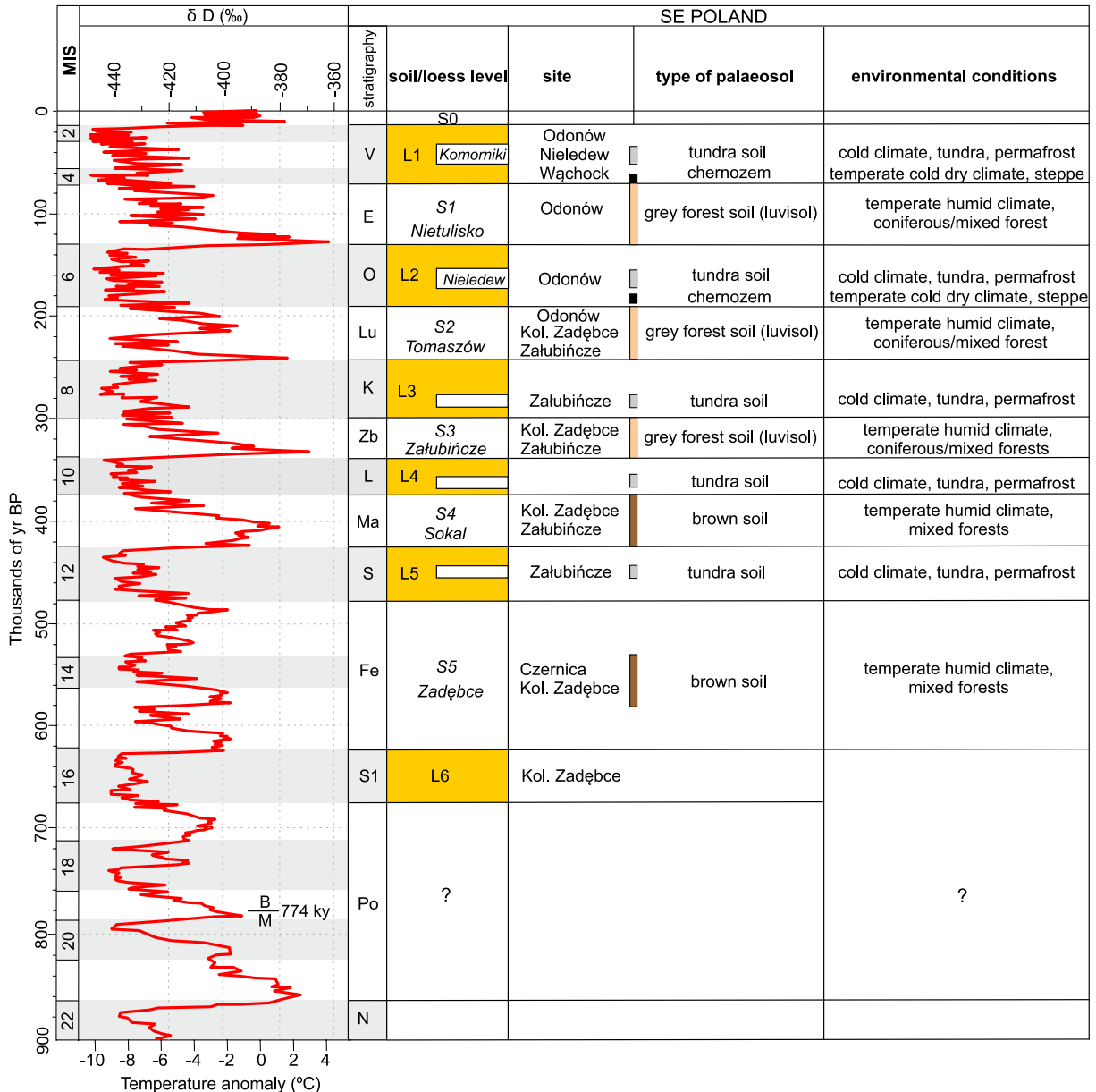
The combined loess-soil profile of south-eastern Poland (Text-fig. 3) is composed of individual sections of soil profiles described in selected sites. It represents merely the younger part of the Pleistocene evolution of loess and palaeosols, in comparison to the profiles of northern France (Antoine *et al.* 2015, 2021; Antoine and Limondin-Lozouet 2024), the Danube region (Marković *et al.* 2011; 2015; Sümegi *et al.* 2020) and Ukraine (e.g. Bogucki *et al.* 1980; Gerasimenko 2000, 2006; Łanczont *et al.* 2019; Alexandrowicz *et al.* 2025). However, it should be noted that the aforementioned point complements paleoenvironmental and climatostratigraphic considerations in the region where loess occurs within the range of the Scandinavian ice sheets (Text-fig. 4, Lindner *et al.* 2004).

