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Krotovinas, pedogenic processes and stratigraphic ambiguities of the Upper Palaeolithic sites Kostenki and Borshchevo (Russia)

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ABSTRACT

The excavations of the Upper Palaeolithic sites of Kostenki and Borshchevo, located in the Middle Russian Plain, bear several meters of loess-derived colluvial deposits of the Middle and Late Valdai, which cover alluvial sediments of the Don floodplain. At least four cultural layers and more than three paleosol units occur within the colluvial deposits. A high number of krotovinas is most obvious, mainly the burrows of *Cricetus cricetus* and *Lagurus lagurus*, which on first view seem only to disturb sediment and soil stratigraphy. To disprove this assumption, the present paper investigates the significance of krotovina fillings within soil research by applying micromorphological analysis. The study gives insight into different filling materials, soil forming processes inside abandoned and filled burrow systems, and surrounding material. In some cases, krotovina fillings in this part of the Middle Russian Plain can be areas of bulking and compaction, of preferential paths of infiltration followed by calcium carbonate depletion, and of drying followed by secondary calcification. Further, burrows are paths for second and third generations of soil faunal activities.

1. Introduction

Bioturbation by burrowing animals is common in the loess landscapes of the Middle Russian Steppe. The ‘krotovinas’, the result of burrowing activities, occur widely in soils of the steppe, and are of different sizes and forms (Formosov, 1928; Gerasimov and Glazovskaja, 1965). The effect of the burrowing animals on soils has been known since the work of Darwin (1896), and especially burrowing activities of small mammals are important in the genesis of the Holocene Chernozem, widespread in the Russian steppe (Dokuchajev, 1883), or in the Great Plains (Schultz and Stout, 1945).

In the discussion about stratigraphy, such burrow fillings have been seen so far only as features which disturb the sediment, and as discontinuous sediment voids of little value. For this reason the phenomenon of krotovina has rarely been studied within stratigraphic research over the last decades, though such studies have been valuable (Schultz, 1934; Gerasimov and Glazovskaja, 1965; Hole, 1981; Johnson et al., 1987, 2005, 2007; Butler, 1995; Willey, 1997; Bateman et al., 2003; Tobin, 2004; Rutter et al., 2006; Velichko, 2009). Burrowing activities have been studied in the context of palaeontological research about the distribution of hamsters (*Cricetus cricetus*), steppe lemmings (*Lagurus lagurus*) and ground squirrels (*Spermophilus* sp.) (Markova et al., 2002; Markova, 2005). Few researchers have taken small mammal activities into consideration when pursuing archaeological research (Wood and Johnson, 1978; Tappen et al., 2002; Prieto et al., 2009; Jin et al., 2012).

Ancient krotovinas were used to identify pedogenic processes such as Chernozem formation in the Missouri Valley, Iowa, USA (Rutter et al., 2006), and in Kostenki, Middle Russian Steppe (Pietsch, 2013). Velichko et al. (2009) took greyish-blue relics of Bg horizons in krotovinas as remnants of former, already eroded soils with distinct redoximorphic properties, as the stratigraphic equivalent of the interstadial “Gmelin soil”. The main micromorphological features of this interstadial paleosol are bioturbation, micritic hypocoatings (secondary calcification), primary carbonates (Cretaceous marl) and depletion hypocoatings (*in situ* decalcification).

Systematic study of stratigraphic ambiguities and filled burrows in the position of paleosols I, II and III (Sedov et al., 2010) occurring in the Upper Palaeolithic sites Kostenki and Borshchevo in 2011 led to the following results (Pietsch, 2013):

(1) Black krotovina fillings (eroded modern Chernozem top soil) as well as humus-speckled fillings (with embedded humus from

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the eroded Early Holocene top soil) are formed by deep-burrowing small mammals such as *C. cricetus*.
(2) Greyish krotovina fillings of shallow-burrowing small mammals may represent eroded former surface soils of Interstadials of the Late Pleistocene.
(3) Burrows provide optimal material for further soil biological activities, seen in the activity of subsequent generations of small mammals or invertebrates.
(4) The fillings of burrows link pedostratigraphy and soil biological activities, especially those of *C. cricetus* around 12 ka cal BP and those of *L. lagurus* around 32–26 ka cal BP.

The present contribution takes a deeper look into the pedogenic processes inside the burrow fillings, the surrounding material and the interface. Against the background of pedostratigraphical research, it is shown that soil micromorphological analyses of krotovina fillings give new insights into soil formation in the steppe landscape.

2. Study area and pedostratigraphy

The two excavations Kostenki (K14) and Borshchevo (B5) are located on the slopes of ravines, filled with reworked loess derived deposits above alluvial sediments of the Don floodplain (Fig. 1). The bedrock in the area consists of Cretaceous marl. At least four cultural layers (Sinitsyn and Hoffecker, 2006; Anikovich et al., 2007; Holliday et al., 2007) and between three and nine paleosols occur within the colluvial deposits (Fig. 2; after Sedov et al., 2010 five paleosol units).

