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CRYOGENIC PROCESSES AND FORMATIONS

IMPRINTS OF CRYOGENIC PROCESSES IN LOESS RECORD

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Analysis of mineral material in terms of cryogenic control on deposition has been tested with samples from two loess sections and found advantageous. Cryogenic fine material and products of its redeposition can be identified using special criteria related to mineral grain sizes. Cryogenesis left imprints in sediments deposited in the conditions of both perennially and seasonally frozen ground in the Pleistocene. Cryogenic processes controlled the composition and properties of thick loess layers.

Loess, cryogenesis, silt fraction, permafrost, seasonal freezing

INTRODUCTION

Loess-soil sequences composed of alternating loess and paleosol layers occupy large areas in the Pleistocene periglacial zone. They are often interpreted as a record of the Pleistocene climate history, with biogenic deposition and soil formation during warm interglacial and interstadial periods and loess deposition during cold stages. Note that the extent of permafrost was larger in the Pleistocene than now.

Loess deposition is commonly attributed to active atmospheric circulation and aeolian sediment transport in cold continental climates [*Kriger, 1965; Sergeev et al., 1986*], when the amount of dust suspended in air was over 30 times greater than during warm interglacials. High contents of fine silt particles were observed in Late Pleistocene ice layers from Greenland and Antarctica ice cores. However, the high relative percentages of mineral fraction in glacial intervals may also result from reduced snow precipitation during formation of ice layers rich in mineral particles under very strong cooling (indicated by stable isotopes in ice).

Another important point is that atmospheric circulation during the last glacial maximum (LGM) should be assessed separately for winter and summer seasons. As shown by modeling of air circulation dynamics in response to changing ice sheets [*Lofverstrom et al., 2014*], mean seasonal wind velocities were especially high in winter. In summer, the skies above periglacial territories were clearer and the weather was anticyclonic, with a warm anomaly near the surface. Thus, aeolian deposition almost stopped in summer, despite the favorable conditions of a snow-free surface and soil exposed to air.

The aeolian origin of loess would be supported by its uniform silt grain-size composition explained by sorting during distant transport of air-borne mineral particles at heights up to 3 km above the surface and their subsequent deposition. According to *Zeuner* [*1959*], this origin of loess is evident from its comparison with the modern aeolian dust (see grain size compositions of different types of silt deposits in Fig. 1 borrowed from the cited publication). Aeolian dust collected on snow after a dust storm within Wroclaw city (Fig. 1, *a*) is very similar in size to typical loess (Fig. 1, *d*, *e*), but it is also similar to fine solifluction deposits from Svalbard (Fig. 1, *b*) which most likely result from frost weathering, while the glacier-derived aeolian dust particles are coarser (Fig. 1, *c*).

Micromorphology of quartz particles would be another line of evidence for the aeolian nature of loess. Almost all quartz grains 0.5–1.0 mm in size, or less often 0.5–0.25 mm, are rounded and have rough pitted surfaces produced by mechanic effects during air transport, as well as by periodic freezing (cryogenesis) [*Timireva and Velichko, 2006*].

The origin of 0.05–0.01 mm particles (loess or coarse silt fraction) and coarser grains (0.10–0.05 mm), which jointly make up to 70–80 % of loess volume, is of special importance.

In soil and permafrost sciences, it has been known since long ago that multiple freezing-thawing cycles in sands, bouldery clay silt, etc., destroy particles larger than 0.25 mm and maintain the deposition of 0.05–0.01 mm silt. This fact stands behind the cryo-eluvial origin of loess and its properties [*Sergeev and Minervin, 1960; Popov, 1967; Sergeev et al., 1986*].

The role of frost shattering in loess formation was noted for the first time in 1882–1889 by Wood (cited after [*Kriger, 1965*]) who inferred it to form outside ice sheets, in permafrost, during seasonal thawing, sliding, and slumping of upper soil layers. The displaced fine products of frost-induced mechanic weathering accumulated in topographic lows. Wood interpreted such deposits as loess for Europe and North America, but did not extrapolate the view to the thick loess of China. His hypothesis was criticized as it failed to explain some important properties of loess (e.g., its carbonate chemistry).

