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THE STRUCTURE AND ORIGIN OF LOESS DOLLS – A CASE STUDY FROM THE LOESS-PALEOSOIL SEQUENCE OF SÜTTŐ, HUNGARY

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Abstract

The research of secondary carbonates from loess-paleosoil sequences focuses not just on the micro-scale types, but as well on the macro-scale ones. Loess dolls or concretions belong to this last category. Concretions are found frequently under the paleosoil levels referring to a very probable connection with leaching processes and precipitation from carbonate-rich solutions.

Research was carried out on the loess-paleosoil sequence of Süttő, Hungary. The methods used in this work were the morphological description of concretions, the analysis of the structure after cutting into two or more parts and treatment with 10% hydrochloric acid. Altogether 29 samples were analysed from the sandy loess layers between the depth of 0.65–5.55 m and 12.70–14.75 m.

Based on the results three main types concerning the inner structure of the concretions were determined: a.) concretions with longitudinal and/or perpendicular cracks; b.) concretions containing one or more condensation nucleus; c.) the combination of the above listed properties. From these different structures more conclusions could be drawn on the origin of loess dolls. The carbonate precipitation could have taken place in or around cavity systems of biogenic origin (as root-related channels or features, and biogalleries) and of non-biogenic origin (because of the structural properties of the sediment). As precipitation nuclei the cementation of hypocoatings played an important role as well. A multiphase development history of the loess dolls were in many cases characteristic.

Key words: loess doll, concretion, secondary carbonate, loess, paleosoil

INTRODUCTION

The genesis and morphology of loess dolls was always an exciting subject, which still has got yet opened questions. The object of this study is on the one hand to present the place of loess dolls and their genesis in the classification of secondary carbonates. On the other hand the aim of this paper is to describe the various morphology and structure of the loess dolls of the Süttő loess-paleosoil section (Hungary) and to draw conclusions concerning their origin and formation environment.

Though the primary carbonate content of the loess derives from the calcite and dolomite crystals, as being the components of the mineral dust (Pécsi 1990, 1993), the formation of secondary carbonates is connected with the resettlement of carbonates during pedogenetic processes in the soil-sedimentary environment (Becze-Deák et al. 1997). In this processes among others biomineralization, the flow of bicarbonate solutions and the weathering of calcium-bearing minerals take part (Pécsi 1990, Gerei et al. 1995, Becze-Deák et al. 1997).

Among secondary carbonates micro- and macro-scale types can be distinguished. The micro-scale features occurring in this study are the followings: a.) calcified root cells: composed of elongated calcite crystals merging into tubes in the consequence of root calcification of mainly grass species (Jaillard et al. 1991, Becze-Deák et al. 1997); b.) hypocoatings: carbonate impregnations around plant biogalleries, which thought to be simultaneous with the dust deposition (Becze-Deák et al. 1997, Durand et al. 2010); c.) carbonate coatings: have different subtypes and formed postsedimentary from the percolating solutions (Horváth et al. 2007, Barta 2011).

The macro-scale secondary carbonates are represented by concretions, among which a distinction based on size can be made. To the nodules belong those pedofeatures, which are not related to natural surfaces or voids of the matrix (Stoops 2003), and do not fill preexisting cracks, respectively (Sellés-Martínez 1996). Nodules have various subtypes based on their internal and external morphology, according to formations factors as texture of the matrix, stability of the sediment structure and alternation of precipitation and dissolution processes (Wieder – Yaalon 1982, Sellés-Martínez 1996, Stoops 2003, Durand et al. 2010). The above mentioned factors and processes could lead to a complex fabric divided into cracks, cavities and/or recrystallized parts (Durand et al. 2010), which are characteristic not just for nodules, but for concretions as well. The morphology and structure of concretions and nodules both are suggesting a multiphase history of the carbonate profile development of the sediment (Khokhlova et al. 2001).

In this study the term of concretion was generally used for (and description was made of) those features which minimum length was equal or larger than 1 cm. By this means nodules were ordered (based also on their characteristics) into a size range, where their maximal length is determined in less than 1 cm. Nevertheless in some cases based on the structural properties the term concretion was used for features in the size range of nodules (above 0.5 cm length).

Concretions appear frequently under paleosoils, suggesting a very probable connection with leaching processes (Ádám et al. 1954, Pécsi 1993, Kemp 1998). Their presence indicates climatic changes since dust accumulation is characterized with more arid conditions, whereas soil development refers to more moisture and relatively stable surface (Kádár 1954, Kemp 1995). The carbonate is leached out from the eluvial horizon of the paleosoil and accumulates in the underlying loess (Jiamao et al. 1997). Concretions are not just linked to leaching processes after the soil was fully developed, but during this evolution when the porosity of loess changes it leads to a loss of carbonate content as well. The percolating solutions dissolve the carbonate of the coated grains and detrital elements of loess and transport it into deeper parts of the sequence (Kádár 1954, Kriván 1955). The formation of loess dolls begins under the soil level as a concomitant of soil development (Kádár 1954). During this redistribution of carbonates the later on infiltrating solutions can also add more precipitated carbonate to the concretions, which cause their growth (Pécsi 1993, Kemp 1998).

