GENESIS AND POSTPEDOGENIC ALTERATIONS OF PALEOSOLS IN LOESSES AND POSSIBILITIES FOR PALEOENVIRONMENTAL RECONSTRUCTION

FINAL REPORT OF NKFIH K119366 RESEARCH PROJECT

The research project NKFIH K119366 entitled **'Genesis and postpedogenic alterations of paleosols in loesses and possibilities for paleoenvironmental reconstruction'** started on 1 October 2016, officially ended on 31 March 2022, after a prolongation of 12+6 months, partly because of the Covid-19 pandemic situation.

We set up two hypotheses:

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a) The more extended and more intensive periods of soil development are not always reflected in growing magnetic susceptibility (κ values), but proxies provide information about the length and strength of the soil development period.
b) Based on the comparison of coeval paleosols in different sites and different positions, the influence of local environmental changes is recognisable.

The particular aims of the project were the following:

1) Identification of different pedogenic and postpedogenic processes of paleosol types, distinguishment between different paleosol developmental stages
2) Understanding the relevance of the identified indicators in the paleoenvironmental reconstruction
3) Understanding the formation of different paleosols and modelling their development compared to the duration of the interglacials/interstadials
4) Detecting the local spatial variability in the paleoenvironment, as well as changes in paleoprecipitation, wind regime, weathering factors and micro-climate
5) Creating a complex database of the investigated paleosols and their characteristics

The results of the project were published in the following peer-reviewed scientific journals: **Aeolian Research** in 2018 (Q1 – IF: 2.864), **Geoderma** two publications in 2018 (Q1/D1 – IF: 4.336), **Quaternary Science Reviews** in 2018 (Q1 – IF: 4.641), **Journal Of Quaternary Science** in 2019 (Q1 – IF: 2.846), **Geophysical Journal International** in 2019 (Q1 – IF: 2.777), **Quaternary International** three publications in 2020, (Q1 – IF: 1.952), **Hungarian Geographical Bulletin** in 2020 (Q2), **Catena** in 2021 (Q1 – IF: 5.198). Our results were presented at different international conferences as well EGU2018, DEUQUA 2018, UKLUM 2019, INQUA 2019, IRQUA 2021 (2nd International Conference on Quaternary Sciences, Gorgan, Iran) and 10th Hungarian Geographical Conference 2021, Palaeoclimate conference 2018. A **PhD dissertation** summarised the detailed results of the studies at Galgahévíz and Hévízgyörk (Csonka, D. 2021.), and the results of the $CaCO_3$ investigations in the new profiles at Basaharc were presented in a diploma thesis (Milinkó, I. 2019).

The changes in the availability of people and the loess-paleosol sequences (LPs) forced us to change the original plans partially. Instead of Dunaszekcső, Galgahévíz entered the project because of its proximity and similar geomorphological position to Hévízgyörk. Only additional measurements were made at Süttő. The results of the investigation of secondary carbonates are only partly published because of the maternity leave of the specialist. Measures were missed partially due to personal capacity and partly due to the epidemic situation: DTA, XRD, TOC, SEM analysis and the usage of the Morphologi instrument. The database creation is also postponed because of the lack of some data. The preparation of soil thin sections was paused due to technical reasons; therefore, it was impossible to prepare thin sections from the Beremend section and the last samples taken from Paks. We proceeded drone recordings in the outcrops of Basaharc, Hévízgyörk, Galgahévíz and Süttő. The data evaluation is in progress; the results will be published.

Due to the COVID-19 epidemic situation, we could not participate in conferences thus we asked for permission from the NRDI Office to buy a modern microscope (Nikon Eclipse E200 Pol polarising microscope) with a Michrome digital camera instead of the 60-year-old one that we have used so far for micromorphological investigations of the paleosol thin sections. The price of the microscope and the accessories was about 4 000 000 HUF. With the permission of the NRDI Office, we also bought a Motic microscope for 300 000 HUF. Shortly before the closure of the project, we were able to obtain equipment (at the Department of Physical Geography) which is suitable for the preparation of soil thin sections. This equipment was necessary because the former possibility of making thin sections ceased.

Results

Our work was divided into two tracks; one primarily focused on the methodological approach, the other one on the analyses, description and synthesis.

