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CRYOGENIC PROCESSES IN LOESS

ABSTRACT. This paper presents a new approach to the analysis of the genetic nature of the mineral substance of loessial rocks. At the present time, the prevailing view on this issue is the eolian accumulation of loess, while the influence of other factors of formation has not been practically taken into account. However, loess accumulation can be explained by other mechanisms, e.g., active processes of cryogenic weathering under a very harsh climate. The latter concept is based on the results of analysis of wedge-shaped structures in loess thickness, as well as numerous data of spore-pollen, microfaunistic, and other types of analysis. Further developing concepts of loess formation, the authors made an attempt to assess the degree of influence of cryogenic processes on the composition and structure of loess. The proposed method is based on a differentiated analysis of the distribution of the main rock-forming minerals (quartz and feldspars) along the granulometric spectrum. Two criteria are proposed – the coefficient of cryogenic contrast and the heavy fraction coefficient (i.e., the coefficient of distribution of heavy minerals) – which allow determining the degree of participation of cryogenic processes, as well as aeolian and aqueous sedimentation, in the formation of loessial rocks. This method was used to study two sections of loessial thickness – in the south of the Russian Plain and within the Loess Plateau of China. The results of the study revealed the role of cryogenic factors in the formation of the composition of the loess horizons of soil-loess sequences of different territories. Particularly clearly the effect of cryogenesis was manifested in the loess section in the south of the Russian Plain. In the section of the Loess Plateau, only the youngest deposits of the last formation stage are affected by cryogenesis. It follows that not only within the long-term periglacial permafrost zone, but also under the conditions of seasonal freezing in the Pleistocene, the processes of cryogenic transformation of deposits could have developed, which contributed to the formation of the composition and properties of loess of sufficiently high thickness.

KEY WORDS: loess, cryogenic processes, silt fraction, permafrost, seasonally frozen condition of ground

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INTRODUCTION

The so-called loess-soil formations are widely developed within the Pleistocene periglacial zone. They represent the alternation of loess horizons and buried soils. Most researchers [Krieger, 1965, Loess …, 1986, Velichko, et al, 2009] believe that cyclic climate fluctuations in the Pleistocene are recorded in the structure of loess-soil formations: soils were formed when biogenic sedimentation was predominant in warm interglacial and interstadial periods, while loess horizons accumulated in cold epochs, in the Pleistocene, during a sharp expansion of the permafrost area.

The prevailing view in the literature is that loess deposits have primarily eolian origin and they accumulated in the cold continental climate, when atmospheric circulation increased substantially [Krieger, 1965; Lessovye ..., 1986]. As a result, the atmosphere was saturated with dust; its content was 30 times higher than in warm interglacial periods. This conclusion is drawn from the analysis of the glacial cores of Greenland and Antarctica, in which an elevated content of micro-particles in the Late Pleistocene horizons of ice has been recorded. However, this can also be explained in another way. The horizons of glacial ice with an increased content of micro-particles correspond to the maximal temperature decrease, as evidenced by the isotopic composition of ice, which causes a decrease in snow precipitation, which, in turn, can lead to a relative increase in the content of micro-particles.

Some authors suggest that the activity of atmospheric circulation in the last glacial maximum should be studied separately for winter and summer periods. Mathematical modeling of changes in the atmospheric circulation of the glacial maximum showed that average wind speeds were particularly high in winter seasons [Lofverstrom et al., 2014]. In summer, the atmosphere had lesser cloudiness over the periglacial areas and a warm anomaly formed at the surface, i.e., in fact, the weather was anticyclonic. Thus, the activity of the eolian processes practically came to naught, despite very favorable environment, since the surface was clear from snow and the subsoil and soil were directly in contact with the air.

A very important argument of the supporters of the eolian origin of loess is its granulometric composition. Many researchers (Lessovye..., 1986) believe that silty and a very uniform granulometric composition of loess is the result of air sorting, in which dispersed mineral matter is carried by the wind in suspended state for long distances (up to several thousand kilometers) at a considerable height (up to three kilometers) from the Earth's surface. The subsequent processes of deposition of atmospheric dust represent, in their opinion, the basis of loess formation. One of the loess researchers, F. Zeiner (1963), wrote, "The eolian nature of loess is most simply revealed by its comparison with modern eolian dust." Fig. 1, reproduced from his work, shows the granulometric composition of various types of silty sediments. Eolian dust accumulated in the snow after a dust storm in the city of Wroclaw (Poland) (Fig. 1, A) is indeed very similar in the granulometric composition to the typical loess (Fig. 1; D and E). However, it also bears a great resemblance to the soliflual fine earth of Spitsbergen (Figure 1, B), whose origin is most likely cryogenic weathering; the eolian glacier dust has a much rougher composition (Fig. 1, C).

