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EVIDENCE OF PERMAFROST IN PALEOSOLS: CRYOTRACEOLOGICAL APPROACH

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Freezing of rocks and formation of permafrost affect soils and produce specific signatures in their solid matrix. The macro- and micromorphological signatures of frost effects remain preserved in buried soils and can serve as explicit or implicit traces of past cryogenic environments. They are, respectively, cryoturbation, aggregation and size sorting of soil particles, gleying and peat formation in well drained soils upon impermeable permafrost. Such signatures are used, in terms of the cryotraceological approach, to reconstruct glacial environments during MIS-3 and MIS-2 events of the marine oxygen isotope stratigraphy in different regions.

Cryogenesis, cryotraceology, permafrost signatures, paleosol, Quaternary

INTRODUCTION

Cryotraceology [*Melnikov et al., 2013*] is a new line in geocryological research which inherits the principles of trasology (detailed study of any possible evidence and trace of events as in criminal science or archeology) and can furnish additional micro- and macro-scale evidence of cryogenic processes. Footprints of past frost effects traceable in rocks and soils can be used for reference to reliably reconstruct Quaternary and earlier permafrost-glacial events in the geological history.

Past glacial settings are commonly reconstructed from evident signatures of frost effects on rocks and landforms: ice of different types or its traces; erosional topographic patterns; cracking, fine grain sizes, and traces on grain surfaces of sediments; ice wedges and casts, etc. [*Popov, 1967; Romanovskiy, 1977; Gasanov, 1981*]. Latent (implicit) signatures of permafrost likewise can store paleocryological information, but the available data remain poorly interpreted and utilized. The implicit signatures may result from subtle mechanisms associated with cyclic changes in freezing and frozen rocks. Identification of these effects requires special procedures.

Both explicit and implicit traces of permafrost paleoenvironments can be found in soils. The soil cover in the uppermost continental lithosphere is a global Earth's sphere (pedosphere) where the rock substrate undergoes *in situ* changes under the effect of different biological, physicochemical, geomorphic, and climate factors and processes. This definition follows the Dokuchaev–Gerasimov triad (factors-processes-properties) of soil formation [*Gerasimov, 1956*]. The pedosphere within the zone of permafrost involved in soil formation belongs, fully or partly, to the cryosphere. Soil profiles in these areas comprise the active layer (except for zones of thick taliks), while soil formation on seasonally frozen ground depends on freezing degree and often penetrates below the active layer.

In terms of soil evolution, permafrost signatures in soils [*Velichko et al., 1996*] make part of their "memory" [*Targulian and Goryachkin, 2004*]: the solid matrix stores record of elementary pedogenic processes induced and affected by permafrost. Formation of modern cryomorphic soils has been quite well studied and discussed in detail in numerous publications [e.g., *Makeev, 1981; Bockheim, 2015*]; *Makeev* [*1999*] coined the term *cryopedology*. However, the experience of using the knowledge for high-resolution deciphering of paleosol records has been very limited.

Progress was achieved in studies of Late Quaternary soils for reconstruction of the Late Glacial event (cryochron) [*Gugalinskaya, 1982; Sycheva, 2012*]. Some research has been performed on imprints of past cryogenic processes in modern soils [*Makeev et al., 1989; Alifanov et al., 2010*], as well as on explicit macro- and microscopic indicators of freezing in paleosols [*Van Vliet-Lanoë, 1998*]. However, the book by *Targuliyan and Goryachkin* [*2008*], which presents a broad scope of proxies in past soil records, misses a special section about signatures of past frost effects in soils.

In our view, cryopedological data remain poorly integrated into the system of paleopermafrost records. Therefore, the approach of finding permafrost traces in soils and rocks, or cryotraceology, is of special value for studying the Earth's history. It is a promising tool of interdisciplinary cryological research, which includes a separate pedogenetic aspect. We have gained some experience in applying the traceological approach and using permafrost signatures in soils for analysis of Late Pleistocene sedimentary sections in the East European Plain and northern West Siberia.

RESULTS AND DISCUSSION

Background information

Soil as a component of the crust may exist either inside or outside permafrost. In any case, soil in the conditions of seasonal or perennial ground freezing undergoes alteration caused by frequent phase transitions between ice, water and vapor associated with changes in type and rate of physicochemical processes. Soil is exposed to various surface or subsurface effects and to the temperature and moisture gradients exceeding those in any other component of the lithosphere. Cryogenesis controls the formation of soil and produces specific imprint on its solid matrix, which preserves even after the soil falls outside the zone of permafrost and its immediate influence. These signatures in buried soils are detectable with the traceological approach and can become reliable proxies of past cryogenic events.

Past frost effects in soils found traceologically are either explicit (evident) or implicit (latent). The explicit signatures appear in the structure and texture of freezing rocks that contain pore ice subject to phase change. The implicit signatures are associated with changes in soil microstructure which can be brought out by micromorphological and physicochemical analyses. We used both types of signatures for reconstructing Quaternary landscapes, especially within the best representative climate cycle of past 100 kyr that spanned stages 5 through 2 of marine $\delta^{18}O$ stratigraphy (MIS). Additionally, we tried to constrain the time in which such indicators are workable as a tool of paleocryological analysis.