Methodological approaches

Stable isotope mass spectrometry

Two institutions carried out the stable isotope analysis. The Leibniz Institute for Applied Geophysics (LIAG, Hannover) provided the measurement of EBS and HC samples from Süttő, Verőce, Paks, Hévízgyörk and Basaharc Northern wall. Since the isotope ratio mass spectrometer was decommissioned in LIAG in 2021, we were looking for a new opportunity. Measurements of EBS samples from the Basaharc Southern wall, Malá nad Hronom and Beremend sections were carried out in the Eötvös Loránd Research Network, Research Centre for Astronomy and Earth Sciences (ELKH CSFK). Only one EBS sample was measured from each 10 cm interval at ELKH CSFK.

We studied the *stable isotope composition patterns of hypocoatings* from the last interglacial, which were preserved in different geomorphological positions in Verőce loess-paleosol outcrop (Barta et al., 2018). Even though we omitted this site from the further investigation, we used the formerly collected samples as the interpretation of patterns and the creation of the critical description to represent a new approach, and the application of these was also made a significant contribution to our project (i.e., in Csonka et al. 2020).

The stable carbon and oxygen isotope composition of three different local variations of the same MIS 5e paleosol horizon were studied in the Verőce loess-paleosol sequence (Barta et al., 2018). These variations developed in the local top, paleoslope and paleovalley topographic positions with characteristic secondary carbonate features, such as hypocoatings (HCs). Based on the $^{13}C/^{18}O$ enrichment or depletion of secondary carbonate samples, a new method called the *'stable isotope matrix' (SIM)* was established. It was used to characterise stable isotope signals as potential paleoenvironmental indicators. The joint application of the SIM and box-and-whiskers plots revealed how climatic stable isotope signals of HCs can be overwritten by the various topographic positions of the hosting paleosols.

The *stable isotope composition of earthworm biospheroids* was investigated by G. Barta, who was awarded a postdoctoral fellowship in 2018 (NRDIO PD128908), which focuses on the paleoenvironmental relevance of earthworm biospheroids. As earthworm biospheroids belong to the group of secondary carbonates, part of her recent results will be used in both projects.

Samples from loess and paleosol sequences at Paks, Verőce, Hévízgyörk, Malá nad Hronom, Basaharc southern and northern wall, Beremend were taken in 10 cm intervals. After the time-consuming preparation of secondary carbonates (wet sieving, separation of subtypes under a binocular microscope, additional cleaning in an ultrasonic bath, grounding for stable isotope analysis), each wet-sieved sample was examined under the binocular microscope, and a detailed morphological description was given. The mentioned description is finished for almost all sequences (at the Beremend profile, half of the section is completed). The Paks sequence was studied until the underlying unit of the Basaharc Double 1 paleosol. To study the distribution and amount of EBS as the function of depth, they were counted in 10 cm intervals for almost all sequences. Until now, the counting process is finished as follows: Paks profile – 10.3 m, 1685 pcs; Verőce profile – 9.5 m; 497 pcs; Süttő profile – 14.9 m, 3622 pcs; Hévízgyörk profile – 7.9 m, 792 pcs; Malá nad Hronom profile – 8.4 m, 1995 pcs; Basaharc southern wall – 10.7 m, 4552 pcs; Beremend profile – 12 m, from which 6.1 m was examined yet, 12016 pcs (extremely high amount).
Measurements of $\delta^{13}C$ and $\delta^{18}O$ of the biospheroids are also completed, as follows: Basaharc northern wall – 494 data pairs from EBS (samples up to 5 pcs/10 cm interval were available for measurements at LIAG), 89 data pairs from HC; Basaharc southern wall – 91 data pair from EBS (1 pc/10 cm interval, ELKH CSFK); Malá nad Hronom – 67 data pair from EBS (ELKH CSFK); Beremend – 120 data pair from EBS (ELKH CSFK). Data was received in 2020 from the Basaharc southern wall when G. Barta (the expert on secondary carbonates) was still on maternity leave. The other data was completed at the beginning of 2022.

Different sedimentary unit types containing EBS were analysed from the Verőce, Süttő, Paks, Hévízgyörk sections. The preliminary results of the first data set were presented in Barta et al. 2019. The high amount of stable carbon and oxygen isotope data was derived from EBS (471 data pairs). With the help of the CCDA (combined cluster and discriminant analysis) method, a statistically optimal group number was defined, and the largest homogeneous groups were determined. Homogeneous groups were composed of EBS from various sedimentary units but indicated similar formation circumstances. The difference was made on a regional basis, where the units of Paks, Süttő and Hévízgyörk belonged to the same group, but those from Verőce were separated entirely. The Verőce section has a particular position in a mountain foreland area, developed on an alluvial fan system. Inhomogeneity was connected to the reworked loess units from the Verőce and Paks sections, which seems to represent the complex interaction of different geomorphological factors.