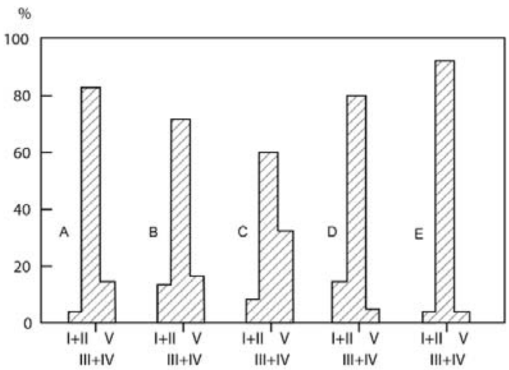


Fig. 1. The granulometric composition of various types of silty sediments (according to F. Zeiner, 1963).

Granulometric classes: I+II – 0- 0.01, III+IV – 0.01-0.07, and V – 0.07-2.0 mm. A - eolian dust accumulated in the snow after a dust storm, Wroclaw, Poland; B - banded solifluction soils, Svalbard; C - eolian dust accumulated on the surface of a glacier, Spitsbergen; D - young loess Saint-Pierre-lès-Elbeuf, Lower Seine, France; E - Mesozoic "loess" of the Triassic age, Bretten, Baden, southwestern Germany.

Another argument in favor of the eolian origin of loess, according to the proponents of this view, is the morphoscopic structure of quartz particles that compose loess. Virtually all quartz grains 0.5-1 mm in size, less often

0.5-0.25 mm, carry traces of mechanical processing in the air: they have a high degree of roundness and micro-pit and matt surface. At the same time, the surface of some grains has patterns associated with cryogenic processes, i.e., periodic freezing [Timireva, Velichko, 2006].

MATERIALS AND METHODS

The origin of 0.05-0.01 mm particles (the so-called loess fraction or coarse dust fraction) and of 0.1-0.05 mm particles, which together account for 70-80% of loess composition, is very indicative from the point of view of loess origin.

The well-known data of numerous soil and permafrost experimental studies show that under the impact of multiple freezing-thawing cycles on different types of deposits (sands, boulder loam, etc.), fractions larger than 0.25 mm degrade and a fraction of coarse dust (0.05- 0.01 mm) accumulates. This served as the basis for the ideas about the cryoeluvial nature of loess and its properties [Sergeev, Minervin, 1960; Popov, 1967].

The importance of frost weathering in the formation of loess was first noted by S. Wood in 1882-1889 [according to Krieger, 1965]. S. Wood suggested that loess was formed beyond the area of glacial development, in the permafrost regions under seasonal thawing, creeping, and slipping of the upper soil layers. When displaced, fine-earth products of frost weathering accumulated in low spots and depressions of the relief. Precisely such loamy deposits formed within Europe and North America were considered by S. Wood to be loess. However, S. Wood had a different view on the origin of loess in China because of its enormous thickness. S. Wood's hypothesis was repeatedly criticized, since his ideas did not explain a number of characteristic features of loess, in particular, its carbonate content. Nevertheless, S. Wood's concept on the distribution of loess mainly in the Pleistocene periglacial zone, or rather within the Pleistocene cryolithozone (the terminology that appeared much later), was supported and detailed by later works [Krieger, 1965, Konishchev, 1981].

To date, the differences between the two processes of formation of the dominant granulometric fraction of loess (0.05-0.01 mm) – whether it is the product of eolian differentiation of mineral matter and its sorting in the air, or it is the result of cryogenic processing of various types of parent rocks – are still unclear.

We proposed specific lithological criteria to identify cryogenic fine earth and products of its redeposition. Our approach is based on long-term studies of loess-like deposits in North Eurasia, in particular, the cover loess-like formations of the Bolshezemelskaya tundra, the northern part of West Siberia, and the deposits of the ice complex in the northern part of Yakutia, and the results of an experimental study of the cryogenic stability of the main rock-forming minerals [Konishchev, 1977, 1981].