Concretions of the loess-paleosoil sequences can be determined as "glomerulus" concretions (Seilacher 2001), referring to a ground water connected derivation. These forms are mostly spheroid and merged with each other, having protuberances on their surfaces. Not just ground water could have taken part in their formation, but any percolating bicarbonate solutions. The different external appearance of concretions makes possible various associations for the description, this is why concretions in loess-paleosoil sequences are often called loess dolls.

Soils which are developed on loess and have different hydromorphic properties, thus they can be characterized by different loess doll types (Dultz – Schäftlein 1999), which could also be characteristic for the paleosoils. It is interesting, that into the loess wells or into loess tunnels (both forms caused by piping) the rainfall is able to infiltrate more effectively and reach the deeper parts of the sequence. These surfaces are mostly paleosoil levels with rather high clay content and are quite impermeable. On these surfaces the precipitation of carbonates is also possible (Bulla 1933).

Loess dolls are not made of pure carbonate, because they contain non-calcareous particles, clay and silt in 30-40 weight% (Pécsi 1993). The carbonate content of the concretions fluctuates between 60-95% (Pávai-Vajna 1909, Kriván 1955) and contains in certain proportion $MgCO_3$ as well (Kriván 1955).

In original (mostly vertical) position loess dolls show an uneven distribution in loess (Kádár 1954). Although they can appear in horizontal or in slope position, referring to reworking processes. After a presumed erosion of a loess layer a lag surface composed of loess dolls may remain in the deposit when dust accumulation continues later on (Kádár 1954).

In undisturbed position the shape of the loess dolls is mostly elongated and cylindrical, in accordance with the precipitation from the downward percolating solutions (Kádár 1954), although the original position is not necessary vertical. The shape of the concretions can be rounded (especially the smaller ones) or irregular (having more than one axis). According also to Dultz and Schäftlein (1999) loess dolls found under well developed soils (e.g. Chernozems) and hydromorphic soils (e.g. Gleysols) usually have protuberances on their mostly smooth surfaces. While concretions developed under mineral soils (e.g. Cambisols) have mostly rounded or from elongated to angular shape with rough, pitted surfaces. Flat loess dolls with plate or disc-like shapes may be built up, when the level of ground water reached the formation zone of loess dolls which results in the lateral spreading of the downward flowing solutions (Kádár 1954). The formation of rattle stones is used to be ordered to such zones. Rattle stones are maybe built up around condensation cores with clay coatings which could dry out and shrink due to later on desiccation. Then the shriveled parts give a clinking noise inside the concretion. Based on Dultz and Schäftlein (1999), the origin of shrinkage cracks in a loess doll is not connected with higher clay content, but possibly is connected with desiccation. When the pores of the concretion are not completely filled with carbonate and are still containing some water, subsequently cracks appear because of loosing water. This may also play a role in the formation of loess doll composites, namely concretion-in-concretion structures, which can also be called as rattle stones. In this case a loess doll was grown around by carbonate from later on precipitation.

The structure of loess dolls can either be compact or hollow (Ádám et al. 1954), but in both cases is often divided into two parts, where an outer crust of various widths surrounds a central core (Sellés-Martínez 1996). When the carbonate is precipitated in a cavity system with biogenic origin, it is going to be represented in the inner structure of the loess doll (Dultz – Schäftlein 1999). Formerly the origin of loess dolls was connected with the effect of the surface vegetation, which means that loess dolls could have been formed around roots. It was also based on the fact, that their various morphology corresponds to the shape of root ramifications or in many cases remains of roots were found inside the concretions (Pávai-Vajna 1909). As it was soon mentioned, the percolation of bicarbonate solutions and leaching processes play a role in the formation of loess dolls, but it should not be left out that the process of capillary uplift may have an effect es well (Ádám et al. 1954, Kriván 1955). Or the carbonate-rich ground water which could have been sluggishly flowing on the surface or seasonally stagnating under it during the interglacials and interstadials (Ádám et al. 1954). Presumably loess dolls were formed in cavity systems of the soil matrix, namely in former root channels, at the ramification of root systems or in biogalleries (Schäftlein 1996). These cavity systems are well exposed to air and the partial CO_2 pressure is lower, which leads to the precipitation of carbonate. Very likely the better aired central part of the system and the individual cavities were preferred by the carbonate precipitation (in connection with the fact, that carbonate content is higher in the central section of the loess doll). It cannot be precluded, that if non-calcareous particles were in the cavity system, they may acted like condensation cores and were overgrown by calcite (Schäftlein 1996).