Magnetic susceptibility

The investigations of the diverse rock magnetic parameters of the loess-paleosol sequences are widespread techniques to characterise the LPs and to draw conclusions concerning the interglacial (interstadial) intensity (low field magnetic susceptibility, κLF; frequency dependence of magnetic susceptibility, volumetric: κFD; mass: χFD) and the reconstruction of sedimentary environments (anisotropy of magnetic susceptibility; AMS) (e.g., Bradák et al. 2018a, 2018b, 2020).

The measurement of the *low field magnetic susceptibility (κLF)* is a routine field method using a portable field susceptibility meter. We used a Kappameter KT-5 portable magnetic susceptibility meter (Geofyzika Brno, Czech Republic) in our studies. The measurement intervals were 5 cm, which provided a quasi-continuous record in practical terms. The Hungarian loesses are characterised by low κLF, whereas paleosols, reflecting precipitation changes, are characterised by high κLF (Bradák et al. 2018a, Bradák et al. 2018b, Csonka et al. 2020). Along with the pedogenic horizons, κLF peaks can indicate the presence of volcanic material (e.g., tephra horizon) due to the higher amount of magnetic mineral components, which appear as a peak on the curves.

Frequency dependence of magnetic susceptibility measurements can estimate the relative content of superparamagnetic (SP) contributors, indicating authigenic ultrafine (nanometric scale) magnetic particle content in loess-paleosol sequences and thus can contribute to the reconstruction of detailed paleoprecipitation variation in glacial-interglacial cycles.

The anisotropy of magnetic susceptibility (AMS) provides a valuable tool for characterising the magnetic fabric of materials. The effects of pedogenic magnetic grains on the magnetic fabric of paleosols were investigated using samples from the Paks loess profile (Hungary). The joint application of rock magnetic experiments and scanning electron microscopy revealed characteristic signatures of (post-)pedogenic influences on the original sedimentary fabric. Various methods of altering or preserving the sedimentary fabric during (post-)pedogenic processes were described. Some processes, such as the hydromorphic effect, weakened the anisotropy of the original fabric and strengthened the orientation of the grains. Meanwhile, other processes, such as post-burial, compaction of materials, and fragmentation, strengthened the foliation with increasing anisotropy. In summary, two characteristic trends can be separated by the AMS study of loess: the primary magnetic fabric, which may be preserved even in the fabric of paleosols, can indicate, e.g., the paleowind direction in the area (i.e., the direction of deposition), and 2) pedogenic processes may re-organise the original sedimentary fabric and creating a so-called secondary fabric, one of the indicators of interglacial (interstadial) periods. (Bradák et al. 2018a).

Reflectance measurements

Spectroscopic techniques are rapid methods for analysing soils and sediments. *Diffuse reflectance spectroscopy (DRS)* has been used in Earth sciences for three decades. Two main uses of DRS analysis have been applied to study loess profiles, such as colourimetric indices and Hematite/goethite ratio. Many investigations showed the relationship between these proxies and paleoenvironment changes. It can note that only a narrow spectral range (400-700nm) can be analysed for the calculation of the abovementioned proxies. Additional information from the entire spectrum (400-4000nm) provides an opportunity for a more sophisticated characterisation of loess/paleosol minerals. Therefore, a new analytical method, so-called "Reflectance stratigraphy", was tested in the frame of this project.

The DRS measurements were elaborated by a combined multivariate statistical technique (hierarchical cluster analysis and Fisher's linear discriminant analysis). This is a new method to evaluate the entire raw spectrum. It sets up groups by investigating the totality of unidentified components in the multidimensional space. This method was tested in LP sequences at Malá nad Hronom: it can be used to make stratigraphic divisions based on spectral features only (Szeberényi et al., 2020a).

Reflectance measurements of samples in different Quaternary sediment successions (Basaharc) were investigated and compared to reveal and quantify the most crucial reflectance properties (Szeberényi et al. 2020b). Several curve sections were identified to characterise and quantify the reflectance properties of samples. The most variable wavelength ranges were separated from the entire measurement range based on our earlier results. We found that (1) the assessment of DRS curves from Quaternary sediment successions indicated the presence and intensity of pedogenic processes; (2) the reflectance properties of DRS curves can be identified by both the mean intensity of the whole reflectance curve and the length of some separated curve sections of the full measurement range. The length of separated curve sections could quantify the differences.

