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THE NATURE OF CYCLIC STRUCTURE OF THE ICE COMPLEX, EAST SIBERIA

ABSTRACT. The features of cyclic structure in the Karga-Sartan Ice Complex (IC) deposits in Northern Yakutia have been studied for the coastal lowlands. We have analyzed cycles of different genesis (cryolithological, structural, lithological, and soil-vegetation) and duration. Climate fluctuation was the major factor of cyclic structure in the IC deposits. Cyclic structure in the IC deposits develops in certain facial-genetic conditions characterized by cryogenic weathering and subsequent re-deposition of eroded soils in river valleys and alas depressions.

KEY WORDS: Ice Complex, cyclicity, content, mineralogy, weathering, soil, origin

INTRODUCTION

Over large areas of the plains and foothills of Eastern Siberia, are widespread deposits of the Ice Complex (IC) – a unique formation of ice-rich permafrost with polygonal-vein structure.

The IC of the Karga-Sartan period (50–40 to 11–12 thousand years ago) is particularly well-developed; it forms the surface of the so-called yedoma. The latter consist of isolated massifs and remnant hills separated by extensive erosion, thermokarst depressions, and river valleys.

In the early 1950s, the Institute of Permafrost of the USSR Academy of Science undertook a comprehensive study of these deposits in different regions of East Siberia, although quite a large volume of information had already existed in the XIXth and even the XVIIIth centuries. One of the first results of these studies was a conclusion on regular

cyclic or rhythmic structure of the IC. A.I. Popov [1955, p.21] wrote: “The general pattern in the structure of all... the ice and organic-mineral complex, appears quite clearly and reflects certain cyclicity and interdependence of its formation (*underlined* by V.K.).

In other words, the most general conclusion has been made: transit, i.e., traced consistently throughout the IC deposits, ice wedges and separating them blocks of frozen organic mineral deposits with segregation ice and ice-cement, both these IC elements, accumulated not in continuous conditions, but intermittently, irregularly, i.e., cyclically; “...a typical unistratal section of a block between two veins always ends with peat” [Popov, 1955, p. 20].

Besides, the cyclic accumulation of the organic-mineral component of the IC and of ice veins is interdependent: “...Deposition of sediments lags behind the upward growth of ice veins. For continuous growth of veins, deposition has to be continuously “catching-up” with the veins” [Popov, 1955, p. 21].

A.I. Popov considered sediment deposition the leading factor in the formation of the polygonal-vein system of the IC “... ice accumulation is an indirect consequence of sediment deposition within the polygons; ...deposition, in the literal sense, defines the entire mode of ice accumulation, conditions of formation, and thickness (vertical) of interstitial ice” [Popov, 1955, pp. 22–23].

Practically at the same time, Ye.M. Katasonov [1954] in his Ph.D. thesis gave a detailed description of deposits, cropping out in the

well-known outcrop Moose Khai (left bank of the River Yana in its lower reaches).

One of the main conclusions of this study was the detailed explanation of rhythmic, or cyclic, structure of the IC thickness, exposed in outcrop Moose-Khai. Ye.M. Katasonov wrote: "The structure of the valley deposits (in the opinion of Ye.M. Katasonov, V.K.) of Moose-Khai outcrop has two specific features: significant thickness (25–30 m) and, the most interestingly, the rhythmic nature."

"In the deposits, there are regular cycles (*underlined* by V.K.) formed by two or three lithological loose rocks (facies)" [Katasonov, 2009, p.79]¹.

At the base of each cycle, there is dark gray greenish ice-rich loam. Up the profile, it transitions to dark-brown peaty loess loam, which is gleyic in some places and has a lighter color. The latter have lower ice content; ice-cement or thin hair layers of ice dominate. The upper horizons are penetrated by threadlike roots of grasses.

Using outcrop Moose-Khai as an the example, Ye.M. Katasonov investigated the relationship of cryogenic structure and lithological facies of sediments and proposed a concept of cryogenic-facies analysis, which allows identifying both the nature of deposits freezing and their facies-genetic origin.

Yu.A. Lavrushin [1963] described a number of sequences of the IC outcrop in the low reaches of the Indigirka River. His detailed descriptions indicate clearly that the IC of these deposits has cyclic structure, though the author does not use this term and talks about alternating "series" and "bands" of deposits.

The Lavrushin's work [1963] completes the important stage of research on the IC. This stage is associated with search of the IC facial-genetic analogies of modern alluvial deposits. To a large extent, the work of

Ye.V. Shantser [1951] on the basic laws of the formation of thick alluvial formations provided the theoretical basis of the IC facial-genetic analysis.

THE ORIGIN OF THE IC DEPOSITS: CONSTRATAL-ALLUVIAL OR CLIMATIC?

The conclusion of the works of A.I. Popov [1953], Ye.A. Katasonov [1954], and Yu.A. Lavrushina [1963] was that the IC deposits are predominantly alluvial formations² formed by the constratal type and in predominantly negative tectonic movements. In the concepts of these authors, the cryogenic features of the IC, i.e., thick transit ice veins, segregation ice, deformation of layers, etc., represent some important features of the general process of sediments accumulation. Therefore, the concept of cyclic structure of the IC sediments means the alternation of different facies in the process of accumulation of thick alluvial strata and their syngenetic freezing.

Almost concurrently with the concept of the constratal mechanism of accumulation of the IC sediments due to the slow tectonic subsidence, there appeared another idea about formation of thick stratas of these deposits. N.A. Shilo [1964, 1971] pointed out contradiction that arises when attempting to apply the constratal mechanism for the entire vast geologically and tectonically diverse territory of the IC development. Indeed, it is difficult to assume unidirectional nature of synchronized tectonic movements in the territory from Alaska to Northern and Central Yakutia with the wide-spread IC deposits.