The paleosols developed during marine isotope stages 3 and 2 (MIS 2 and 3). The "Gmelinsk"-temporal soil (MIS 2, paleosol Ib, coinciding with cultural layer I, 26–25 ka cal BP after Hoffecker et al., 2008) is most important for the present study. It was discovered to have been complete in the landscape (K21) and found incomplete in K14, truncated without an Ag horizon (Velichko et al., 2009; Sedov et al., 2010). The paleosol in its complete form was only found at a location near section K21 in

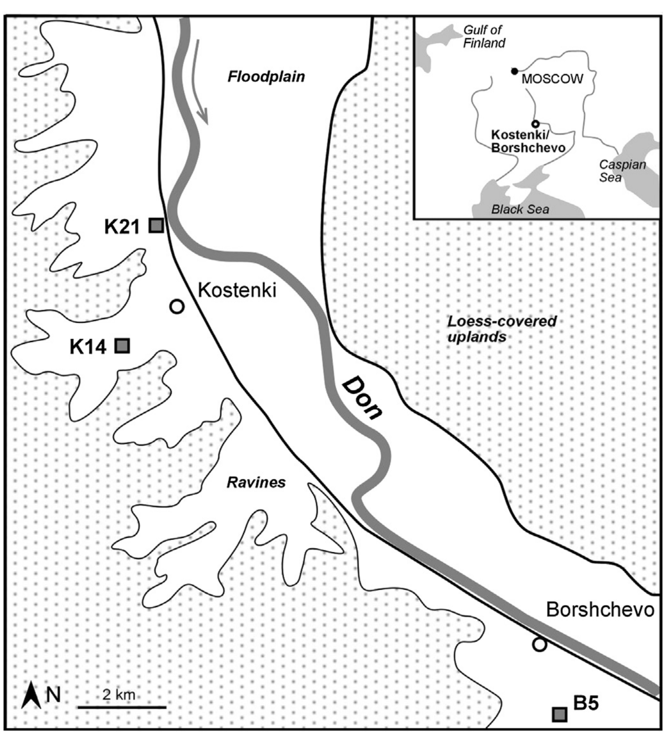

Fig. 1. Location of excavations in Kostenki and Borshchevo (after Sinitsyn, 2003).

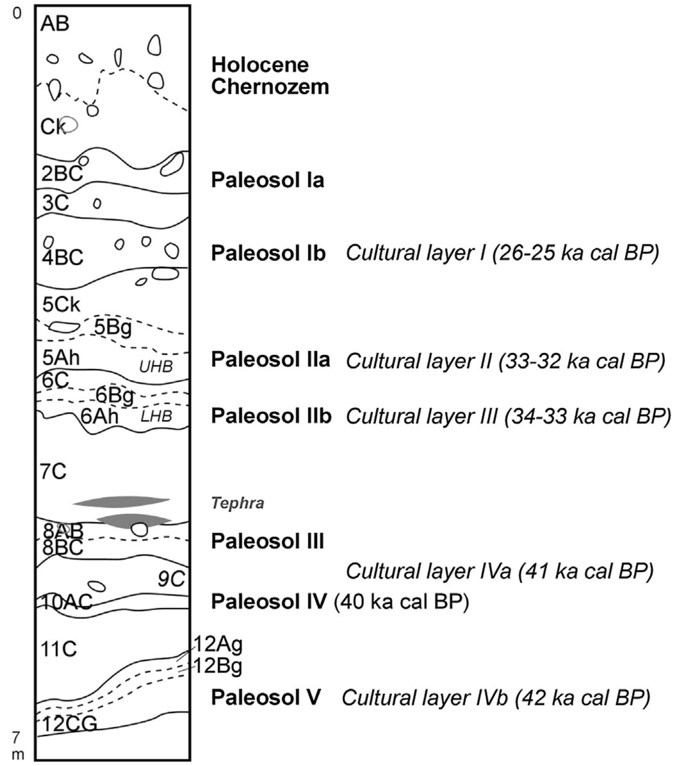

Fig. 2. Pedostratigraphy of the key section K14 (after Sedov et al., 2010, paleosol Ib is the stratigraphic equivalent for the "Gmelinsk"-temporal soil) and palesols IIa and IIb are equivalents of the "Bryansk"-temporal soil, UHB: Upper Humic Bed, LHB: Lower Humic Bed; chronostratigraphy of cultural layers (after Sinitsyn and Hoffecker, 2006).

2008. There, it has an Ag and a Bcg horizon above a Bw horizon. The Bw horizon shows whitish fissures, the result of repeated freeze-thaw. In K14, however, only a brownish 3Bwk horizon is preserved. The 2Bwk horizon is assumed as the origin of the material (groundmass) in the humus-speckled krotovinas at more than 2.0 m depth. Humus aggregates originate from the Holocene Chernozem (Pietsch, 2013).

3. Materials and methods

To decipher the origin of materials inside the burrow, and the kind of pedogenic processes such as bioturbation, decalcification and secondary calcification, two krotovinas, their surrounding material as well as overlying soils and loessic sediments were selected: one krotovina from section K14, Krot 31 and one from section B5, Krot 112 (Fig. 3). In total, 118 mixed burrow fillings of the western and eastern trenches of K14 and of the southwestern trench of B5 have been described using a newly developed classification system (Pietsch, 2013: Table 1).

Table 1
Soil chemical data from krotovinas, reworked loess derived sediments/surrounding material, Chernozem and "Gmelinsk"-temporal soil (* and ** are mean values of all data, cf. Pietsch, 2012: Table 2 and Fig. 5).