Besides DRS, we tried the *DRIFT (Diffuse Reflectance Infrared Fourier Transform Spectroscopy) measurements*, which provide meaningful results in the case of loess-paleosol samples in the mid-infrared spectral range. Clay fractions of two loess-paleosol profiles (Paks) were investigated by IR spectroscopy and controlled by XRD. However, the results were compatible, but the "carbonate anomaly" can cause uncertainty, which leads to the modification of the predicted values. The "carbonate anomaly" was discovered in this project based on detailed spectroscopic and XRD results of the clay fraction for the first time. The degree of this phenomenon is definitely related to the thickness of the carbonate crusts on the minerals. Its importance in loess-paleosol sequences is significant because the vertical distribution of carbonates is a determining factor in the system (Szeberényi et al., 2021).

Geomathematical analyses

Mathematical, statistical methods (e.g. discriminant analysis, determination of Wilks' lambda values, principal component analysis, box-and-whiskers plots) were used to process large amounts of data and to explore relationships between each proxy for DRS analyses (Szeberényi et al., 2019) and to interpret stable isotope data (Barta et al., 2018), as well as in Bradák et al. (2021) to detect similarities and differences between stratigraphic units.

In the case of cluster analysis, the samples were grouped based on the similarity of the measured parameters. Wilk's Lambda statistics determined the parameters in which "strong order" influenced the obtained grouping. The adequacy of the grouping is examined by discriminant analysis. Principal component elemental analysis was used to assess background factors.

Geophysical measurements

In the loess covered Gödöllő hilly region, we aimed to investigate the spatial distribution of the paleosols described in the outcrops of the Galga valley (Hévízgyörk and Galgahévíz).

In 2017 the geoelectrical measurement in the vicinity of Hévízgyörk failed due to the non-characteristic differences in the electrical resistance in the loess-paleosol series. In 2022 due to the further development of *seismic measurements*, the possibility arose to study LP series with more minor differences within the stratigraphical units so that we can also follow the spatial changes of the paleosol layer. The method was applied in the Galgahévíz area, along a line running north-east from the outcrop, in a length of 1 km, intersecting the loess ridges striking NW-SE.

The purpose of the *P- and S-wave seismic survey* is to map the thickness and thickness change of the loess-paleosol series and explore any stratification observed in it. Seismic profiling was performed using an electromechanical S-wave vibroseis source and a P-wave seismic hammer. 80 channel LandStreamer system with 3C geophones was used for sensing, consisting of two parts, the first 40 channels section with 0.5 m geophone distance, while the second 40 channels with 2 m geophone distance. The total recorded section provided a 100 m offset range during the survey.

Geoelectrical measurements were applied along the seismic survey line as *Multielectrode (MUEL) direct current profiling*. Multielectrode profiling aims to image the near-surface loess layer, the underlying clay below the loess ridges, and determine the boundary of the coarser-grained river sediment in the southern part of the profile. Mapping the lateral variation of the coarser-grained river sediment along the profile was also targeted. The measurement was performed using a multichannel system with 72 electrodes in a Dipole-Dipole electrode configuration. Elevation changes along the profile were also measured and taken into account during the data inversion.

Based on the results of the seismic and multielectrode sections at three selected points, exploration of the stratigraphy with a *spiral drill* was performed. The purpose of drilling was to check the thickness of the loess-paleosol series to calibrate the geophysical sections and identify any detectable paleosol layer. Two drillings stopped at around 6 m depth because of the presence of a clay-rich layer, the third drilling at the lowest part of the survey line crossed fluvial sediments, which underlie the LP.

The geophysical surveys carried out in 2022 in the vicinity of Hévízgyörk could not resolve the internal layering of the loess-paleosol series. Still, the thickness variation of the loess-paleosol series and the paleogeomorphology of the formations underlying the LPs is clearly visible on the P- and S-wave seismic and on the MUEL profiles. This knowledge and further studies can help understand the geomorphological development of this area and thus indirectly provide information on the distribution and morphology of the loess cover.

Grain size measurements

Five loess sequences (Süttő, Basaharc, Hévízgyörk, Villánykövesd, Beremend) were sampled in fine resolution (from every 2 cm) for grain-size analysis. Time frames for the investigations were elaborated by luminescence (pIRIR290) and Amino Acid Racemization (AAR) dating. The samples were only treated with 1% ammonium hydroxide. Therefore, they can be considered bulk samples. Grain-size distributions were determined using a Beckman-Coulter LS 13320 PIDS laser diffraction particle size analyser, covering a range of grain sizes of 0.02-2000 µm at the Leibniz Institute for Applied Geophysics (LIAG) in Hannover.

