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MORPHOLOGICAL RECORD OF PEDOGENESIS AND LANDSCAPE EVOLUTION IN THE UPPER QUATERNARY PEDOSEDIMENTS WITHIN THE UPPER VOLGA RIVER BASIN

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The morphological record of pedogenesis (mostly at a micromorphological scale) and the features of paleosols developed at the northern geographical extremity of the MIS3 paleopedoshpere (including the Bryansk fossil soils) are described. The profiles of the MIS3 paleosols (dark humic gley and peaty gley with the ^{14}C-age around 29–50 cal kyr BP) are located within the periglacial zone in the centre of the Russian Plain (56.7°–58.5° N) within the Upper Volga drainage basin. An assemblage of stable micromorphological features of paleosols studied includes the following: 1) ferruginous nodules and other pedofeatures, occasionally fragmented; 2) concentration (separation) of sand grains within certain microzones; 3) inclusions of raw organic matter, often deformed and oriented to different degrees within the matrix. Despite being buried for a long time period and superimposed by the Holocene pedogenetic processes (clay illuviation), the paleosols preserve some features of short-term (10^1–10^2 yr) and medium-term (10^2–$10^{3–4}$ yr) elementary pedogenetic processes (EPP). The short-term EPP include gleying, structure forming and cryogenic processes. The medium-term EPP include humus formation, peat formation and organic matter accumulation. A hypothesis of cryogenic formation of the paleosols studied is substantiated. Only an almost impermeable layer of permafrost could cause water-logging and gleying in these geological and geomorphological conditions.

Key words: Bryansk paleosols, MIS3, the Russian Plain, periglacial, micromorphological diagnostics, pedosediments.

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INTRODUCTION

The environmental change is a subject of continuous scientific and public attention and interest, which accounts for a growing demand for palaeoclimatic and palaeoecological data in recent years, especially, because of concerns about global warming prospects and consequences. Paleosols or fossil soils that formed on a landscape of the past have been recognized as one of the most important and precise records of the landscape evolution.

The Quaternary Period being the latest and shortest (last 2.6 million years) period in the geological history of the Earth is very special for palaeoclimatic and palaeoecological studies. It is characterized by global, contrasting and rapid changes in palaeoclimate known as glacial-interglacial cycles and respective changes in ecosystems, landscapes and geological processes on the land surface. Data on those changes can be very important in modelling the future climatic fluctuations and their consequences. Paleosols are key bearers of information on the Quaternary climate history.

Reconstruction of the palaeoenvironment and ancient landscapes of the Marine Isotope Stage 3 (MIS3, ~60–25 kyr BP), when climate was relatively mild for the last glacial period (referred to as Valdai Glaciation in Eastern Europe), is still being a subject of active discussion. Recently a better understanding of rapid climate change has been achieved on the basis of interpreting and correlating geological records of high temporal resolution, i.e., ice cores in Greenland and Antarctica (Dansgaard et al., 1993; De Angelis et al., 1997) as well as marine sediments (Bond et al., 1995). Yet the contribution of Valdai paleosol data has been relatively small at a global scale. That could be explained by a suppressed pedogenesis under generally cold conditions during the Valdai Glaciation period and a lack of mature and thick paleosols of that period. The Valdai paleosols discovered within temperate regions of Europe were usually thin, weakly developed, disturbed by cryogenic processes, etc. In the Quaternary geology, such paleosols have only been used as markers in some regional continental chronostratigraphic charts.

Revealing the diversity and spatial differentiation of paleosols as components of ancient pedosphere allows understanding the MIS3 ecosystem palaeogeography. Paleosols formed during the MIS3 (including the Bryansk megainterstadial) have only been studied within temperate regions, but very little has been known about their northern varieties formed in periglacial areas. In particular, most literature sources on the Middle Valdai paleosols within the East European Plain are devoted to paleosols formed loess-like and/or mantle deposits (mainly within the loess belt) relatively far south from the Valdai periglacial area. In our opinion, a potential applicability of the Valdai paleosol data in palaeoecology has been seriously underestimated. Actually, their "soil memory" is particularly valuable as it can give us a high "spatial resolution", i.e., very local rather than only regional data (Targulian and Goryachkin, 2004, 2008).

