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THE ROLE OF CRYOGENIC PROCESSES IN THE FORMATION OF LOESS DEPOSITS

ABSTRACT. The paper describes a new approach to the analysis of the genetic nature of mineral substances in loess deposits. In permafrost under the influence of multiple alternate freezing and thawing in dispersed deposits, quartz particles accumulate the 0.05–0.01 mm fraction, while feldspars are crushed to a coarse fraction of 0.1–0.05 mm. In dispersed sediments formed in temperate and warm climatic zones, the granulometric spectrum of quartz and feldspar has the opposite pattern. The proposed methodology is based on a differential analysis of the distribution of these minerals by the granulometric spectrum. We have proposed two criteria – the coefficient of cryogenic contrast (CCC) and the coefficient of distribution of heavy minerals, which allow determination of the degree of participation of cryogenic processes in the formation of loess sediments and processes of aeolian or water sedimentation.

KEY WORDS: loess deposits; granulometric distribution, mineral composition; cryogenesis; cryolithozone; periglacial zone; historical and genetic approach

INTRODUCTION

Among researchers who have studied the problem of loess, there are virtually no large disagreements in the definition of their basic properties [Krieger 1965]. The properties include homogeneity of the size distribution, vertically and horizontally, within the vast expanses. Usually the silt content of the primary particles is in the range of 30–55 %, at the total porosity of 40–45 %; it contains lime and microaggregates and has a relatively high content of soluble salts; it is laminated, with the ability to maintain the vertical wall in the outcrops; it subsides when wet and often forms mantles and contains buried soils.

The situation is quite different in the genetic interpretation of the above characteristics and properties of loess, favored by a number of researchers. There are opposite points of view which show lack of understanding of the problem and lack of sufficiently certain genetic criteria for the interpretation of a particular characteristic or characteristics of loess.

The most revealing in this respect is the size-distribution of these deposits.

Many researchers believe that the loess cover was formed in the cold Pleistocene era and is a product of the deposition of atmospheric dust. During glaciation maximums and coolings and accordingly, arid climate, there was an intensification of the atmospheric circulation. This caused the saturation of the atmosphere with dust; its content was 30 times higher than the dust content in the interglacial atmosphere [Broecker, 2000].

Even colder intervals of the Antarctic and Greenland ice cores are enriched with dust [Kotlyakov, Lorius, 2000]. In warm periods of Neopleistocene, the accumulation of dust either stopped or significantly slowed down and soils were forming on the surface of the deposits. Thus loess-soil sequences appeared which are considered very important nature sites in terms of completeness of paleoclimatic information.

The formation of loess horizons of the loess-soil sequences coincides with the cold stages of the oxygen isotope scale, while the formation of buried soils coincides with the warm phases [Bassinot et al, 1991]. According to many researchers, the aeolian nature of loess is most simply revealed [Zeuner, 1965] by comparing the size distribution of modern aeolian sediments on snowfields, glaciers, and other surfaces after dust storms in many modern parts of the world [Chapman, 1934 and al.; Page, 1934; Russel, 1936]. The leading role in the composition of these deposits is played by a large primary particles of aleurolite (0.05–0.001 mm), i.e., more than 40–50 %.

The work of many researchers has shown that transfer of disperse mineral matter is accompanied by differentiation of the particles by size and mineralogical composition [Rukhin, 1961; Sidorenko, 1956]. Quartz, feldspar, and other light minerals dominate; there are small quantities of heavy minerals.

Atmospheric dust carried over considerable distances contains varied sizes of particles and minerals, including heavy, i.e. is polymineral and polydisperse, but with predominance of the primary particles, 0.05–0.01 mm in size.

It is important to emphasize that the bulk of heavy minerals concentrate within the fraction 0.05–0.01 mm, while quartz, i.e., the most stable mineral, tends to have larger particles.

Fig. 1 shows the particle-size and mineralogical composition of clusters of aeolian dust collected on the right branch of the glacier Shokalski (Trans-Ili Alatau, Tien Shan); altitude 3950 m; the rock framing is located at a distance of 800–900 m from the sampling site. Even at such a short distance, there is a noticeable particle size sorting accompanied by mineralogical sorting expressed in the distribution of heavy minerals (specific density of the granulometric spectrum is greater than 2.9). The maximum weight of heavy minerals is associated with the fraction 0.05–0.01 mm. This sedimentary distribution of the heavy

Fig. 1. The particle-size and mineralogical composition of aeolian fine earth on the right branch of the glacier Shokalski (Trans-Ili Alatau, Tien Shan, altitude 3950 m, rock framing is 800–900 m from the sampling site).

1 – size distribution S_{fr} ; 2 – content of the heavy fraction S_{HM} ; 3 – distribution of the quartz content by size-fractions (S_{LM} %); 4 – distribution of feldspar content by size-fractions (S_{LM} %); 5 – distribution of quartz/feldspar (N) ratio by size-fractions; 6 – distribution of rock fragments by size-fractions (%).

fraction by the granulometric spectrum is a general law for the truly aeolian deposits. In the aqueous environment, a similar granulometric and mineralogical sorting occurs, but in a somewhat less pronounced form, since the maximum effective sorting of mineral matter occurs in air.

Unfortunately, despite the huge amount of grain-size, microaggregate, and mineralogical analyses of loess and loess deposits, the data on the distribution of the mineral content of both light and heavy granulometric fractions are virtually absent in the literature. And, most importantly, the authors do not consider these parameters to have any significance for detection of genetic nature of the mineral matter of loess.

The same applies to the atmospheric dust studied under the framework of international projects. The proceedings of international conferences contain data on particle-size distribution of dust carried in the atmosphere

and the general content of minerals, including heavy, but recent data on the distribution by the granulometric spectrum are not available.