Clay-, silt- and sand content and U-ratio were calculated from the grain-size distribution of each sample, and these values were plotted against the depth of the profiles. The grain size distribution of the sediment depends on the wind speed, the wind direction and therefore, the source area (distance, coverage) and the place of deposition (windward, leeward). Therefore, any change in the grain size distribution of the sediment cannot only be attributed to wind speed change, but one has to consider the alteration in the source area or landscape evolution.

Temporal and spatial changes could be concluded by comparing the variation of clay-, silt-, and sand content at different locations.

a) Since all measured samples are bulk samples, an increase in clay content primarily implies soil development or very fine carbonate powder (Horváth et al. 2021b).

b) One soil development period is usually represented by higher values on the clay content curve. Double or triple peaks within one paleosol might indicate two-three soil formations superposed on each other (e.g.: Hévízgyörk upper paleosol, Basaharc upper (MF) and middle paleosol (BD)) (Csonka et al., 2020, Csonka 2021, Horváth et al., 2021a).

Comparing the variations of the sand content curves at each locality, spatial and temporal changes are revealed:

a) Spatial change: general coarsening from the South to the North is detectable. This might reflect the distance from the source area at each locality, except Hévízgyörk, where intermediate grain-sized sediment is associated with the shortest distance (Novothny et al., 2019). Besides, the wind speed can also be expressed by this. The pattern of the average wind speed and direction of the present shows similarity with those in the Pleistocene pattern.
b) This general trend does not change over time; therefore, significant variation in the source area and wind direction is not very likely.
c) Temporal change: for each profile – at least a part of – MIS 6 and MIS 10 can be characterised by coarser sediments. Therefore, higher wind speed is generally supposed during MIS 6 and 10 compared to other glacial periods in the Carpathian Basin (Novothny et al., 2019).

Luminescence dating

Several loess successions (Basaharc, Hévízgyörk, Galgahévíz, Beremend, Malá nad Hronom) were dated by luminescence to make age constraints for the deposition and formation of loess layers. Different luminescence dating protocols like pIRIR290, TT-OSL, VSL on different grain size fractions (fine and coarse-grained) were tested. The pIRIR290 protocol on polymineral fine grains resulted in the best ages; however, only minimum ages could be determined for the loess and paleosols beyond the BD paleosol. TT-OSL ages, determined from fine-grained quartz, yielded significantly underestimated ages (~100 ka), probably due to the low thermal stability of the signal and therefore also considered as minimum ages. The VSL signal for fine-grained quartz was too dim and nonsensitive; therefore, it could not be used for age determination.

Analytical and synthetical approach

In the chosen profiles (Hévízgyörk, Galgahévíz, Basaharc, Paks and Beremend) we focused on paleopedological, secondary carbonate, stable isotope, grain size and complex paleomagnetic (magnetic susceptibility and magnetic mineralogy) analysis. The luminescence and radiocarbon dating provided time constraints for developing the younger (<250 ka) soil horizons and supported the correlation among the different LP sections.

Hévízgyörk and Galgahévíz

We studied two, until now, poorly investigated loess-paleosol series, Hévízgyörk and Galgahévíz, in the Galga river valley, Gödöllő hilly region. In the lower part of both outcrops, the Bag Tephra (~350ka), a widespread marker horizon of the Carpathian Basin, was described from the loess. This fact already suggested that the loess-paleosol sequences cannot be complete; paleosols and loess units are missing from the sections, despite no apparent signs of erosion.

A multi-proxy analysis, including grain size, magnetic susceptibility, calcium-carbonate content, micromorphology (Micromorphological Soil Development Index, MISODI), AAR and luminescence dating, diffuse reflectance and the examination of stable isotopes of hypocoatings, was performed on the loess-paleosol successions at Hévízgyörk and Galgahévíz (Csonka et al., 2020, Csonka 2021).

At Hévízgyörk, two pedogenic and three sedimentation periods; at Galgahévíz, two sedimentations and one pedogenic phase were expected based on the field investigations. In contrast to the field observations, the fluctuations of the climatic proxies (GSD, MS, DRS) in the upper paleosol at Hévízgyörk suggested more than one paleosol formation merging into one polygenetic paleosol, which could develop during the MIS 7e - MIS 5(a-c) periods.

Based on the position of the Bag Tephra, the lower paleosol at Hévízgyörk can be correlated to the paleosol at Galgahévíz, although the two sections developed differently. The well-developed polygenetic paleosol at Galgahévíz represents (at least four) pedogenic periods between the MIS 9 - MIS 6 periods. Both LP sequences have hiatuses but most probably not from the same period. Based on the results of our investigations from the Galgahévíz section, the MIS 8 loess, while from Hévízgyörk probably the MIS 6 loess and the MIS 5 paleosols are missing.