STUDY AREA

The study site is the loess-paleosoil section of Süttő, Hungary (*Fig. 1*). The sequence is covering the Süttő travertine complex exposed in the Hegyháti quarry, not far from the settlement of Süttő. The freshwater limestone is deposited on the right bank of the river, on the V. Danube Terrace in the foreland of the Gerecse Mountains. The age of the travertine was recently determined by uranium-series dating (Sierralta el al. 2010) and the complex was dated to the Middle-Pleistocene. On the loess-paleosoil complex different investigations were carried out (such as optically stimulated luminescence dating, amino-acid racemization, radiocarbon dating and magnetic susceptibility, see Novothny et al. 2009, 2011). The Süttő loess-paleosoil site is a perfect mine of information about the paleoenvironmental changes of the Late Pleistocene.

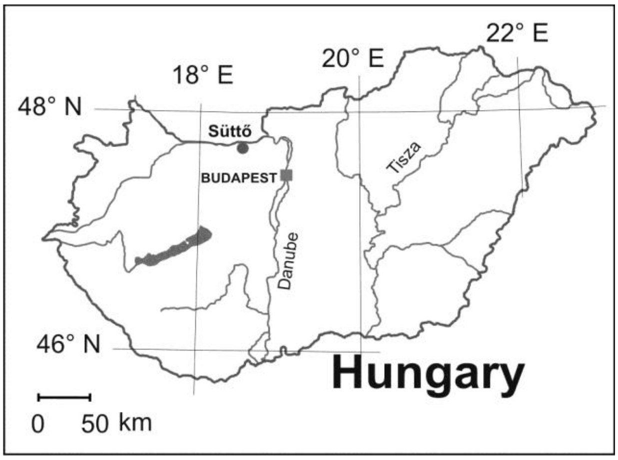

Fig. 1 The location of Süttő, Hungary

The sequence (*Fig. 2*) could be divided into different units based on the properties of the sediment. During the examinations of loess dolls this division of Novothny et al. (2011) was used. The succession is compartmentalized into sandy loess (Units 2, 4, 7, 16), laminated greyish sandy loess (Units 3, 5), loess (Units 9, 11, 13) and sand (Unit 8) horizons. Paleosoils are represented by a light brown paleosoil (Unit 6), two brownish paleosoils (Units 10, 12) and a well developed pedocomplex (Unit 14 as a dark chernozem-like paleosoil and Unit 15 as a reddish brown paleosoil).

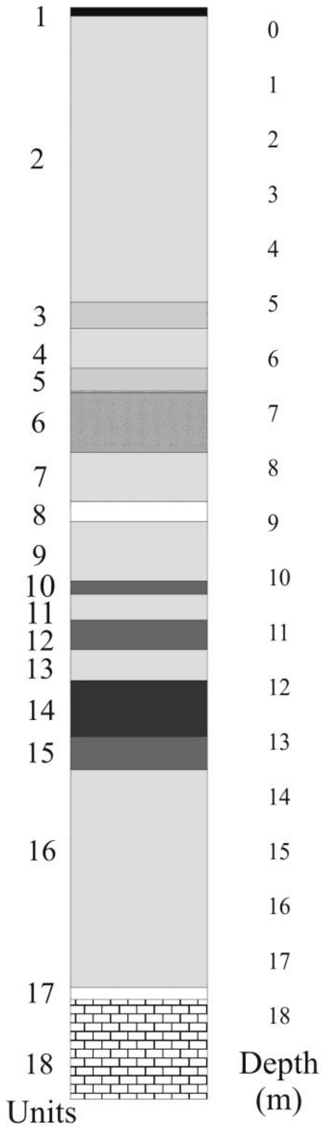

Fig. 2 The loess-paleosoil sequence of Süttő, Hungary (based on Novothny et al. 2011)

Unit 1 – recent soil (chernozem); Unit 2, 4, 7, 16 – sandy loess; Unit 3,5 – grey, laminated sandy loess; Unit 9, 11, 13 – loess; Unit 6 – light brown paleosoil; Unit 8 – sand; Unit 10, 12 – brown paleosoil; Unit 14 – dark chernozem-like paleosoil; Unit 15 – reddish brown paleosoil; Unit 17 – sand; Unit 18 – travertine