The particle size of atmospheric dust captured by special dust collectors is often an order of magnitude smaller than the large particles of dust dominant in loess deposits (0.6–3.0 microns). The ice cores in Greenland and Antarctica have increased contents of microparticles in the Late Pleistocene ice; it corresponds to the maximum decrease in temperature, which caused a decrease in rainfall, leading to a relative increase in the content of the microparticles. At the same time, we cannot, of course, completely deny the increased activity of the atmospheric circulation.

Evidence of permafrost processes, such as permafrost patterns and textures (pseudomorphs of ice wedges, cryoturbation and involution, post-schlieren texture, etc.) represent the proofs of cold climatic conditions. Long-term studies of paleopermafrost loesses, their classification, and mapping were carried out by A.A. Velichko and his followers [2004]. At the same time, these researchers adhere to the aeolian concept of loess formation. Despite the exhaustive classification of paleopermafrost phenomena, including microstructural features of mineral matrix of loess typical of loess-soil series within the East European Plain and Western Europe, the researchers have clearly underestimated the actual lithological aspect of repeated cycles of freezing and thawing, accompanied by accumulation of mineral mass of loess.

Many researchers wrote on the role of frost weathering processes in the formation of the loess fraction (0.05–0.01 mm). N.I. Krieger [1965] published a very good historical overview of this problem. Later, the problem was studied mainly by permafrost scientists. Numerous experiments have shown that under the influence of multiple cyclic freezing – thawing in various rocks, both monolithic (granite, sandstone, etc.) and dispersed (sands, sandy loams, loams), the loess fraction was accumulating due to

both disintegration of larger particles (quartz, feldspar, etc.) and aggregation of clay particles.

Yet this did not mean that a criterion for differentiating between products of wind cryogenic separation and cryogenic transformation of mineral substances has been found.

RESEARCH METHODS

An earlier method of experimental research on cryogenic weathering based on testing of polymineral and polydispersed samples has led to conclusions about the accumulation of loess fraction in soils, but no analysis of any specific product of cryogenic mineral destruction has been performed. Therefore, uncertainty remained regarding genetic interpretation of the particle-size distribution of loess and loess deposits.

Particular characteristics of cryogenic weathering were identified only in the study of cryogenic stability and monomineral and monodisperse fractions. For the first time this approach to experimental research of cryogenic stability was carried out by [Konishchev, Rogov, Schurina, 1976]. They have determined that quartz grains break down to a fraction of 0.05–0.01 mm, while feldspar grains, not altered by earlier processes of pelitization, crush to a size of 0.1–0.05 mm. The limits of cryogenic destruction of other minerals have been established; however, it did not matter much because their content in the original deposits is usually small, i.e., no more than a few percent, whereas quartz and feldspar comprise the bulk of the deposits and their content is generally greater than 90–95 %

These findings were confirmed by the results of the experiments of A.V. Minervin [1982]. This experiment also studied cryogenic resistance of monomineral and monofractional samples, but the number of cycles of freezing-thawing was 1000, and the experiment lasted for more than 3 years, i.e., both were substantially greater than in our experiment (Table. 1).

Table 1. Results of modeling of large-silt loess fraction formation under different conditions based on [Minervin, 1982]

№ of experiment	Experimental conditions		Mineral	% content of fractions, diameter of particles in mm					
				0.25–0.1	0.1–0.05	0.05–0.01	0.01–0.005	0.005–0.001	<0.001
1	Before experiment		quartz	100	–	–	–	–	–
			microcline	100	–	–	–	–	–
			calcite	100	–	–	–	–	–
			biotite	100	–	–	–	–	–
2	Freezing (–10°) – Thawing (+15°–+20°)	water saturated	quartz	11	20	68	1	–	–
			microcline	7	44	48	1	29	–
			calcite	6	15	20	30	–	–
			biotite	98	1	1	–	–	–
3	Freezing (–10°) – Heating (+50°)	air-dry	quartz	98.5	1	0.5	–	–	–
			microcline	98.5	1.5	1	–	–	–
			calcite	93.5	5	–	–0.5	–	–
			biotite	100	–	–	–	–	–
4	Wetting-drying (in laboratory; +18°–+ 20°)		quartz	100	–	–	–	–	–
			microcline	100	–	–	–	–	–
			calcite	100	–	–	–	–	–
			biotite	100	–	–	–	–	–

However, the result, as follows from the table, was the same, but manifested more clearly – quartz disintegrated into smaller particles (up to 0.05–0.01 mm) compared to feldspar (microcline) – up to 0.1–0.5 mm. Unfortunately the author did not consider this result important, he simply did not notice it.

In fact, this conclusion is of fundamental importance. Firstly, it is clear why there is an absolute predominance of particles 0.05–0.01 mm in cryogenic-weathering products; this is determined by the dominant role of silica in the composition of sedimentary rocks (moraine, alluvial, marine, and other), which were the source parent rocks, subsequently altered by cryogenic weathering.

Secondly, there are special requirements to the procedure of analyzing the composition of disperse deposits in order to determine the role of cryogenesis in their formation. It is necessary to determine the mineralogical composition not in the bulk deposits,

but individually for separate granulometric fractions and primarily in fractions 0.05–0.01 mm and 0.1–0.5 mm that typically make up the large, and the largest in loess, part of the mineral mass.

A large number of studies are devoted to determination of relationships between granulometric and mineralogical composition of disperse sedimentary deposits [Ananiev, 1966; Lazarenko, 1964; Rukhin, 1961; Ryasina, 1961; Sergeev, 1954; Sidorenko, 1956; Strakhov, 1962; Fadeev. 1968 et al.; Tsekhomskiy, 1956].

In his major work, N.M. Strakhov [1962] summarized the vast amount of material and introduced the concept of distribution of minerals by the particle-size spectrum of different facies types formed in humid conditions, predominantly outside the cryolithogenic zone (Fig. 2). There is a region of maximum mineralogical diversity, limited by 0.25–0.01 mm particles. The granulometric spectrum maximums inside this area do not

Fig. 2. Redistribution of the main mineralogical properties by particle-size during cryogenesis [Konishchev, 1981].