The solutions obtained in the course of our pioneering study will be reported in several successive publications because it is impossible to cover them all in a short paper. Below we present examples of using the traceological approach for detecting permafrost traces in soils from well documented Late Quaternary reference sections.

Permafrost traces in MIS-3 soils from upper Volga and middle Ob catchments

The time span between ~55 and 25 kyr BP corresponding to marine isotope stage (MIS) 3 is of special value for paleogeographic reconstructions and has received much recent attention. It was a period of relative warming (thermochron), when the climate was slightly more severe than that of the present warming and the first humans of the modern type colonized Europe. The MIS-3 event is equated to the Middle Würmian and Middle Valdai (Bryansk) interstadials in Europe and to the Karga interstadial in Siberia. Paleosols of the respective ages are present at several levels in most of regional stratigraphies and have been used, since long ago, as markers for interpretation of loess sections. They are, specifically, the *Iskitim* pedocomplex in southern Siberia [*Zykina and Zykin, 2012*], the *Bryansk* paleosol in the Russian Plain [*Morozova, 1981*], and the *Stillfried B* (Austria) and *Lohne* (Germany) paleosols in Western Europe [*Terhorst et al., 2015*]. However, the MIS-3 paleosols north of the Loess Belt remain poorly investigated. Our cryotraceological studies allowed extending considerably the knowledge of past events. We revealed frost-affected paleosols of MIS-3 in the Volga upper reaches and in northern West Siberia, far north of the Loess Belt (Fig. 1).

In the upper Volga, they are dark humus-gley and peaty-gley soils with ^{14}C ages of ~28–50 kyr BP that formed upon the Early Valdai (and/or Mikulino) lacustrine sediments and Moscow moraine substrates and later Holocene sod-podzolic soils (retisols) upon the Late Valdai subaerial loam [*Rusakov and Sedov, 2012*]. The soil profiles preserve signatures of short (10–100 years) and medium (100–10 000 years) elementary soil formation events, in spite of prolonged burial and Holocene surface processes (such as illuviation). The short events include cryogenesis proper and the ensuing structure formation and gleying, while accumulation of organic matter and formation of humus and peat occur in longer cycles. These events left imprint in the soil memory as micro- and meso-scale traceological indicators. In the more detailed consideration below, we compare sections in the upper Volga and northern West Siberia in this respect.

Watershed sections are assumed to be the most reliable sources of paleogeographic data, but we rather support the idea of S. Sycheva [*Targulian and Goryachkin, 2008*] that sediments in depressed landforms, when dated and correlated properly, store the most complete records. The Cheremoshnik section in a gully terrace, a reference one for the upper Volga area, contains the Middle Valdai dark humus-gley paleosol within the MIS-3 interval [*Rusakov et al., 2015*]. This soil formed in an environment dominated by dwarf birch and alder vegetation, in three morphogenetically similar rhythms. In stable surface conditions, each soil was buried under gully sediments, which became a substrate for another similar soil. Rhythms of this kind, as several successive profiles of peaty gley soils, were revealed also in the Koskovo reference section (Fig. 2) [*Rusakov and Sedov, 2012, 2016; Rusakov et al., 2015*].

Proceeding from the upper Volga MIS-3 dataset north of the Loess Belt, we expected to find similar soil patterns east of the Urals. However, no relevant information was available from Siberia, where nobody looked for paleosols, and still less for footprints of past frost effects. The reason is that most of Quaternary geologists in the 1960s assumed the existence of a vast continental ice sheet in northern West Siberia (though permafrost scientists disagreed), which would leave little chance for preservation of paleosols because of glacial erosion and sedimentation.

Given that controversy, we have carried out our own research in northern West Siberia, with reference to the available data for [*Zemtsov, 1976; Arkhipov, 1997; Grosswald, 2004*] and against [*Danilov, 1978; Kuzin, 2005; Vasil'chuk and Vasil'chuk, 2010; Streletskaya et al., 2015*] the existence of ice sheets. We found evidence of a self-evolving Quaternary river network and evidence of deep freezing but no signatures of extensive glaciers [*Sheinkman et al., 2017*]. Inasmuch as soil formation was possible anyway under those conditions, the search focused on paleosols that were reasonably expected to experience freezing in the absence of an ice cover in the Subarctic zone.

Fig. 1. Location map of study areas.

1 – upper Volga catchment; 2 – eastern Siberian Hilly Plain.

Fig. 2. Peat-bearing gley paleosols in the upper Volga catchment, Koskovo section:

a: general view; *b*: paleosol profile in the middle of the section; *c*: mesoscale morphology of gley horizon. Photograph by A.V. Rusakov.

Paleosols with distinct traces of frost effects were discovered soon (and identified reliably for the first time) in the eastern Siberian Hilly Plain (called *Sibirskie Uvaly* in Russian), in two sections of river terraces (Fig. 1): Belaya Gora (Vakh River) and Zelenyi Ostrov (Sabun River, Vakh tributary) [*Sedov et al., 2016; Sheinkman et al., 2016, 2017*]. The top of the sampled terraces lies at 110–130 m above the sea level and joins the surface of a 30–40 m high alluvial terrace, presumably part of the Ob terrace III system [*Arkhipov, 1997; Kuzin, 2005*]. The terrace sections include two pedocomplexes (Fig. 3): one present in both sections under a few meters of laminated lacustrine-fluvial sediments and the other in the middle of the 30–40-m high Belaya Gora section. Radiocarbon dating of the two soils gave, respectively, ages of ~25–35 Kyr BP (latest MIS-3) and a few unrealistic ages. The latter soil was re-dated by the more reliable U-Th method, which gave ~100 Kyr BP, or late MIS-5 [*Sheinkman et al., 2017*]. In all the cases, the sampled soil profiles were well preserved and consisted of dark peat-humus and gley horizons. The soils have pH ~7, unlike the modern podzol with lower pH, while the surface Holocene podzol is free from hydromorphic signatures.