### Environmental conditions of Pleistocene pedogenesis

It is relatively easy to assess the climatic conditions that prevailed during the formation of poorly developed fossil soils with traces of gleying. These occurrences manifest as thin layers, particularly in younger loess (L1), during brief intervals in aeolian accumulation. Gleying is defined as the result of biochemical deoxygenation of mineral matter in conditions of high humidity and in the presence of organic matter. It is a characteristic phenomenon of tundra conditions (Jersak 1976b; Maruszczak 1991; Dolecki 1993; Jary 2007; Systematyka gleb Polski 2019). Consequently, the reduction processes in the sediment result in the transformation of iron compounds from trivalent to divalent, and the substrate assumes a greenish-blue coloration, frequently manifesting as ash grey or greyish. In their seminal study of contemporary soils in wet tundra areas, Klimowicz and Uziak (1995) emphasised the pivotal



Text-fig. 3. Synthetic profile of loess and palaeosols in south-eastern Poland (based on: Jersak *et al.* 1992; Dolecki 1993; Nawrocki and Wójcik 1995; Dzierżek *et al.* 2020) in relation to contemporary soil profiles. Symbols of soils and loess levels based on Łanczont *et al.* 2019; Dzierżek and Lindner 2024; Alexandrowicz *et al.* 2025).



Text-fig. 4. Environmental conditions for soil development in south-eastern Poland against the background of the Pleistocene climate change curve (Yozuel *et al.* 2007; Lisiecki and Raymo 2005). Stratigraphy based on Dzierżek and Lindner (2024). B/M – Brunhes-Matuyama reversal and its age.

role of moisture from permafrost thawing. Based on actual comparisons, Uggla (1981) determined that tundra soils were formed at the mean temperature of the warmest month (MTW) ranging from +10 to +15°C. However, it should be remembered that many studies suggest regional differentiation of climate characteristics in the latitudinal direction (continentalisation) (cf. Alexandrowicz *et al.* 2025). According to Gerasimenko (2000), the formation

of the interstadial soil in loess L1 took place in a cold and continental climate, with a predominance of meadow steppes and meadows, and a scarcity of deciduous trees (Text-fig. 4). The existence of a cold steppe-forest steppe environment was identified during the early Weichselian glaciation, a period during which the interstadial palaeosol developed in the Great Hungarian Plain (Sümeği *et al.* 2013, 2015).

Interpretation of the climatic conditions that prevailed during the development of thicker and more complex soils is more challenging. The pedogenesis period has been found to be significantly longer (cf. Jersak 1991; Sümegei *et al.* 2020), encompassing both variable palaeoclimatic conditions during interglacials and subsequent interstadials. The *Nietulisko soil complex (S1)* in many profiles in south-eastern Poland is recorded as a very well-developed interglacial–interstadial pedocomplex (Eemian–Early Glacial), consisting of lessive soil and superimposed chernozem (Jersak 1991). Komar *et al.* (2009) hypothesize that the region under study was dominated by open forest environments, which were later replaced by mixed forests and closed boreal environments. These authors believe that during the first phase of soil formation processes in the Eemian interglacial the summer temperature (MTW) in this area ranged from +13.6°C to +21.5°C (Komar *et al.* 2009). This roughly corresponds to the estimates of Uggla (1981), who determined the temperature necessary for the development of these soils to be from +15 to +20°C. During the brørup pedogenesis the vegetation is characterized by open spaces with patches of pine and birch forests (Komar *et al.* 2009).