Nevertheless, the occurrence of loess mainly within the Pleistocene periglacial zone was confirmed and specified in later studies [*Kriger, 1965; Konishchev, 1981*].

The two processes responsible for the formation of the main 0.05–0.01 mm fraction of loess remained poorly discriminated for a long time: whether it resulted from aeolian differentiation of mineral material and its sorting in air or from cryogenic impacts on different rock types.

Years-long studies of loess deposits in northern Eurasia, including subaerial loess in the Bolshaya Zemlya tundra and northern West Siberia and the ice complex in northern Yakutia, as well as experimental studies of cryogenic stability of main minerals allowed us to suggest lithological criteria for identifying cryogenic fine material and products of its redeposition [*Konishchev, 1977, 1981*].

This became possible only when we found out that main loess minerals (quartz, feldspar, and micas) had different relative stabilities to mechanic weathering under cryogenic effects and under temperate and warm conditions. This general inference was specified for grain-size fractions of different minerals (quartz, feldspar, etc.).

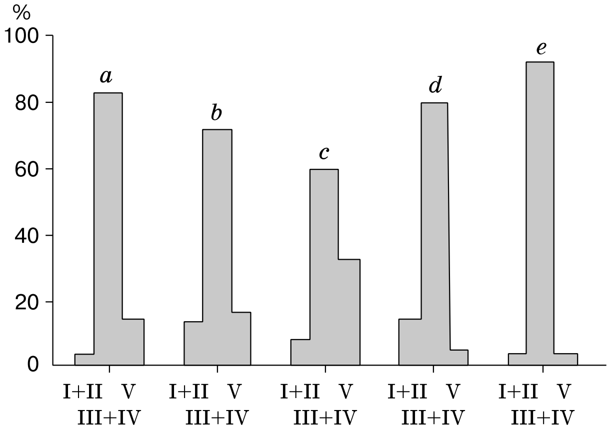


Fig. 1. Grain-size distributions in different types of silty sediments [*Zeuner, 1959*].

a: aeolian dust collected on snow after a dust storm, Wroclaw, Poland; *b*: banded solifluction soils, Svalbard; *c*: aeolian dust collected on a glacier surface, Svalbard; *d*: young loess Saint-Pierre-lès-Elbeuf, Seine-Maritime, France; *e*: Mesozoic (Triassic, Bretten) loess, Baden, southwestern Germany. Grain-size classes (mm): I + II – 0–0.01; III + IV – 0.01–0.07; V – 0.07–2.0.

This approach to experimental studies of cryogenic stability was first applied in [*Konishchev et al., 1976*] and confirmed by later experiments [*Minervin, 1982*]. Alternating freezing and thawing effects were found out to shatter quartz till the 0.05–0.01 mm fraction, while the feldspar grains that survived earlier shattering broke down into 0.10–0.05 mm particles. This difference is due to different thicknesses and properties of unfrozen water films adsorbed on the surfaces of mineral grains subject to cryogenesis [*Konishchev, 1981*].

Therefore, the maximum contents of main minerals in cryogenic eluvium and products of its most proximal redeposition form the descending grain-size series feldspar → quartz → heavy fraction minerals. This series is inverse with respect to that for sediments deposited in humid conditions of warm and temperate climates outside the zone of cryogenesis (Fig. 2) [*Strakhov, 1962*]. The maximum contents of minerals do not coincide within the domain of great-