A – qualitative diagram: 1 – distribution of the content of the main mineral components by particle-size of the original rock, 2 – distribution of the main mineral components in products of cryogenesis.

B – quantitative diagram of redistribution relative to the bulk content of heavy minerals by particle-size at a constant absolute content: 1 – the original rock with the sedimentary-type distribution of the heavy fraction; 2 – supergene type of the heavy fraction content in products of cryogenesis.

coincide and are arranged consecutively in a series from the larger to finer particles: quartz → feldspar → heavy mineral fractions.

The nature of the upper limit of clastic minerals is inherited and is the function of their regular size in the original massive-crystalline deposits.

The lower limit of the particle-size spectrum of the predominantly clastic minerals (0.001 mm) is due to a sharp increase of the instability of mineral grains in relation to the factors of chemical weathering in the course of their size-degradation. The crucial factor in localization of heavy minerals is specific weight and degree of sediment sorting. In the sorted sediments, the total maximum content

of heavy minerals is mainly associated with the fraction 0.05–0.01 mm.

Numerous studies on the analysis of particle-size distribution and mineralogical composition of the typical loess practically do not apply this differentiated approach; a high degree of particle-size sorting has been considered the sufficient criterion for conclusions about genetic facial conditions of formation of these deposits.

At the same time, our studies on the composition of loess deposits in the modern cryolithozone, where typical carbonate loess formations are absent, showed that only a differentiated approach to the study of the composition allows one to judge more

objectively both the cryo-climatic and facial-genetic conditions of accumulation of mineral matter in these deposits.

Therefore, we propose a special coefficient as a characteristic of the degree of participation of cryogenic weathering in the formation of deposits; more specifically, it considers the limit fraction sizes within which these minerals accumulate during cryogenesis.

$$CCC = \frac{Q_1}{F_1} : \frac{Q_2}{F_2}.$$

It was named the *Coefficient of Cryogenic Contrast*, where Q_1 – quartz content in the fraction 0.05–0.01 mm; F_1 – feldspar content in the fraction 0.05–0.01 mm; Q_2 – quartz content in the fraction 0.1–0.5 mm; F_2 – feldspar content in the fraction 0.1–0.5 mm.

The deposits formed in the cryolithozone must have a CCC value greater than 1. Whereas the deposits formed outside the zone, i.e., in temperate and warm climates, have the values of CCC based on N.M. Strakhov's scheme [Strakhov, 1962], i.e., lower than 1.

Generalization of a large volume of data on the composition of deposits formed within and outside the zone of cryogenesis, has fully

justified the proposed parameter [Konishchev, 1981].

ANALYSIS OF THE OBJECTS UNDER STUDY

Particular characteristics of the composition of products of cryogenic transformation have been most clearly revealed in the analysis of the composition of mantle loess-like formations of the Bolshaya Zemlya tundra. A comprehensive description of these deposits is given in [Konishchev 1981]; therefore, we will focus on the features of their differentiated granulometric and mineralogical composition. We should only note that mantle loess loams of the Bolshaya Zemlya tundra covers entirely tundra watersheds and are absent on the first terrace and in the river valleys; their thickness is 1.5–1.8 m and varies from 0.2–0.5 m to 3–3.5 m within interblock depressions of the polygonal relief. Mantle loams occur with a gradual contact on rubbly loams and, less often, on sands, which is reflected in their composition; they conjoin the polygonal system of frozen ground veins.

Differentiated mineralogical analysis (for individual granulometric fractions) showed that the maximum content of silica is observed in the most representative fraction of very fine sand – 0.05–0.01 mm (Fig. 3).

Fig. 3. Distribution of mineralogical parameters by granulometric range of mantle loess-like formations of the Bolshaya Zemlya tundra (for legend, see Fig. 1).

The amount of quartz in this fraction ranges from 74 to 85 %; it is markedly reduced in larger-size fractions (in 0.1–0.05 mm, 59–70 %; in 0.1–0.25 mm, up to 46–58 %) and in smaller-size fractions. The character of the particle-size spectrum of the feldspars content in all cases is the same and is characterized by a maximum of 30–42 % in the fraction 0.1–0.05 mm. In finer fractions, the content of feldspars is reduced (up to 15–26 % in the fraction 0.05–0.01 mm and up to 9–18 % in a larger fraction 0.1–0.25 mm).

As one can see, the ratio of distribution of the main rock-forming minerals (quartz and feldspar) by particle size of mantle loess-like formations of the Bolshaya Zemlya tundra is exactly opposite of the behavior of these minerals in the deposits formed in warm climatic conditions.

In the literature, there is a widespread point of view that loess and loess-like deposits are characterized by very insignificant weathering [Ryabchenkov, 1955; Khalcheva, 1975], which made it possible to deny the significant effects of weathering processes in their formation. This judgment is fraud with an obvious logical inconsistency. The essence of the weathering coefficient, defined as the ratio of stable minerals to the sum of unstable minerals in the total mass of deposits, without separation of granulometric fractions is the ratio (!) of physical processes (fragmentation of minerals) to chemical processes (their decomposition, transformation) of weathering. Low values of weathering coefficient mean low intensity of chemical weathering, not weathering in general, and high intensity of physical desintegration of minerals without alteration of their mineralogical composition.

The association of high quartz content with the most typical size fraction (0.005–0.001 mm) of mantle loess formations of the northern part of European Russia and the maximum content of feldspars in a larger fraction (0.01–0.05 mm) reveal the main mineralogical essence of the process of formation of these deposits, i.e., cryogenic fragmentation of

minerals of the original deposits (rubby loams, sands) to the characteristic of these minerals limits – 0.05–0.01 mm and 0.1–0.05 mm for quartz and feldspar, respectively, which is in accordance with the experimental and theoretical conclusions on the cryogenic stability of minerals.