Such hiatuses in the successions (which implies enhanced erosion activity at different periods or lack of sedimentation) at adjacent areas and the superimposed two- or morefold paleosols suggested the higher significance of the local paleogeomorphological processes compared to the role of the changes in the paleoclimate. We assumed that the investigated loess-paleosol successions were formed in a slope position, where the erosion could be more intense or the dust accumulation was less enhanced, or the alteration after sedimentation was less characteristic.

Basaharc

Basaharc is one of the key loess sections of the European loess belt. The recently investigated sections allowed for the description of so far unknown facies of the Basaharc Double (BD) and Basaharc Lower (BA) paleosols (Horváth et al., 2019). A new continuous profile on the western part of the quarry was investigated by multi-proxy methods. The studies clearly showed the diverse development of coeval paleosols, indicating different paleoenvironments. The correlation between the key ('classical') profiles and the recently opened ones was based primarily on the OSL ages and the similarities of the MS curves. The uppermost paleosols (MF1-2) in the new section are weaker developed, and they are in a higher topographical position than in the 'classical' profiles. The presumption is that the pedogenesis could not keep up with the aggradation of the surface by the dust accumulation during MIS 5. However, the outcrop is seemingly in a local hilltop position (Horváth et al., 2019).

The most detailed paleosol micromorphological investigations were made in the outcrop of Basaharc. In this well-investigated loess-paleosol series, we discovered contradictions and striking values in the proxies in this well-investigated loess-paleosol series. Using the micromorphological analyses, we were able to prove that the high ratio of clay (>20%), with low κLF values in the loess between BD1 and BD2, does not represent a soil formation. Still, they are present because there is a large number of micritic calcites in <5µm fraction besides the clay minerals. The high κLF values with low (<15%) clay content below BA paleosol points out another soil formation (BA2) in MIS 9 before BA development, which is supported by the presence of clay coatings in micromorphological thin sections. The two peaks on the κLF curve in BA1 paleosol show the presence of soil formations in MIS 9a and MIS 9c (BA1a-1b), which is not visible on the field but confirmed by micromorphological investigations. The two peaks on the κLF curve in BD1 paleosol show the presence of soil formations in MIS 7a and MIS 7c (BD1a-1b), which is confirmed by micromorphological investigations.

It is the first time in the Hungarian loess stratigraphy that all three substages of MIS 7 (e,c,a) and MIS 9 (e,c,a) have been confirmed (Horváth et al., 2021b)**.**

Malá nad Hronom (Slovakia)

The loess succession at Malá nad Hronom (Slovakia) represents a poorly-known part of the European Loess Belt (ELB). It provides a valuable opportunity to investigate differences in soil formation in various topographic positions. Four different sections were studied with the semiquantitative characterisation of the paleosols (based on physical properties, texture, the characteristics of peds, clay films, and horizon boundaries) and high-resolution field magnetic susceptibility measurements. The correlation of the outcrops was based on the luminescence dating (Bradák et al., 2021, Szeberényi et al., 2020).

The comparison of various proxies revealed the differences in soil formation in a dynamic aggradational microenvironment for the same paleosol horizons located in various positions along the slope. Contrary to expectation, paleosols developed in local top or slope positions did not display significant differences, e.g., in their degree of development or the characteristics of their magnetic susceptibility curves. In the paleosols in lower slope positions, signs of quasi-permanent sediment input could be recognised as being present as early as during the formation of the soil itself. This sediment input would seem to be surpassed in the case of pedogenesis strengthened by the climate of the last interglacial (marine isotope stage - MIS 5). Pedogenesis appears to be sustained by renewed intense dust accumulation in the Late Pleistocene in MIS 3, though compared to MIS 5, the climate of MIS 3 did not favour intense pedogenesis. Despite the general belief that loess series formed in plateau positions can preserve terrestrial records without significant erosion, this is different in the case of the LP at Malá nad Hronom. Compared to the sequence affected by erosional events in the local top position, the series affected by quasi-continuous sediment input in the lower slope position seems to have preserved the soil horizons intact (Bradák et al., 2021).