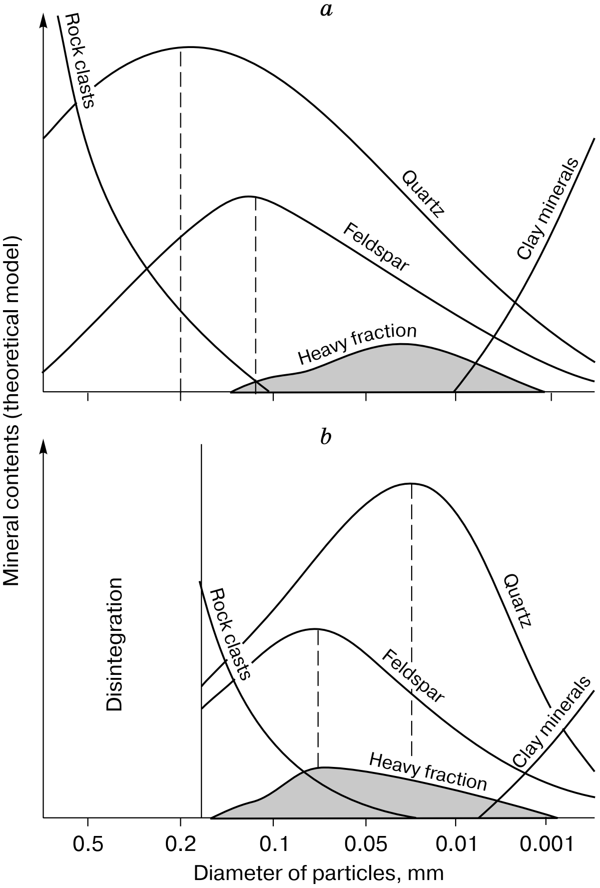


Fig. 2. Grain-size variations in minerals from fine-grained sediments deposited in warm climates (*a*) [*Strakhov, 1962*] and in permafrost (*b*) [*Konishchev, 1981*].

est mineralogical diversity, which is limited by 0.25–0.01 mm particles (Fig. 2). Thus, the grain-size distributions of minerals (mainly quartz and feldspar) within and outside the zone of cryogenesis are different.

Our studies of permafrost loess in the Bolshaya Zemlya tundra and in the ice complex of North and Central Yakutia show that reliable knowledge of cryogenic (climatic) and facies (genetic) deposition environments requires differentiated approach to analysis of sediments.

METHODS

We suggest to measure the contribution of cryogenic weathering to loess formation with a special coefficient we call *cryogenic contrast ratio* (CC). It refers to distribution of quartz and feldspar grains according to sizes or, more exactly, to the limit sizes of fractions accumulated during cryogenesis [*Konishchev and Rogov, 1994*]:

$$\mathrm{CC} = (Q_1/F_1):(Q_2/F_2), \tag{1}$$

where Q_1, F_1 and Q_2, F_2 are, respectively, the contents of quartz and feldspar in the 0.05–0.01 mm and 0.10–0.05 mm fractions. CC > 1 in sediments deposited in permafrost conditions and CC < 1 in those of warm and temperate climates, according to the model of *Strakhov* [*1962*].

In addition to the CC parameter as a proxy of cryogenic origin of minerals, we use another parameter as a proxy of sorting. It is the *heavy fraction ratio* (HFR) [*Konishchev, 1981*]

$$\mathrm{HFR} = \frac{\Sigma_{\mathrm{hm}}\, 0.05-0.01\,\mathrm{mm}}{\Sigma_{\mathrm{hm}}\, 0.10-0.05\,\mathrm{mm}},$$

or a ratio of weight contents of heavy minerals (Σ_{hm}) in two fractions (0.05–0.01 mm to 0.10–0.05 mm). It can discriminate between sediments sorted by water or wind during long transport (HFR > 1) and cryogenic fine sediments of eluvial origin redeposited by slope wash or proluvial mechanisms within short distances (HFR < 1).

The two ratios were applied to ice complex sediments in Northern and Central Yakutia, which largely consist of loess, and revealed that the greatest part of mineral material results from frost shattering [*Konishchev, 2013*]. In this study we classify ice complex loess according to origin on the basis of the CC and HFR ratios, especially the cryogenic fine fraction redeposited to short and long distances in different dynamic conditions in water.