Thus, Ya.A. Lavrushin, contradicting to the constratal-tectonic concept that he shared, wrote: "Its extremely wide areal distribution (the IC of the Vorontsov suite, V.K.) indicates that its formation is attributed not only to such major rivers as the Yana, Indigirka, and Kolyma, but also to the network of small and

¹ This work was published as a monograph (Ye.M. Katasonov, 2009).

² These authors had different views on the facial conditions of the formation of the IC: according to A.I. Popov and Ye.M. Katasonov – floodplain facies; according to Yu.A. Lavrushin - near-channel and ice facies.

shallow rivers and streams ... the climate of the formation of the Vorontsov suite was very severe. This has led to intense frost weathering of rocks and transport to the rivers of a large volume of crushed fine-earth material. As a result, the relation between water flow and sediment transport to the rivers appears to have been such that the rivers were overloaded with sediments and the rivers' channels were segmented into many small branches and channels whose beds were rising due to the accumulation of material". [Lavrushin, 1963, pp. 139].

Not only depressions of the erosion genesis were filled, i.e., practically all erosion network from the valleys of large rivers to small valleys of rivers and creeks, but alas depression, whose area was comparable with the area of the erosion network itself, was filled as well.

We can point to many studies that indicate that during the phase of cold climate, in periglacial lithogenesis, subaqueous accumulation was replaced by subaerial (mainly slope). In the valleys of large rivers, thick strata of "periglacial" alluvium was forming [Ravsky, 1972]; in the valleys of small rivers and streams, alas valleys and depressions were being filled with slope and proluvial sediments; terraces were transforming into terrace-ridges, in the foothills, thick benches of slope sediments were forming [Dedkov, 1975; Brinks 1975; Gravis, 1981].

This implies that the IC deposits are genetically heterogeneous entities and represent paragenesis of many genetic types, united by the fact that they were formed in the harsh climate [Zubakov, 1966; Konishchev, 1981].

In the relation between sedimentogeneous and cryogenic factors, the latter play the leading role.

VARIETY IN THE IC CYCLIC STRUCTURE

Considering the overall climatic influence of the IC accumulation, it is feasible to assume that its cyclic structure is also climate-

dependent. In the syngenetic IC sediments, two types of cycles can be distinguished, which either coincide or not. The nature of lithologic cyclicity, first described in detail by Ye.M. Katasonov [1954], is treated by the majority of authors as narrowly sedimentogeneous [Popov, 1967, Lavrushin, 1963].

However, along with the lithologic cycles in the IC sediments, there may be isolated cycles and rhythms formed by cryogenic textures. Initially, the cryogenic rhythms were described by A.I. Popov [1967] who also suggested the mechanism of their formation.

Textural rhythms in syngenetic permafrost result from a certain ratio of sedimentation and cyclic changes in the depth of seasonal thawing.

The incremental increase of the permafrost thickness due to transition of the bottom seasonally thawed layer (STL) to the IC is not gradual but rapid and irregular, during the reduction of the depth of seasonal thawing. The latter is a function of the long-term climatic regime that determines the main factors affecting the depth of the STL (temperature, humidity).

The idea of textural cryogenic rhythmicity was developed by N.N. Romanovsky [1993] who stated that the STL depth depends mainly on changes of the amplitude of annual temperature variations on soil surface and the degree of hydration of this layer. Changes in the STL depth are due to fluctuations of average air temperature while soil plays a secondary role.

Facial-lithology cyclicity of the IC sediments is closely connected with the polygonal nature of the sedimentation surface, which in turn determines the water content of the surface and, therefore, the water content of the STL, its depth, and the differentiation of the vegetation cover. The nature of the polygonal relief is clearly reflected in the deformations of frozen deposits on contact

with ice veins. The degree of deformation of deposits varies in the IC series; the thickness of these series is usually 0.3-0.5 m. The series unconformably overlie one above the other and cut each other. The grain size composition of the sediments that form different series is identical, but the ice content differs significantly. The greatest deformation on contact with ice veins occurs in ice-rich aleurites with thick-schlieren and ataxitic-schlieren cryotextures. The aleurites with massive-, micro-, and fine-schlieren cryotextures are practically undeformed and in the contact zone with ice veins, cut deformed layers of ice-rich aleurites (Fig. 1)

Cyclic or rhythmic structure changes consistently down the profile of IC. This is expressed most clearly in the lower part of the IC. As a rule, in outcrops (Vorontsov Yar, Chukochee Yar), this sequence is not fully exposed and its thickness is about 5-6 m, however, in some cases it crops out completely, for example in Moose-Khai outcrop (the Yana River) where its depths is 14.7 m. This sequence has a distinctive greenish color. It is characterized by alternation in the vertical profile of strongly

deformed at contact with ice veins icy layers of aleurites with lenses of poorly decomposed peat that lies in the cores of ancient polygons, and of less icy and almost undeformed layers. Higher in the profile of the IC, the layer of greenish-gray aleurites, usually with clear contact, is covered by the layer of monotonous and very homogenous brown unclear laminated aulerite completely penetrated by vertically spaced roots of grasses. In general, the thickness has micro- and fine-schlieren cryotextures. The most important feature of the brown aleurites is the absence of deformations at contacts with syngenetic ice veins independent of the depth of the latter. The cyclicity in this layer is not expressed as clearly as in the lower greenish-gray aleurites. However, it also exists and can be traced either in the form of humus interlayers of buried soils or as alternation of the layers with massive- and micro-schlieren cryotextures. The thickness of the brown aleurites varies in different outcrops of the IC from 5–10 m (a site of Duvanny Yar outcrop, upstream the Kolyma River) to 25 m (a site of Chukochee Yar outcrop, downstream the Kolyma River). As a rule, the thickness of this



Fig. 1. The cyclic structure of the IC deposits. New Siberian Islands (Bolshoi Lyakhovsky Island). Photo by V.Ye. Tumsky

layer is 10–12 m. The layers of the brown aleurites of small depth (less than 1 m) (in terminology of Ye.M. Katasonov [2009] – loess loams) are separate cycles in the underlying thick greenish-gray aleurites.