Sample no	C_t[a]	$CaCO_3$[b]	C_{org}[c]	Al_2O_3[d]	CaO[d]	Na_2O[d]	K_2O[d]	CIA[e]
	%							
Krotovina filling								
K14 Krot 31	6.0	47.4	0.3	7.0	26.5	0.6	1.2	18
B5 Krot 112	3.9	27.2	0.6	8.6	14.6	0.6	1.7	34
*Mean Krotovina**	*4.8*	*38.1*	*0.3*	*8.0*	*19.9*	*0.7*	*1.6*	*27*
Surrounding material								
K14 3Bwk	5.1	40.5	0.2	6.6	21.8	0.5	1.5	22

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Table 1 (*continued*)

Sample no	C_t[a]	$CaCO_3$[b]	C_{org}[c]	Al_2O_3[d]	CaO[d]	Na_2O[d]	K_2O[d]	CIA[e]
	%							
K14 3Ck	6.1	47.7	0.3	6.5	26.8	0.5	1.3	19
K14 4Bg + Ck (Krot 31)	5.9	46.7	0.3	7.2	25.8	0.6	1.3	21
B5 Ck	5.3	46.7	0.0	6.9	23.2	0.6	1.4	22
B5 2Bwk	3.4	27.5	0.1	8.3	14.7	0.6	1.5	33
B5 3Bwk (Krot 112)	3.3	25.6	0.2	8.9	14.6	0.7	1.7	34
*Mean surrounding m.**	*5.8*	*47.8*	*0.2*	*6.5*	*23.4*	*0.5*	*1.3*	*21*
Other soil horizons								
K14 Ah (Chernozem)	4.5	7.6	3.6	10.2	5.7	0.7	2.3	54
B5 ABg(h) ("Gmelin")	1.9	15.0	1.7	12.2	1.6	0.8	2.5	71
K21 "Gmelin soil"								
K21 Ag	1.8	15.1	0.0	–	–	–	–	–
K21 Bg	1.5	12.9	0.0	–	–	–	–	–

*Mean value of all samples (cf. Pietsch, 2013: Table 1).
Mean values are indicated in italics.
[a] Total carbon, determined after heat combustion (1150 °C) with an element analyser.
[b] Gasvolumetric determination of $CaCO_3$ content (after Blume et al., 2000).
[c] Organic carbon, $C_{org} = C_t$-($CaCO_3$*0.12).
[d] Major elements, determined by XRF (H. Taubald, IAG Tübingen).
[e] Chemical Index of Alteration, CIA = $Al_2O_3/(Al_2O_3+CaO + Na_2O + K2O)*100$, CaO : silicate bound Ca (Nesbitt and Young, 1982) – not determined.

Horizon designation was carried out according to the FAO Guidelines for Soil Description (FAO, 2006). Sixteen burrow fillings and 23 bulk samples from the surrounding sediments and the Holocene Chernozem were analysed (calcium carbonate, organic carbon, major elements); the soil organic matter of two fillings have been dated by ^{14}C AMS (Pietsch, 2013: Table 2). In the laboratory, bulk samples were air-dried and sieved <2 mm. Fine earth <2 mm was used for gas volumetric determination of $CaCO_3$ (Blume et al., 2000). A portion of each <2 mm sample was ground with a ball mill and used to determine the total carbon content (C_t) after heat combustion (1150 °C) with an element analyser (Elementar Vario EL III): $C_{org} = C_t - C_{CaCO3}$. Major and trace elements were extracted from finely-ground earth with a ratio of Li-Metaborate to soil of 1:5, and then measured with a wavelength dispersive XRF-spectrometer Bruker AXS S4 Pionier (H. Taubald, IAG Tübingen). Pedogenic processes including silicate weathering were deduced from the depth function of weathering indices, such as the Chemical Index of Alteration (CIA) = $[Al_2O_3/(Al_2O_3 + CaO^* + Na_2O + K_2O)] \times 100$ (after Nesbitt and Young, 1982), where CaO* is the amount of silicate-bound CaO. Undisturbed, oriented samples for micromorphological analysis were taken. After air-drying, the blocks were impregnated with Oldopal P80-21 and cut and polished to 6.0 × 8.0 cm slices. Soil thin section description at two fringes of krotovinas followed Stoops (2003) with the aim of comparing pedogenesis inside and outside the burrow filling.

Table 2
Comparison of pedogenic features based on micromorphological data (– not occurring, x weakly developed, X well developed).

Pedogenic features	Krotovina filling	Fringe (interface)	Surrounding material
Secondary bioturbation features by meso-fauna	x	X	x
Plant tissues	x	x	–
Humus enrichment	X	X	–
Sparitic pseudomorphs	x	–	–
Micritic hypocoating	x	x	X
Passage features (infillings)	x	x	x
Depletion hypocoating	x	–	–