Signatures of permafrost are evident in both upper Volga and West Siberian paleosols. Undisturbed MIS-3 paleosol samples from the upper Volga and middle Ob sections examined under a microscope in thin sections show similar evidence of frost effects. Their peat and humus horizons contain abundant poorly degraded plant tissues, which are randomly oriented and partly deformed, while the organic detritus is mixed up with mineral material, apparently by cryoturbation (Fig. 4, *a*).

Particles of different sizes in mineral layers are unevenly distributed: coarse sand grains form clusters (or occasionally, circular structures) or aggregates adjacent to microzones of fine silt-clay particles (Fig. 4, *b*), as a result of frost sorting [*Gerasimova et al., 1992*]. Frost cracking split some coarse sand grains into fragments shifted relative to one another (Fig. 4, *c*) [*Rogov, 2009*].

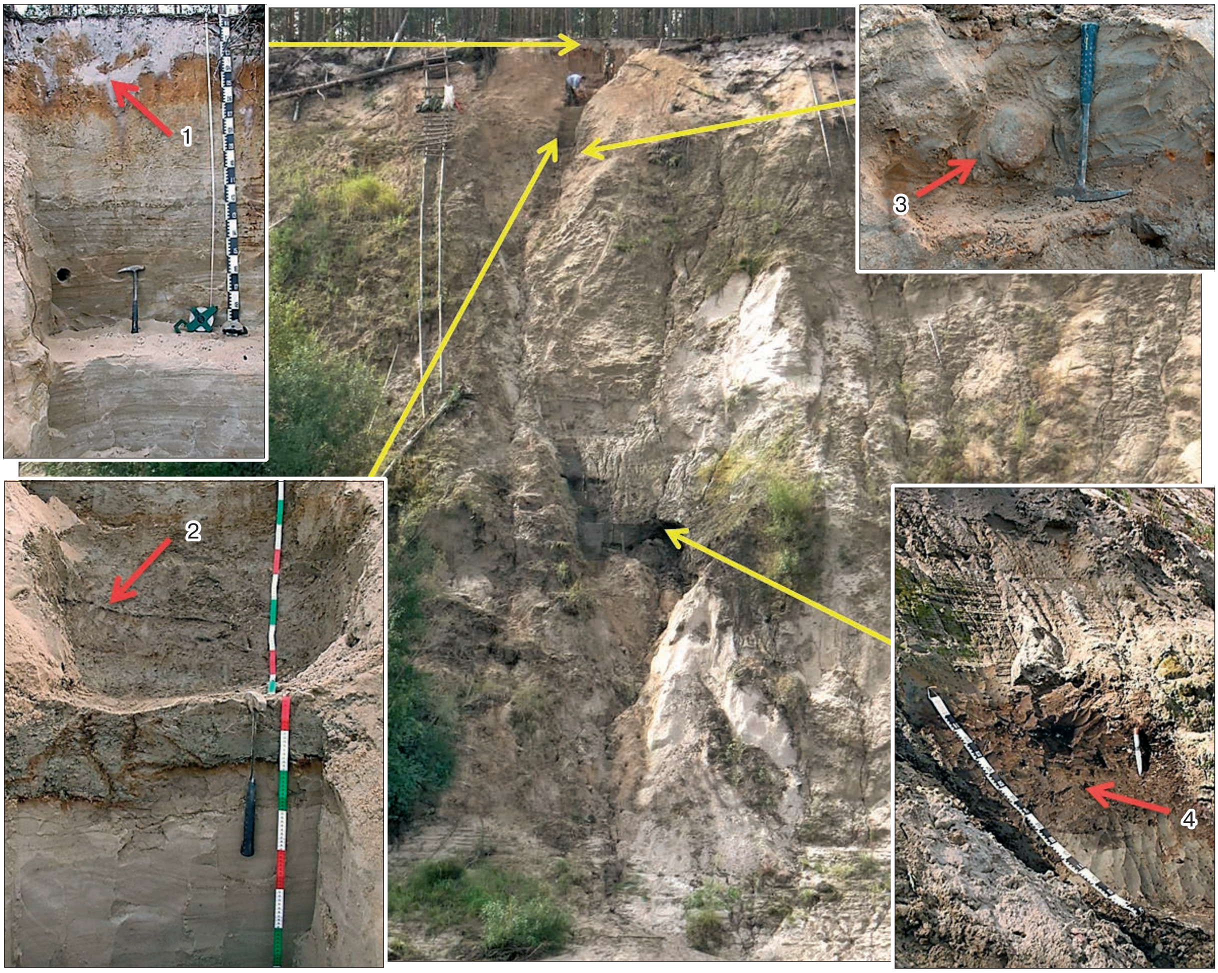

Fig. 3. Belaya Gora section (35-m high terrace).