Analysis of the spore-pollen data of the major key sections of the IC (12 sections in total) performed by T.N. Kaplina [1979] showed that the coastal lowlands of the Yakutia IC have two types of spore-pollen spectra. The first of them is with a significant role of tree pollen and, especially, of shrub-pollen (from 10 to 40% and more).

These spectra have been named “shrub” and interpreted as forest-tundra and tundra. The “shrub” spectra are similar to the spectra of the modern southern margin of wet tundra, however on average, the ancient spectra yield to the subfossil spectra in relation to the pollen content of trees and shrubs, i.e., they reflect slightly cooler conditions than the present.

The second type does not have modern analogies; however it reflects treeless and shrubless landscapes with predominance of grasses (steppe- tundra). They were named “grassy” and they reflect very harsh climatic condition of the time of accumulation of the enclosing deposits. T.N. Kaplina [1979] has concluded that the spectra of these two types are distinctly confined to certain cryolithological layers of the IC. The “shrub” spectra are characteristic of the lower parts of the IC sections composed, as a rule, by yellow-green ice-rich aleurites with deformed layers at contacts with syngenetic ice veins. The “grass” spectra are characteristic of the horizon of the brown ice-poor aleurites with massive- or micro- schlieren cryogenic textures without deformations at contacts with ice veins that lie in the upper parts of the IC sections. It is important to note that in outcrop Duvanny Yar (the right bank of the Kolyma River), the “grass” spectra are found also in some layers (cycles) of the lower part of the IC section. The same pattern is characteristic of the bottom horizon of the IC of outcrop

Moose-Khai, in the low reaches of the River Yana [Kondratyeva et al, 1976] where layers (cycles) with “grass” and “shrub” spectra alternate.

Thus, these data is a quite convincing argument in favor of the conclusion that the cyclic structure of the IC deposits is a result of climatic conditions, which in turn is determined by the cryogenic facial features of both isolated layers-cycles and their complexes – the layer of ice-poor brown and the layer of greenish-gray ice-rich aleurites.

The conclusion about the climatic origin of the IC cyclic structure is confirmed by the analysis of buried soils – a very characteristic component of these deposits [Gubin, Zanina, 2004]. On the territory of the Kolyma lowland, in the Karga period, there was repeated alternation of synlithogenic and epigenic pedogenesis [Zanina, 2006]. In complete sections of the IC, there have been found Early and Late Karga pedocomplexes. Epigenic peat and peat-gleyic soils formed in polygonal relief, when the flow of mineral deposit weakened, i.e., soils have recorded the final stages of the accumulation cycle. Hydromorphism of peaty soils indicates that the enclosing layers (cycles) have high ice content, and they are likely strongly deformed. The periods of synlithogenic pedogenesis, on the contrary, had intense sediment accumulation due to mineralization and humification of plant litter and dominance of detritus formation over peat accumulation. Synlithogenic pedogenesis, most likely, coincided with the accumulation of layers (cycles) of the brown aleurites with low ice content and the absence of deformation of the layers. The conclusion here is quite obvious: the cause of transition from syngenetic to epigenic formation was warming and not vice versa [Zanina, 2006]. Radiocarbon data indicate the following stages of the epigenic pedogenesis: 40, 37–35, 33–31, and 28 thousand years ago, which gives an idea of the duration of the individual cycles of the IC.

THE CYCLIC NATURE OF TRANSIT SYNGENETIC ICE VEINS OF THE IC

It was mentioned above that the first idea about the cyclic structure of vein polygons, i.e., both of rock blocks and enclosing syngenetic ice veins, was stated by A.I. Popov [1935]. As far as the cyclic structure of the latter is concerned, this issue has not been well studied. Recently, when isotope research on the composition of thick syngenetic ice veins became widely conducted, this problem practically dropped out of sight researchers. Meanwhile, in the literature there are enough specific data to understand the cyclic structure of syngenetic ice veins. B.I. Vtyurin [1975] based on the study of sections of vein polygons formed over thousands of years, has shown that, in the process of syngenetic growth, the veins not only slowed the upward growth and increased the growth sidewise, but periodically stopped growing. Discontinuity in the growth of syngenetic veins is a natural and common feature. The growth of veins, due to a combination of processes of cracks filling with water, its freezing, and squeezing up of ice [Leffingwell, 1915; Blaok, 1952; Konishchev, Maslov, 1968], outpaces sedimentation; ridges on the surface are formed. This, in turn, is the cause of interpolygonal small lakes and wetlands, which leads to destruction of ridges due to initial thermokarst and partial thawing of the upper parts of the ice veins. This process is manifested through the presence of lenses and interlayers of thermokarst-cave ice or soil at different depths of repeated wedge-ice.