The CC and HFR ratios were used previously to characterize loess-soil sequences within the Pleistocene periglacial zone of the East European Plain, outside the present permafrost conditions, and interesting generally positive results were obtained [*Konishchev et al., 2005*].

Below we present analysis of two loess-soil sequences from the southern margin of the European loess province (Beglitsa) and from the China loess plateau (Caoxian).

Minerals were identified by X-ray diffraction of 0.05–0.01 and 0.10–0.05 mm grains selected by sieving. The Beglitsa samples were analyzed at the Laboratory of Cryotraceology, Institute of Earth's Cryosphere (Tyumen), on a *D2 Phaser* diffractometer (by A.N. Kurchatova); the Caoxian samples were analyzed at the Subdepartment of Marine Lithology, Geological Department of the Moscow State University, on a *Dron* diffractometer (by D.G. Shmelev).

BEGLITSA AND CAOXIAN SECTIONS

The Beglitsa section is located at 47°07′ N, 38°30′ E, about 25 km west of Taganrog, in the northern side of the Taganrog Gulf of the Azov Sea (Neklinovka district, Rostov region), where the Beglitsa terrace deposits crop out over a distance of ~3 km in a bluff rising 16–17 m above the sea level (17.8 m the highest). The section exposes a sequence of late Valdai loess with buried soils of the Bryansk and Mesinsk pedocomplexes; the lower section consists of Late Khazar lagoonal-fluvial deposits.

The Caoxian section is located at 36°24′ N, 104°36′ E, about 50 km from Jinyuan district of Shanxi, in the middle reaches of the Huang He River. The sediments are exposed in a steep (30°) side of a gully, with a prominent terrace level in the lower part. The total section height from the plateau surface to the river bed is about 300 m. The section includes quite a uniform ~55 m thick loess layer. Loess is pale yellow to grey, locally brownish, with whitish carbonate encrustation along thin rootlet holes, punctuated with brown spots or layers. The sediments have uniform coarse silt grain sizes. Soils are absent from the section, except for some signatures of soil formation at depths of 11.5, 34.5 and 43.5 m (brown color and manganese stains). In this respect, the section resembles the so-called last glacial soil-free loess in the northern China loess plateau [*Zykina and Zykin, 2012*].

RESULTS AND DISCUSSION

We analyzed nine samples from the Beglitsa section and seven samples from the Caoxian section using the above approach (Fig. 3). The Beglitsa samples were uniformly distributed along the section (Fig. 3, *A*), some were from loss layers and some from soil complexes. All loss samples showed CC > 1 and HFR < 1, i.e., origin by frost shattering rather than by normal sedimentation. Thus, mineral material in the loess layers corresponds to typical cryogenic fine-grained deposits.

The results can be interpreted in more detail with reference to a relationship between CC and