The morphological record of pedogenesis (mostly at a micromorphological scale) and the features of paleosols developed at the northern geographical extremity of the MIS3 paleopedoshpere, i.e., within the Valdai periglacial area in the centre of the Russian Plain (the Upper Volga drainage basin of Yaroslavskoe Povolzhie) are presented in this paper.

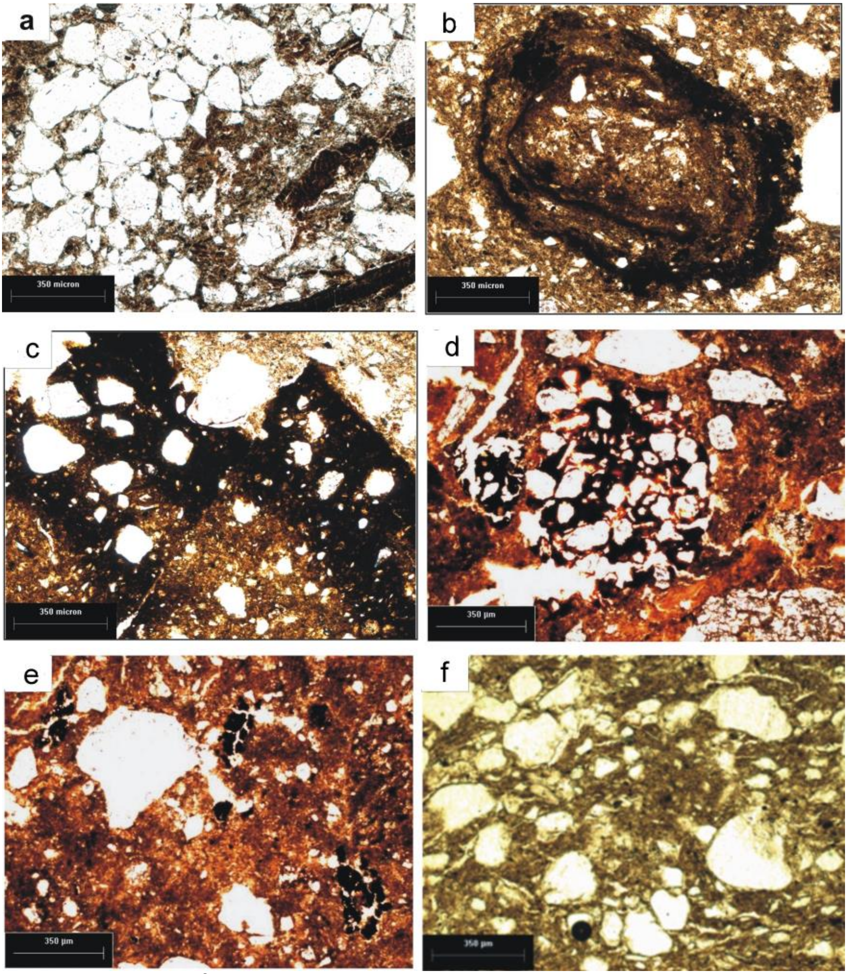
MATERIALS AND DISCUSSION

The MIS3 pedosedimentological profiles are located within a periglacial region (at the edge of the Valdai Glaciation area) in the centre of the Russian Plain (latitudes 56.7°–58.5° N), within the Upper Volga drainage basin of Yaroslavskoe Povolzhie. In this region we have conducted a long-term research on the heterochronous pedosedimentological profiles with dark humus gley and peaty gley paleosols, which formed during the MIS3 (^{14}C-age of ~29–50 cal kyr BP) (Rusakov et al., 2007; Rusakov and Sedov, 2012; Rusakov et al., 2015). The paleosol-containing pedosedimentological profiles include lacustrine sediments of the Early Valdai and/or Mikulin Interglacial, moraines of the Moscow Glaciation and subaqual sediments the Late Valdai Glaciation with the Holocene soddy podzolic soils at the surface. It should be mentioned that all these heterochronous pedosedimentological profiles are found on uplands with good natural drainage.