Information about the structure of thermokarst-cave ice can be found in the works of P.A. Shumsky [1960], Sh.Sh. Gasanov [1969], B.I. Vtyurin [1975], G.E. Rosenbaum, et al [1978], and others. The participation of thermokarst-cave ice in the formation of powerful, transit, and syngenetic ice veins is not always easy to recognize, as this ice in the further growth of ice veins "is consumed" by ice of elementary frost cracks penetrating it from the top [Rosenbaum et al, 1978]. As a result, in the body of the veins there remain only

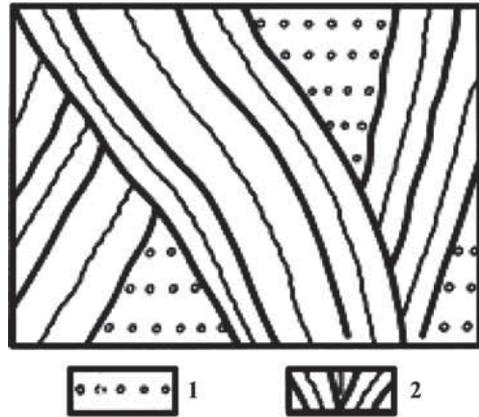


Fig. 2. Drawing of ice vein texture, Chukochee Yar (according to [Rosenbaum, et al, 1978]).

1 – thermokarst-cave ice; 2 – elementary veins

fragments of thermokarst-cave ice, which can be mistaken for ice of different genesis (Fig. 2).

The interlayers and lenses of thermokarst-cave ice in ice veins represents undeniable evidence of change of thermal and moisture condition on the surface of forming polygonal-vein structure. At the present time, it is not quite clear what interlayers of thermokarst-cave ice in the body of ice veins correspond to what layers (cycles) of soil blocks. On the one hand, the interlayers should correspond to the icy and highly deformed layers of the greenish-gray aleurites that reflect the conditions of the polygonal-ridge micro-relief with interpolygonal lakes that are the cause of the destruction of ridges and of the embryonic local thermokars in ice veins. However on the other hand, the cause of the local thermokarst on the polygonal surface could be associated with deeper seasonal thawing that took place during the accumulation of layers (cycles) of the ice-poor undeformed brown aleurite. At that time, soil moisture was greatly reduced, vegetation transformed from shrub to grassy, and peat-gleyic soils were replaced by humified interlayers. As a result, seasonal thawing increased, which could have led to the local thermokarst in depressions (ditches) of the polygonal relief over ice veins and the bounding ridges.

This issue requires further study.

THE GENETIC ORIGIN OF THE MAIN HORIZONS OF THE IC – BROWN AND GREENISH-GRAY ALEURITES

Speaking again about the genetic origin of the two main horizons of the IC (the upper ice-poor brown and low ice-rich greenish-gray) it should be noted that initially they were viewed as different facies of the genetically homogeneous layer of the IC, i.e., deposits of the riverine and inner zones of floodplain [Popov, 1953; Katasonov, 1954]. Proponents of the concept of the alluvial origin of the IC still adhere to this position. However, even Ye.M. Katasonov [1954] pointed out that the brown aleurites have a very homogenous composition (70–90% of fraction 0.1–0.01 mm) and a very small amount of sand fractions, while the greenish-gray aleurites are characterized by considerably more diverse grain-size distribution and include much more of sand fractions compared with the brown aleurites (Fig. 3).

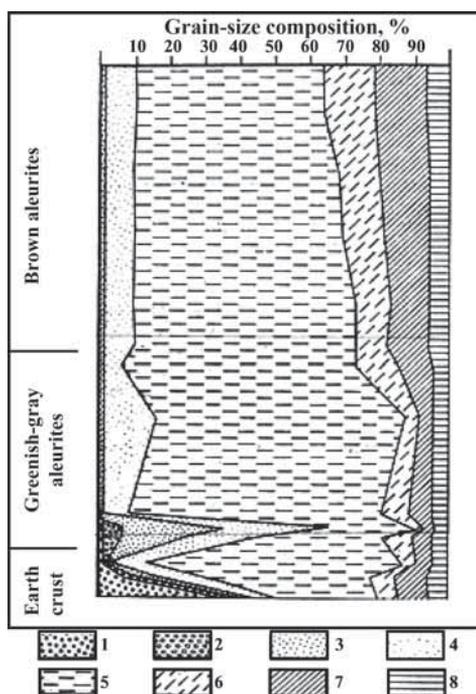


Fig. 3. The grain-size distribution of the IC sediments in the Yana-Omoloy interstream area.

Size fractions in mm: 1 – <0.5; 2 – 0.5–0.25; 3 – 0.25–0.1; 4 – 0.1–0.05; 5 – 0.05–0.01; 6 – 0.01–0, 005; 7 – 0,005–0,001; 8 – <0.001

Our research and data of other authors indicate that these differences are observed in other sections of the IC [Konishchev, 1981, Tomirdiario, 1980]. Inconsistency in the grain-size distribution on the one hand and the nature of the cryogenic structure between the layers of the brown and greenish-gray aleurites of the IC on the other hand, are not related to differences in facial conditions of sedimentation on the floodplains of major rivers, but to other causes. Another explanation is the idea of the primary aeolian genesis of the brown aleurites with the micro- schlieren cryotexture, which has being developed by a number of researchers [Tomirdiario, 1980, Gubin, 2002]. Recently, some researchers who adhere to the alluvial concept started to lean toward the aeolian genesis of these deposits [Kaplina, 2009] due to new data on entomofauna and seed and leaf flora that indicate sharply continental and dry climate with little snow in the Late Pleistocene. "It is more feasible to accept the aeolian processes in these conditions than the impact of large rivers and active slope discharge on vast territories" [Kaplina, 2009, p.170].