Table 1 Frequency distribution of loess dolls

Sequence	*Depth (cm)*	*Frequency distribution of loess dolls**	*Sequence*	*Depth (cm)*	*Frequency distribution of loess dolls**
Unit 2	0.65-0.75	++	Unit 2	4.15-4.25	++
	0.75-0.85	++		4.25-4.35	++
	0.85-0.95	-		4.35-4.45	++
	0.95-1.05	+		4.45-4.55	+++
	1.05-1.15	-		4.55-4.65	++
	1.15-1.25	++		4.65-4.75	+
	1.25-1.35	-		4.75-4.85	-
	1.35-1.45	-		4.85-4.95	-
	1.45-1.55	+++		4.95-5.05	-
	1.55-1.65	++		5.05-5.15	-
	1.65-1.75	+++		5.15-5.25	-
	1.75-1.85	+		5.25-5.35	-
	1.85-1.95	+		5.35-5.45	-
	1.95-2.05	+		5.45-5.55	-
	2.05-2.15	-	Unit 6	12.70-12.75	+
	2.15-2.25	++		12.75-12.85	+++
	2.25-2.35	+++		12.85-12.95	++
	2.35-2.45	+		12.95-13.05	+
	2.45-2.55	+		13.05-13.15	+
	2.55-2.65	-		13.15-13.25	++
	2.65-2.75	-		13.25-13.35	++
	2.75-2.85	-		13.35-13.45	++
	2.85-2.95	-		13.45-13.55	+
	2.95-3.05	-		13.55-13.65	+
	3.05-3.15	-		13.65-13.75	+
	3.15-3.25	-		13.75-13.85	-
	3.25-3.35	-		13.85-13.95	+
	3.35-3.45	-		13.95-14.05	+
	3.45-3.55	-		14.05-14.15	+++
	3.55-3.65	-		14.15-14.25	+
	3.65-3.75	-		14.25-14.35	++
	3.75-3.85	-		14.35-14.45	++
	3.85-3.95	-		14.45-14.55	+
	3.95-4.05	-		14.55-14.65	++
	4.05-4.15	-		14.65-14.75	+

*Frequency distribution based on the number of samples (L=loess doll): +: $1 \le L < 3$; ++: $3 \le L < 6$; +++: $6 \le L \le 9$

METHODS

The loess-paleosoil sequence was analysed in 10 cm vertical resolution and loess dolls were collected based on this division on the field. Smaller concretions were separated after wet sieving of the bulk loess/paleosoil samples, according to the 10 cm vertical resolution from 100-150 g material on a 500 μm sieve.

Different kinds of investigations were carried out on samples from Unit 2 and Unit 16. Concerning to whole profiles loess dolls were described first on the grounds of their morphology connected with the horizon in which they were found. Altogether 23 samples were cut into two or more parts according to the size of the loess doll: 3 samples from Unit 2 and 20 samples from Unit 16. Experiments were carried out on certain samples by using 10% hydrochloric acid to dissolve their carbonate content. The treatment with 10% hydrochloric acid was gradual, loess dolls were dipped into the acid then taken out and put into distilled water. This process was repeated successively until the samples were totally dissolved. The aim was to check the phases of the dissolution and describe the inner structure of the loess dolls (and also to determine the insoluble residues). Altogether 6 samples were treated this way: 4 samples from Unit 2 and 2 samples from Unit 16.

Loess doll samples were only taken from Unit 2 and 16. From Unit 3 to Unit 9 in the meanings of the classical description no loess dolls were found. In the Units 6-9 some features appeared in the maximal length of 2 cm, but their morphology could be linked more to the hypocoatings, although these samples had a more massive and cemented substance than hypocoatings. These features may act like the first stage of becoming a loess doll or maybe they are just being stuck in this phase because there was no significant leaching (and by this means not enough amount of percolating solutions).

From the Units 10-15 no samples were taken either. Under the two brown paleosoils (Units 10 and 12) no loess dolls were found, because these levels have not gone through a strong leaching (Unit 10 has a carbonate content varying between 14-15%; while Unit 12 has 9-14%; Barta 2010). However a probable gap during sedimentation also cannot be left out of account. The dark chernozem-like paleosoil (Unit 14) and the reddish brown paleosoil (Unit 15) are very strongly leached and their carbonate content is re-precipitated under the pedocomplex. Secondary carbonates are only available on the both sides of the upper and lower decalcification boundary in the forms of hypocoatings and calcified root cells.

RESULTS – UNIT 2

Loess dolls are found in Unit 2 between two depth ranges: a.) under the recent soil level (below 0.70 m) to 2.55 m, almost in every 10 cm intervals with the frequency distribution of one to nine samples; b.) between the depth range of 4.25 and 4.75 m with the same frequency distribution (*Table 1*). Below the recent soil to the depth of 2.55 m carbonate concretions are quite frequent and to the depth of 1.15 m they generally have rough, porous surfaces divided with channels. Their mean length is 1 cm and mean width is 0.5 cm.

At 1 m depth loess dolls are characterized with elongated, curving shapes with the length of 0.5-3 cm and width of 0.3-1.3 cm. Their surface is divided with small channels, in which calcified root cells or calcitic membranes can be found in some cases. Such small concretions occur also which take a shape of a former land snail shell. It means that the bicarbonate solutions could have been percolating through the shell and then precipitated the carbonate within, but later on the shell could have been broken off. Some concretions were quite easy to break into parts with hands, which revealed two different inner colours: a.) greyish colour of the compact, crystallized inner part; b.) yellowish to light brownish colour of the more porous than compact inner part (having the same colour as the outer crust of the concretion).

From the depth between 1.15 m to 1.25 m concretions appeared to have the same morphology as above described with mean length of 1.8 cm, but mostly became thinner on their central part. The concretions from the depth between 1.45 m to 2.55 m have length between 0.5-2 cm and can be characterized with an outer crust and an inner core in the colour of grey, which is compact. Such kind of concretion appeared as well, which had a small channel leading through it.