Paks

Correlation of LPs in a short distance based on the studies of the most detailed accessible loess-paleosol sequence from almost the entire Pleistocene in the middle part of the Carpathian Basin at Paks brickyard and drilling cores (PA-I (∼85 m) and PA-II (∼50 m)) deepened on loess covered ridges (Novothny et al., 2020). All records seemed to represent a plateau position loess, but the development of the LPs was different *(Fig. 1.)*. Therefore, despite the similarities suggested by the MS studies and the macro- and micromorphological investigations of the paleosols, only the OSL provides a clear correlation with the age range of 20–200 ka *(Fig. 2.)*. The different thicknesses and the present altitude of the coeval loess and paleosols imply differences and changes in paleogeomorphological positions of the investigated profiles during the Pleistocene. Significant subsidence and, or tectonic movements are the leading causes of the deficient appearance of MIS 6-3 sediments in the Paks brickyard outcrop compared to the more complete sequences of the cores. We emphasised that any correlation solely based on MS data or soil morphology, without any numerical age control, must be taken with great caution.

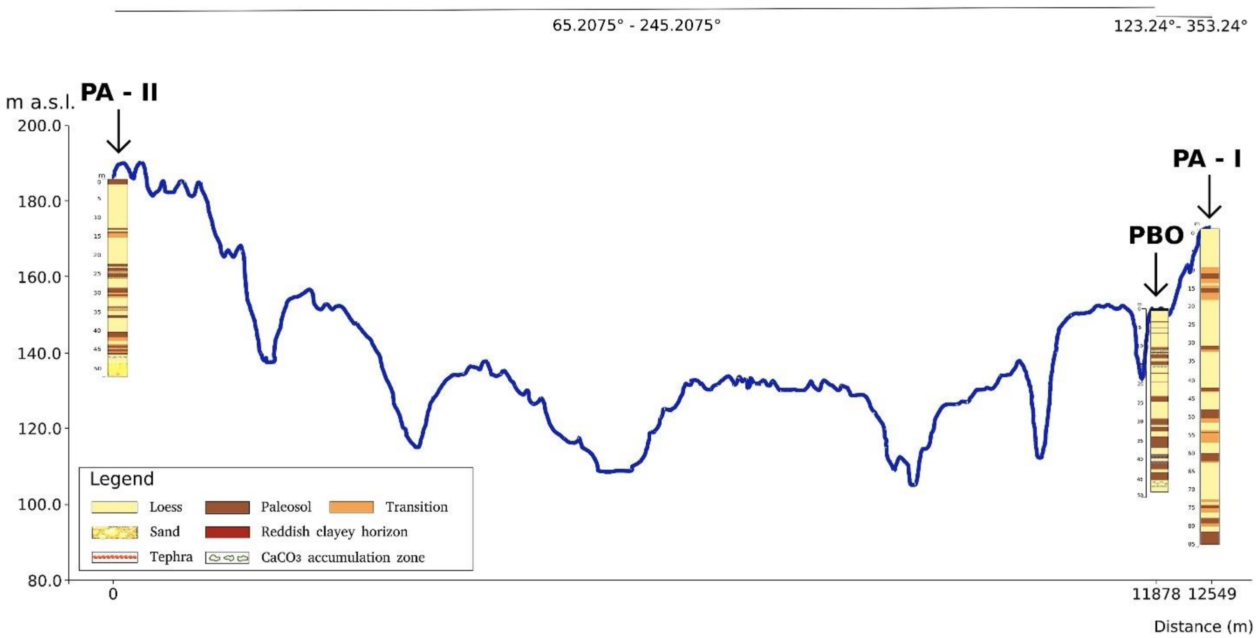

Fig. 1. Cross-section and stratigraphic log of the profiles through the area of Paks. The location of the Paks brickyard outcrop and the boreholes (PA-I and II) are marked. (Novothny et al., 2020)