This became possible only after it had been established that the stability series of the main rock-forming minerals (quartz, feldspar, mica) with respect to cryogenic weathering (the process of alternating freezing-thawing) is directly opposite to the stability of these minerals in temperate and warm climates. This general position was concretized through the determination of the cryogenic stability of monodisperse granulometric fractions of various rock-forming minerals (quartz, feldspar, etc.).

For the first time this approach was used in experimental studies of cryogenic stability presented in [Konishchev, Rogov, Shchurina, 1976] and later in research by [Minervin, 1982]. It was found that, under alternating freezing-thawing, the grains of quartz break down to the fraction of 0.05-0.01 mm, and the grains of feldspar, unchanged by earlier pelitization processes, are crushed to the fraction of 0.1-0.05 mm.

The differences in the limits of cryogenic disintegration of various minerals are due to the differences in the thicknesses and properties of unfrozen water films adsorbed on the surface of various minerals during their cryogenesis [Konishchev, 1981].

Thus, the position of the maxima of contents of the main rock-forming minerals within the granulometric spectrum of cryogenic fine earth (cryogenic eluvium) and the products of its nearest redeposition should not coincide and should represent a sequential series from larger to smaller particles: feldspar → quartz → minerals of heavy fraction. This cryogenic series is mirror-like to the scheme of mineral distribution within the granulometric spectrum of deposits of various facies-genetic types formed in humid conditions of warm and moderate climates, outside the zone of cryogenesis, established by fundamental research of N.M. Strakhov [Strakhov, 1962] (Fig. 2). As can be seen from the figure, within the range of the maximum mineralogical diversity limited by particle sizes 0.25-0.01 mm, the maxima of the mineral contents do not coincide. Therefore, it can be stated that the position of the main rock-forming minerals (primarily quartz and feldspar) within the granulometric spectrum is radically different inside and outside the zone of cryogenesis.

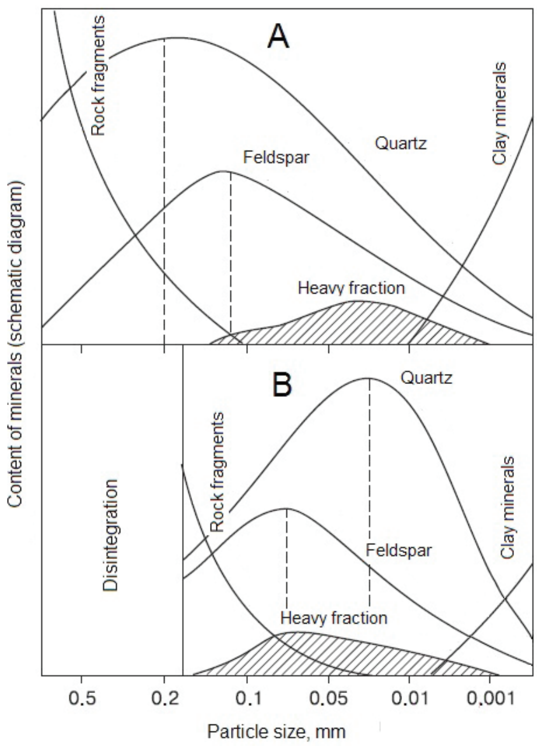


Fig. 2. Change in the content of minerals by grain size in dispersed rocks formed under warm climate conditions (A - according to [Strakhov, 1962]) and the zone of cryogenesis (B - according to [Konishchev, 1981])

Research on the composition of loess-like formations within the modern cryolithozone (the cover loams of the Bolshezemelskaya tundra and the ice complex of northern and central Yakutia) carried out by the authors have shown that only a differentiated approach to composition analysis allows assessing more objectively the cryogenic-climatic and facies-genetic conditions of the accumulation of mineral matter of these deposits.

A special coefficient was proposed as an explicit indicator characterizing the degree of participation of the cryogenic weathering process in the formation of deposits. It takes into account the distribution of quartz and feldspar within the granulometric spectrum, more precisely by the limiting sizes of fractions in which these minerals accumulate in the course of cryogenesis [Konischev, Rogov, 1994]. This coefficient was called the coefficient of cryogenic contrast (CCC):

$$CCC = Q_1/F_1 : Q_2/F_2,$$

where Q1 and F1 are the contents of quartz and feldspar, respectively, in the fraction 0.05-0.01 mm; Q2 and F2 are the contents of quartz and feldspar, respectively, in the fraction 0.1-0.05 mm.