The most important consequence of this process is the distribution of the overall total content of heavy minerals by particle-size (weight percentages of heavy minerals in certain size-fractions). In all analyzed samples of mantle loess-like loams, the maximum relative weight content of heavy minerals is observed in the fraction 0.1–0.05 mm and not in a finer fraction 0.05–0.01 mm (the shift of the maximum content of heavy minerals towards a larger fraction is a direct consequence of the cryogenic fragmentation of basic rock-forming minerals – quartz and feldspar (see. Fig. 2, A2).

From this, a fundamentally important conclusion follows: if the considered mantle loess-like formations had sedimentary origin and their high degree of particle size sorting were associated with the properties of sediment accumulation in water or air environment, one would expect that the distribution of the relative weight of heavy minerals by particle-size corresponds to the sedimentogenous distribution, as is the case in true aeolian deposits (see. Fig. 1).

The principle rock-forming position of quartz in the original deposits, the high degree of cryogenic crushability of quartz particles compared to other minerals, and stability of quartz particles 0.05–0.01 mm lead to the fact that during cryogenic transformation of the complex, in respect to the complex-composition mineral mass, the maximum content of quartz particles in the fraction 0.05–0.01 mm is reached; this fraction is the limit of the cryogenic fragmentation of this mineral. The process inevitably distorts the original distribution of heavy minerals by granulometric spectrum reducing their content in the fraction 0.05–0.01 mm, where

they are “substituted” with quartz grains and, thus, the maximum of the relative weight content of heavy minerals is shifted towards larger size fractions (see. Fig. 2, B2).

The established specific (non-sedimentagenous) nature of the distribution of the relative total weight of heavy minerals by the granulometric spectrum of mantle loess formations of the Bolshaya Zemlya tundra is one of the basic characteristics of the cryogenic eluvium (with a corresponding value of CCC) and proves that its high degree of particle-size sorting has cryogenic origin and is not associated with aeolian sedimentation, as stated in some publications [Astakhov, 2011].

Other features of the mantle loess-like loams of the Bolshaya Zemlya tundra are their close association with permafrost ground structures [Popov, 1958, 1962]; the micropolygonal microstructure of the mineral mass [Konishchev 1981] is even more convincing of the cryogenic eluvial nature of these formations. Primary, i.e., not redeposited, mantle loams have low thickness (up to 1.5–18 m), which generally corresponds to the thickness of the layer of seasonal thawing. The increased thickness (up to 3.5 m) is characteristic of inner depressions of the polygonal-block relief. However, there are no sedimentagenous features in the mineral composition, although the bands of peat and bog soils are sometimes present.

Under such conditions, mantle loams are the product of the nearest redeposition of cryogenic eluvium.

Mantle loams of the Bolshaya Zemlya tundra can be seen as a model for identifying the degree of participation of cryogenic factors in the formation of any of the types of loess material in different regions.

Along with the CCC parameter (see above), which specifically allows assessing cryogenic nature of mineral substances of the studied deposits, there is a need to introduce one

more index that can be called the index of heavy fractions.

It 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 sorting impact of aqueous or air environment on the formation of deposits or its absence, which means the principle influence of cryogenic fragmentation of light-fraction minerals, primarily of quartz, on the formation of loess deposits.

Application of the above-mentioned coefficients to the analysis of genetic nature of the “ice complex” of Northern and Central Yakutia, much of which is represented by loess deposits, has allowed us to establish the leading role of cryogenic fragmentation in the formation of mineral matter of these deposits.

We have isolated various facial-genetic types of loess-like deposits of the “ice complex” and, first of all, the products of the nearest redeposition of cryogenic eluvium, with certain values of the suggested indices, and deposits that are the products of redeposition of cryogenic silt in various dynamic conditions of the aqueous environment [Konishchev, 1981, 2013].

Mantle loams of the northern part of East European Plain represent the most northern part of the expanse of non-carbonate loess-like formations [Chizhikov, 1982]. To the south, they transition to low-carbonate loess loams that occur from the southern margins of the sod-podzolic zone. Further south there is a zone of carbonate loess loam and carbonate loess [Chizhikov, 1982].

Such a natural geographic association of different types of loess sediments is a good reason to consider them genetically related, which has been repeatedly expressed by many researchers, although they have put a different meaning in the genetic relatedness of these deposits.

N.I. Krieger in his fundamental study "Loess, its properties, and the connection with the geographical environment" [Krieger, 1965] quite rightly concluded that "since the area of distribution of loess is related only to the peripheral part of the territory of distribution of permafrost phenomena, ... one can reach the most probable conclusion that loess is confined to the margins of the periglacial (subarctic) zone and mainly to the temperate climate zone. Loess-like deposits are confined to the areas with more pronounced cryogenic phenomena associated with continuous permafrost" [Krieger, 1965, p. 24].

Somewhat generalizing the above formulation, it can be said that the area of distribution of loess, the whole range from the typical loess to non-carbonate mantle loess-like loam, almost coincides with the area of the Late Pleistocene cryolithozone. This pattern is most pronounced in Europe, North America, and Asia (Fig. 4).

Nevertheless N.I. Krieger [1965] is of the view that the typical loess is a subaerial formation, mainly of aeolian origin. This point of view is shared by many researchers and currently by [Velichko, 1965; Zykina, Zysin, 2012].

Within the East European Plain, thickness of loess formations increases from north to south; at the same time, their structure is becoming more complicated. As was mentioned above, in the far north, in the Bolshaya Zemlya tundra, the primary not re-deposited mantle loams have thickness of 1.5–1.8 m and have a single-tier structure, i.e., without layers of buried soils. Their thickness increases to the south, reaching 5–8 m, and even further, reaching 10 m and more. The loess structure becomes multi-tiered. Along with the increase in thickness of the loess layer, the complexity of its structure increases too; there is an increasing number of buried soils with soil complexes, which allowed the isolation of the loess-soil formation or the loess-soil sequence. Since alternating

Fig. 4. Distribution of loess, loess-like sediments and the modern Late Pleistocene Cryolithozone (compiled by V.N. Konishchev and N.A. Koroleva).

loess and buried soils horizons are further complicated by horizons of cryogenic structures (pseudomorphs of ice vein and initially-ground wedges), some researchers call these deposits the loess-soil-cryogenic formation [Velichko, 1965, 2004; Makeev, 2012]. The reason for the development of the latter is the paleogeographic predetermination of the off-glacier area of the East European Plain. This resulted in the alternation in the area of periods of loess accumulation, the formation of permafrost structures during cold phases, and the formation of soils during warm phases of paleogeographic development.