Then concretions appear again from the depth of 4.15 m to 4.75 m. These samples have a longitudinal axis but irregular shapes in the length between 3-5 cm and width between 0.5-1.5 cm. In Unit 2 below this depth no more concretions were found.

Loess dolls cut into two or more parts

Samples were taken from the depth of 0.85 m, 1.05 m and 1.55 m (*Fig. 3*). These concretions have a longitudinal axis ranging between 1.2 - 1.8 cm and their width is varying between 0.5-0.9 cm. Their form is mostly elongated with rough surfaces, while their inner parts are less compact and crystallized. The inner structure of the concretions can be characterized by cracks either parallel with the longitudinal axis or perpendicular to it.

In the sample from 0.85 m two main cracks appear parallel with the longitudinal axis, while the sample from 1.55 m has only got one crack parallel with the longitudinal axis. The concretion from 1.05 m has one crack parallel with the longitudinal axis, which is connected to a crack at an angle of 45° (like forming of a letter of “V”).

Loess dolls treated with 10% hydrochloric acid

The sample from the depth of 0.85 m has rough, pitted surface divided with channels. It seemed to be built up from different parts through cementation. During the gradual treatment with 10% hydrochloric acid many small

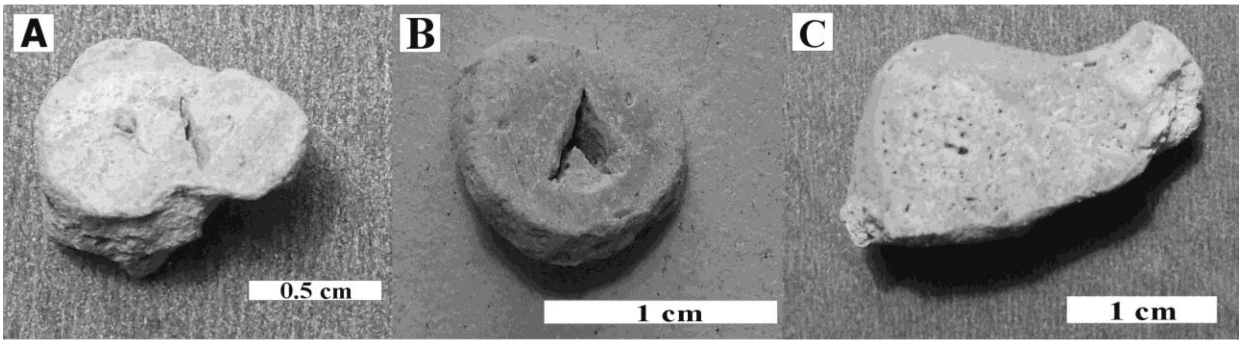

Fig. 3 Inner structures of loess dolls after cutting into parts

Samples taken from: A – 0.85 m; B – 1.05 m; C – 13.55 m. The concretions A and B are divided into cracks, while the sample C has a porous inner structure with a double core (double condensation nuclei) channels emerged also with calcified root cell structures. The longitudinal axis of the concretion was marked with two transversal smaller cracks. The inner structure was not porous, but compact and well crystallized.

The sample from the depth of 0.95 m has a length of 1.5 cm and width between 0.4-1.1 cm. During the gradual treatment with 10% hydrochloric acid the small channels with the outer crust have been dissolved and showed the inner core with a crack system. Inside the crack system a calcified root cell structure was found.

The inner structure of the sample from the depth of 1.55 m is characterized by a crack system. During the gradual treatment with 10% hydrochloric acid the structure of the sample was continuously checked under a binocular microscope. On the surface of the crystalline inner matrix a brownish fading was recognized and the rest material after the total dissolution of the concretion were gelatinous membranes in the extension of 2x6 mm. It was the only sample in which these features were present.

The concretion from the depth of 2.45 m has an outer crust and compact, well crystallized inner core in the colour of grey. This inner core is characterized with a small channel. Walls of the channel have the same yellowish colour like the outer crust. During the gradual treatment with 10% hydrochloric acid two parallel channels appeared along the longitudinal axis of the concretion. It was also observable that the inner parts dissolved faster than the outer crust.

RESULTS – UNIT 16

Loess dolls are present in high amount in Unit 16, they are detectable from the whole sequence from every 10 cm interval with the exception of 13.75 m – 13.85 m (*Table 1*). Along Unit 16 the size of the loess dolls is alternating in length between 0.4-4 cm and in width between 0.2-2 cm. In general their surface is rough, divided with small channels (which are often filled with calcitic membranes). In the upper third of Unit 16 calcified root cells and manganese infilling can occur also in these small channels of the surface. Concretions with smooth surfaces occurred in the lower third of Unit 16 together with the ones with rough surfaces. After cutting into parts the loess dolls showed different structures.