The deposits formed in cryolithozone have the CCC values greater than 1, whereas the deposits formed outside this zone, i.e., under temperate and warm conditions, according to N.M. Strakhov's scheme, have the CCC values less than 1.

Along with the CCC parameter which specifically allows assessing the cryogenic nature of mineral matter of the sediments, it is necessary to use another indicator that can be called the heavy fraction coefficient (HFC) [Konishchev, 1981]:

$$HFC = \Sigma_{HM} 0.05 - 0.01 \text{ mm} / \Sigma_{HM} 0.1 - 0.05 \text{ mm},$$

where HFC is the heavy fraction coefficient and HM is content of heavy minerals.

HFC is the ratio of the weight content of heavy minerals in the fraction 0.05-0.01 mm to the weight content of heavy minerals in the fraction 0.1-0.05 mm; it characterizes the degree of exposure to the aqueous- or air-sorting process or lack thereof.

The HFC values greater than 1, characteristic of the sedimentogenic distribution of heavy minerals by grain size, indicates the presence of aqueous- or air-sorting. The HFC values less than 1 point to the eluvial origin or the nearest redeposition (slope or proluvial) of cryogenic fine earth.

The use of theses indices in the analysis of the origin of the ice complex in Northern and Central Yakutia, much of which is made up of loess deposits, allowed us to establish the leading role of cryogenic disintegration in the formation of mineral matter of these deposits [Konishchev, 2013]. Different facies-genetic types of loess-like deposits of the ice complex were isolated. These are, first of all, the products of the nearest redeposition of cryogenic eluvium with the corresponding parameters of the proposed indices and the products of redeposition of cryogenic fine earth in various dynamic conditions of the aqueous environment (Fig. 3).

The application of the proposed indices (CCC and HFC) to the analysis of individual sections of soil-loess formations within the Pleistocene periglacial zone of the East European Plain, outside the zone of modern cryogenesis, also yielded interesting and generally positive results [Konishchev et al., 1985].

BASELINE DATA AND RESEARCH RESULTS

The purpose of the paper presented herein is to discuss the application of the method to analysis of the composition of sediments of two sections of loess-soil formations located on the southern margin of the European range of loess deposits (the Beglitsa section) and within the Loess Plateau in China (the Zhaoxian section)

This study was made possible by Professor A.A. Velichko who, together with his colleagues, had invited the authors to take part in an integrated international project. The authors were provided with samples from the above-mentioned sections, which were analyzed using the approach described above.

