Pleistocene climate fluctuations recorded in the magnetic susceptibility of the most complete East European loess-palaeosol sequences and regional stratigraphic correlation

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1 Introduction

The cyclical structure of loess-palaeosol deposits reflects the patterns of climate change and is a valuable archive of palaeoenvironmental information. The similarity of magnetic susceptibility (MS) variations and other indicators of palaeoclimate (ratio of oxygen isotopes etc.) in coeval marine sediments confirms the viability of palaeoclimatic reconstructions. Additionally, palaeomagnetic methods (magnetostratigraphy) are successfully used in establishing independent chronologies in a wide range of geological archives.
Loess-palaeosol deposits occupy 70% of the territory of Ukraine and are unique in Europe in terms of their stratigraphic completeness. A lack of reliable data from this area, which is exceptionally rich in most complete Quaternary sequences, reduces the quality of overall palaeoclimatic reconstructions. The aim of our work was to correlate the amplitudes of established palaeoclimatic change with those of the global marine oxygen isotope (MIS) scale (Shackleton et al., 1990), performed by rock magnetic and palaeomagnetic research on two key loess-palaeosol sections of Ukraine as well as integration of Ukrainian pedostratigraphy into the pan-Eurasian stratigraphic schemes (Marković et al., 2015; Sümegi et al., 2018).

2 Regional setting and methods

The Roksolany section is located on the coast of the Dniester estuary west of Roksolany village (46°11' N; 30°26' E), 40 km south of Odesa. This is one of the most representative exposures of Pleistocene loess in the western Black Sea region. The succession was originally classified by Gozhik et al. (1995). It contains nine main soil units, interbedded with thick loess layers, almost 55 m thick. Furthermore, the uppermost 30 m of the section including two well-developed palaeosols until recently was correlated with MIS 2-4 (Gozhik, Bogucki, Łanczont et al., 1995-2018, cited in Hlavatskyi and Bakhmutov, 2020).
The Vyazivok section is located in Vyazivok village (49°57' N; 32°57' E), 180 km SE of Kyiv, on the western bank of the River Sula, a tributary of the Dnieper. Described for the first time by Veklich et al. (1967), it remains to be known as one of the most complete Quaternary records in Eastern Europe and the most complete section studied within the formerly glaciated Middle Dnieper area (Matviishina, Gerasimenko et al., 2001-2016). This is an almost 59 m thick sequence of eight strongly developed palaeosols which alternate with thick loess units. Evidence of erosional hiatus of the Potyagaylivka soil (pt, V-S2), Oril (or, V-L3) and Middle Zavadivka (zv2, V-L4) loess units has not affected the final interpretation of our findings.

In the present work high-resolution MS measurements were implemented on 802 samples collected at Roksolany and on 749 samples from the Vyazivok section. To avoid potential future confusions, a simplified provisional nomenclature adapted from the Chinese and Danube (Marković et al., 2015) loess labelling system was used for the lithostratigraphic description. Updated magnetostratigraphic interpretation (Hlavatskyi and Bakhmutov, 2020) has been used as means to derive a revised chronostratigraphy.

3 Results and discussion

Our results revealed a strong variability of loess deposition and pedogenesis at Roksolany and Vyazivok during the past 1 Ma. Relatively weak susceptibility values in loess units show a small fluctuation (5–10×10^{-8} m^3kg^{-1}), while these values in soils are much higher (up to 50-80×10^{-8} m^3kg^{-1}). The strong correspondence between the MIS variations and MS patterns implies a complete palaeoclimate record in the area (Fig. 1). A comparison of magnetic susceptibility, palaeomagnetic data, palaeoenvironmental properties and accumulation rates has led us to the following interpretation.

The uppermost palaeosol R-L1S1 (our nomenclature; Prychornomorya unit, pc, after Gozhik et al., 1995) at Roksolany and V-L1S1 (Vytachiv unit, vt, after Veklich et al., 1967) at Vyazivok, represented by weakly developed brownish soils, in our opinion, correspond to interstadial MIS 3.