Similarly, the *Tomaszów soil complex (S2)* correlated with the Lublin interglacial (MIS 7) developed over a long time in conditions of changing climate and vegetation cover. During the warmest period of pedogenesis in Central Europe, boreal taiga forests prevailed, which was conducive to the formation of forest soil (Gerasimenko 2006). However, temperature curves (Lisiecki and Raymo 2005) suggest that this period was several degrees cooler than the Eemian interglacial period. This is also confirmed by the analysis of malacofauna in loess-soil profiles in northern France, which shows that the climate in MIS 7 in western Europe was colder and drier than in other Pleistocene interglacial periods (Antoine and Limondin-Lozouet 2024). Janczyk-Kopikowa (1991) posits that the conditions that prevailed during the formation of this soil in south-eastern Poland may be comparable to those of a warm interstadial. The layer of chernozem resting on forest soil was formed during the initial phases of the subsequent cold period (MIS 6, Odranian Glaciation, Text-fig. 3). During this period, park or forest-steppe vegetation was predominant in the area under discussion, thereby contributing significantly to the development of chernozem through the production of substantial amounts of humus (Maruszczak 1991; Gerasimenko 2006).

The hypothesis that the scheme of soil complex formation from the interglacial period to the onset of glaciation can also be applied to older cycles is supported by studies of loess-soil profiles in the upper Dniester River basin (Łanczont *et al.* 2019). Also Antoine and Limondin-Lozouet (2024) believe that the pattern of climate and environmental changes recorded in long loess-soil sequences in northern France repeats for all interglacial–early glacial cycles from MIS 11 to MIS 5 and is expressed by the following pattern: Bt horizon of brown leached soil, Bth horizon of grey forest soil, and Ah horizon of humic soil.

The palaeosol of *Zahubińcze type (S3)* was formed during the optimal part of the Zbójnian warming period, primarily as grey forest soil under a temperate humid climate and boreal environment. The presence of solifluction traces in the upper layers of the soil suggests a periglacial climate that is slightly colder and wetter (Dolecki 1993; Nawrocki and Wójcik 1995). In the upper Dniester river basin (Łanczont *et al.* 2019), long-lasting soil processes during the Zbójnian warming (MIS 9) led to the almost complete transformation of the lower-lying Liwiecian loess (L4).

The process of soil pedogenesis *S4 (Sokal)*, during the Mazovian interglacial (MIS 11), was also long and varied regionally as evidenced by numerous Ukrainian profiles, particularly the Dubrivka profile. This is recorded in the form of a thicker (1–4 m) mature luvisol, with a very well-developed Bt horizon and a well-developed Et horizon. The presence of pollen from coniferous species such as pine, Swiss pine, spruce, fir, heather, ferns, club mosses, and herbaceous plants characteristic of coniferous forests, along with alder and willow, indicative of wetlands, suggests a temperate climate (Łanczont *et al.* 2019).

However, we would like to emphasize that the temperature reconstructions cited above may be subject to significant error, as pointed out by the authors of these analyses themselves (Komar *et al.* 2009; Marković *et al.* 2021; Radaković *et al.* 2023). This is due to the inaccuracy of the method and the wide variation in local palaeoclimatic conditions.

### Trans-regional stratigraphic correlation of palaeosols

The aggregate loess-soil sequence obtained from south-eastern Poland is an encouragement for stratigraphic correlation with long profiles from Ukraine and other regions of Europe (Text-fig. 5). The Saint-Pierre-Lés-Elbeuf profile in France, reanalyzed by Coutard *et al.* (2019) and Antoine and Limondin-Lozouet (2024),

was known to Polish researchers thanks to the work of Laotridou (1982) and cited in an academic textbook on Quaternary geology (Lindner 1992). The four soils preserved in this profile (Elbeuf I–IV) document the warming, probably of an interglacial nature, prevailing in the Massif Central: Ribains, Le Bochet, Landos, Praclaux (Reille and de Beaulieu 1995; Reille *et al.* 2000). These warming periods correspond to the same Pleistocene stages that have been documented in Poland in the fossil lake deposits (Text-fig. 5; cf. Lindner and Marciniak 1998, 2008). Recently, Pidek *et al.* (2022) also point out that the interglacial warming events described in the Massif Central, younger than MIS 11 (Holstein=Praclaux), show similar climatic conditions (cf. de Beaulieu *et al.* 2001). Therefore, in Poland, in the case of the Zbójnian (cf. Lindner and Brykczyńska 1980) or Lublinian (Krupiński and Marks 1986) floristic succession, it cannot be ruled

that they represent new “Eemian-like” interglacials (cf. Pidek *et al.* 2022). The stratigraphic correlation of the lower part of the Pleistocene is supplemented by sites in Normandy, primarily the extremely important Grâce-Autoroute profile (Antoine *et al.* 2021; Antoine and Limondin-Lozouet 2024). Regional correlation of interstadial soils distinguished in Polish SE profiles is not possible at this time.