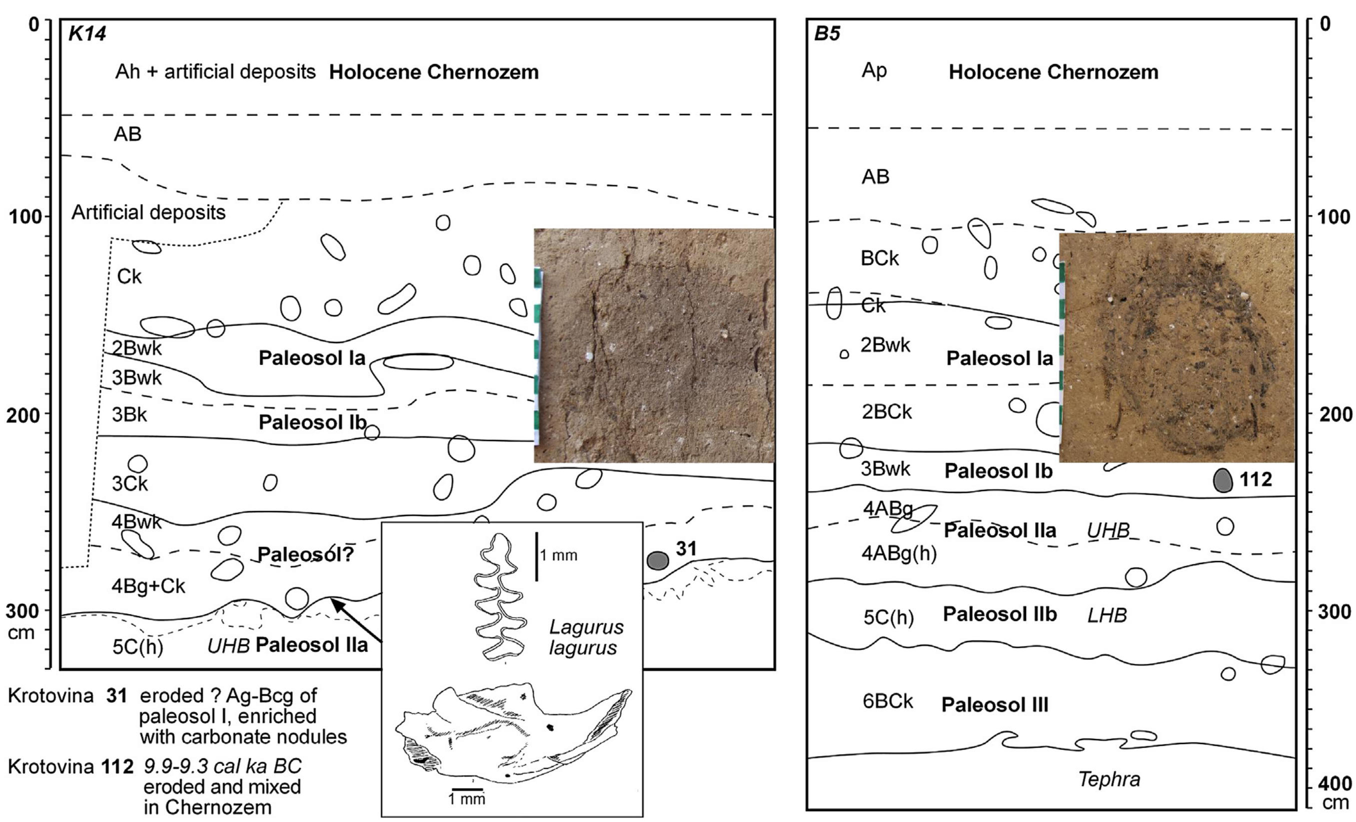

Fig. 3. Left: Section K 14 in 2011. The krotovina filling (Krot 31) might result from erosion of interstadial grey soil, mixed with marl fragments during the burrow activities of steppe lemmings (?) in the Late Pleistocene. The tooth of *Lagurus lagurus* comes from the UHB; right: Section B 5 in 2011. The humus-speckled krotovina filling (Krot 112) results from Early Holocene Chernozem and brownish 2Bwk material.

4. Results

4.1. Field data

Generally, the filling materials of the krotovinas contain (a) loess derived sediments and (b) black humic Ah material or brownish Bwk material. In some cases, fillings are enriched with macroscopically visible humus aggregates (Ah horizon material) or with carbonate fragments (Cretaceous marl). A few burrow systems have been used at least twice, as represented by two discrete fringes of krotovinas (small mammals) or by secondary bioturbation features seen at the interface between burrow and surrounding loess derived material (invertebrates). Occasionally, greyish remnants of assumed interstadial soils occur (Ag-Bcg material? of Krot 31, Fig. 3 left). Fine, distributed humic components in the black krotovinas come from the Holocene Chernozem (Krot 112, Fig. 3 right).

Krot 112 in B5 is at 2.30 m depth. The burrow, presumably starting in the Ap (ploughed, previously Ah horizon) passes through 5 horizons to the 3Bwk horizon of paleosol Ib. This humus-speckled krotovina has a brownish filling with aggregates of the Holocene Chernozem on top of the profile. The brown colour may originate in the 2Bwk material of paleosol Ia. Most obvious is the humus-enriched and frayed fringe.

Krot 31 in K14 is at 2.70 m depth. The burrow, presumably starting from the 3Bwk horizon at 1.80 m, which might have been under- or overlain by a Bg horizon, passes through 4 horizons to the 4Bg + C horizon (stratigraphic equivalent of 5Ag, cf. Fig. 2). This krotovina has an atypical greyish filling which clearly differs from the surrounding material. The large number of fragments of Cretaceous marl inside the filling originates from the 3Ck horizon above, and do not occur in the 4Bg + C horizon.

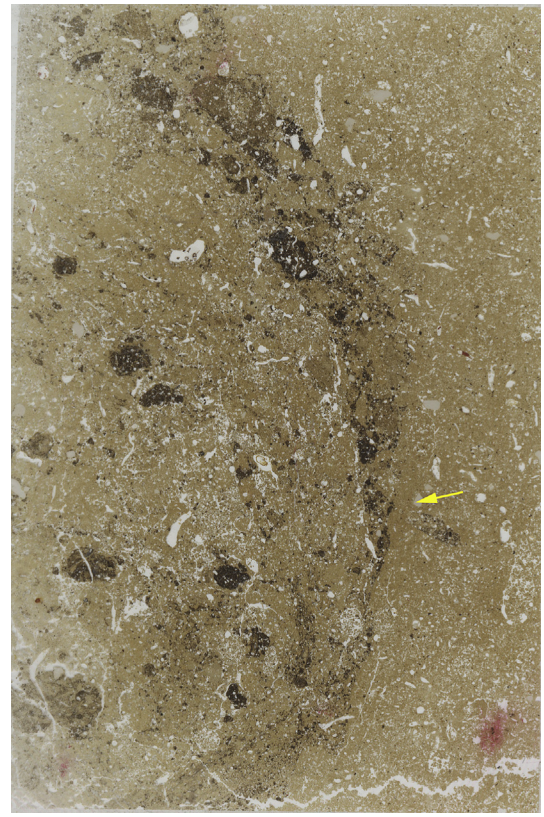

Fig. 4. Thin section (5 × 8 cm) of B5 Krot 112 (see Fig. 3 right).