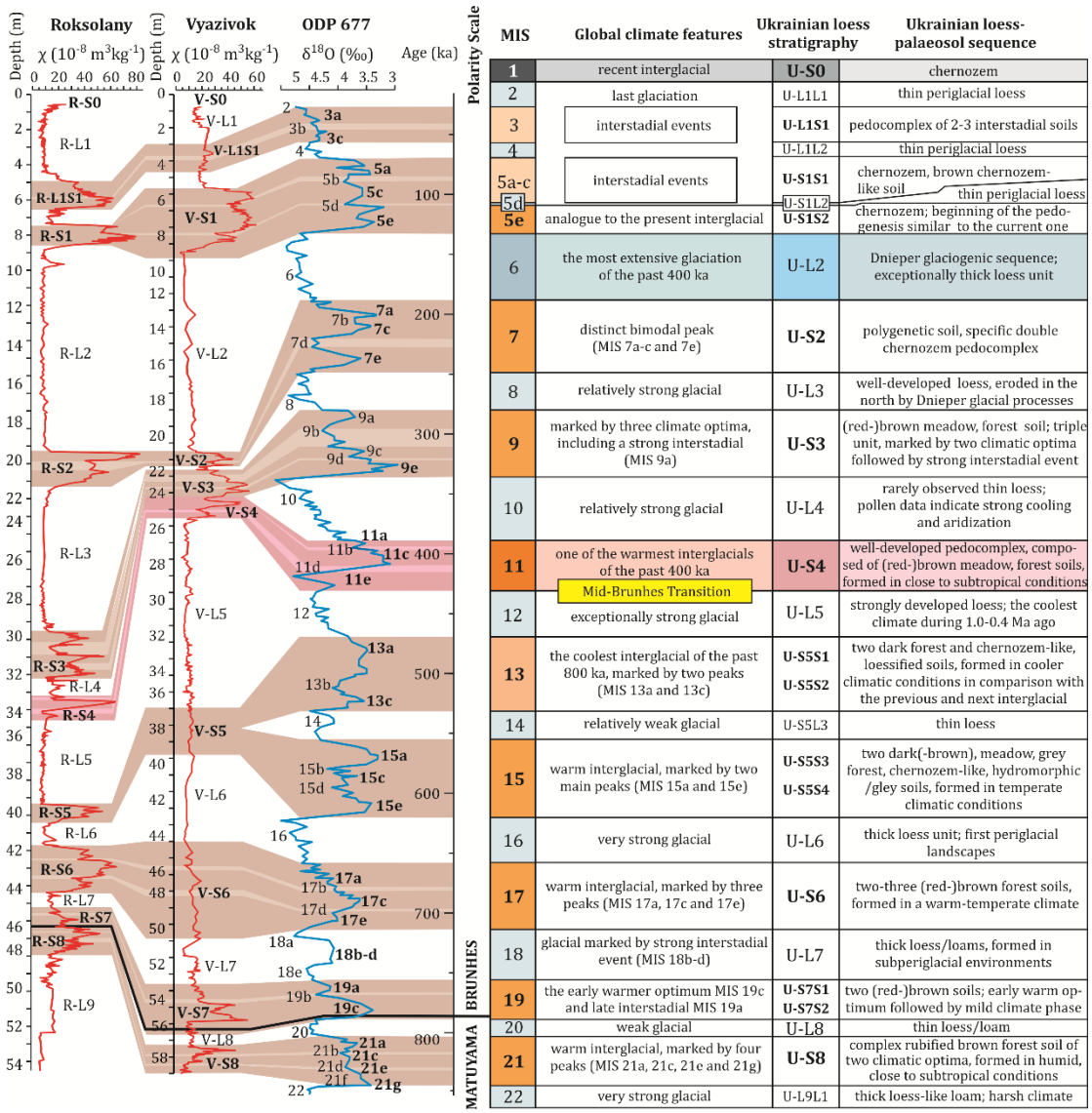
The R-S1 (considered as Dofinivka, df) and V-S1 (welded Pryluky, pl, and Kaydaky, kd) pedocomplexes, represented by grey and brown chernozem-like soils, by the specific MS pattern are clearly correlated with MIS 5 (Fig. 1). Consequently, the thickest R-L2 (considered as Bug, bg) and V-L2 (Dnipro, dn) loess units correspond to MIS 6 (and not to MIS 2 and MIS 8 as proposed by Gozhik et al., 1995). This is supported by OSL dating results obtained in different loess sections (see review in Hlavatskyi and Bakhmutov, 2020).

The R-S2 (Vytachiv) and V-S2 (Potyagaylivka) palaeosol units, represented by polygenetic (chernozem-like, with signs of rubification at Roksolany) soils, in our view, are correlated with the double chernozem pedocomplex S2 in the Danube loess sequence, corresponding to MIS 7 (Fig. 1).

The specific Roksolany profile triple red-brown pedocomplex R-S3 (Pryluky) and strongly developed brown palaeosol complex V-S3 (Upper Zavadivka, zv_3) at Vyazivok, also composed of three soils, taking into account pedological features and characteristic MS structures are securely correlated with MIS 9. The upper strong interstadial soil (zv_{3c}) in both sections corresponds to MIS substage 9a (Fig. 1).

Well-developed rubified pedocomplex R-S4 (Kaydaky) at Roksolany and brown palaeosol complex V-S4 (Lower Zavadivka, zv_1) at Vyazivok, both formed in wetter and warmer climatic conditions, are clearly correlated with very warm interglacial MIS 11 (Fig. 1). Strongly developed loess units R-L5 (Dnipro) and V-L5 (Tyligul, tl) thereby correlate with one of the strongest glaciation of the Pleistocene, MIS 12.