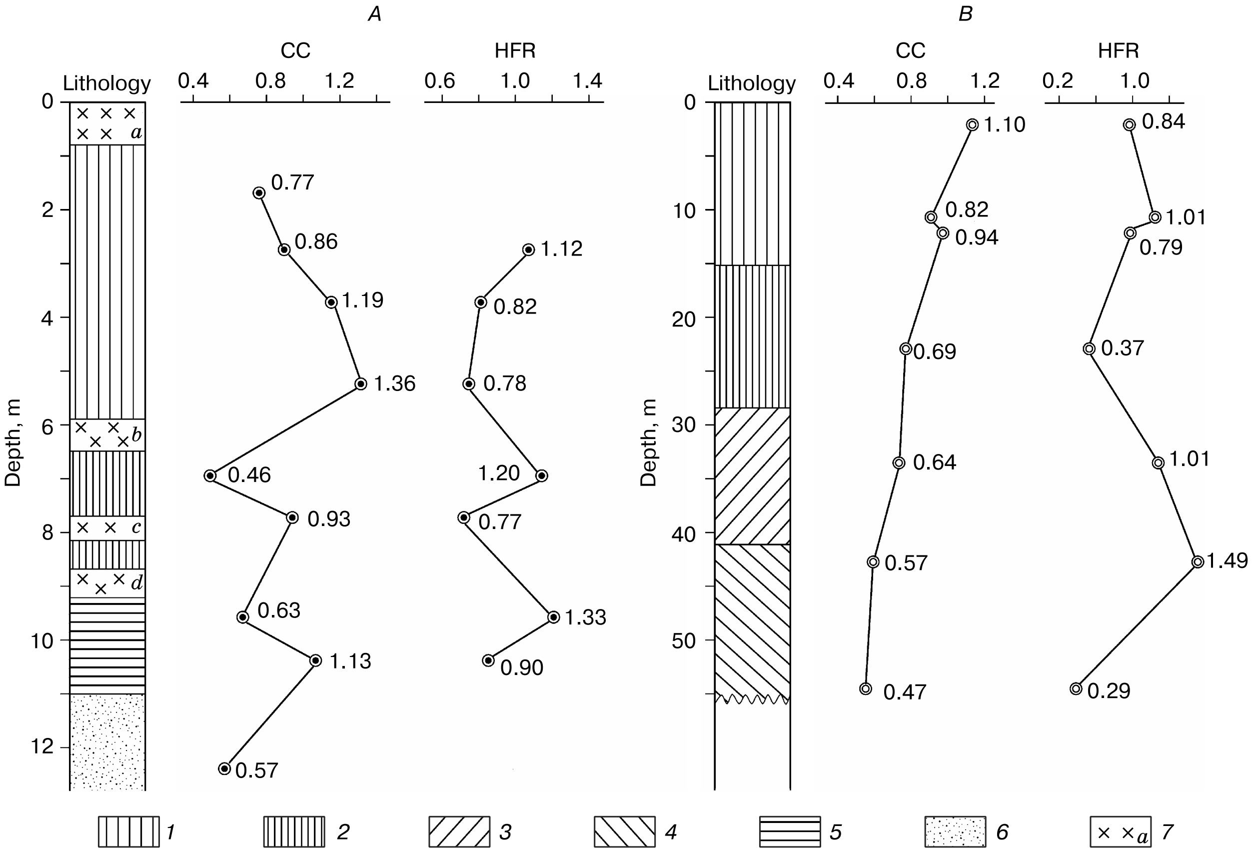


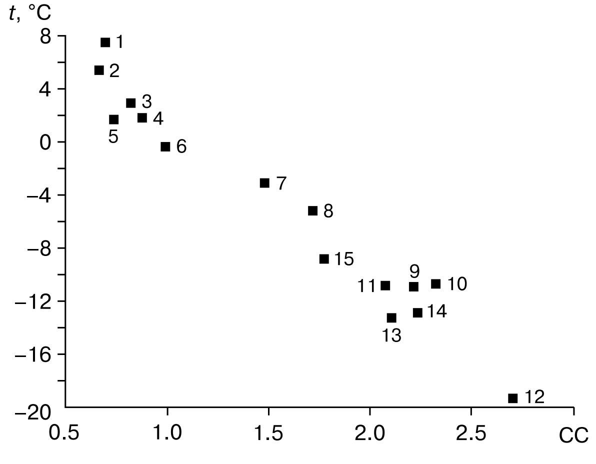
Fig. 3. CC and HFR ratios in Beglitsa (*A*) and Caoxian (*B*) sections.

1 – pale grey loess; *2* – light pale loess; *3* – grey-yellow loess; *4* – yellow-brown loess; *5* – grey-brown loessy silt; *6* – silty sand; *7* – soils: modern (*a*), Bryansk (*b*), Mesinsky, Krutitsky horizon (*c*), Mesinksy, Salyn horizon (*d*).

mean annual ground temperature (Fig. 4) [*Konishchev, 1999*]. The CC ratio is the highest (1.36) in the late Valdai loess above the Bryansk soil, which prompts the existence of thin high-temperature permafrost at that time. The lower CC ratio (1.13) during deposition of the middle Valdai loess indicates

Fig. 4. CC ratio vs. mean annual ground temperatures *t* at the depth 50 cm.