4.2. Laboratory data

The $CaCO_3$ content inside the filling of Krot 112 is around 27%, and is comparable to the material of the 2Bwk horizon. In contrast, the C_{org} content of the filling is 0.6% higher than the C_{org} content of the adjacent material, and does not correlate with the high C_{org} content of the Ah horizon of the Chernozem (3.6%). Weathering intensity inside and outside the burrow is similar (CIA 34).

The $CaCO_3$ content of Krot 31 and its surrounding material does not differ significantly (47%), but is in contrast to the "Gmelinsk"-temporal soil (12–15%). The C_{org} content of the filling is rather low (0.3%) and similar to the surrounding and overlying materials. Weathering intensity of the krotovina filling is lower (CIA 18) than in the 4Bg + C horizon (CIA 21). For soil chemical data of all investigated krotovina fillings and surrounding materials, refer to Pietsch (2013: Table 1 and Fig. 5).

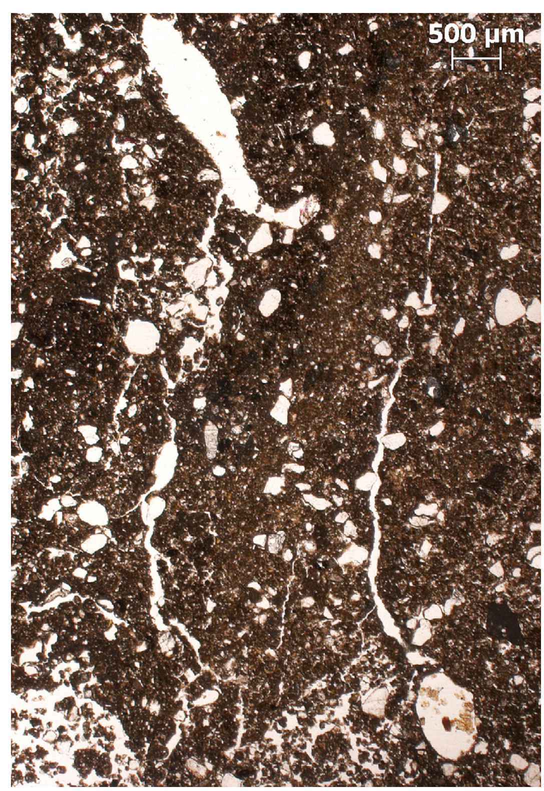

Fig. 5. Passage features with loose crumby infillings. Plant cells in a channel. Note the higher porosity in the filling (left hand side) – one polarizer, B5 Krot 112.

4.3. Soil micromorphology

4.3.1. Borshchevo 5 Krot 112

The thin section Krot 112 (5 × 8 cm) shows the transition zone (fringe) of the filling and the surrounding material of the krotovina (Fig. 4). The burrow filling consists of Chernozem aggregates up to a 2 cm, but most of the filling is made of brownish loess-derived material. The characteristic microstructure of the filling is a channel to spongy, and partly compacted crumb microstructure. Numerous passage features (predominantly crescent channel fillings and loose crumby discontinuous infillings, Fig. 5) outside and inside the krotovina indicate a high degree of reworking of the krotovina filling and the surrounding material by soil meso-fauna.

Numerous larger humus-rich soil fragments (around 500 µm) were most probably fragmented during the filling process and do not occur outside the burrow. Black humus-rich crescent infillings of channels outside the krotovina show redistribution of deposited organic matter, leading to an enrichment of organic matter outside the filling. These dark fillings were subject to bioturbation, expressed by a brown channel infilling with small amounts of organic material crossing a humus-rich infilling (Fig. 4). Brown to reddish-brown tissue residues or plant cells can be found in some channels (Fig. 5).

The lower boundary of the krotovina is wavy (Fig. 4). Lower porosity, indicating compaction, is noticeable in the adjacent material of the lower half of the krotovina (Fig. 5). Here, different layers of humus-rich material form the lower side of the krotovina. The characteristic micromorphological features of the surrounding material are partly compacted granular microstructure, crystalline b-fabric, and numerous passage features (predominantly crescent infillings) and loose crumby infillings. Decalcification features were not detected.

The only noticeable pedogenic process outside the krotovina is secondary calcification in the form of well developed micritic hypocoatings (Fig. 6). Weakly developed micritic hypocoatings were found inside the filling (Fig. 7).

4.3.2. Kostenki 14 Krot 31

The thin section Krot 31 (5 × 8 cm) shows the transition zone of the krotovina filling (right hand side) and the surrounding material (Fig. 8). Numerous passage features (mostly N–S oriented crescent infillings) are present. The characteristic micromorphological features of the surrounding material are channel microstructure, crystalline b-fabric, numerous passage features (predominantly crescent infillings), and frequently occurring sparite in the groundmass. Decalcification features were not detected. The outer fringe of the krotovina can easily be recognized by a dense micritic hypocoating (Fig. 9) on the groundmass of the surrounding material.

The characteristic microstructure of the filling is channel to spongy microstructure. Depletion hypocoatings (Fig. 10) around channels in the filling are the result of preferential flow in macropores with accompanying carbonate redistribution and partial decalcification. Secondary calcification features including micritic hypocoatings are weakly developed.

Light grey areas in plane polarized light (Fig. 11) occur in some parts around peds in the krotovina filling. Fluorescence light reveals that these light grey areas are passage features and infillings of channels (Fig. 12).