Thus the idea that loess is a component of the glacial (more precisely, cold) epochs became widespread; this loess formed as a result of synchronous processes of accumulation, mainly by air, of the predominantly aleurolitic mineral mass and of its transformation under the complex impact of the arid synlithogenic soil forming process and cryogenic weathering [Makeev, 2012; Zykina et al., 2012]. However, uncertainty remains: what is the decisive factor in the formation of the mineral matter of loess silt – aeolian accumulation or cryogenic weathering, and how they relate to the stadial lithogenetic sequence.

Of fundamental importance is the fact that the spatial consistency of the loess-soil series in watersheds and their significant thickness (up to several dozens of meters), should leave no doubt, according to some researchers, that the leading factor of accumulation of rather homogeneous silty loess horizons was aeolian accumulation.

However, there is evidence in the literature, casting doubt on the objectivity of the above picture of the conditions of occurrence of loess-soil series. Analysis of information on the conditions of occurrence of loess-soil series contained in large generalizations [Zykina, et al., 2012; Loess Deposits..., 1966; Makeev, 2012] leads to the conclusion that the most general law is that in the watershed areas of the East European Plain, as well as in the south of the West Siberian Plain, the loess

thickness varies from 1.5–2.0 m to 80 m and more; the thicker loess deposits occur mainly in depressions of the pre-loess relief.

This pattern is typical of the territory of Belarus, where large areas of loess deposits have thickness of 0.5–1 m. Within the Azov Upland watershed areas and the Bug-Dniester watershed, loess has thickness of 1–5 m [Loess Deposits..., 1966].

The most complete sections of loess in the Dnepropetrovsk region are in somewhat low areas of the faulted plateau. In Transcarpathia, in the areas of inclined piedmont plains, there is an increase in loess thickness in low parts to 15 m, sometimes up to 20 m [Loess Deposits..., 1966].

Most of the territory occupied by loess deposits includes gentle slopes and extensive river valleys and ravines. Loess deposits cover interfluvies and line the micro- and meso-relief, down to the valleys of rivers and streams, where they are gradually replaced by water-glacial deposits of high terraces [Makeev, 2012].

In Western Siberia, most of the areas occupied by loess deposits are slopes [Zykina et al., 2012].

Thickness of loess deposits usually increases from the central portions of interfluvies to the slopes of the main valleys.

In the descriptions of the specific sections of the loess-soil series, the authors [Zykina et al., 2012] have repeatedly pointed to the admixture of sand, gravel, and fine gravel both in the soil horizons and in the loess deposits.

Some authors [Zykina et al., 2012] show that in the layers of buried soils, hydromorphic soils formed under excess of moisture are often found as related genetic types.

All these features, in our opinion, indicate that loess-soil series were forming in depressions that were filling with aleuritic fine-grained soil,

often with an admixture of detrital material (gravel, crushed stone, pebble), coming from the nearest slopes. Recently, some researchers have directly written about paleo-incisions (buried forms of meso-relief) where thickness of the Late Pleistocene deposits (soil-loess series) reaches 10 and more meters in contrast to the upland sections [Sycheva, 2011].

However, in some places of the uplands, gentle hills are composed entirely of loess, which gives an impression of its mantle cover. Such cases are explained by the inversion of the relief in the period of its development after the accumulation of loess strata. Loess, having increased structural strength due to its carbonate content, in cases of catastrophically fast washing-out, when its long-term occurrence and subsidence are ruled out, is somewhat more stable compared, for example, with sandy strata. Thus massifs of loess can be isolated by fast erosion from the surrounding massifs composed of other loose sediment deposits and they can represent secondary (inversion) uplands.

HISTORICAL-GEOLOGICAL (FORMATIONAL) APPROACH TO THE ANALYSIS OF THE GENESIS OF LOESS DEPOSITS

The data presented above can be interpreted not only from the point of view that in the era of aridity and activation of the atmospheric circulation, the atmosphere was saturated with dust which was deposited and formed loess horizons that divided the buried soils.

It is logical to assume that this complex covering complex was formed as explained by the classical lithogenetic scheme set out in the fundamental work of N.M. Strakhov [1962].

With regard to the theoretical scheme of sedimentation staging by N.M. Strakhov [1962], specific formational stages of loess, as a result of permafrost lithogenesis, look like the following: cryogenic weathering of the original source rocks (moraines, fluvio-glacial, alluvial) in the layer of seasonal

thawing and the formation of primary not redeposited mantle loess loasm, up to 2–2.5 m in thickness; transfer of cryogenic aleuritic fine-grained material along slopes and its partial deposition even during transport into local depressions; and, finally, flow of cryogenic aleuritic fine-grained material into large depressions of relief (paleo-incisions, lacustrine basins) and footslopes. This is also evidenced by the dependence of the CaCO_3 content in loess and loess-like deposits on the terrain [Krieger et al., 1965, see below].

Cryogenic processes (cryogenic weathering, solifluction, cryogenic creep, frost cracking that causes primary ground veins, repeated ice wedges that later melt down during warm phases and turn into pseudomorphs) play the leading role at all stages of the formation of loess deposits. During Pleistocene, cryochrons and the corresponding stages of cryolithogenesis alternate with thermochrons that correspond to the stages of soil formation, which ultimately leads to the formation of loess-soil series.