1 – podsol soil upon lacustrine-glacial deposits (Belarus, area of Minsk city); 2 – podsol soil upon moraine clay silt (Belarus, Poozerie); 3 – sod-podsol and podsol soils upon subaerial clay silt (southern taiga, Klinsk-Dmitrov ridge); 4 – podsol soil upon subaerial clay silt (middle taiga, area of Syktyvkar city); 5 – podsol soil upon subaerial clay silt (West Siberia, Laryk village); 6 – gley-podsol soil upon subaerial clay silt (northern taiga, Troitsk-Pechorsk city); 7 – peat-gley soil upon subaerial clay silt (southern tundra, Vorgashor village); 8 – peat-gley soil upon subaerial clay silt (Bolshaya Zemlya tundra, area of Vorkuta city); 9 – clay silt and shale eluvium (Yan-Omoloi interfluve, Kular ridge); 10 – tundra gley soil upon ice complex deposits (Indigirka River, area of Vorontsov Yar); 11 – tundra gley soil upon ice complex deposits (East Siberian Sea shore, Chukochiy Cape); 12 – eluvial-solifluction deposits (Pamirs, 6200 m asl, edge of firn plateau); 13 – eluvium of sand-clay shale (East Siberian Sea, Svyatoi Nos peninsula); 14 – eluvium of sand-clay shale (East Siberian Sea, Shirokostan peninsula); 15 – eluvium of sand-clay shale (lower reaches of Kolyma river).



sporadic permafrost. The samples from soils and layers below them do not show signatures of cryogenic origin in mineral material, possibly, because soil formation processes affected the original cryogenic grain-size distribution typical of loess.

In the lowest sand sample, transitional to lagoonal-fluvial deposits, the CC ratio is 0.57, which is evidence of deposition in a very warm climate.

Thus, the obtained data on the composition of loess layers in the Beglitsa section allow interpreting them as produced by cryogenic rework of primary sediments (most likely, lagoonal-fluvial deposits of the Khazar transgression), which were redeposited in subsided depressions of the multi-level delta. As the territory underwent subaerial evolution, the topography smoothened out, and the rough surface of lagoonal deposits became buried under the subaerial loess-soil sequence. This inference is consistent with geological data along the southeastern shoreline of the Taganrog gulf and the Don estuary [*Tesakov et al., 2013*].

The samples in the Caoxian section are from depths between 3 and 55 m. The CC values are distributed rather uniformly from 1.10 at the depth 3 m to 0.47 at 55 m (Fig. 3, *B*). The relationship of the CC ratio with mean annual ground temperature (Fig. 4) suggests that CC = 1.1 corresponds to conditions of sporadic permafrost, while CC = 0.9–0.6 record large seasonal frost depth and lower CC values indicate shallower freezing to 0.7–0.8 m.

The HFR values for the uppermost sample (HFR > 1 show a certain contribution of cryogenesis to deposition) correspond to non-sedimentological grain-size distribution of the heavy fraction. This is additional line of evidence for the cryogenic origin of mineral material in the sample. Some other samples (from the depths 12, 23 and 55 m) likewise demonstrate rather cryogenic control of the distribution of heavy minerals, which contradicts the idea of mostly aeolian origin of deposits at these depths. On the other hand, samples from depths of 11.5, 34.5 and 43.5 m, with soil formation signatures, have HFR > 1. Therefore, some processes during deposition within these intervals may have changed the cryogenic grain-size distribution of heavy-faction minerals.

The case of this section demonstrates that cryogenic deposition of fine material, which becomes redeposited within short distances to produce thick loess, is possible in regions of permafrost and seasonally thawed active layer, as well as in conditions of seasonal freezing.