In south-eastern Poland, no palaeosol from the Podlasiian interglacial (MIS 21–17) has been documented to date. In Ukraine, the Zahvizdya soil complex (S8–S6) has been linked to this climatic warming in long loess profiles, with the Brunhes-Matuyama reversal being maintained (Łanczont *et al.* 2019). However, soils of this age are also likely to occur in northern France (Coutard *et al.* 2019; Antoine *et al.* 2021) and in the Danube Basin (Marković *et al.* 2011, 2015).

MIS	Chronostratigraphy		Main loess (L) and soil complexes (S)					
	Western Europe (Gibbard and West 2020; Marks 2023, Antoine and Limondin-Lozouet 2024)	Holy Cross Mts (Dzierżek and Lindner 2019)	Northern France (Antoine <i>et al.</i> 2020; Coutard <i>et al.</i> 2019)		Western Ukraine (Łanczont <i>et al.</i> 2019)	SE Poland (this paper)		
			Grâce- Autoroute	St. Pierre lès Elbeuf				
1	Holocene	Holocene	Holocene	Holocene	Holocene	S0	Holocene	
2- 5d	Weichselian	Vistulian	loess	loess	L1			
5e	Eemian	Eemian	Grâce I	Elbeuf I 164±12 ka	Horokhiv	S1	Nietulisko	
6	Saalian complex	Drenthe+Warthe	Odranian	loess	loess	L2		
7		Interglacial Intrasaale 2	Lublinian	Grâce II	Elbeuf II 292±23 ka	Korshiv	S2 Tomaszów	
8		Wacke+Dömnitz	Krznanian	sandy loess	loess	L3		
9		Interglacial Intrasaale 1	Zbójnian	Grâce III	Elbeuf III 310±25 ka	Lutsk	S3 Załubińcze	
10		Fuhne	Liwiecian	sandy loess	loess	L4		
11	Holsteinian	Masovian	Grâce IV	Elbeuf IV	Sokal	S4	Sokal	
12	Elsterian	Sanian 2	slope deposits	sandy loess 475±38 ka	L5			
13 14 15	Cromerian complex	Cromerian IV	Ferdynandovian	Grâce V		Solotvyn	S5	Zadębcze
		Glacial C		sandy loess				
		Cromerian III		Grâce VI				
16		Glacial B	Sanian 1	sandy loess		L6		
17 18 19- 21		Cromerian II	Podlasiian	Grâce VII			Zahvizdya	S6- S8
	Glacial A	B/M 774 ka	sandy loess		B/M		?	
	Cromerian I							
22	Dorst	Nidanian	?		L7			

Text-fig. 5. Age position and stratigraphic correlation of the main levels of loess (L) and interglacial palaeosols (S) in the Pleistocene of selected areas of Europe. B/M – Brunhes-Matuyama reversal and its age.

The oldest *Zadębce soil (S5)*, correlated with the Ferdynandovian interglacial (MIS 15–13) distinguished in the Kolonia Zadębce and Czernica profiles, were recommended to be linked with the Solotvyn soil (Łanczont *et al.* 2019). The Grâce V soil is located in this age position within the Grâce-Autoroute profile in northern France (Antoine and Limondin-Lozouet 2024), and is correlated with interglacial IV in the Cromerian complex. It is noteworthy that this profile also contains two older soils, Grâce VI and Grâce VII, which are separated by layers of sandy loess (Text-fig. 5). We suggest that the younger soil recorded in the Kolonia Zadębce and Załubińcze profiles, correlated with the Mazovian interglacial (MIS 11), connects with *Sokal soil (S4)* in western Ukraine (Łanczont *et al.* 2019), and name it the same. In the profiles of northern France, soil levels Grâce IV (Antoine and Limondin-Lozouet 2024) and Elbeuf IV (Coutard *et al.* 2019) correlate with the MIS 11 (Holsteinian=Pracaux interglacial) (Reille and de Beaulieu 1995; Reille *et al.* 2000).