The leading role of cryogenic processes in the formation of loess deposits of the cryolithozone, including, the unique strata of the ice complex in North and Central Yakutia, which is essentially a cryogenic version of the loess-soil series, has been demonstrated in several studies [Gravis, 1969; Zubakov, 1966; Konishchev, 1981]. Two lithological criteria for assessment of the degree of involvement of cryogenic processes in the formation of not only loess-like strata of the modern cryolithozone, but also for analysis of the mineral substances of loess strata in general, have been suggested to prove the cryogenic nature of mineral matter of these deposits.

INVESTIGATION OF THE COMPOSITION OF LOESS DEPOSITS WITHIN THE PLEISTOCENE PERIGLACIAL ZONE

To date, studies that use the technique described above within the Pleistocene periglacial zones have not been carried out. The exception, perhaps, is a special study of

paleocryogenic structures (pseudomorphs, ground veins) and the microstructure of the mineral mass [Velichko, 1965; Zykina, 2012], which, however, the authors do not connect specifically with the genesis of the aleuritic mass of loess deposits.

Nevertheless, there is some evidence pointing to the prospect of the use of specifically cryolithological analysis of mineral substances of loess deposits within Pleistocene cryolithozones.

Even today, the data by S.S. Morozov [1949] on the chemical and mineralogical composition and properties of different-size fractions of loess in the Dnieper region and genetically close deposits, remain unique. Table 2 shows some parameters of the composition of loess and other types of cover deposits from five locations of the East European Plain. Unfortunately, four samples were taken from the surface, 2.5 m deep, layer and only one (Mstislavsky loess) was taken from a depth of 3 m. Therefore, the interpretation of the composition has to consider the influence of the Holocene and modern soil processes that lead to "loess removal" and the destruction of cryogenic evidence [Golovanov, Verba, 1998]. Four samples from the mantle formations exhibit non-sedimentogenic distribution of the heavy fraction weight. This property, typical of cryoeluvial formations, is also associated with the interformational Paleogene crust of weathering of sedimentary deposits. It can be assumed that the anomalous, in terms of sedimentogenesis, distribution of the heavy fraction is associated with the eluvium of sedimentary deposits in general. Taking into account the environment of occurrence of the samples analyzed by S.S. Morozov, this parameter may reflect the general manifestation of the supergenesis factors. And only in a sample of the Mstislavsky loess, one can specifically link the anomalous distribution of the heavy fraction with the Pleistocene cryogenesis because it lies at the depth of 3 m, which apparently excludes, in these conditions, a significant influence of the modern soil processes.

Mineralogical analysis showed enrichment of the fraction 0.05–0.01 mm with quartz compared with larger grains in the samples of the Mstislavsky and Tula loess loams, i.e., in the most northern points of the investigated area. When interpreting the values of the quartz-feldspar ratio in various-size fractions, one also needs to consider the possibility of the influence of the supergenesis processes imposed later, which could have changed this ratio. In the sample of the Mstislavsky loess (depth of 3 m), the distribution of quartz and feldspar in two size-fractions corresponds to that of the cryogenic. In other samples, this parameter characterizes a non-cryogenic type of supergenesis, which can be explained by the influence of the modern soil-forming processes.

More definite results were obtained in the study of the composition of loess-like loams and underlying sediments from the city of Roslavl area, 100 km to the east of the area where S.S. Morozov collected the Mstislavsky loess. A.A. Velichko [1961, 1965] and T.P. Kuznetsova [1976] described there thick wedge- and related mantle formations of the Late Pleistocene cryogenic epoch, similar to polygonal structures of other regions of the paleocryogenic area and various locations of the modern permafrost tundra of Bolshaya Zemlya, Central Yakutia, and other regions. [Popov, 1958a, 1962].

According to T.P. Kuznetsova [1976], in the quarries of a brick factory located within the extensive depressions of relief near the city of Roslavl, the super-moraine layer of sediments is clearly divided into two parts: the lower one is subaqueous, composed of blue-gray loam with plant residues; the upper one is subaerial, composed of light gray and light brown homogeneous loess loam. In subaerial-subaqueous layer, there are thick wedged-shaped structures of a two-tier type. The lower and narrower ends of the veins are manifested very distinctly; they are wedge-shaped and are located in the subaquatic horizon. The upper broad structures that open at the surface "dissolve" in the layer of loess-

Table 2. Selected parameters of composition (%) of different fractions (mm) of loess on the Russian Plain

Deposits, Region	Depth, m	Granulometric composition (without removal of carbonates)						SiO ₂ content in carbonate-free samples		Yield of heavy minerals		Ration of quart to feldspar contents	
		1–0.25	0.25–0.05	0.05–0.01	0.01–0.005	0.005–0.001	<0.001	0.05–0.01	deposit in general	0.25–0.05	0.05–0.01	0.25–0.05	0.05–0.01
Penza cover clay reddish-pale, rich with car- bonates; N 52°50'	1.44–1.54	0.40	2.35	17.12	29.86	4.49	45.09	83.40	66.01	0.17	0.08	3.319	3.284
Tula loess loam, pale, with red- dish shade; N 53°30'	2.0	0.06	2.76	42.78	26.06	4.80	23.18	86.47	73.64	traces	0.13	3.424	3.595
Priluky loess, pale, porous; N 50°30'	1.8–1.9	0.05	5.42	57.44	21.28	1.44	13.67	89.11	83.23	0.62	0.08	4.503	4.319
Mstislavsky loess, pale; N 54°30'	3.0	1.97	11.47	49.00	22.91	3.91	10.43	85.53	79.17	0.21	0.02	2.144	3.51
Trubachev loess, pale, porous; N 52°30'	2.5	0.23	9.38	67.47	11.98	2.01	8.52	88.28	85.06	0.13	0.08	6.129	4.030

Note: Bold font is for the values that, in the author's opinion, indicated cryogenic nature of the mineral matter of the studied loess samples.