Weakly developed reddish-brown soil R-S5 (Potyagaylivka after Gozhik et al., 1995) at Roksolany we consider as a truncated palaeosol corresponding to MISs 13-15. The coeval V-S5 (Lubny, lb) palaeosol unit at Vyazivok is represented by three chernozem-like, meadow, brown, grey forest, and hydromorphic/gley soils, formed in a more temperate climate, than Lower Zavadivka soils. Similar pedological features are characteristic of the H-S5 pedocompex (MIS 13-15) in the Hungarian loess sequence (Sümegi et al., 2018). The coeval weakly developed soil V-L6S1 is observed in Vojvodina loess-palaeosol sequence, but not present at the nearest Romanian and Bulgarian loess profiles. Therefore, the Zavadivka superunit contains two interglacial soil units (MIS 9 and MIS 11), separated by thin periglacial loess zv_2 (MIS 10).



MIS	Global climate features	Ukrainian loess stratigraphy	Ukrainian loess-palaeosol sequence
1	recent interglacial	U-S0	chernozem
2	last glaciation	U-L1L1	thin periglacial loess
3	interstadial events	U-L1S1	pedocomplex of 2-3 interstadial soils
4		U-L1L2	thin periglacial loess
5a-c	interstadial events	U-S1S1	chernozem, brown chernozem-like soil
5d		U-S1L2	thin periglacial loess
5e	analogue to the present interglacial	U-S1S2	chernozem; beginning of the pedogenesis similar to the current one
6	the most extensive glaciation of the past 400 ka	U-L2	Dnieper glaciogenic sequence; exceptionally thick loess unit
7	distinct bimodal peak (MIS 7a-c and 7e)	U-S2	polygenetic soil, specific double chernozem pedocomplex
8	relatively strong glacial	U-L3	well-developed loess, eroded in the north by Dnieper glacial processes
9	marked by three climate optima, including a strong interstadial (MIS 9a)	U-S3	(red-)brown meadow, forest soil; triple unit, marked by two climatic optima followed by strong interstadial event
10	relatively strong glacial	U-L4	rarely observed thin loess; pollen data indicate strong cooling and aridization
11	one of the warmest interglacials of the past 400 ka	U-S4	well-developed pedocomplex, composed of (red-)brown meadow, forest soils, formed in close to subtropical conditions
	Mid-Brunhes Transition		
12	exceptionally strong glacial	U-L5	strongly developed loess; the coolest climate during 1.0-0.4 Ma ago
13	the coolest interglacial of the past 800 ka, marked by two peaks (MIS 13a and 13c)	U-S5S1 U-S5S2	two dark forest and chernozem-like, loessified soils, formed in cooler climatic conditions in comparison with the previous and next interglacial
14	relatively weak glacial	U-S5L3	thin loess
15	warm interglacial, marked by two main peaks (MIS 15a and 15e)	U-S5S3 U-S5S4	two dark(-brown), meadow, grey forest, chernozem-like, hydromorphic /gley soils, formed in temperate climatic conditions
16	very strong glacial	U-L6	thick loess unit; first periglacial landscapes
17	warm interglacial, marked by three peaks (MIS 17a, 17c and 17e)	U-S6	two-three (red-)brown forest soils, formed in a warm-temperate climate
18	glacial marked by strong interstadial event (MIS 18b-d)	U-L7	thick loess/loams, formed in subperiglacial environments
19	the early warmer optimum MIS 19c and late interstadial MIS 19a	U-S7S1 U-S7S2	two (red-)brown soils; early warm optimum followed by mild climate phase
20	weak glacial	U-L8	thin loess/loam
21	warm interglacial, marked by four peaks (MIS 21a, 21c, 21e and 21g)	U-S8	complex rubified brown forest soil of two climatic optima, formed in humid, close to subtropical conditions
22	very strong glacial	U-L9L1	thick loess-like loam; harsh climate

Figure 1 Correlation of magnetic susceptibility (χ) of Roksolany and Vyazivok loess-palaeosol sections with the marine oxygen isotope (δ18O) record from ODP site 677 (Shackleton et al., 1990) (left) and comparison of major palaeoclimate events and palaeoenvironmental character of loess-palaeosol succession of Ukraine (right). Ukrainian loess stratigraphic nomenclature and the position of the Matuyama–Brunhes boundary after Hlavatskyi and Bakhmutov (2020).