Another younger *Zalubińcze soil (S3)*, identified in the Kolonia Zadębce profile, correlated with the warming of the Zbójnian (MIS 9), in Ukrainian profiles, corresponds to the Lutsk soil (Bogucki *et al.* 1995; Łanczont *et al.* 2019). In northern France, they correspond to Grâce III soils (Antoine and Limondin-Lozouet 2024) and Elbeuf III soils—dated to  $310 \pm 25$  ka (Coutard *et al.* 2019). This soil was correlated with the Landos interglacial (Reille and de Beaulieu 1995; Reille *et al.* 2000), and currently with the Intrasaale 1 interglacial (Text-fig. 5).

Conversely, the well-developed soil complex, designated as *Tomaszów soil (S2)* in south-eastern Poland, is associated with the Lublinian warming (MIS 7). The proposal is to assign it to the Korshiv soil in western Ukraine and Kaydaky in central Ukraine (Łanczont *et al.* 2019). In the Grâce-Autoroute profiles, the equivalent is the Grâce II soil level (Antoine and Limondin-Lozouet 2024), and the Elbeuf II level, dated to  $292 \pm 23$  ka (Coutard *et al.* 2019). French researchers have associated the formation of these soils with the Intrasaale 2 interglacial, formerly known as Le Bochet (Reille and de Beaulieu 1995).

The formation of the *Nietulisko soil complex (S1)*, which is clearly visible in numerous profiles in south-eastern Poland, is associated with the last interglacial period (Eemian) and the beginning of the last glaciation (Vistulian). This complex has been shown to correlate with complexes in Ukraine: including Mezin (Velichko 1995) and Pryluky (Veklich 1979; Gozhik 1995; Lindner *et al.* 2004). In the scheme developed by Łanczont *et al.* (2019), this soil level

(*S1*) is designated as Horokhiv soil (Bogucki 1987). In profiles from northern France, the equivalents of this complex are the Grâce I levels, with a condensed lithological record (Antoine and Limondin-Lozouet 2024) and Elbeuf I (Coutard *et al.* 2019).

## CONCLUSIONS

The selected loess-soil sequences described in south-eastern Poland have been shown to accurately reflect the rhythm of climate change in the Middle and Late Pleistocene. These sequences are recorded in a composite profile in loess levels from L6 (MIS 16) to L1 (MIS 2), separated by interglacial soils from *S5* (MIS 15–13) to *S1* (MIS 5e) and interstadial soils.

- Older interglacial soils: *S5 – Zadębce*, from the Ferdynandovian interglacial (MIS 15–13) and *S4 – Sokal* from the Mazovian interglacial (MIS 11) were developed in a temperate warm and humid climate, most often as brown soils, in mixed and deciduous forest environments.
- Soils of younger interglacial periods: *S3 – Zalubińcze* from the Zbójnian interglacial period (warming) (MIS 9), *S2 – Tomaszów* from the Lublinian interglacial (warming) (MIS 7) and *S1 – Nietulisko* from the Eemian interglacial developed in a temperate warm and humid climate, most often as forest soils, in mixed and coniferous forest environments.
- The *S2 – Tomaszów* and *S1 – Nietulisko* soils, pedocomplexes in which the interglacial soil is covered with a humus layer of chernozem, were developed in a moderately cool and dry climate, in a steppe or park environment, representing the younger early glacial phase.
- Tundra soils (initial) documented in almost all loess levels in south-eastern Poland developed in a cold, periodically humid climate with sparse vegetation. So far, the two youngest interstadial soils have their own stratigraphic names: *Komorniki* within loess L1 (MIS 3 – Vistulian, Weichselian) and *Nieledew* within loess L2 (MIS 6 – Odranian).
- Our analyses have supported the views on regional variation in types and characteristics of palaeosols within loess profiles in Poland.
- The palaeosols documented in south-eastern Poland correlate with the corresponding sections of long loess-soil sequences in Ukraine (Łanczont *et al.* 2019) and other regions of Europe outside the range of Pleistocene ice sheets (Coutard *et al.* 2019; Antoine and Limondin-Lozouet 2024).

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