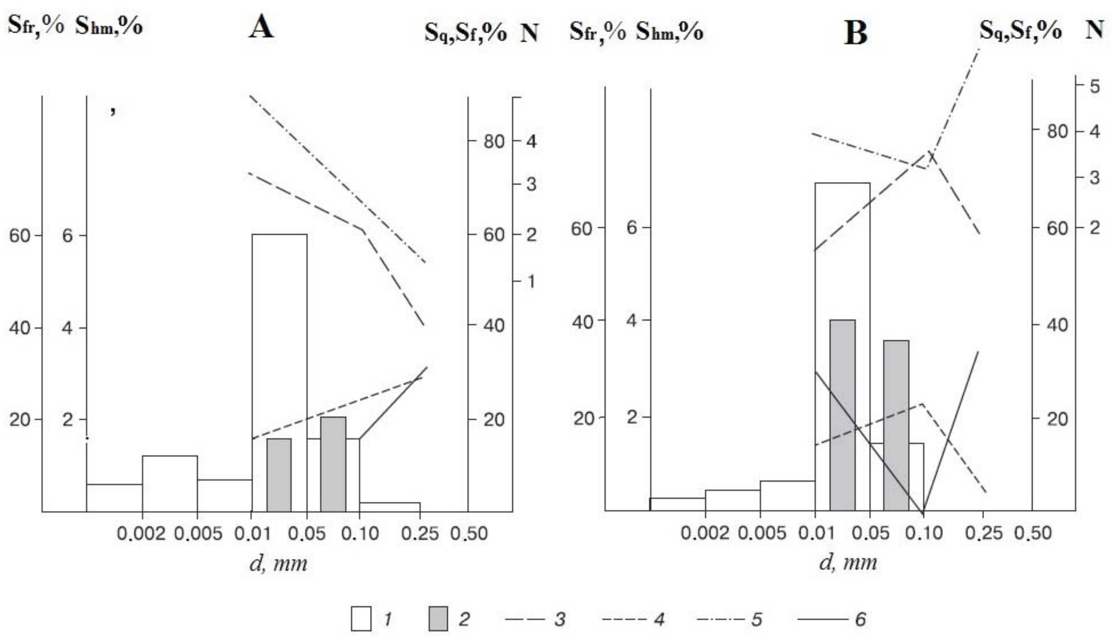


Fig. 3. The relationship between granulometric and mineralogical parameters in the sections of Mus-Khay outcrop of "brown" aleurite (A - depth 4.4 m) and of greenish-gray aleurite (B - depth 19-20 m).

1 - granulometric composition (Sfr,%); 2 - content of heavy fraction (Shm,%); 3 - distribution of quartz content by fractions (Sq,%); 4 - distribution of feldspar content by fractions (Sf,%); 5 - distribution of the quartz/feldspar ratio (N) by fractions; 6 - distribution of rock fragments by fractions (%) [Konishchev, 1981].

The main method of studying the mineralogical composition of the loess samples was X-ray diffraction analysis. The fractions 0.05-0.01 mm and 0.1-0.05 mm were isolated by sieving. The Beglitsa section samples were analyzed by A.N. Kurchatova at the Cryotrasology Laboratory of the RAS Institute of the Earth's Cryosphere with D2 PHASER diffractometer; the Zhaoxian section samples were analyzed by D.G. Shmelev at the Department of Lithology and Marine Geology, Faculty of Geology, Lomonosov Moscow State University, with DRON diffractometer.

The Beglitsa section is located approximately 25 km west of Taganrog on the northern coast of the Gulf of Taganrog, the Azov Sea (Neklinovsky District, Rostov Oblast), on a 3km long steep seashore; the section exposes the so-called Beglitskaya terrace soils. The coordinates of the section are N47°07', E38°30' The maximum height of the cliff at the site where the section is located is 17.8m, and the average height is about 16-17m a.s.l. The section exposes the Late Valday loess with the horizons of the buried soils of the Bryansk and Mezinsky pedocomplexes; the lower part of the section is composed of the liman-alluvial Late-Khazarian deposits.

Nine samples from the Beglitsa section were analyzed; these samples were uniformly distributed within the section (Fig. 4, A). Some of the samples were taken from the loess while others were taken from the sediments of the pedocomplex. In all loess samples, the CCC values were greater than 1 and the HFC values were less than 1, thus pointing to a non-sedimentary nature. Therefore, mineral matter of the loess horizons is generally a typical cryogenic fine earth.

The results may be interpreted in more detail using the relationship between the CCC and the average annual temperature of the soil surface obtained earlier by one of the authors [Konishchev, 1999] (Fig. 5). The highest CCC value (1.36) is associated with the Late Valday loess horizon above the Bryansk soil. This allows us to assume the existence of shallow high-temperature permafrost during that period. A lower CCC value (1.13) associated