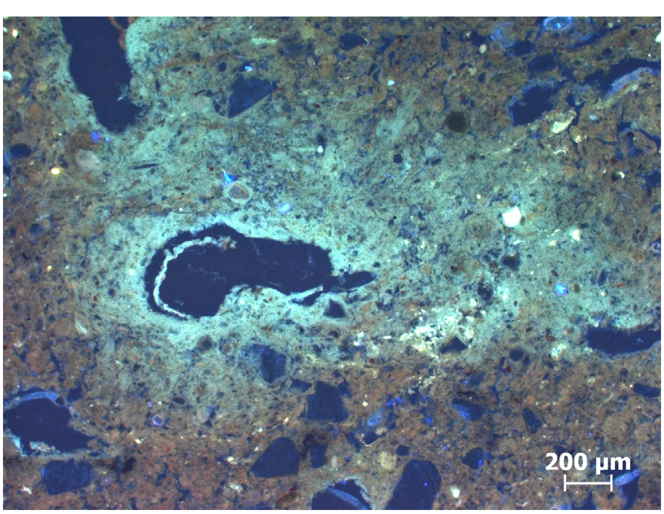

Fig. 6. Well developed micritic hypocoatings – FL, 365 + 470 nm/multipass filter, surrounding 3Bwk material of B5 Krot 112.

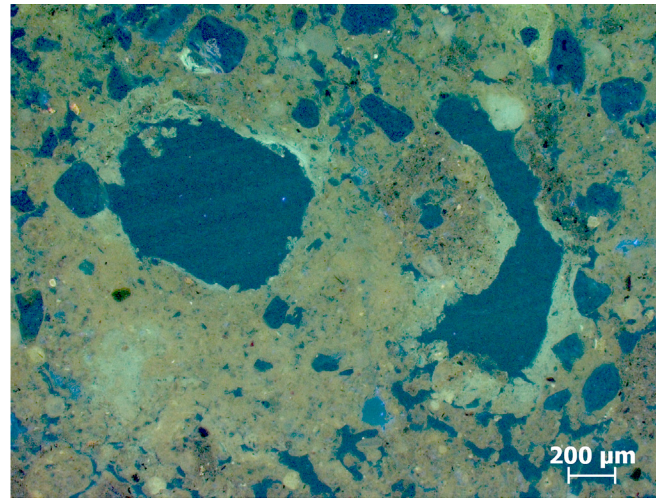

Fig. 7. Weakly developed micritic hypocoatings– FL, 365 + 470 nm/multipass filter, B5 Krot 112.

5. Discussion

5.1. Pedogenic processes inside and outside krotovinas

5.1.1. Bioturbation by fauna and roots

In contrast to the loess derived surrounding material, the burrow fillings are characterized by strong meso-fauna activities (passage features) and rooting (channel infillings with cell residues;

Fig. 8. Thin section (5 × 8 cm) of K14 Krot 31 (see Fig. 3 left). Light grey areas are fragments of Cretaceous marl originating from the 3Ck horizon. The thin section shows numerous passage features, mostly N–S oriented crescent infillings.

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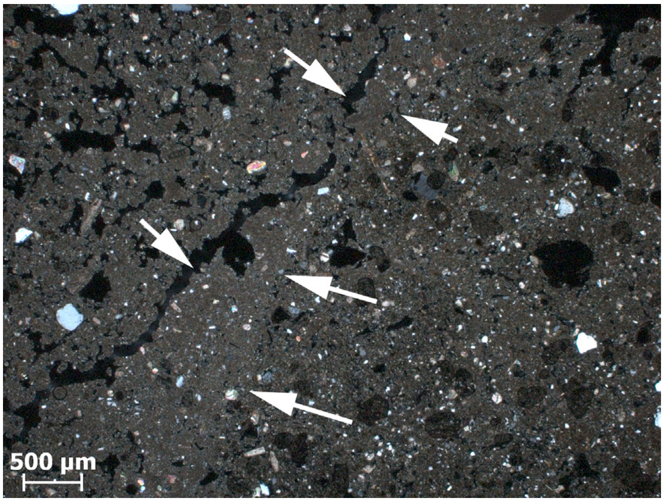

Fig. 9. Transition zone filling (upper left corner) and adjacent material. Micritic hypocoating (white arrows) on adjacent material of the krotovina. Note the occurrence of mammillated vughs and the higher porosity in the filling – cross polarized light, K14 Krot 31.

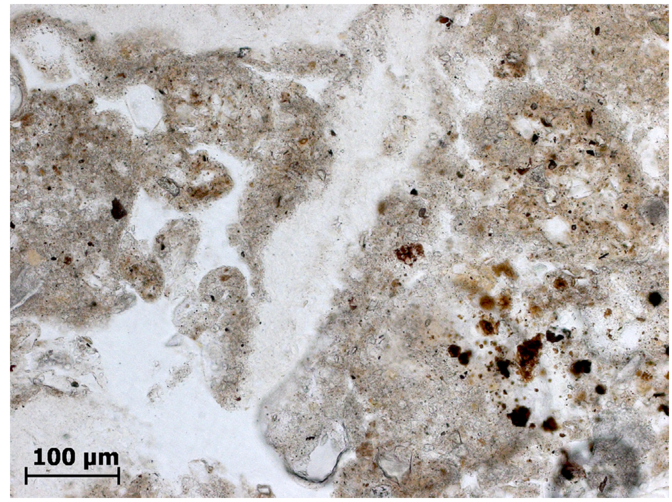

Fig. 11. Channel fillings (greyish areas) – plane polarized light, K14 Krot 31.

Kooistra and Pulleman, 2010), a prominent feature at the fringe (Table 2). The environmental conditions and the soil material within the krotovinas were ideal for soil biological activities. The lower wavy boundary of the krotovina can be interpreted to result from scratching of the burrowing animal during the initial construction of the channel (Fig. 4). The bulk density inside the abandoned and filled krotovina is often lower (Pietsch, 2013), except from compaction along the fringe, seen in a lower porosity due to burrowing activity. Tissue residues indicate rooting and bulking inside the filling (Fig. 5).