Fig. 5. The character of differentiation of the mineral substances of loess and other types of deposits uncovered in the city of Roslavl area:

A – wedge-shaped structure of loess loam (sketch by A.G. Kostyaev: 1 – brownish-yellow loess; 2 – pale loess with spots of ooze; 3 – light green loess with spots of ferrugination; 4 – light-green loess; 5 – brownish-gray loam; 6 – brownish-blue-gray loam with tubular iron concretions; 7 – sand; 8 – moraine sandy loam, reddish-brown; 9 – depth of sampling.

B – granulometric composition: *a* – of brownish-yellow loess (depth 3.1 m), *b* – of light-green loess (depth 4.2 m); *c* – of inclosing subaqueous loam (depth 3.6 m). For legend, see Fig. 1.

like sandy loams that fill the whole structure and change the color to gray or pale green at the bottom of the wedged-shaped part. The two-tier type of the structures, according to T.P. Kuznetsova [1976], can be attributed to their original ground type and reflects the contact of the two horizons of cryolithogenesis, i.e., permafrost and the layer of seasonal thawing.

Fig. 5 presents a sketch of a typical structure in one of the quarries of the city of Roslavl. A.G. Kostyaev kindly provided us with some samples of the main types of deposits of this cross-section.

The lower, subaqueous horizon of the mantle layer (3.6 m) has clearly sedimentary features, i.e., the yield of the heavy fraction is maximum in the finest grains of the sandy-aleuritic range (Fig. 5). The values of quartz, feldspars, and the quartz-feldspar coefficient in the fractions of 0.05–0.01 and 0.05–0.1 mm indicate the cryogenic type. CCC here is 1.2, while $K_{h.f.} = 1.1$.

Loess-like deposits in the upper and lower parts of the relict cryogenic structure are more uniform in terms of mechanical composition, especially due to the decreased content of the finely dispersed (< 0.005 mm) particles; the content of the large-aleuritic fraction increases by 25–30 % compared with the subaqueous loam. Despite greater uniformity and particle-size sorting of the loess-like sandy loams, the distribution of the heavy fraction by the granulometric spectrum is reversed, i.e., it is clearly non-sedimentary. $K_{h.f.} = 0.6$ и 0.4. There is a clear trend in the distribution of the main deposit-forming mineral components (quartz, feldspars). In the pale-yellow loess-like sandy loam (depth 3.1 m), the quartz content consistently increases from the fraction 0.25–0.1 mm to the fraction 0.05–0.01 mm, as well as in the upper horizon of the most homogeneous loess-like formations of the Bolshaya Zemlya tundra.

However, it should be noted that in general contrast of the contents of the minerals listed above in the comparable-size fractions is

slightly lower compared with the loess-like formations of the modern permafrost.

The reason is the large initial degree of weathering of feldspars in the source deposits in the city of Roslavl area (the taiga zone) compared with the parent rocks of the mantle loess-like formations of the Bolshaya Zemlya tundra.

More specific results, indicating a decisive influence of cryogenic weathering on the composition of loess-soil series, were obtained from the Nikitino and Suvorotino sections (Fig. 6). Loess and buried soils alternate in the sections. Cryolithogenetic analysis of the sediments in the Nikitino section showed the following (Fig. 7). In the modern soil, CCC is 0.51. In the underlying loess horizon (loess II + III according to Velichko [1961]), CCC reaches 1.4 in the upper part of the horizon, decreasing to 1.08 at the bottom. In the underlying buried soil, presumably Bryansk [Velichko, 1961], at a depth of 370 cm, CCC is smaller than 1 (0.59). Further down the section of loess I, CCC is greater than 1 (1.31). In the underlying lacustrine sediments, CCC is 1.08 in the middle part of the layer; at a depth of 610 cm, CCC is 1.06.

Fig. 6. Location of the Nikitino and Suvorotino sections.

In the Suvorotino section, there is the upper layer of modern soils with two horizons of loess and two horizons of buried soil below – the Bryansk and the complex Mezensky soil body [Velichko, 1961, 1965].

In the modern soil, CCC ranges within 0.59–0.63. In the underlying loess II + III at the

Fig. 7. CCC values of deposits of the loess-soil series in the Nikitino (A) and Suvorotino (B) sections. The explanation is in the text.

1 – modern soils; 2 – loess-like loam (loess II + III); 3 – buried soil; 4 – loess-like loam (loess I); 5 – silty sand with lenses of gravel; 6 – CCC values.

very top of the horizon and directly below the modern soil, CCC is 0.38; further down, at a depth of 140 cm, CCC reaches 1.23. In the Bryansk soil, CCC in the upper part is 0.44, while in its lower part at the contact with loess I, CCC is 1.12. In the underlying horizon of loess in its middle part at a depth of 300 cm, CCC is 1.2. In the Mezensky buried soil body, CCC decreases sharply to 0.35 in the upper part. However, in the very bottom part of the Mezensky soil body, probably at the boundary with the underlying loess that was not revealed in the section, CCC increases to 1.45.

These data show that the CCC parameter rather clearly reflects the role of cryogenesis in the formation of loess horizons and its absence in the phases of formation of buried soils. These data agree well with the conclusions of paleogeographers on the course of the natural process during formation of loess-soil series in the center of the East European Plain. Unfortunately,

in the examined sections, determination of the coefficients of distribution of the heavy mineral fraction was not conducted as it has been done for the section in the Rostov region (see above). This would have also allowed drawing definite conclusions about sedimentation environment of the loess horizons formation.

Analysis of individual samples of loess sediments of the periglacial areas of Central Germany (near the section in the Lengenboden region, to the south of Berlin) also showed promising prospects of cryolithological analysis of mineral matter in the territory of the periglacial zone of Western Europe [Konishchev, Rogov, Lebedeva-Verba, 2005].