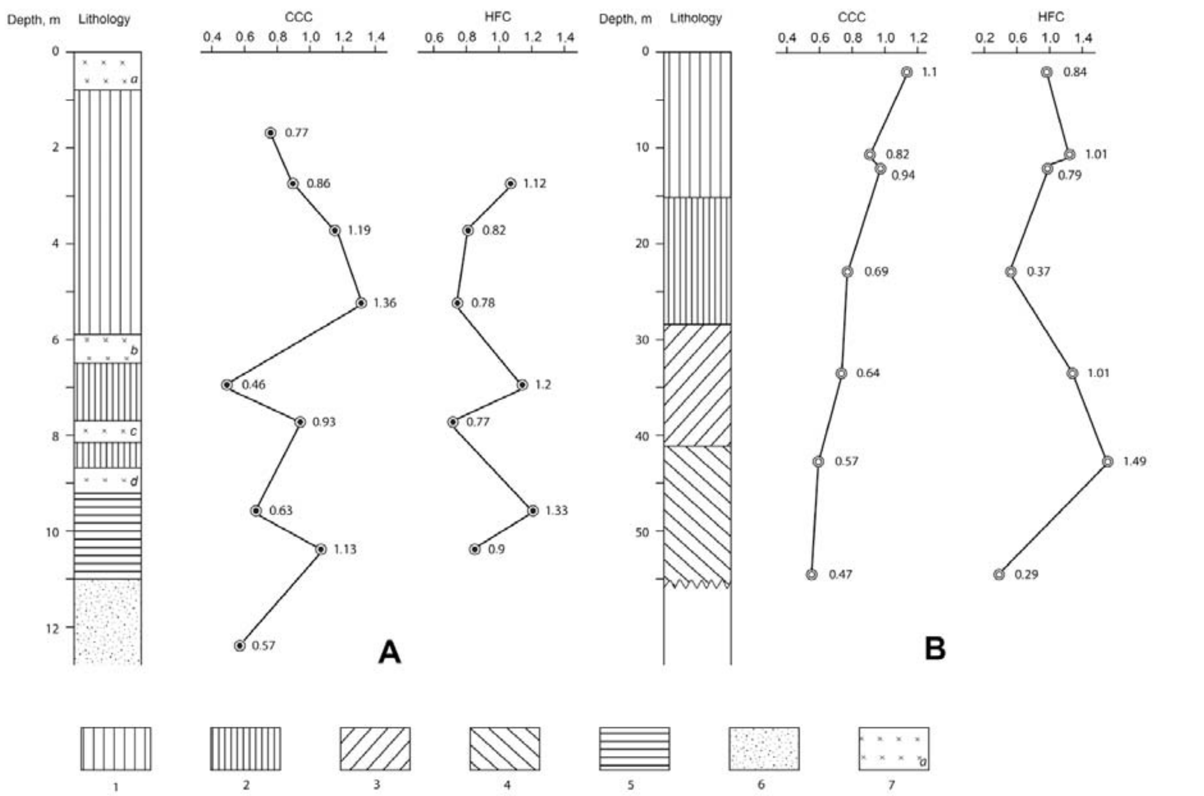


Fig. 4. Distribution of the CCC and HFC values in the Beglitsa (A) and Zhaoxian (B) sections.

1 - pale-gray loess, 2 - light-pale loess, 3 - gray-yellow loess, 4 - yellow-brown loess, 5 - gray-brown loess-like sandy loam, 6 - silty sand, 7 - soil horizons: a-modern soil, b - Bryansk paleo-soil, c - Mezinsky paleo-soil, Krutitsky horizon, d - Mezinsky paleo-soil, Salynsky horizon

with the period of formation of the Middle Valday loess, suggests a possible existence of island permafrost in this region. The samples taken from the soil and underlying horizons do not manifest the cryogenic nature of mineral matter. Obviously, this is the result of the effect of soil processes on the initially-cryogenic distribution of the mineral parameters within the granulometric spectrum characteristic of typical loess.

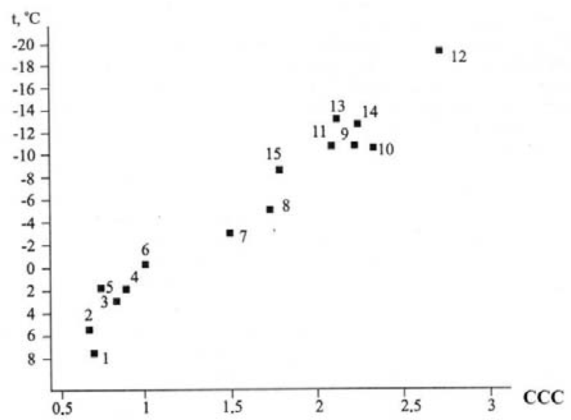


Fig. 5. The relationship between CCC and the average annual soil temperature at a depth of 40-50 cm.