In the same krotovina 112, layers of humus-rich material form the lower side of the krotovina filling, which might be the result of successive deposition of humus when the burrow was in use. The C_{org} content of this filling is 0.6%, double the C_{org} contents of other fillings and surrounding materials (Table 1). Meso-fauna (most probably invertebrates) make secondary use of the filled burrows and transport organic material across the krotovina fringe into the loessic deposits (Fig. 4). Whether or not further burrow activities date to the Early Holocene period of Chernozem formation or to modern times still remains unresolved (e.g. Ivanov, 1992). However, the origin of numerous larger humus-rich soil fragments (around 500 μm) in mottled krotovina fillings (cf. Krot 112, Fig. 3 right) is clear: they represent fragmented and eroded aggregates of the Ah horizon of the Chernozem (Fig. 4) as result of the filling process after the abandonment of the burrow. Those aggregates do not occur outside the krotovina filling.

5.1.2. Depletion of calcium carbonates

Weakly developed features of decalcification (depletion hypocoatings) could be detected inside the filling of Krot 31 (K14), the result of calcium carbonate redistribution within the krotovina (Fig. 10). Depletion hypocoatings around channels inside the filling are the result of preferential flow in macropores with accompanying carbonate redistribution and partial decalcification (Pietsch and Kühn, 2009; Durand et al., 2010). Although this process seemed to be weak, it cannot be demonstrated by pedochemical laboratory data: the $CaCO_3$ content of this filling is as high as the surrounding material and the assumed original material (Table 1). As humus aggregates, decalcification features could not be detected in the surrounding material.

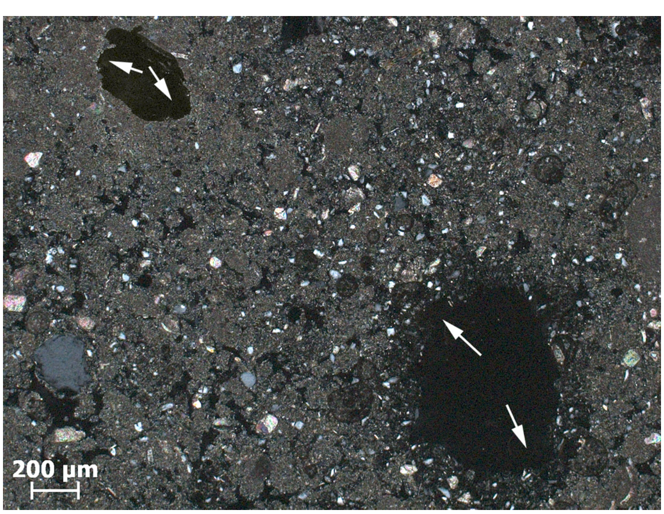

Fig. 10. Depletion hypocoatings (right arrows) around channel and micritic hypocoatings (left arrows) – cross polarized light, K14 Krot 31.

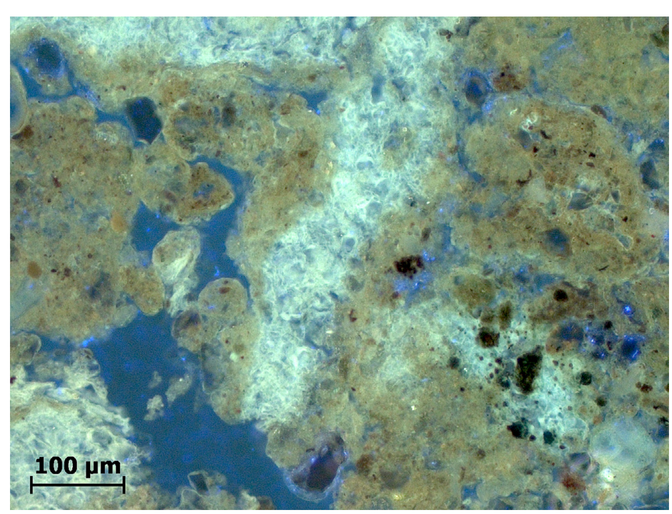

Fig. 12. Channel fillings (whitish areas) consist of calcium carbonate – FL, 365 + 470 nm/multipass filter, K14 Krot 31.

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5.1.3. Secondary calcification and primary carbonates

The only noticeable pedogenic process outside the krotovina, inside the 2Bwk horizon (B5), is secondary calcification in form of well developed micritic hypocoatings (Fig. 6). Weakly developed micritic hypocoatings were found inside the fillings of Krot 112 and 31 (Figs. 7 and 10). The outer fringe of Krot 31 can easily be recognized by a dense micritic hypocoating on the groundmass of the surrounding material (Fig. 9). Micritic hypocoatings are the result of alternating wet and dry phases with carbonate precipitation before (distinct boundary) and most probably also after the burrows were filled. Micritic hypocoatings occur usually directly below decalcified horizons, or below horizons in which decalcification processes took place (e.g. Dultz and Kühn, 2005: Table 2; Gerasimova et al., 1996). Here, however, a linear occurrence of decalcification and recalcifiaction processes along the krotovinas seems to be very likely. Features related to rhizoliths (cf. Durand et al., 2010; Gocke et al., 2011) were not detected. That filled burrows are preferential paths of infiltration cannot be shown from the present results on secondary calcification, but can be inferred from the prevalent spongy to channel microstructure, which implies a higher porosity compared to the surrounding material (Figs. 1 and 5).