1 – modern Podzol; 2 – paleosol MIS-3; 3 – boulders set in alluvium; 4 – paleosol MIS-5. Photograph by V.S. Sheinkman.

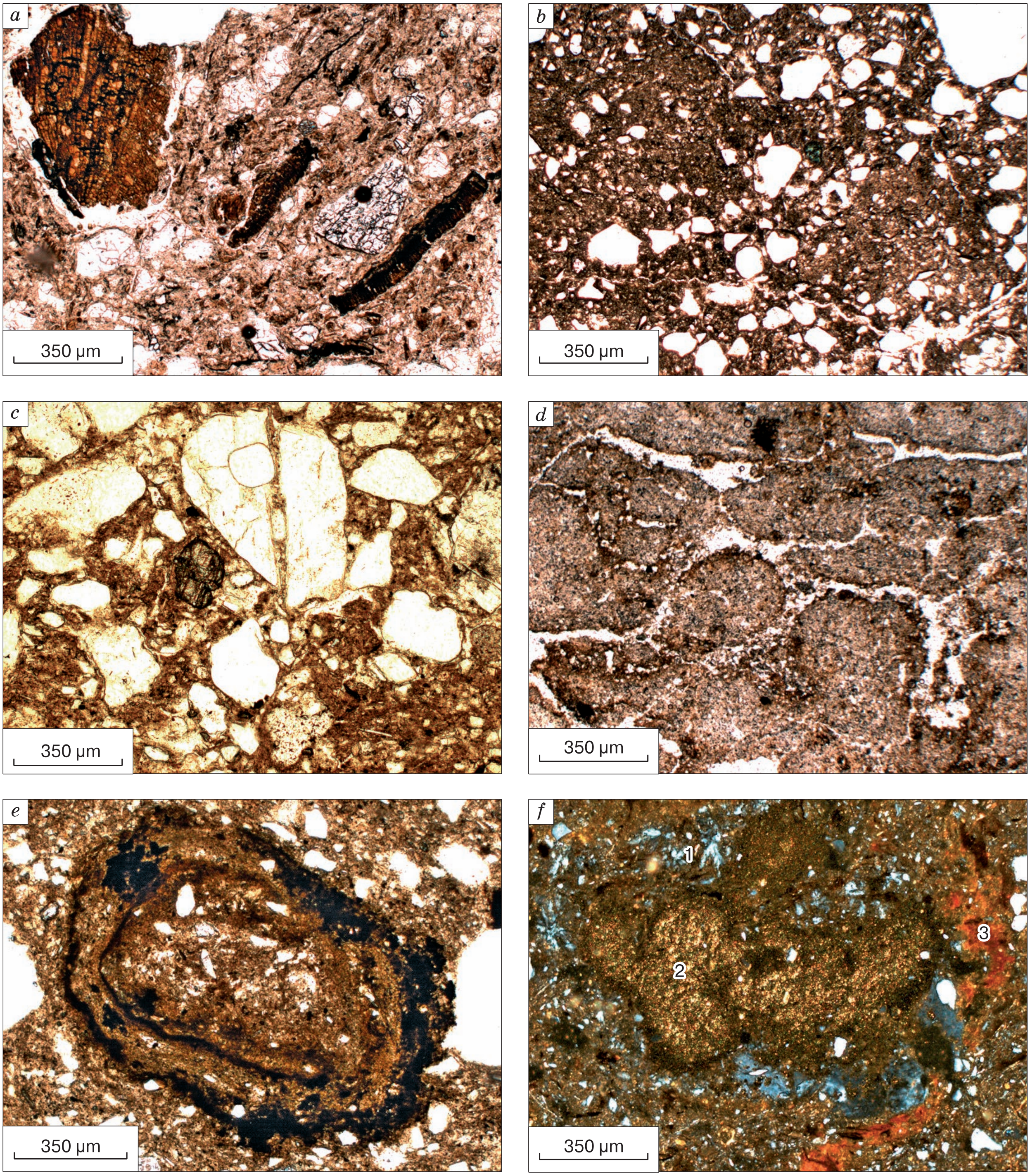

Fig. 4. Micromorphology of MIS-3 paleosols with revealed cryotraceological signatures.

a: randomly oriented plant detritus mixed with mineral material; Koskovo pedocomplex (upper Volga), horizon Hb; *b*: circular arrangement of sand grains, with silt-clay material in the center, Koskovo pedocomplex (upper Volga), horizon Crb; *c*: frost cracking of quartz sand grains, Cheremoshnik pedocomplex (upper Volga), horizon Agb3; *d*: blocky and platy cryostructure associated with ice lenses, Belaya Gora section (Vakh river, right side of the middle Ob'), horizon Bgb; *e*: concentric iron concretion in paleosol from Puzhbol section (upper Volga), horizon DG2; *f*: gypsum (1) and iron hydroxide particles (3) grown around secondary pyrite (2) in paleosol, Zelenyi Ostrov section (Sabun River, right side of the middle Ob'), horizon Ahb. Photograph by S.N. Sedov. The images are obtained at transmitted light, without analyzer (*a*–*e*), and at combined transmitted and cross-polarized reflected light (*f*).