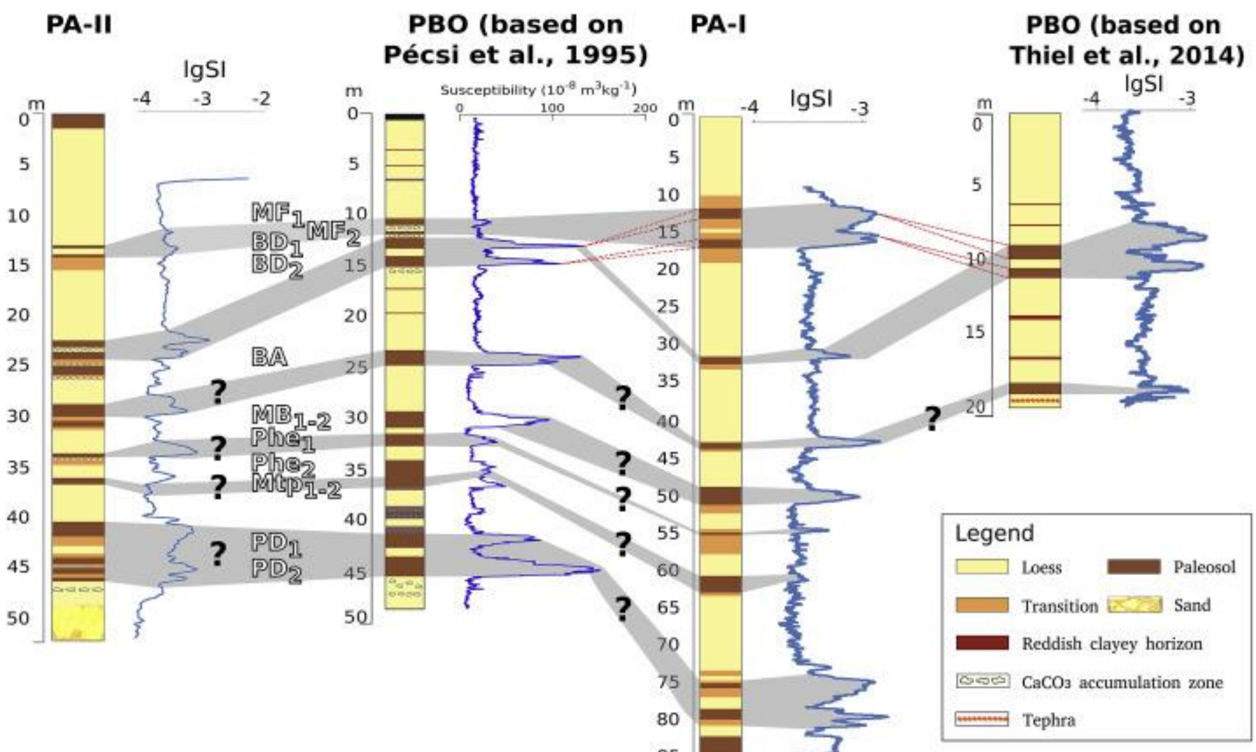

Fig. 2. Correlation based on MS curves of the Paks brickyard outcrop (PBO) and PA-I and II boreholes. Dashed lines refer to the first attempt of correlation solely based on MS patterns. Question marks indicate those correlations where no numerical dating was available.

The climate strongly influences the development of the paleosols, but the local paleoenvironment has a significant influence on it as well. Some sites (Basaharc, Verőce, Hévízgyörk and Galgahévíz) provide an outstanding possibility to investigate coeval paleosols in different geomorphological positions and therefore recognise the distinct balance among pedogenesis-erosion-sediment accumulation (Horváth et al., 2019, Barta et al., 2018, Csonka et al., 2020, Csonka 2021). At Verőce, the local top, the paleovalley and the paleoslope landscape positions were clearly characterised by different soil features of the same paleosol (Barta et al., 2018). At Basaharc, various environments (fluvial, eolian) and geomorphological processes (a reworking of the material, erosion) were described as well (Horváth et al., 2019). The multiproxy analysis of the LPs at Hévízgyörk and Galgahévíz revealed the hiatuses and the superposition of the paleosols. It drew attention to the importance of the geomorphological position during the formation of the loess-paleosol sequences (Csonka et al., 2020, Csonka 2021).

Conclusion

We can conclude that the paleosols developed in higher landscape positions (like local plateaus or intervalley ridges) without or with a weak influence of material transport from the higher position and loss of material towards lower areas are generally more suitable for the determination of the intensity (the strength) of the interglacials and interstadials, and based on it for the interregional correlation. Other geomorphological positions (slopes and valley bottoms) were more sensitive to the local changes; therefore, they carry information about the development of their local environment. An exception to this may be the occurrence of an erosion event of extreme magnitude (e.g., after the MIS 5e period) that may also remove material from the plateau. In these cases, the preservation of loess/paleosols is mostly only possible at the bottom of slopes or in valleys, as was described at Malá nad Hronom and Süttő, where the paleosols remained on the slope or in valley positions.

Since the local environment has a significant influence on the development of the paleosols, the growing magnetic susceptibility (κ values) not obviously reflects lengths and the intensity. However, proxies provide information about the length and strength of the soil development period. Likewise, the resolution and the extension of the age determinations cannot provide an acceptable timeframe for the development history yet. We strongly believe that besides the diverse analyses, the visual, namely the micromorphological studies of the material, are needed to recognise the chronological order of the processes.

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