1 - podzolic soil on glaciolacustrine sediments (Belarus, near Minsk); 2 - podzolic loam soil on moraine (Belarus, Poozerye); 3 - sod podzolic and podzolic loam soil on cover loam (the Klinsko- Dmitrovsky Ridge, southern taiga); 4 - podzolic loam soil on cover loam (middle taiga, near Syktyvkar); 5 - podzolic loam soil on cover loam (Western Siberia, settlement Laryk); 6 - gley-podzolic soil on cover loam (northern taiga, Troitsko-Pechorsk); 7 - peat-gley soil on cover loam (southern tundra, settlement Vorgashor); 8 – peat-gley oil on cover loam (Bolshezemelskaya tundra, near Vorkuta); 9 - loamy eluvium sandstones and shales (the Yano-Omoloy interfluve, the Kular Ridge); 10 - tundra gley soil on the ice complex sediments (the Indigirka River, near Vorontsov Yar); 11 - tundra gley soil on the ice complex sediments (the coast of the East Siberian Sea, the Chukchi Peninsula), 12 – eluvial-solifluction deposits (Pamir, elevation 6 200 m, the edge of a firn plateau); 13 - eluvium of sandy-argillaceous shale (the East Siberian Sea, the Svyatoy Nos Peninsula); 14 - eluvium of sandy-argillaceous shale (the East Siberian Sea, the Shirokostan Peninsula); 15 - eluvium of sandy-argillaceous shale (low reaches of the Kolyma River).

In the lowest sand sample associated with the transition layer of liman-alluvial sediments, the CCC value is 0.57, which indicates that these deposits were formed under a rather warm climate.

Thus, the data on the composition of the loess horizons in the Beglitsa section allow us to interpret them as products of cryogenic transformation of the original rocks (most likely, these are liman-alluvial deposits of the Khazar transgression) that were redeposited in depressions of the multiple terraced delta. At the subaerial stage of the territory development, the relief leveled out and all surface irregularities of the liman deposits were buried under the subaerial layer of the soil-loess sequence. This conclusion is also supported by a geological profile along the southeastern coastline of the Gulf of Taganrog and the mouth of the Don River [Putevoditel..., 2013].

The second studied section, Zhaoxian, is located 50 km of Jinyuan, Gansu province, in the middle reaches of the Huang He River. The coordinates of the section are N36°24', E104°36'. The section outcrops in the slope of a 30° steep clough. In the lower part of the slope, there is a well-defined terrace-like bench. The total depth from the plateau surface to the bed is 300 m. The section has a sufficiently homogeneous, 55 m thick, loess layer. The section deposits include pale gray loess, sometimes with a brown tint, a whitish powder of carbonates along fine root traces, occasionally with brown streaks and spots. The granulometric composition is very homogeneous over the whole studied stratum and is composed of coarse aleurite. Soils in this section are absent for large intervals; only at depths of 11.5, 34.5, and 43.5 m, there are some signs of soil processes: reddish-brown and brown color and manganese patches. In this respect, this section is very similar to the section of the "last glacial" [Zykina, Zykin, 2012] loess that does not contain soils and is located in the northern part of the Chinese Loess Plateau. Seven samples from depths of 3-55 m of this section were analyzed (Fig. 4, B).

The CCC values shown in Fig. 4 (B) are distributed quite consistently with depth – from 1.1 at 3 m to 0.47 at 55 m. Based on the relationship between the CCC values and the average annual temperature of the soil surface (Fig. 5), it can be asserted that the CCC value of 1.1 corresponds to the existence of island cryolithozone; the CCC values from 0.9 to 0.6 point to conditions of deep seasonal freezing, and even lower CCC values point to that the depth of seasonal freezing was only 0.7-0.8 m.