The mineral horizons of paleosols are very dense, with few pores and poorly expressed microstructure, in the upper Volga sections but consist of blocks and lens-shaped aggregates separated by a network of cracks in the Belaya Gora (Vakh) samples (Fig. 4, *d*). The latter microstructure commonly results from multiple freezing cycles [*Van Vliet-Lanoë, 2010; Gubin, 2016*].

Gley horizons from all paleosols contain round and concentric iron microconcretions (Fig. 4, *e*). The soil from the Zelenyi Ostrov section (right side of the Vakh) unexpectedly enclosed framboidal pyrite coexisting with iron hydroxides and gypsum crystals (Fig. 4, *f*), possibly resulting from sulfide oxidation. The secondary minerals record redox reactions caused by water logging of soil.

The MIS-3 soil profiles from the upper Volga and West Siberian regions are similar also in the presence of surface humus-peat horizons over high-gley mineral layers, locally with frost-affected microstructure. When interpreting these paleosols, it is important to bear in mind their formation in geomorphic settings unfavorable for gleying. Note that gleying commonly requires moisture saturation (hydromorphic soil formation) and creates a reduced environment that maintains mobilization of iron. Therefore, gley soils most often form in depressions or upon clay on flat poorly drained watersheds which provide prolonged water logging. On the contrary, gleysols in the sampled sections were located in well drained upper parts of slopes, on watersheds, or high terraces. They are free from signatures of ongoing water logging, as well as the surface Holocene Retisols from the Volga area and the Ob Podzols, which have not experienced stagnation gleying. Permafrost appears to be the only reasonable explanation for this contradiction: nothing but impermeable permafrost could ensure stagnation of moisture and induce the redox reactions capable of generating the signatures of gleying.

Suprapermafrost gleying is a widespread indicator of tundra and taiga soils in the permafrost zone [*Gerasimova et al., 1992*]. In our case, the presence of permafrost is confirmed by other features of paleosols: cryoturbation (upper Volga soils), deformation of humus horizons, and cryogenic structure formation (middle Ob soils). All soil samples bear signatures of frost effects: mixing, turbation, and sorting. The paleosols formed in tundra or permafrost-taiga landscapes, with vegetation and faunas typical of tundra-steppe and forest-tundra ecosystems [*Zinoviev et al., 2016*].

The analyzed fossils soils differ markedly from coeval soils in loess sections: the Bryansk soils with brown profiles containing carbonates in European Russia (similar to the modern taiga soils in Yakutia [*Morozova, 1981*]) and the Iskitim pedocomplex composed of immature chernozem in West Siberia [*Zykina and Zykin, 2012*]. Therefore, it appears reasonable that the gleysols with prominent traces of frost effects, which were found in the northern East European and West Siberian plains [*Sedov et al., 2016*], did exist during MIS-3 within a particular northern permafrost zone. That zone may have extended eastward, to Northeastern Siberia and Beringia, where coeval paleosols with similar features may reside in ice complex deposits [*Zanina et al., 2011*].

Permafrost traces in MIS-2 in soils from Central Europe and the Taz catchment

The MIS-3 event was followed by the MIS-2 cooling (cryochron). The MIS-3/2 transition was of special importance as MIS-2 was the coldest event and comprised the Last Glacial Maximum in areas occupied by ice sheets. Deposition during the transition period produced thick sedimentary sequences in several loess sections of Western and Central Europe consisting of pure loess and syndepositional paleosols of weak pedogenesis. They are the sequences deposited in the latest MIS-3 and the earliest MIS-2 that include paleosols with signatures of abundant gleying expressed as uneven coloration of the substrate and pale bluish or bright ochreous stains (Fig. 5). In the German literature, they are called *Naβboden* (wet soils) or *Tundragley*. These soils were used broadly for stratigraphic correlations, but they turned out to have still greater cryotraceological value.

As shown by studies of loess sections in the Danube region, tundragley soils form in drained environments unfavorable for gleying: in the upper part of slopes or on watersheds. These sections bear no traces of ongoing water stagnation, and gleying is absent from both the Holocene Luvisol above and the Cambisol below corresponding to MIS-3. Neither the geological conditions are favorable for gleying: loess is a porous rock with good internal drainage, and it contains carbonates which limit Fe mobilization.

Like in the case of the MIS-3 gley paleosols in the upper Volga and in the right side of the middle Ob, the presence of impermeable permafrost is the only realistic explanation for the formation of tundra gley soils. This hypothesis is supported by evidence of cryoturbation and solifluction. These conditions during the formation of gley paleosols in the loess-soil sequence imply stronger cooling than in the previous event. The onset of that cooling coincided with the MIS-3/2 transition, which agrees well with other regional and global records [*Terhorst et al., 2015*].