No characteristic crack system leads through the concretion

These kind of loess dolls are characteristic for the whole Unit 16. Samples were taken from the depth of 12.75 m, 13.15 m, 13.35 m, 13.45 m and 13.95 m. In general these concretions are 1-2 cm in length and 0.5-1 cm in width and have a more porous outer crust than their inner core.

Appearance of cracks

The loess doll from the depth of 12.75 m in the shape resembling a hut, has a length of 6 cm and width between 1.2-4 cm. Its outer crust is more porous, while the inner core is compact. In the middle zone of the concretion there is a main crack perpendicular to the longitudinal axis, and into which four smaller cracks are joining with a certain degree. The main crack does not lead through the whole length of the concretion. Besides the cracks smaller pores and nuclei are visible, but they are mostly present in the ending of the concretion.

Porous inner part

The loess doll from the depth of 13.55 m has a length of 5.5 cm and width between 1.0 and 2.5 cm (C on *Fig. 3*). It is characterized with a double core in which lot of small sized channel are found, which makes it so porous like a sponge.

Loess dolls from the depth of 14.15 m show the same sponge-like structure but have only one core. Another loess doll from this depth resembled the same structure, but with two separated larger pores besides the many small ones.

The loess doll from the depth of 14.55 m is also divided into many small pores which are present in a higher amount towards the outer crust of the concretion.

Inner core consisting of more parts

Two loess doll samples are examined from the depth of 13.15-13.25 m. The one with a length of 5.3 cm and width between 1-2 cm has a compact inner core surrounded ring-like by another compact layer, which is followed by the outer, thinner and more porous crust. A slice of the sample shows a small nucleus in the inner core. The other loess doll has a length of 2.5 cm and width of 1.8 cm and resembles the same structure, just without having a nucleus.

Relatively homogeneous inner structure

The loess doll from the depth of 13.35 m has a length of 1.9 cm and width of 1 cm, while the samples from the depth of 14.45 m has a length of 3 cm and width between 0.7-1.5 cm. Both concretions have no cracks or nuclei in their inner structure and are relatively homogeneous.

Septarian structure

The loess doll taken from the depth between 12.70 m and 12.75 m, right beneath the reddish brown paleosoil, has a length of 5 cm (longitudinal axis) and maximal width of 5.5 cm which is narrowing for 1-3 cm. After cutting into parts and smoothing the concretion three main nuclei appeared, one of them showing a septarian pattern (*Fig. 4*).

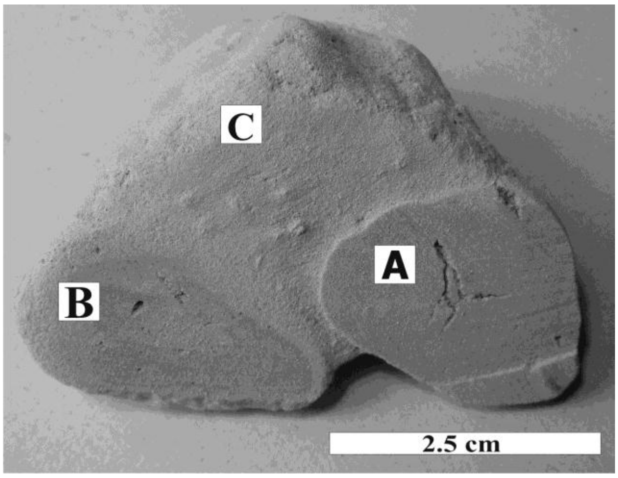

Fig.4. Loess doll with septarian structure from the depth between 12.70 m – 12.75 m

The three cores are marked with the letters A (septarian cracks); B (mass of small channels) and C (cementated hypocoatings)

Loess dolls treated with 10% hydrochloric acid

The sample taken from the depth between 12.70-12.75 m, also right beneath the reddish brown paleosoil, has a length of 7.8 cm and a maximal width of 4.6 cm, which grow narrow to 0.8-2.7 cm. The shape of the loess doll resembles a croissant. During the gradual treatment with 10% hydrochloric acid different structure elements were presented in the loess doll. The concretion was divided into two main layers: a.) the outer crust built up from sandy loess, which was easier dissolving, in the same colour as the surrounding matrix; b.) the very compact, strongly cemented inner core in the colour of grey and brown. The outer crust, which was dissolving normally, showed gradually many hypocoatings joining to each other. The inner core was dissolving very slowly (maybe it refers to a higher dolomite content, than calcite), showed parallel cracks along the longitudinal axis.

The sample from the depth between 13.05 m and 13.15 m has a length of 4 cm and width between 0.3-1 cm, and its surface is divided into small pores and channels. After the gradual treatment with 10% hydrochloric acid the inner structure of the loess doll seemed not be compact and one main crack appeared along the longitudinal axis with some small perpendicular cracks.