The Koskovo profile is located on a free-drained levelled surface of the IV tire of the Ovinishchenskaya Upland (171 m a.s.l.). The pedosediment is split by deep (up to 5 m) frost wedges. The pedosedimentological profile includes two pedostratigraphic units formed within the last ~50 kyr. The first pedostratigraphic unit (0–2.6 m deep) includes agrogenous soddy podzolic soil with gleyed lower horizons (Ap–EB–Bt1–Btg2–BCtg–Cg1–Cg2) derived from partly layered silty loams. The second pedostratigraphic unit (2.6–3.9 m deep) includes the MIS3 paleosols/horizons derived from lacustrine heavy loams: gley horizons (G1b–G2b–G3b), eutrophic peaty soil (Hb–G3b) and dark humic gley soil (Agb–G3b). The radiocarbon dates have been obtained: 51460 ± 4560 cal BP (IGAN 3322) for the Hb peat horizon and 35620 ± 480 cal BP (Ki-15480) for the Agb humus horizon.

The micromorphological analysis of the Koskovo profile allows identifying the Middle Valdai pedogenesis features in some horizons. The G3b has a very compact consistency, with pores being practically absent, the matrix composed of angular and rounded sand-sized grains (from coarse to very fine) uniformly distributed within the clay material, with no pedogenetic features. The Hb peaty horizon consists mostly of plant residues of elongated shapes with a parallel orientation and varied colours, from yellowish to brown. There are some mineral grains in spaces between those plant residues. The Agb horizon above is quite different and contains mostly very fine plant detritus. There are fragments of charcoal and microzones enriched in sand grains at the background of disperse matter finely coloured by humus, with a distinct separation of a cluster of sand grains being a distinguishing feature of the Agb horizon (Fig. a). The G2b middle gley horizon has characteristic features of ferrugination – dense ferruginous nodules and films as well as reduction areas free from iron oxides. The upper part of this horizon contains occasional plant residues integrated into the mineral matrix, generally similar to those found within the Hb, but vey deformed. The G1b upper gley horizon contains less redox features, but there are thin clay coatings with bright interference colours on fissure walls.

The Puzhbol profile is located 160 km to the southeast of the Koskovo profile, on the Middle Pleistocene terrace surface in the western end of the Borisoglebovskaya Upland, which borders the Rostov Lowland (with the Nero Lake) forming a regional-scale cliff ~25–30 m high. The first pedostratigraphic unit includes the Holocene soil (Ap–EB–Bt1–Bt2–Bthk3–BCtg) derived from silt clays and loams. The upper part (0–1.6 m) of this unit is represented by agrogenous soddy podzolic soil, with the Ap–EB–Bt1–Bt2 sequence being characteristic of texturally differentiated soils with clay coatings. The lower part of this unit (1.6–2.0 m) contains the Bthk3 horizon with the following micromorphological diagnostic features: 1) dark brown, almost black, thick humus-clay coatings on ped faces and walls of fissures and large



Micromorphology of the MIS3 paleosol horizons within the Upper Volga basin. The Koskovo profile: a – microzones enriched in sand grains (on the left), fine colouring by humus within disperse matter (on the right) and a fragment of deformed plant residue within the mineral matrix (lower right corner), the Agb horizon, NiI. The Puzhbol profile: b – complex concentric pedofeatures consisting of ferruginous circles and oriented clay circles, the upper part of the DG2 horizon, NiI; c – ferruginous pedofeatures, disintegrated, with material shifted along fissures, the upper part of the DG2 horizon, NiI. The Shetinskoe profile: d – spherical ferruginous pedofeature with protruding mineral grains within a packing pore, the 2Atgb horizon, NiI; e – compact consistency with visible planar fissures and cracked charcoal fragments inside a soil ped, the 2Atgb horizon, NiI. The Cheremoshnik profile: f – compact consistency with a circle of sand grains, the Agb3 horizon, NiI.

pores; 2) irregularly shaped and oval whitish calcareous nodules (“*zhuravchiki”*), 2–4 cm in diameter, occurring mostly on ped surfaces and rarely inside the peds. Below, the BCtg horizon (2.0–2.5 m) has gleying features and humus-clay coatings on the walls of large channels in place of former roots. The second pedostratigraphic unit (2.5–4.1 m) is represented by the Late Pleistocene soil (Dtg–DGt1–DG2–DG3) derived from ancient lacustrine clays. There are rusty-coloured ferruginous bands and large rohrensteins (ferruginous tubes formed along ancient root channels) within the gley horizons. The third pedostratigraphic unit (4.1–4.8 m) consists of the AGb humus horizon containing peaty lenses. Radiocarbon dating of this AGb horizon the Puzhbol profile revealed its Middle Valdai age (39740 ± 2270 cal BP, IGAN 3323), which is close to the age of the Agb horizon in the Koskovo profile. Therefore, the both paleosols were formed during the Bryansk megainterstadial.