Interestingly, artefacts found in Upper Paleolithic sections in the Austrian Loess Belt (including the famous Krems-Wachtberg site) mainly occur within MIS-3 nongley paleosols while the overlying MIS-2 tundra gley soils are archaeologically barren. The cooling was likely so strong that the Paleolithic hunters left the territory. Comparison of cryotraceological evidence from Austria with those from the upper Volga and middle Ob regions indicates that the

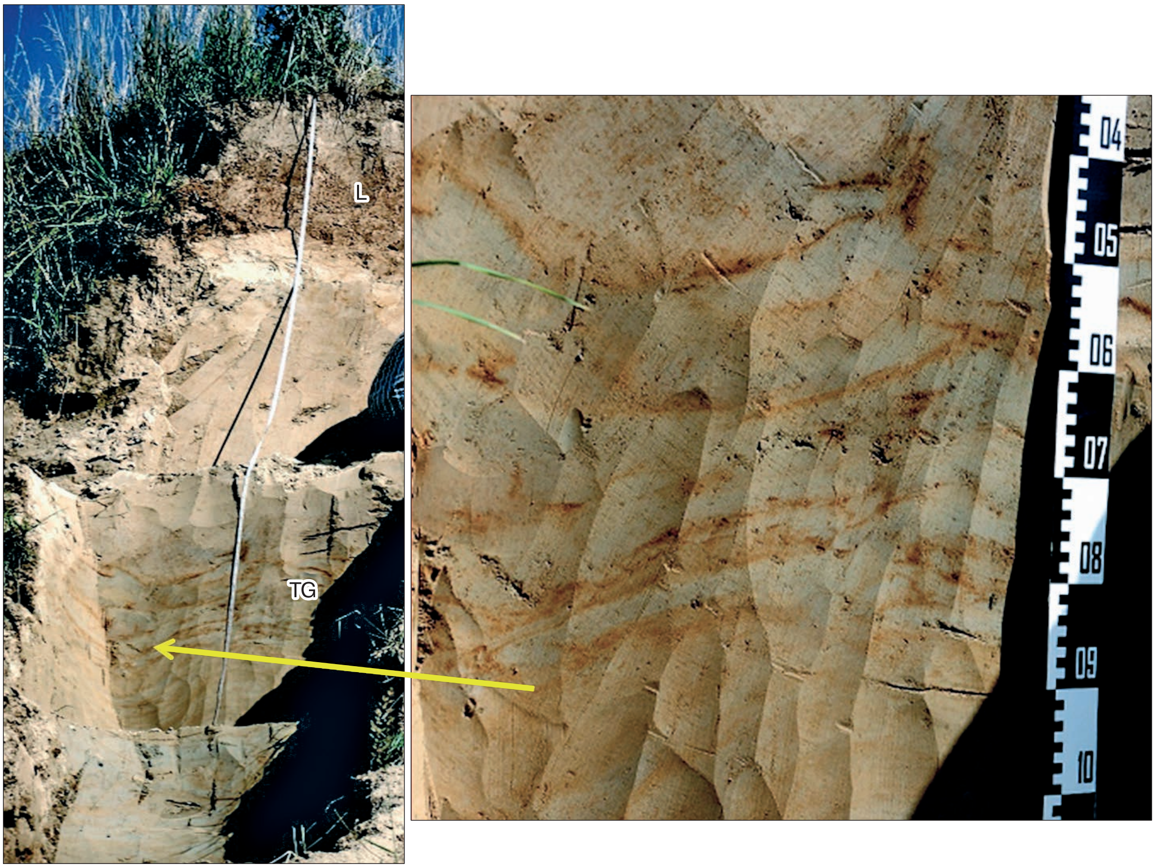

Fig. 5. Gundering profile (Austria).

Gley-free luvisol surface Holocene soil (L) and buried *Tundragley* paleosol (TG) with carbonate loess between them. Photograph by S.N. Sedov.

zone of cryohydromorphic soil extended more than 1000 km southwestward at the MIS-3/2 transition. There are many other cases of cryohydromorphic soil formation in the beginning and in the end of the MIS-2 cryochron in Europe, besides tundra gley soils (e.g., the Trubchevsk gleysol of presumably 16 Kyr BP known from loess-soil sequences in the East European Plain) [*Velichko, 1997*].

The Pyulky section in the Taz upper reaches (Fig. 1) likewise contains gley paleosols that formed at the Pleistocene-Holocene transition (Fig. 6) on well drained sand terraces where the Holocene soils consist of well developed Podzol free from gleying signatures. The paleosol levels in the section are close to casts after prominent Sartan ice wedges, and the soil penetrates into sediments that fill the ice casts. Humus from samples of a rusty-brown horizon around one ice cast has a calibrated calendar ^{14}C age of 10 889 ± 146 yr (ICA 17OS/0629), which corresponds to the end of MIS-2.

When interpreting paleosols of this kind, one has to bear in mind that cryogenesis causes double control over suprapermafrost gleying. The formation of permafrost that would act as an aqueclude and maintain moisture stagnation requires quite a cold climate, but cold suppresses microbial mediation in the reduction and oxidation of iron during gleying. As the climate becomes colder, the reduction reactions attenuate because oxygen is more soluble in cold pore waters while micriobial activity slows down for the lack of heat. Therefore, the gleying process decelerates and leaves no morphological signatures, despite the shallow depth of the permafrost table and water logging of the active layer. According to *Sokolov* [*1980*], this is nongley hydromorphic soil formation which produces cryosols (cryozem) in the coldest continental permafrost areas.

These climatic limitations on gley cryopedogenesis have to be taken into account in cryotraceological interpretation of soil data. Frost-affected gley soils form during cryochrons and differ markedly from nongley soils of the predating or postdating warm events. Thus, their presence in soil-sediment sequences deposited during different phases of large Pleistocene climatic cycles records events of cooling and growth of permafrost. On the other hand, gley

Fig. 6. Upper Pyulky section in the Taz upper reaches.