Note that the conclusions are based on only seven samples, and extending the scope of research is required for better reliability. Nevertheless, cryogenesis obviously was an important agent in the Caoxian loess deposition. Aeolian deposition cannot be excluded in this case, though its role was inferior to cryogenic rework. Thus, there arises the question of the sediment provenance, which must have been not far from the loess plateau, given the large size of the latter and the previously presumed mainly aeolian deposition patterns [*Zykina and Zykin, 2012*]. The source area apparently provided sediment inputs during the last glacial maximum (LGM) when enormous masses of eroded rocks got into rivers through a system of valleys that dissected and drained the mountains. The shed material was carried by rivers and was deposited on valley sides producing loess plateau-type surfaces.

Cryogenic effects in the studied samples are evident also in grain morphology. Their signatures were revealed by *LEO 124* electron microscopy of sand-size (1.0–0.5 and 0.5–0.25 mm) particles in samples with high CC ratios (Fig. 5). They are, namely, angular

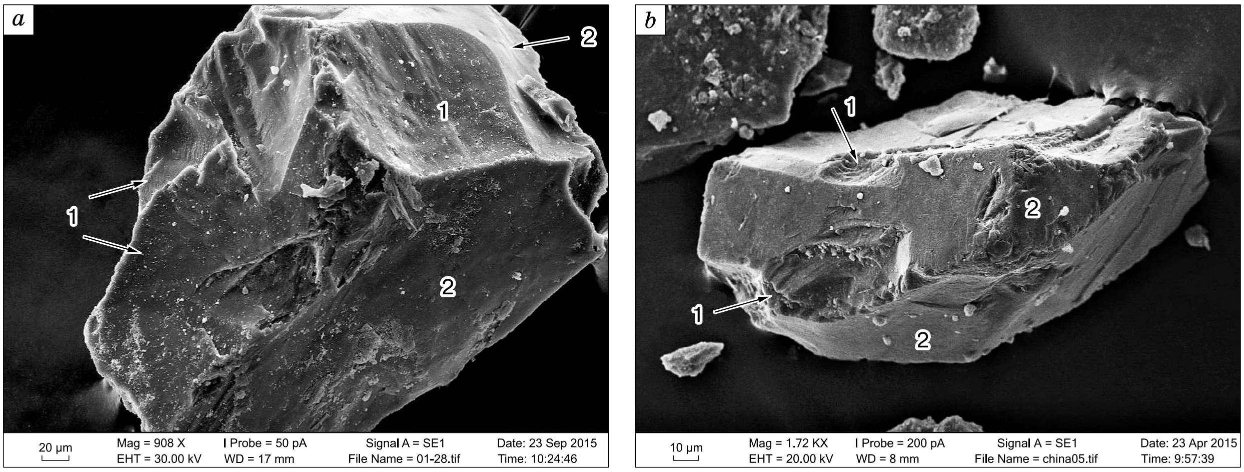


Fig. 5. Morphology of sand-size particles in loess from Beglitsa section (5.2 m below the surface) (*a*) and Caoxian section (3 m below the surface) (*b*).

1 – fresh conchoidal fracture; 2 – sites of polished and pitted (aeolian) surfaces.

shapes of grains, cracks, and chips very similar to those in present active layer samples from Canada, Svalbard, and Mongolia [*Woronko and Pisarska-Jamrozy, 2015*].

CONCLUSIONS

The reported studies of two loess sections have demonstrated the advantages of the chosen approach to analysis of mineral material. It allowed us to reveal a significant or even critical role of cryogenesis in the deposition of loess-soil sequences, especially in the Beglitsa section. The approach was also useful in the case of the Caoxian deposition, in which aeolian inputs cannot be excluded but cryogenic effects are evident. Thus, cryogenic rework affected sediments in conditions of both perennially and seasonally frozen ground in the Pleistocene, and led to the formation of rather thick loess layers.

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