Let us consider in greater detail the arguments provided above and the features of the aeolian genesis of the brown aleurites.

Indeed, the brown aleurites, as in the form of the upper horizon of the IC and as isolated interlayers (rhythms) alternating with ice layers in the low horizons of the IC sections, appear by-sight to be very dry. Ye.M. Katasonov [2009, p.146] called these sediments "dry permafrost."

However, laboratory measurements of the moisture content of the brown aleurites have shown that its value in relation to the weight of dry soil reaches 80% and 40%–60% for micro- schlieren and massive cryotextures, respectively [Kondratyeva et al, 1976]. The results of an intriguing experiment are presented in the work of the authors who have being consistently developing the concept of the aeolian genesis of the aleurites with micro-schlieren

cryotexture [Tomirdiario, Chernenky, 1987]. A sample of such sediments with 40% moisture content collected in outcrop Oyagosky Yar was melted and then frozen as monolith in laboratory conditions. The freezing temperature is not specified. As a result, at the initial moisture content, there emerged “thick ice schlieres and laminated thick-schlieren texture formed” [Tomirdiario, Chernenky, 1987].

The authors attributed this to a low speed of aeolian accumulation (1–1.5 mm per year), resulting in the same annual rise of the active layer - the upper limit of permafrost. Therefore, with such a small increase in the permafrost layer, the formation of thick ice schlieres was not possible and the developing deposits had strictly micro-schlieren cryotexture. Weakness of this explanation is obvious. A.I. Popov explained this phenomenon; he indicated that the increase of the syngenetic frozen layer is a result of mutual processes of sediment accumulation and dynamics of the STL (see above).

We have given a different explanation of cryogenic structure of the brown aleurites with micro- and massive schlieren cryotextures [Konischev, 2002]. Analysis of the brown aleurite microstructure showed that ice-cement there belongs to the basal type. Weak differentiation and the mineral component of this layer at the sufficient moisture content and a rather favorable, for ice formation, aleurite composition is due to a very high speed of freezing ($4.5\text{--}5.0 \cdot 10^6$ m/sec) at which fixation of water in place was occurring. Obviously, these conditions are very common in extremely continental climate, where due to strong cooling during the polar night, temperature drops to -70°C and below. However, soil moisture was sufficient for the development of highly productive and abundant vegetation, as evidenced by numerous thin roots of herbs that penetrate the thick brown aleurite.

The general perception of many researchers is that during the accumulation of the brown

aleurite, a particular type of landscape – tundra, dominated; it had mixed flora and fauna of vertebrates and insects.

In contrast to the findings of most climate reconstructions of the time of accumulation of the brown aleurites and perceptions on steppe-tundras as cold landscapes with only tundra and even arctic deserts, the work of [Alfimov, Berman, 2004] has been developing a concept on conditions that provide for existence of the “steppe component.” Based on the analysis of fossil insects, the authors concluded that in most of North East Asia of the Sartan period, summer temperatures were higher than the modern temperatures in the tundra zone. According to [Alfimov Berman], 17–18 thousand years ago in the lower reaches of the Kolyma River, summer temperatures were $12\text{--}14^\circ\text{C}$, which is higher than the present that vary from $6\text{--}7^\circ\text{C}$ in the mouth to up to $11\text{--}12^\circ\text{C}$ in 100 m upstream.

Judging from the descriptions of various sections of the IC, the brown aleurites are characterized by abundance of plant residues in the form of thin fibrous roots of plants and presence of humus spots, sinters, and interlayers. This indicates a significant impact of soil processes on the brown aleurites. The carbon content there reaches 1.5% [Zanina, 2006].

As mentioned above, the contact between the layers of the ice-poor brown and the ice-rich greenish-gray aleurites is usually very contrast. Moreover, in some outcrops, it has typical characteristics of erosive nature (Fig. 4). Recently, there have been descriptions of deep, up to 20–30 m, gullies filled with the brown aleurites of the Sartan period in the low reaches of the Yana River and the southern bank of Bolshoi Lyakhovsky Island [Tumsky, 2012]. Thus, this phenomenon is regional.

The reason for this phenomenon is lowering of the sea level at the beginning of the Sartan period and, as a consequence, change of the basis of erosion [Tumsky, 2012]. Agreeing with this explanation, we should provide some clarification. Since the thickness

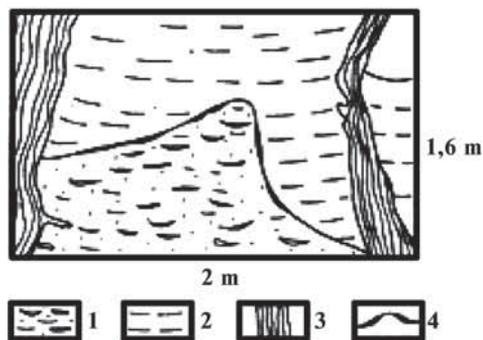


Fig. 4. The contact between the brown and greenish-gray aleurites in outcrop Duvanny Yar (the Kolyma River downstream):

1 – greenish-gray aleurites, icy, with lenticular cryotexture; 2 – brown aleurites, with micro-schlieren cryotexture; 3 – ice vein; 4 – contact between brown and greenish-gray aleurites, fixed by the interlayers and pockets of white porous firn

of the underlying Karga IC, similar to the horizon of the brown aleurites was formed in conditions of sea regression, the regression rate had surged prior to the formation of the brown aleurites and, most likely, was because of accumulation due to the glacial-ecstatic factor. Therefore, the cause of the erosion contact between the brown and greenish-gray aleurite is climatic. Besides, the landscape conditions changed dramatically and, in particular, the nature of the land cover. In the steppe-tundra landscapes characteristic of the time of accumulation of the brown aleurites, thermo-erosional processes were probably manifested more intensely than in shrub-tundra.