Passage features and infillings of channels are common within the filling of krotovina 112 (Fig. 12). These passage features are the result of bioturbation after the krotovina was filled. Such features could not be detected in the surrounding material. Sparite frequently occurs in the groundmass of krotovina 31, assumed to be the result of bioturbation, fragmenting sparitic pseudomorphs after root cells and biogenic calcite (Durand et al., 2010). Pseudomorphs after root cells are characteristic for horizons with higher carbonate content and features of secondary calcification (Gerasimova et al., 1996). Primary carbonates come from the calcareous loess-derived material (Ck horizons, Table 1 and Pietsch, 2013: Fig. 6) and from etched coarse fragments of Cretaceous marl (Fig. 8).

5.2. Stratigraphic ambiguities – paleosol relics

5.2.1. Humus-speckled krotovina fillings (Early Holocene)

Krotovina fillings with embedded humus from the eroded Early Holocene top soil (Fig. 3 right, Krot 112) are from deep-burrowing small mammals, such as *C. cricetus*, which can burrow through sediments of 3 m thickness. The Krot 112 in B5 is at 2.30 m and the burrow passes through 5 horizons. Dating of soil organic carbon supports the idea of the embedment of Early Holocene Chernozem material (10 ka cal BC; Pietsch, 2013) into Late Pleistocene sediments (3Bwk material). The C_{org} content of the filling is 0.6% higher than the C_{org} in the surrounding 3Bwk material and other materials above, and is also higher than the brownish groundmass of the filling originating from the 2Bwk horizon/paleosol Ia (Table 1). It does not correlate with the high C_{org} content of the Ah horizon of the Chernozem (3.6%) because of mixing with calcareous reworked loess. The $CaCO_3$ content inside the filling of Krot 112 is around 27%, and does not differ much from the original material of the 2Bwk horizon/paleosol Ia.

5.2.2. Greyish krotovina fillings

It was proposed that greyish krotovina fillings are the results of shallow-burrowing small mammal activities, and that they might represent eroded surface soils of the Late Pleistocene. As the paleosol Ib ("Gmelinsk"-temporal soil) is known from the area around the excavations and from previous sections (Velichko et al., 2009; Sedov et al., 2010), relics of this paleosol, i.e. reworked Ag or Bcg horizons, were expected to occur in the burrows. Low $CaCO_3$ contents (12–15%) and a C_{org} content of zero differentiate this paleosol from other soils in Kostenki and Borshchevo (Pietsch, 2013). The grey colour cannot be correlated with any under- or overlying loessic deposits or paleosol (Haesaerts et al., 2004; Holliday et al., 2007; Velichko et al., 2009; Sedov et al., 2010). Shallow-burrowing small mammals such as *L. lagurus* normally burrow through 0.5–0.9 m of sediment. In the present case, burrowing might have started at a surface where an Ag-Bcg horizon might have been present above the 3Bwk horizon. The burrow, presumably starting at 1.80 m, crosses 4 horizons down to the 4Bg + C horizon (stratigraphic equivalent of 5Ag, Fig. 2). The fissures of the original soil (K21, Pietsch, 2013: Fig. 2) resulting from freeze-thaw processes were destroyed during the relocation of the soil material into the burrow, and therefore cannot be considered relics of paleosol Ib. On the other hand, an indication could be the high amount of Cretaceous marl fragments in the filling (Fig. 3 left and Fig. 8), which clearly originate from the 3Ck horizon above and which do not occur in the 4Bg + C horizon.

One main challenge in solving stratigraphic questions related to Late Pleistocene loess-paleosol sequences is the estimation of erosion rates or the identification of erosional phases or hiatuses (e.g. Kreutzer et al., 2012). The original thickness of the loess-derived colluvial deposits cannot be reconstructed yet, which complicates the interpretation of the origin of the greyish and some other krotovina fillings. At the current stage of research, it may be proposed that greyish fillings represent eroded Ag–Bg horizons of the Valdai period. This preliminary result will be tested in further investigations.

6. Conclusion

This study demonstrates that filled burrows of small mammals provide a valuable archive of pedogenic processes inside and outside krotovinas which, in the present case, originate from the Late Valdai to the very beginning of the Early Holocene. Pedogenic features are secondary bioturbation by mesofauna, humus enrichment, formation of sparitic pseudomorphs, micritic hypocoating (secondary calcification), enrichment with primary carbonates (Cretaceous marl) and depletion hypocoating (*in situ* decalcification). Which of the soil forming processes, especially along preferential paths, proceeded after 10 ka (Fig. 3) until today is not clear. Field observations, laboratory data and micromorphology provide evidence that description and analysis of krotovina fillings helps:

(i) to compare pedogenic processes occurring in the fillings and in the surrounding materials and to get information about the source of the filling material,
(ii) to define pedogenic features such as secondary calcification in the surrounding materials and depletion of calcium carbonates inside krotovinas, and bioturbation at krotovina fringes
(iii) to refine pedostratigraphy, in the present case to prove the relic occurrence of the Early Holocene Chernozem and the "Gmelinsk"-temporal soil in this two investigated archaeological sections.

Laboratory data and micromorphological data on secondary bioturbation (invertebrates), calcification and humus enrichment help to distinguish pedogenic processes inside and outside krotovinas. Macroscopically visible features such as colour (humus-speckled, greyish), shape, stratigraphic position of the krotovina filling (deeply burrowing or shallowly burrowing animals) as well as supporting palaeontological data (e.g. fossils of burrowing small mammals indicating the occurrence of *L. lagurus* between 32 and 26 ka) can help to clarify stratigraphic ambiguities.

The krotovina approach will be extended by further field and laboratory investigations in the Upper Palaeolithic excavations of Kostenki and Borshchevo. Further soil chemical analysis, micromorphology, analysis of small-mammal fossils and phytolith analysis will be continued in the future.

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