DISCUSSION

Unit 2

Two kind of inner structures are characteristic for the concretions of Unit 2: a.) appearance of cracks; b.) presence of a main crack (or cracks) parallel with the longitudinal axis of the loess doll (A and B on *Fig. 3*). The concretions are generally smaller in size than the ones of Unit 16. The size extension of these loess dolls ranges between 0.5-3 cm. The size properties may be connected with a less significant degree of leaching from the recent soil level and a probably young formation age. Other conditions of the matrix of the sediment can exert influence on the formation environment, like the changes of the partial CO_2 pressure or the capacity of carbonate uptake for the percolating solutions.

The formation of the concretions could be connected with carbonate precipitation in a well aired cavity system of different size and origin (Schäftlein 1996). Every examined sample from Unit 2 showed a certain kind of crack system.

The loess doll from the depth of 0.95 m was containing in its inner part a calcified root cell structure, which refers to a combined formation environment. It means that the formation was both connected with precipitation in a cavity and around a condensation core. The cavity could have been of biogenic origin, which means it was formed by roots of presumably grass species. First the calcificaton of the roots took part, which thought to be contemporaneous with the dust accumulation (after Becze-Deák et al. 1997). Later the cavity, which was left behind by the living root, was filled up with the calcified root cell structure, which acted as a nucleus for carbonate precipitation. These assumptions raise the possibility that this concretion is of younger age than the calcified root cell structure and was formed later on (and was still in an early development phase).

At the case of the sample from the depth of 0.85 m the calcified root cell structure was found not in the central part of the concretion, but as the part of its outer crust. It may also refer to an early development phase, during which the surface of the concretion adheres continuously more carbonate and cements to itself more components of the surrounding matrix.

The insoluble residues of the concretion from the depth of 1.55 m were gelatinous membranes. From this feature and the inner crack system of the concretion it may be concluded, that the carbonate content of the percolating solutions was accumulated in a cavity system of branching roots. During its formation it could have included the living root as well, which started to decay, but since than there was not enough time for the plant rests for the total decomposition. It may also refer to a quite young age of the loess doll compared to the level in which it was found.

To sum up, it can be stated that the examined concretions of Unit 2 were presumably developed in cavity systems connected with roots (based also on the works of Pávai-Vajna 1909, and Schäftlein 1996). Besides the formation in root related cavities the cracks in the concretions may have a connection with hypocoatings, namely carbonate could have been precipitated around hypocoatings (Barta 2011). It can be supported by the presence of small channels dividing the surface of some concretions, and which are seem to be referring to hypocoatings during the gradual treatment with 10% hydrochloric acid. The origin of hypocoatings, which are $CaCO_3$ impregnations around the pores of the soil matrix (Becze-Deák et al. 1997, Durand et al. 2010), can either be connected with root-suction related carbonate precipitation (Wieder – Yaalon 1982) or evaporation of calcium-rich solutions, or with carbonate precipitation from percolating solutions respectively (Becze-Deák et al. 1997). Although yet none of these hypothesis is proved or denied.

Unit 16

Loess dolls appear soon right under the paleosoil complex composed of the dark chernozem-like paleosoil (Unit 14) and the reddish brown paleosoil (Unit 15) and in addition generally in larger size compared with the concretions of Unit 2. This diversity of size can be connected with the different degree of leaching of the soil horizons. The pedocomplex is very strongly leached, which means that its carbonate content is mostly 0%, except the depth between 12.55 m and 12.65 m, where it reaches 2.08%. The effect of the strong leaching could have caused higher carbonate precipitation and accumulation rates under the paleosoil horizon. The effect of the downward percolating solutions could have been strengthened by a possible lateral groundwater flow and by valley floor position, respectively. The bicarbonate solutions were leaching through the pedocomplex and their carbonate content was precipitated in the underlying sandy loess deposits of Unit 16. In the loess the percolating solutions found different conditions of porosity and changes in the partial pressure of CO_2. The results of the precipitation were on the one hand the formation of carbonate coatings and on the other hand the concretions (Barta 2010).

Based on the examined loess dolls, three main observations can be established in connection with their origin: a.) carbonate precipitation around nuclei (C on *Fig. 3*); b.) carbonate precipitation in cavity systems; c.) multiphase origin (*Fig. 4*).

In the case of the concretions having relatively homogeneous inner structure or no characteristic crack system within, may be stated that they have been precipitated around certain nuclei (like small pores and channels) and are still in an earlier phase of development.

The appearance of cracks in the loess dolls can refer either to precipitation around more nuclei or small cavities. Around these individually developed features later on more carbonate was precipitated and caused merging into a new concretion. For this new complex form it was easier to adhere carbonate and carry on the growth. Among the loess dolls characterized by mostly porous inner parts, appears a concretion having a double core at the depth of 13.55 m (C on *Fig. 3*). Presumably it was developed around two nuclei which were growing through more carbonate precipitation and merged together, just as described above. This double core was containing lots of small sized channels and seemed to be as porous as a sponge. The possibility may be raised that these nuclei were connected with bunches of hair-thin roots which decayed later.