Many researchers, and especially soil scientists, isolate a special type of synlithogeic soils – cryopedoliths (Zanina). In the Sartan brown aleurite layers (outcrop Duvanny Yar, the Kolyma River), a small buried burrow, was found, which belonged to small rodents; it was filled with well-preserved bedding consisting of herbs. In the layers of the brown aleurites (cryopedoliths) in the underlying Karga layer of the IC, several buried rodent burrows were found [Gubin et al., 2001].

All this is undisputable evidence of the fact that summer temperatures did not prevent

but contributed to the spread of thermophilic steppe-tundra ecosystems and vegetation on the shelf during sea regression beyond the boundaries of the modern terrain; the temperature supported living conditions (food) not only for small rodents, but for larger representatives of the mammoth fauna. During the regression of the Arctic seas, the effect of the polar day significantly increased: thawing index (the sum of summer air temperatures) increased with strongly reduced cloudiness (now, in coastal areas, it is 65–70%) and the temperature effect of direct solar radiation increased as well.

Thus, hygrothermal conditions of the summer period provided for the formation of a continuous grass cover and a rather powerful soil horizon.

Compared to the current conditions, the prevalence of open landscapes of steppe-tundras with a large role of grasses caused the increase in the depth of seasonal thawing of not less than 1 m (now, 40–50 cm). Similar values of the STL are also obtained from analysis of the depth of locations of fossil rodent burrows [Gubin et al., 2001].

The data presented contradict in general to the aeolian genesis of the brown aleurites layer from the point of view of a local source of aeolian material, because solid and sufficiently dense and productive land cover prevented wind erosion. Nevertheless, this does not contradict the fact that the source of aeolian dust was not associated with local wind erosion, but with some fairly remote areas. In this case, aeolian dust is a product of distant transfer, perhaps the result of global transport of material, which, in the opinion of some scholars, was very characteristic of the cold Pleistocene.

According to some researchers, specifically the deposition of atmospheric dust is the source of formation of loess deposits over large areas, including the IC deposits in Eastern Siberia. In the XIXth century already, it has been shown [Udden, 1898] that a transport system ability of sorting material

is inversely proportional to its carrying capacity and, thus, the density. Therefore, wind transport is the most effective means of sorting. These considerations represent one of the reasons for the use of the aeolian theory to explain the genesis of the IC that differs from other types of deposits in terms of high grain-size differentiation.

The grain-size distribution of sediments is very sensitive to wind impact; directional changes in mineralogical composition occur along with mechanical differentiation. This has been shown in numerous publications on aeolian sediments of different facies [Buchanan, 1947; Sidorenko, 1956; Romanov, 1968; etc.].

Aeolian differentiation of particles by size and mineralogical composition leads to a certain relationship between the grain-size distribution and mineralogical composition of aeolian deposits. According to L.B. Rukhin [1961], the content of heavy minerals (specific gravity more than 2.9) in the size fractions of aeolian deposits consistently decreases with increase in grain size (Fig. 5). The maximal content of the heavy mineral

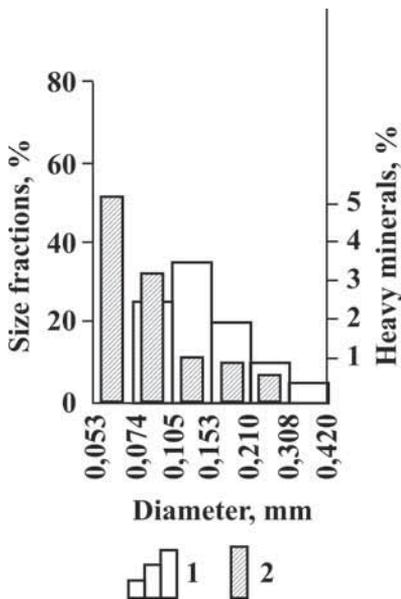


Fig. 5. Percentage of heavy fraction in relation to the grain-size of aeolian sands.

1 – size fractions (histogram); 2 – heavy minerals

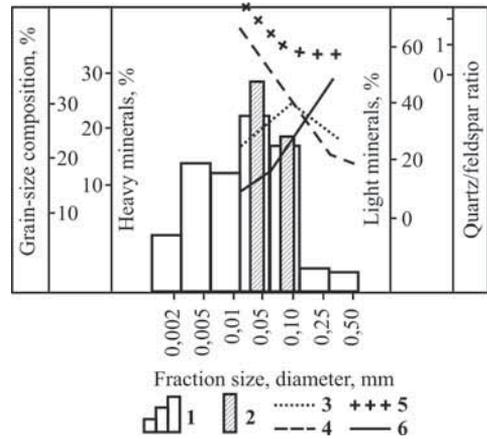


Fig. 6. Grain-size and mineralogical composition of aeolian fine earth on the right branch of Shokalskiy glacier (Zailiyskiy Alatau, Tien Shan, H = 3950 m, rocky setting is located at 800–900 m from the sampling site).