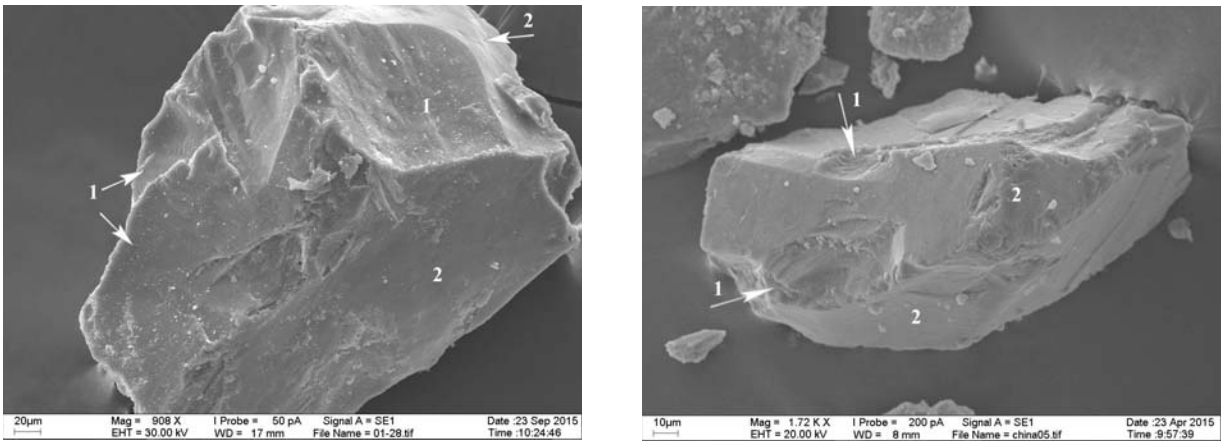
The HFC values are also very indicative. In the uppermost sample, where CCC is above 1, which suggests a certain role of cryogenesis processes in the formation of dispersive properties of the deposits of this horizon, a non-sedimentogenic distribution of the heavy fraction within the granulometric spectrum is observed. This is an additional argument in favor of the cryogenic nature of mineral matter in this sample. In a number of other samples (12 m, 23 m, and 55 m), a non-sedimentogenic distribution of heavy fraction minerals is also observed, which does not agree with the determining role of the eolian genesis of the deposits at these depths. In samples taken from depths of 11.5, 34.5, and 43.5 m, where some signs of soil processes were noted, the HFC values, on the other hand, were greater than 1. Therefore, probably during the accumulation of sediments at these depths, processes altering the cryogenic distribution of heavy fraction minerals within the granulometric spectrum were in play.

This section clearly indicates that cryogenic fine earth can accumulate not only in the cryolithozone environment and in the layer of seasonal thawing, but also under the influence of seasonal freezing; this fine earth serves as the source of the formation of rather thick loess strata (with the nearest redeposition).

The validity of the conclusions presented in this paper is based on a rather limited number of samples, which implies the need to expand the scope of the study.

Nevertheless, it is quite obvious that cryogenic factors played a very important role in the formation of the analyzed section of the Zhaoxian loess stratum. In this case, the influence of eolian sedimentation cannot be completely excluded, although its significance, in any case, was not decisive; thus, the question on the sources of mineral matter arises. If these were not primarily eolian accumulations, as was suggested in many publications [Zykina, Zykin, 2012], it is important to note that the Loess Plateau, despite its fairly large size, is located not so far away from the alimentation zone. Precisely it could be this source during the last glacial maximum, when, through a system of valleys dissecting and draining mountain structures, huge masses of disintegrating rock material entered the river valleys and were deposited on the slopes, forming accumulative surfaces such as the Loess Plateau.

The manifestations of cryogenesis in the samples of the studied sections were also noticeable at the morphological level. The sand fractions particles (1-0.5 and 0.5-0.25 mm) were investigated with the LEO 1240 scanning



A B

Fig. 6. Morphology of the loess sandy fractions particles of the Beglitsa section (5.2 m deep) (A) and the Zhaoxian section (3 m deep) (B).

1 - fresh conchoidal cryogenic shear surface;

2 –patches of smooth polished and micro-pitted (eolian) surface.

electron microscope. The form and the surface of the particles in samples with high CCC values had features indicative of the cryogenic action (Fig. 6). These include an angular shape, shears, and fractures, which are very similar to those in the sediments of the modern active layer of the regions of Canada, Spitsbergen, and Mongolia [Woronko, Pisarska-Jamrozy, 2015].

CONCLUSIONS

The analysis of the samples from the two loess sections demonstrated the validity of the cryolithological method in studies of mineral matter. The authors have shown a significant, if not decisive, role of cryogenic factors in the formation of the composition of the loess horizons of soil-loess sequences. This is particularly clearly seen in the example of the Beglitsa section. The potential of cryolithological analysis of the Loess Plateau loess is also evident in the example of the Zhaoxian section. Without denying the role of the eolian mechanism in the formation of loess horizons of soil-loess formations, the analysis of the studied samples proved that not only within the periglacial permafrost zone, but also under conditions of seasonal freezing in the Pleistocene, processes of cryogenic transformation of deposits were active, which contributed to the formation of composition and properties of the sufficiently thick loess layer.

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