1 – modern podzol; 2 – paleosol over paleopermafrost of latest MIS-2. Photograph by V.S. Sheinkman.

soils within cryochrons represent spells of relatively higher temperatures, when seasonal warming of suprapermafrost soil allowed reactivation of microbially mediated reduction reactions. For instance, such warm spells in the East European Plain occurred early and late during the MIS-2 cooling, while gleying was suppressed during the coldest phases in the middle of the event.

CONCLUSIONS

Summing up the reported data, we suggest that cryotraceology is a promising approach for detection of past frost effects in soils. Such signatures reveal the marked difference of paleosols in the northern West Siberia and upper Volga from coeval soils in loess sequences in the south. This discovery supports the idea that a particular zone of cryohydromorphic soil existed during MIS-3 in the northern plains of East Europe and West Siberia.

Gleying is not the only soil process sensitive to frost effects. Freezing and ice crystallization leave diverse macro- and micromorphological traces associated with ice segregation or drying of soils upon freezing. Frost cracking of mineral grains, another consequence of permafrost, is especially active in soils exposed to frequent freezing and thawing. Cracking affects grain sizes and leaves traces on mineral surfaces.

Formation of secondary mineral phases likewise leaves specific signatures in frost-affected soils. The presence of permafrost controls migration of substances, including suprapermafrost accumulation of chemical compounds.

These and other proxies of past cryogenic processes in soils can preserve long after burial and may exist also in pre-Quaternary sediments, down to the Archean. Therefore, after being tested on the most representative Quaternary objects, soil cryotraceology can become an advantageous tool of paleocryological reconstructions for older events in the Earth's history. First steps on this way have been already undertaken [*Retallack et al., 2015*].

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References

Alifanov, V.M., Gygalinskaya, L.A., Ovchinnikov, A.Y., 2010. Paleocryogenesis and Soil Diversity in the Central East-European Plain. GEOS, Moscow, 178 pp. (in Russian)

Arkhipov, S.A., 1997. Chronology of Late Pleistocene geological events in West Siberia. Geologiya i Geofizika (Russian Geology and Geophyscs) 38 (12), 1863–1884.

Bockheim, J.G., 2015. Cryopedology. Springer Press, Heidelberg-New-York-Dordrecht-London, 177 pp.

Danilov, I.D., 1978. Polar Lithogenesis. Nedra, Moscow, 238 pp. (in Russian)

Gasanov, S.S., 1981. Permafrost Analysis. Nauka, Moscow, 194 pp. (in Russian)

Gerasimov, I.P., 1956. Dokuchaev's theory on modern soil formation factors. Pochvovedeniye, No. 8, 1–11.

Gerasimova, M.I., Gubin, S.V., Shoba, S.A., 1992. Soil Micromorphology of the USSR Climate Zones. Center for Biological Research, Pushchino, 215 pp. (in Russian)

Grosswald, M.G., 2004. The Arctic during the Last Glacial Maximum and in the Holocene: ocean outbursts, continental and marine ice, their movement and relation with climate. Materialy Gliaciol. Issled. Issue 96, 47–54.

Gubin, S.V., 2016. Role of cryogenesis in macro-, meso- and micro-scale soil structuring, in: Soil Morphology: from Macro- to Submicrolevel. Dokuchaev Soil Institute, Moscow, pp. 70–84. (in Russian)

Gugalinskaya, L.A., 1982. Late Pleistocene Soil Formation and Cryogenesis in the Central Russian Plain. Center for Biological Research, Pushchino, 204 pp. (in Russian)

Kuzin, I.L., 2005. Geomorphology of the West-Siberian Plain. The Polar Academy, St. Petersburg, 176 pp. (in Russian)

Makeev, A.O., Dubrovina, I.V., Kulinskaya, E.V., Yakusheva, T.E., 1989. Paleocryogenesis and soils of the Russian Plain, in: Proc. VIII All-Union Congress of Soil Researchers. Book 6. Institute for Soil Science and Agrochemistry, Novosibirsk, pp. 281–287. (in Russian)

Makeev, O.V., 1981. Facies of Soil Cryogenesis and Features of Structuring in their Soil Profiles. Nauka, Moscow, 88 pp. (in Russian)

Makeev, O.V., 1999. Soil, permafrost, and cryopedology. Pochvovedeniye, No. 8, 947–957.

Melnikov, V.P., Gennadinik, V.B., Brouchkov, A.V., 2013. Aspects of cryosophy: cryodiversity in nature. Kriosfera Zemli XVII (2), 3–11.

Morozova, T.D., 1981. The Late Pleistocene Soil History in Europe. Nauka, Moscow, 281 pp. (in Russian)

Popov, A.I., 1967. Permafrost Phenomena in the Crust. Moscow University Press, Moscow, 304 pp. (in Russian)

Retallack, G.J., Gose, B., Osterhout, J., 2015. Periglacial paleosols and Cryogenian paleoclimate near Adelaide, South Australia. Precambrian Res. 263, 1–18.