The micromorphological analysis of the Puzhbol profile revealed that all the DG horizons have a similar sand-silt composition of matrix. Ferruginous pedofeatures are rare within the lower part of the DG2 horizon, but more numerous and diverse within its upper part including complex dendroidal pedofeatures, some of which are split into fragments with subsequent dislocations along the fissures as a result of cryogenic processes (Fig. c). At the same depth there are peculiar pedofeatures of ooidal oriented clay surrounded by fine-textured material or sand grains as well as complex concentric pedofeatures consisting of ferruginous circles and oriented clay circles (Fig. b). Such ferruginous pedofeatures are typical for Bryansk paleosols (Morozova, 1981; Morozova and Nechaev, 2002). Similar rounded aggregates formed by coagulation processes occur in modern soils of permafrost regions (Gerasimova et al., 1992).

The BCtg horizon within the upper pedostratigraphic unit differs from the Middle Valdai DG horizons by its matrix composition, with lesser proportion of sand and greater proportion of silt. This BCtg horizon contains rounded ferruginous clay granules (<0.5 mm) and diffuse ferruginous mottles, which are drastically different from ferruginous pedofeatures in the DG palaeogley horizons lower down the profile.

The Shetinskoe profile is a catena of the Middle Valdai paleosols on a terrace-like surface of the Vologodskaya Upland (~160 m a.s.l.). The upper layer (0–0.7 m) of the pedosediment is composed of the Late

Valdai non-calcareous silt loams with rare inclusions of pebble and stratification features within the lower part. Below, there is a moraine of the Moscow Glaciation (0.7–2.1 m) underlain by sand-rich moraine loam (2.1–3.0 m) and deeper – by gravelly sand (down to 20–25 m). The pedosedimentological profile is vertically dissected by wide and deep (up to 2.5 m) frost wedges and cracks.

The Shetinskoe profile includes two pedostratigraphic units formed within the last 30 kyr. The first pedostratigraphic unit is represented by the Holocene agrogenous soddy podzolic soils formed on non-calcareous silty loams, the second unit – by the Late Pleistocene paleosols/horizons formed exclusively on moraine. The second unit includes dark humus gley paleosol (2Agtb–2Gtb) and the 3Agtb and 3AGtb humus horizons. Radiocarbon dates for these 2Agtb and 3Agtb horizons are 28790 ± 2040 and 35620 ± 1650 cal. BP, respectively, being within a period of the Bryansk megainterstadial.

The macro- and meso-morphological analyses have revealed a good preservation of the Middle Valdai pedogenic features, particularly, fragments of charcoal and relic gley features (rusty mottles, ferruginous coatings and films, Fe-Mn nodules, etc.). In the 2Agtb horizon, there are some peds with horizontal ferruginous films inside and thick argillans over vertical faces. The latter are probably relatively recent in age.

The *micromorphological* features of the humus and gley horizons within the paleosol profile (2Agtb–2Gtb) include the following: planar fissures, dense consistency, blocky structure and peculiar ferruginous globules in spaces between peds (Fig. d). All these pedofeatures are indicative of the Bryansk Period. There are numerous fine mineral grains protruding from their surface, which is a result of cryogenic processes and cementation by ferruginous compounds. Preserved features of the Middle Valdai pedogenesis also include ferruginous films inside large pores, small cracked charcoal fragments inside peds (Fig. e), ferruginous nodules and fibrous goethite pedofeatures within the palaeogley horizon.