1 – grain-size composition; 2 – percentage of heavy fraction; 3 – quartz content by size fractions (%); 4 – feldspar content by size fractions (%); 5 – quartz/feldspar ratio by size fractions; 6 – rock fragments distribution by size fractions (%)

fraction is in a fraction similar in size to coarse aleurite (0.05–0.01 mm). A similar, but slightly subdued situation is associated with deposits of water genesis. Fig. 6 shows the results of our research of the accumulation of aeolian dust on the Tien Shan Mountains, in which different mineralogical parameters were studied in several size fractions. These deposits – typical products of differentiation of mineral matter in the atmosphere, have a clear sedimentagenous distribution of the total content of heavy minerals by particle size: the maximal content of heavy minerals is in the coarse fraction of aleurite (0.05–0.01 mm).

The studied sediments of the brown aleurite from several sections of the IC have a fundamentally different pattern (Fig. 7).

Despite a high degree of granulometric sorting (the content of coarse aleurite particles reaches 50–60) there is non-sedimentagenous distribution of the heavy mineral fraction% in all samples; its maximum is localized in the fine sand fraction (0.1–0.05 mm) and not in the fraction of 0.05–0.01 mm, as it should have been in the case of the aeolian

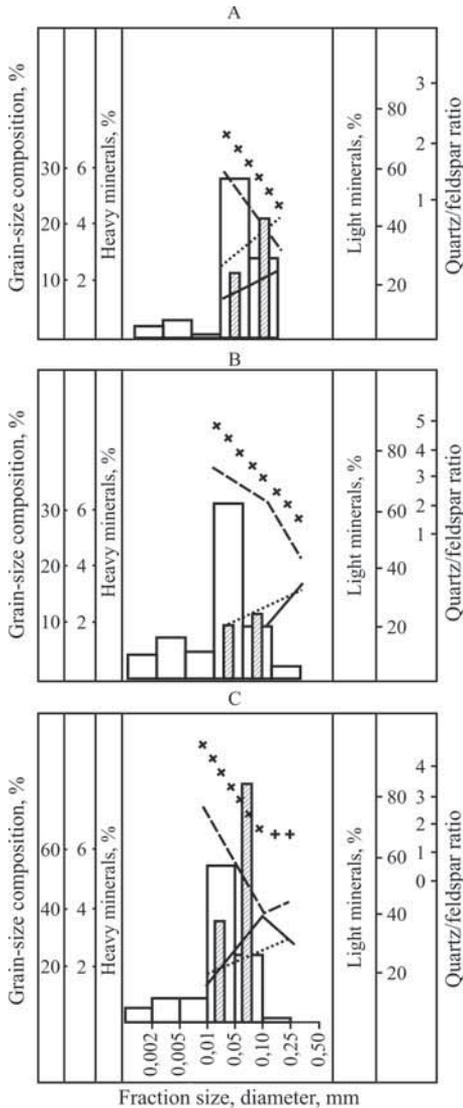


Fig. 7. Relationship between grain-size and mineralogical parameters in the sections of brown aleurites:

A – foothills of the Kular Ridge (Northern Yakutia);
B – outcrop Moose Khai, depth 4.4 m (low reaches of the Yana River);
C – outcrop Chukochee Yar (the Chukochee River), depth 4.0 m. For symbols, see Fig. 6

fine earth sediments on the glaciers. From the position of aeolian or water genesis of these sediments, the disagreement between granulometric and mineralogical sorting is unexplainable. Such non-sedimentagenous distribution of the heavy fraction within the granulometric range is associated with eluvium of bedrock and slope sediments [Konishchev, 1981]. This suggests that the brown aleurites

of the IC is a product of the nearest re-deposition of elluvial formations or, more simply, of slope deposits. Here, we mean not the eluvium of bedrock, but cryogenic eluvium – the product of cryogenic impact (multiple cycles of freezing and thawing) on any original dispersed rocks. Numerous experimental data have shown that exposure to repeated cycles of freezing – thawing of various fine-grained soils (sand, loamy sand, sandstone, and other rocks) leads to significant changes in the size distribution, the result of which is the accumulation of 0.05–0.01 mm fraction due to destruction of larger particles and aggregation of fine clay particles [Konishchev, Rogov, 1976; Minervin, 1982].

Experimental and theoretical studies of the process of destruction of various minerals in alternate freezing and thawing have led to a conclusion that there is a specific stability sequence of minerals [Konishchev, 1981].

A fundamental feature of this sequence compared with other known sequences of mineral stability is a lower stability of quartz grains in relation to fresh and unchanged, by preceding processes of weathering or hydrothermal effects, feldspar grains – the most common rock-forming minerals. The limits of cryogenic disintegration of quartz grains are 0.05–0.01 mm, for feldspar – 0.1–0.05 mm, for biotite – 0.25–0.1 mm, for muscovite – 0.5–0.25 mm. Cryogenic organization of matter is expressed, thus, in a certain distribution of minerals within the granulometric range.

The main feature of this approach is not the absolute concentration of minerals, but the distribution of minerals between the particle size ranges of the granulometric fractions.

In all samples of the brown aleurite, the distribution of particle size fractions of the major minerals (quartz, feldspar, and quartz/feldspar ratio) was typical cryogenic. The deposits of warm and temperate climate zones have the opposite, mirror character (Fig. 8, A). This refers to the well-known scheme of N.M. Strakhov [1962].