Well-developed reddish-brown palaeosols R-S6 (Zavadivka) at Roksolany and V-S6 (Martonosha, mr) at Vyazivok have been preliminarily correlated with MIS 17. The Matuyama–Brunhes boundary (780 ka) has been detected in the base of palaeosol units R-S7 (Lubny) and V-S7 (Shyrokyne, sh), respectively (Hlavatskyi and Bakhmutov, 2020). We conclude that the reversal in both sections belongs within the same palaeosol unit, the Shyrokyne (and not the Martonosha as suggested by Gozhik et al., 1995), which corresponds to MIS 19.

Reddish-brown sandy palaeosol R-S8 (Martonosha) at Roksolany has been identified as an equivalent of the V-S8 (Kryzhanivka, kr) rubified brown forest soil at Vyazivok corresponding to MIS 21. Thick Roksolany profile loess unit R-L9 (previously considered as Pryazovya, pr) corresponds to the specific thick loess unit L9 (MIS 22-24) seen on the Danube and Chinese

loess-palaeosol sequence, the thickest one below the Matuyama–Brunhes boundary (Fig. 1). Below the Kryzhanivka unit, Veklich et al. (1967) described in different areas of Ukraine the Berezan (br) loess-like loams and the Beregove (bv) red and brick-red calcareous soils and clays, in our opinion, corresponding to MISs 22-24 and 25-(?), respectively.

Table 1. Correlation of the Quaternary stratigraphic schemes of Ukraine with national loess stratigraphies in the Danube Basin and China, and with the marine isotope stratigraphy

Central Ukraine (Dyazivok; Veklich et al., 1967)	Southern Ukraine (Roksolany; Gozhik et al., 1995)	Ukraine (Hlavatskyi and Bakhmutov, 2020)	Hungary (Sümegi et al., 2018)	Serbia (except Mošorin; Marković et al., 2015)	Romania (Mircea Voda /Zimnicea)	Chinese Loess Plateau	MIS
hl	hl	U-S0	H-S0	V-S0	S0	S0	1
bg		U-L1L1	H-L1L1	V-L1L1	L1L1	L1LL1	2
vt	pc	U-L1S1	H-L1S1	V-L1S1	L1S1	L1SS1	3
ud		U-L1L2	H-L1L2	V-L1L2	L1L2	L1LL2	4
pl+kd	df	U-S1	H-S1	V-S1	S1	S1	5
dn	bg	U-L2	H-L2	V-L2	L2	L2	6
pt	vt	U-S2	H-S2	V-S2	S2	S2	7
or	ud	U-L3	H-L3	V-L3	L3	L3	8
zv_3	pl	U-S3	H-S3	V-S3+V-S4	S3 /S3+S4	S3	9
zv_2	ts	U-L4	H-L4	V-L5	L4 /L5	L4	10
zv_1	kd	U-S4	H-S4	V-S5	S4 /S5	S4	11
tl	dn	U-L5	H-L5	V-L6L1	L5/ L6	L5	12
lb	pt	U-S5	H-S5	V-L6S1		S5	13-15
sl	or	U-L6	H-L6	V-L6L2		L6	16
mr	zv	U-S6	H-S6	V-S6	S6 /S6S1	S6	17
pr	tl	U-L7	H-L7	V-L7		L7	18
sh	lb	U-S7	H-S7	V-S7	S7 /S6S2	S7	19
il	sl	U-L8	H-L8	V-L8		L8	20
kr (sh_1?)	mr	U-S8	H-S8	V-S8		S8	21
br_3	il	U-L9L1	H-L9	V-L9	L7	L9LL1	22
br_2 (kr_3?)	(sh?)	U-L9S1	(upper H-S9)	L9SS1 (V-S9)		L9SS1	23
br_1		U-L9L2				L9LL2	24
v_3 (kr_1?)		U-S9	H-S9	Basal complex		S9	25

In Table 1 we present regional correlation scheme between loess stratigraphies in Ukraine, southeastern Europe, China, and the MIS scale. Our correlations support the recent Eurasian stratigraphic model proposed by Sümegi et al. (2018).

4 Conclusions

Application of the MS record in the best developed loess-palaeosol sequences of Ukraine allowed their precise correlation and resolved a number of urgent stratigraphic issues: the timing of the Dnieper glaciation (U-L2; MIS 6); the pedostratigraphic position of the weakly

developed Lubny soil (U-S5; MIS 13-15) and strong rubified Lower Zavadivka palaeosol (U-S4; MIS 11) in southern Ukraine; final determination of the Matuyama–Brunhes boundary in the Shyrokyne unit (U-S7; MIS 19) in remote areas of Ukraine. Stratigraphic correlation, achieved between loess sections in the Danube Basin and China as well as regional magnetostratigraphy (Sümegi et al., 2018) have been supplemented by the representative data from Ukraine. The proposed climatostratigraphic model can be helpful in a better understanding of the palaeoclimate mechanisms of formation of the loess-paleosol sequences in Eastern Europe.

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