Chinese permafrost scientists [Guoqing Qiu and Cheng Guodong, 1995] have successfully used the CCC method to determine the altitudinal limit of the cryolithozone in the Chinese Tien Shan during the late Pleistocene cryochron, by collecting samples of loess at different altitudinal

levels. The CCC values were greater than 1, starting from a height of 2100 meters, which is 1,000 meters lower than at present.

GENESIS OF THE CARBONATE CONTENT OF LOESS DEPOSITS

A characteristic feature of the typical loess is its high carbonate content, which defines a number of specific properties of these deposits, especially the ability to maintain the vertical wall in the outcrops and subsidence at wetting.

First of all, there is a question about the sources of carbonates in loess. There are a large number of views on this account in the literature, whose analysis is provided in the work of N.M. Krieger [1965]. In our opinion, the closest to the correct understanding of this problem, are the authors who believe that the source of carbonates in loess is the original rock, whose minerals provided the basis for the formation of the composition of loess. This is evidenced by the fact of a joint presence in loess of both primary clastic and secondary chemogenic carbonate. And these are not the exceptional cases, but practically a rule, which follows from the analysis of the fundamental generalizing works [Loess deposits..., 1966; Loess cover..., 2001].

The process of transformation of primary carbonates in the original source rocks (dissolution and migration of the hydrocarbon solution) and precipitation of secondary carbonates in the course of the modern loess forming process in the alpine steppes of inner Tien Shan was well described by A.G. Chernyakhovsky [1966].

Something similar was happening during the formation of the typical loess in the periglacial zone in the Pleistocene cryochrons.

Cryogenic process played also a certain role. Table 1 indicates that the process of multiple alternating freezing-thawing cycles leads, in moist conditions, to the almost complete disintegration of the original 0.25–0.1 mm carbonate grains into fine sandy and clay particles, 0.005–0.001 mm in size.

Under natural conditions, this process significantly increases the rate of dissolution of primary carbonate particles. A.G. Chernyakhovsky [1966] indicates that different areas of modern loess formations are in harsh climate – the winter temperature is $-38 \div 40$ °C and the summer temperature is rather high, up to + 30 °C. In summer, night frosts are frequent, when 15 cm thick ice forms on lake surfaces. In swampy areas, permafrost is developed. Naturally, the rest of the area has seasonal and short term freezing, which, we believe, contributes to the disintegration of the original bedrock, including destruction of carbonate grains in the latter rocks to a powdered state, which contributes to a more rapid dissolution.

The content of carbonates in loess of the East European Plain and the southern regions of Western Siberia ranges from the first fraction of a percent up to 15–20 %. Fluctuations of the carbonate content are observed not only over the vertical profile of loess, largely depending on the buried soils, but also horizontally, depending on the terrain.

B.B. Polynov [1952] has already emphasized geomorphological localization of loess carbonate as the accumulative (*underlined by the author, V.K.*) weathering crust. It lies on the cleaved surface area above the chloride-sulphate accumulative weathering crust and below the area of sialite weathering. This law has been established by B.B. Polynov [1952] for the mountain areas of the Kenteya and Khangai territories. The summarizing work of N.I. Krieger [1965] gives examples of the content of CaCO_3 depending on the relief not only for the mountain areas, but also for plains, although the data are limited and require further study of this problem.

Cryogenic processes have contributed not only to the disintegration of the primary carbonate to a fine state, and thus, their dissolution, but also to the formation of several generations of authigenic (secondary) carbonate minerals that precipitate out of solution in the process of freezing of loess sediments, as observed in the syncryogenic

Pleistocene sediments of Northern Yakutia [Kurchatov Rogov, 2013].

According to some researchers, the formation of the typical (carbonate) loess was occurring in the Pleistocene periglacial areas, in cold steppes [Krieger, 1965; Chernyakhovsky, 1966]. The hydrothermal conditions of the loess layer were largely determined by cryogenic processes (alternate freezing and thawing) and allowed the movement of calcium solution by ground and soil water and its precipitation in the form of new formations and secondary carbonate [Rozanov, 1952; Krieger, 1965]. In Holocene, the carbonate content of the typical loess has been preserved as the northern boundary of the typical loess is close to the northern boundary of steppe and forest-steppe, and the Pleistocene soils buried in loess of the semiarid zones are similar to the modern soils [Krueger, 1965; Zykina, 2012]. To the north of this boundary in more humid conditions of the periglacial zones, there are non-carbonate or low-carbonate loess deposits; in these regions, the processes of leaching were occurring more intensely.

CONCLUSIONS

1. The proposed lithological criteria (the coefficients of cryogenic contrast and of the heavy fraction) allow distinguishing the genetic nature of the particle-size distribution of loess deposits, whether it is a product of cryogenic weathering or aeolian sedimentation.

Thus, in hydromorphic conditions of relief depressions and on footslopes, there was

accumulation of secondary carbonate during cold phases of the loess-soil series formation. During phases of relative warming, decrease in the input of cryogenic melkozem and retardation of soil formation, there was partial or complete leaching of CaCO_3 along with partial disturbance of the cryogenic distribution of quartz and feldspars by granulometric spectrum. To the north of this boundary in more humid conditions of the periglacial zones, non-carbonate or low-carbonate loess deposits are common; there, the processes of leaching were occurring more intensely.

2. Wide application of these criteria to the study of the genetic nature of loess non-carbonate deposits (mantle loam of the northern part of European Russia, Western Siberia, and the ice complex of East Siberia) of the current cryolithozone, where evidence of the Pleistocene periglacial areas remained, made it possible to establish the cryogenic nature of mineral matter of these deposits.

3. Within the typical carbonate loess area, analysis of the genetic nature of their particle-size distribution using the proposed criteria have not yet received wide application. Nevertheless, the data provided in this paper on the composition of loess in different areas (center of the European part of Russia, Tien Shan) indicate its cryogenic nature. Certainly, further research with methodological positions proposed in this paper is necessary; it would reveal areas of loess of both the cryogenic nature of its mineral matter and sedimentary origin, including aeolian. ■

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