The Cheremoshnik profile is located in the western part of the Borisoglebovskaya Upland. This is one of the most important sites of the Quaternary pedogenesis research within the European part of Russia. It has been studied and intensely discussed by geologists, soil scientists and other specialists for over 60 years (Serebryany and Chebotareva, 1963; Problems of Stratigraphy…, 2001). Our attention has been focused on the upper and middle parts of this pedosedimentological profile that were not properly studied or dated before. We have conducted a detailed investigation of dark humus gley paleosol (Agb–Gb) formed on moraine containing occasional boulders during the Middle Valdai period within the accumulative terrace of a dry valley that is known to comprise an entire record of the last climatic cycle (MIS5–MIS1). According to palynological data, the regional vegetation was dominated by dwarf birch and alder at the time of this paleosol development.

Three cycles of ephemeral pedogenesis have been identified, with resultant paleosols being similar in their morphological and genetic characteristics. Each of the pedogenetic cycles began after the surface stabilization and ended after its burial under new proluvial deposit. The latter subsequently served as a parent rock for the new soil-forming cycle. The radiocarbon dates are 22920 ± 470 cal. BP (LU 7189) for the lower horizons (Agb2 and Agb3) and ≥41800 cal. BP (X27620) for a small fragment of charcoal within the pedosediment.

The micromorphological analysis of the paleosols has revealed a dense consistency, weak aggregation and low porosity, with very few isolated pores-fissures present. Both humus and gley horizons have features of separation of coarse particles, including sand, from silty-clayey mass with a weak grey pigmentation. In most cases, the sand-sized grains are arranged in circles (Fig. f). Such patterns are also characteristic of modern cryogenic soils. The sand and silt fractions of paleosols studied are characterized by diverse mineralogical composition with predominance of quarts, feldspars, mica, hornblende and epidote and with larger fragments of igneous and metamorphic rocks being also present. Coarse grains of quarts are often split into fragments as a result of cryogenic processes. There are cracked fragments of charcoal surrounded by coarse skeletal grains inside peds in both humus and gley horizons of Bryansk paleosols. Ferruginous pedofeatures are typically represented by nodules, rounded as well as irregularly shaped.

CONCLUSION

Micromorphological analyses of the MIS3 paleosol profiles of the Upper Volga drainage basin allowed us to identify an assemblage of stable micromorphological features according to generally-accepted guidelines (Kühn et al., 2006). This assemblage includes the following: 1) ferruginous nodules and other pedofeatures, occasionally fragmented; 2) concentration (separation) of sand grains within certain microzones; 3) inclusions of raw organic matter, often deformed and oriented to different degrees within the matrix.

Despite being buried for a long time period and superimposed by the Holocene pedogenetic processes (clay illuviation), the paleosols preserve some features of short-term (101–102 yr) and medium-term (102–103–4 yr) elementary pedogenetic processes (**EPP**). The short-term EPP include gleying, structure forming and cryogenic processes. The medium-term EPP include humus formation, peat formation and organic matter accumulation. The short-term EPP prevailed in the Middle Valdai pedogenesis. Their traces in form of specific morphological (mostly, meso- and micromorphological) features still remain stable and constitute a part of the soil memory.

The MIS3 paleosols of the Upper Volga Region are represented by profiles consisting of humic-peaty surface horizon and/or humus accumulative horizon underlain by mineral horizons that are compacted and strongly gleyed from below. A palaeoecological interpretation of the paleosols studied is rather problematic. It should be taken into account that these paleosols were formed in topographic positions unfavourable for gleying. The latter requires saturation of soil with ground water (hydromorphic pedogenesis), which creates reducing conditions, which in turn cause iron mobilization being responsible for the appearance of gley features. Normally, gley soils occur within topographic depressions or on levelled divides with poor natural drainage that accounts for water-logging. By contrast, the paleosols studied occupy positions with the best natural drainage – upper parts of slopes and convex divides that are not water-logged, with the modern soddy podzolic soils not gleyed.

The above-described contradictions created a basis for the only acceptable hypothesis of formation of the paleosols studied – the cryogenic hypothesis. Only an almost impermeable permafrost layer could cause water-logging and gleying in such geological and geomorphological conditions. Our conclusion is confirmed by several cryogenic indicators, including pedoturbation features in the Upper Volga paleosols. According to the landscape studies, these are former tundra and taiga permafrost soils. The palaeobotanical and palaeontological data are indicative of the former tundra-steppe and forest-tundra ecosystems.

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