Rogov, V.V., 2009. Foundations of Cryogenesis. Geo Publichers, Novosibirsk, 203 pp. (in Russian)

Romanovskiy, N.N., 1977. Formation of Ice Wedges. Nauka, Novosibirsk, 215 pp. (in Russian)

Rusakov, A., Nikonov, A., Savelieva, L., Simakova, A., Sedov, S., Maksimov, F., Kuznetsov, V., Savenko, V., Starikova, A., Korkka, M., Titova, D., 2015. Landscape evolution in the periglacial zone of Eastern Europe since MIS5: Proxies from paleosols and sediments of the Cheremoshnik key site (Upper Volga, Russia). Quatern. Intern. 365, 26–41.

Rusakov, A., Sedov, S., 2012. Late Quaternary pedogenesis in periglacial zone of northeastern Europe near ice margins since MIS 3: Timing, processes, and linkages to landscape evolution. Quatern. Intern. 265, 26–41.

Rusakov, A.V., Sedov, S.N., 2016. Morphological palaeorecords of the Late Quaternary pedogenesis and landscape evolution in soil-sedimentary sequences in the Upper Volga Basin, in: Soil Morphology: from Macro- to Submicrolevel. Dokuchaev Soil Institute, Moscow, pp. 183–198. (in Russian)

Sedov, S., Rusakov, A., Sheinkman, V., Korkka, M., 2016. MIS3 paleosols in the center-north of Eastern Europe and Western Siberia: Reductomorphic pedogenesis conditioned by permafrost? Catena 146, 38–47.

Sheinkman, V.S., Melnikov, V.P., Sedov, S.N., Parnachev, V.P., 2017. New evidence of the nonglaciated development of the Northern Part of the Western Siberian Lowland in the Quaternary Period. Doklady Earth Sci. 477, pt. 2, 1430–1433.

Sheinkman, V., Sedov, S., Shumilovskikh, L., Korkina, E., Korkin, S., Zinovyev, E., Golyeva, A., 2016. First results from the Late Pleistocene paleosols in northern Western Siberia: Implications for pedogenesis and landscape evolution at the end of MIS 3. Quatern. Intern. 418, 132–146.

Sokolov, I.A., 1980. Hydromorphic nongley soil formation. Pochvovedeniye, No. 1, 21–32.

Streletskaya, I.D., Vasiliev, A.A., Oblogov, G.E., Tokarev, I.V., 2015. Reconstruction of paleoclimate of Russian Arctic Late Pleistocene–Holocene on the basis of isotope study of ice wedges. Earth's Cryosphere (Kriosfera Zemli) XIX (2), 86–94.

Sycheva, S.A., 2012. Paleopermafrost events in periglacial area of the Central Russian Upland at the end of the Middle and Late Pleistocene. Kriosfera Zemli XVI (4), 45–56.

Targulian, V.O., Goryachkin, S.V., 2004. Soil memory: Types of record, carriers, hierarchy and diversity. Revista Mexicana de Ciencias Geológicas 21, 1–8.

Targulian, V.O., Goryachkin, S.V. (Eds.), 2008. Soil Memory: Soil as the Memory of Biospheric-Geospheric-Anthropospheric Interactions. LKI, Moscow, 692 pp. (in Russian)

Terhorst, B., Sedov, S., Sprafke, T., Peticzka, Kühn, P., 2015. Austrian MIS 3/2 loess–palaeosol records–Key sites along a west–east transect. Palaeogeography, Palaeoclimatology, Palaeoecology 418, 43–56.

Van Vliet-Lanoë, B., 1998. Frost and soils: implications for paleosols, paleoclimates and stratigraphy. Catena 34, 157–183.

Van Vliet-Lanoë, B., 2010. Frost action, in: Stoops, G., Marcelino, V., Mees, F. (Eds.), Interpretation of Micromorphological Features of Soils and Regoliths. Amsterdam, Elsevier, pp. 81–106.

Vasil'chuk, A.K., Vasil'chuk, Y.K., 2010. Palynological evidence for non-glacial origin of ground ice. Engineering Geology, No. 1, 24–38.

Velichko, A.A. (Ed.), 1997. The loess-soil sequence of the East-European Plain. Palaeogeography and Stratigraphy. Institute of Geography, Moscow, 144 pp. (in Russian)

Velichko, A.A., Morozova, T.D., Nechaev, V.P., Porozhnyakova, O.M., 1996. Palaeocryogenesis, Soil Cover and Agriculture. Nauka, Moscow, 148 pp. (in Russian)

Zanina, O.G., Gubin, S.V., Kuzmina, S.A., Maksimovich, S.V., Lopatina, D.A., 2011. Late Pleistocene (MIS 3–2) palaeoenvironments as recorded by sediments, palaeosols, and ground-squirrel nests at Duvanny Yar, Kolyma lowland, northeast Siberia. Quatern. Sci. Rev. 30, 2107–2123.

Zemtsov, A.A., 1976. Geomorphology of the Northern and Central West-Siberian Plain. Tomsk State University, Tomsk, 344 pp. (in Russian)

Zinoviev, E.V., Borodin, A.V., Trofimova, S.S., Sheinkman, V.S., Rusakov, A.V., Sedov, S.N., Bobkov, P.A., 2016. Late Pleistocene entomological complexes in the Belaya Gora Section and their ecology. Eurasian J. Entomol. 15 (5), 483–498.

Zykina, V.S., Zykin, V.S., 2012. The Pleistocene Loess-soil Sequence and Climate History in West Siberia. Geo Publishers, Novosibirsk, 477 pp. (in Russian)

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