For the formation of loess dolls having mostly porous inner parts the idea came up, that the high amount of small channels (which are responsible for the porous structure) may possibly belong to hypocoatings, which were gradually cemented together. The cementation of hypocoatings may also be conceivable for the case of the concretion from the depth between 13.05 m and 13.15 m. In its inner structure perpendicular cracks were crossing through the main longitudinal crack and the appearance of the whole system resembled a possible cementation of hypocoatings.

Although the above presented loess doll types were soon examples for a multiphase development, the case of the following concretions also serve this reinforcement. The loess doll with the inner core consisting of more parts is characterized by a ring-like structure. Presumably the two ring-like more compact inner cores can be connected with different carbonate precipitation events (and so does the outer crust as well). It might be in connection with the assumed alternation of moist and arid phases in Unit 16 (Barta 2010).

The loess doll beneath the paleosoil complex, which is resembling a croissant, presumably also originated through more phases: like the inner core could be connected with the primary leaching of the pedocomplex, while the outer crust was built up from the later on percolating solutions (also through more than one phase).

Loess doll with septarian structure was found also right beneath the pedocomplex. The term septarian means a radial crack pattern, where the cracks are narrowing towards the external boundaries of the concretion (Bullock et al. 1985). This kind of structure was also described from concretions in shales (Seilacher 2001). In this loess doll three different cores are present resembling the junction of channels or cracks. But these channels may belong to cementated hypocoatings based on the appearance of the core marked with "C" (*Fig. 4*).

To confirm the role of hypocoatings in the multiphase development of loess dolls, a pedofeature was found from the depth between 14.45 m and 14.55 m. It is soon cementated and hard, but the tube shapes of the hypocoatings are still very well to be seen (*Fig. 5*). This structure act like if being in the early phase in becoming a concretion.

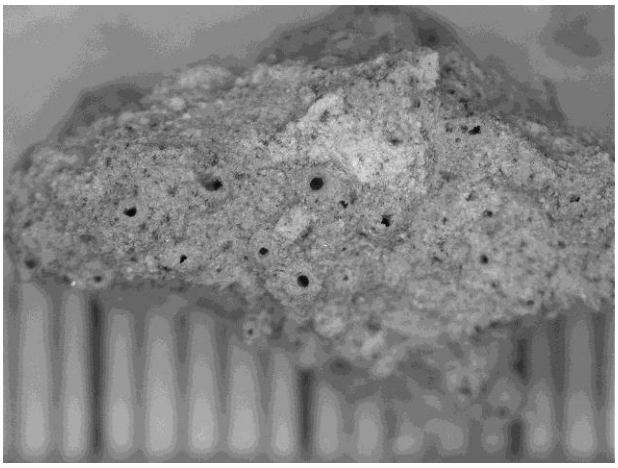

Fig. 5 Cementated hypocoatings – presumably an early phase in the formation of concretions

CONCLUSION

The loess dolls of the loess-paleosoil sequence of Süttő could be divided into three main types based on their inner structure: a.) concretions with longitudinal and/or perpendicular cracks; b.) concretions containing one or more condensation nucleus; c.) the combination of the above listed properties. These structures are summarized in *Table 2* (marked with letters from A to G), according to the depth of the sequence.

From the various inner structures of loess dolls more conclusions can be drawn concerning their origin. Carbonate precipitation took place in or around cavity systems either of biogenic origin (as root-related channels or features, and biogalleries) or of non-biogenic origin (because of the structural properties of the sediment). The cementation of hypocoatings can also act like precipitation nuclei and be the first phase in the concretion development. For the origin of the concretions of Unit 2 mostly the root-related cavity system theory was characteristic, while the loess dolls of Unit 16 were related to a multiphase development history concerning the role of cavity systems, precipitation nuclei and cementation of hypocoatings.

The knowledge of the morphology and structure of loess dolls provide information on their formation environment and may be a good complementary method in the research of secondary carbonates.

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Table 2 The structural characteristics of the examined loess dolls

Sequence	Depth (m)	Number of samples examined	Characteristics of the structure
Unit 2	0.75-0.85	2	C: main crack parallel with the longitudinal axis
	0.95-1.05	2	B: appearace of cracks; C: main crack parallel with the longitudinal axis
	1.45-1.55	2	B: appearace of cracks; C: main crack parallel with the longitudinal axis
	2.35-2.45	1	C: main crack parallel with the longitudinal axis
Unit 6	12.70-12.75	4	A: no characteristic crack system; B: appearance of cracks; C: main crack parallel with the longitudinal axis; G: septarian structure
	13.05-13.15	4	A: no characteristic crack system
	13.15-13.25	2	E: inner core consisting of more parts
	13.25-13.35	3	A: no characteristic crack system; F: relatively homogeneous inner part
	13.35-13.45	2	A: no characteristic crack system
	13.45-13.55	2	D: porous inner part
	13.85-13.95	1	A: no characteristic crack system
	14.35-14.45	3	D: porous inner part; F: relatively homogeneous inner part
	14.45-14.55	1	D: porous inner part

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