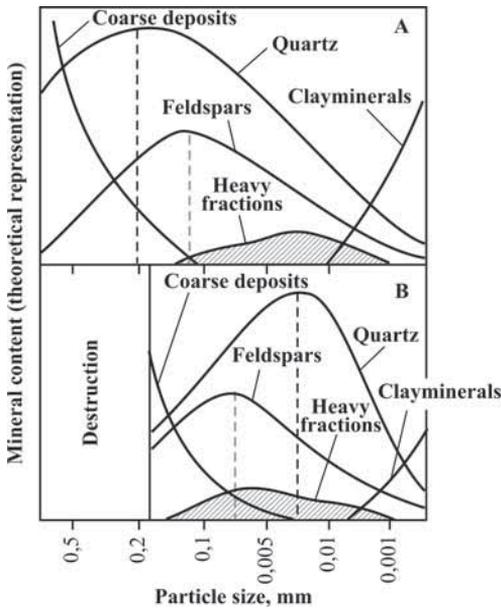


Fig. 8. Mineral content by the grain-size range in fine sediments formed:

*A – under warm climate (according to N.M.Strakhov [1962]);
B – within the cryolithozone (according to the author)*

The data of the immersion method analysis of minerals, which was used in the study of the sediments of the IC, is also supported by the results of the total chemical analysis for different fractions (Fig. 9). It is clear that the maximum SiO_2 content is typical of a 0.05–0.01 mm fraction, whereas in sediments and soils of temperate and warm climates, the maximal SiO_2 is observed in larger-size fractions.

The particle size distribution histograms of the brown aleurite, to some extent, correlates with the mineral composition: the predominant size fractions: 0.05–0.01 mm – up to 60%, and 0.1–0.05 mm – up to 25%, reflect the ratio of quartz and feldspars. This indicates, in addition to the above discussion, the leading role of cryogenesis in the formation of the composition of the brown aleurite. Fig. 8, B shows schematical representation of transformation of the original deposits in the course of their cryogenic weathering, whose basic content is associated with a prevailing destruction of quartz grains larger than 0.1 mm and concentration of this mineral in a 0.05–0.01 mm fraction – the limits of size for this mineral.

In general, the maximal content of light minerals (quartz and feldspar) is typical to smaller size fractions. The maximal content of heavy minerals hardly changes its position in the range of particle size and, therefore, relatively light minerals are shifted to larger-size fractions. The maximal contents of quartz and feldspar are reversed in accordance with their cryogenic stability.

The facies of the greenish-gray aleurites in the low part of the IC sections are characterized by different cryogenic sedimentation distribution of mineralogical parameters within the granulometric range. The distribution of the heavy fraction is typical sedimentogeneous, i.e., the maximum content is in the fraction of 0.05–0.01 mm. At the same time, quartz, feldspar, and their ratio have the cryogenic type of distribution (Fig. 10). Exactly the same distribution of mineralogical indicators is characteristic of the underlying subaqueous (lacustrine or floodplain) deposits. Thus, while the lower horizons of the IC, not to mention the underlying sediments, were formed under the impact of sorting aquatic environment, the upper layers of the brown aleurite represent typical cryogenic fine earth.

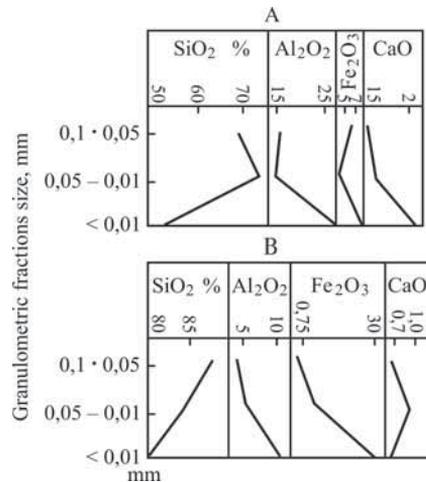


Fig. 9.

A. Distribution of chemical components within the particle size fractions of soils of temperate and warm climates [Kovda, 1973]

B. The gross chemical composition of different size fractions in the cryolithogenic sediments of the Kolyma lowland

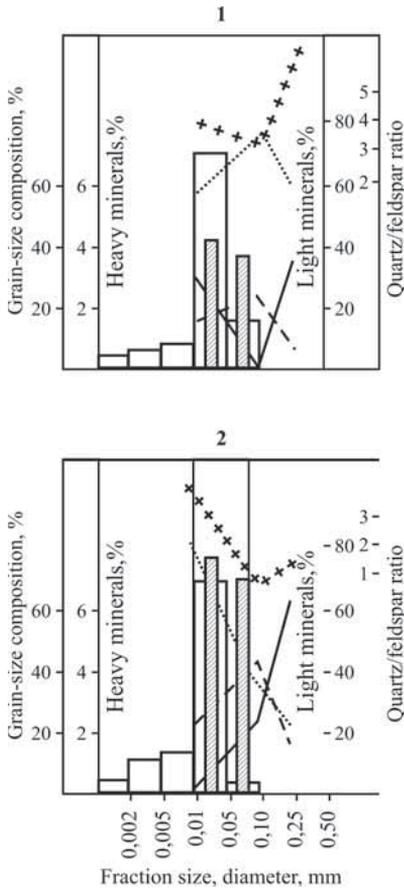


Fig. 10. Relationship between grain-size and mineralogical parameters of the greenish-gray aleurites of the IC

1 – outcrop Moose Khai (the low reaches of the Yana River), depth 19–20 m; 2 – outcrop Oyagossky Yar (the Laptev Sea coastal area), depth 15.5–16.0 m. For symbols, see Fig. 6

PALEOGEOGRAPHIC FACIAL CONDITIONS OF SEDIMENT ACCUMULATION OF THE IC

The Karga-Sartan interval of the Late Pleistocene was an extremely favorable time for the accumulation of products of cryogenic weathering – the basis of thick layers of different facies of the IC. In the phase of sufficiently cold (the Karga period) and, then, in the phase of very cold and relatively dry climate (the Sartan period), large masses of particulate material, mostly of aleurite composition, the result of cryogenic weathering, entered valleys of different orders – from large to very small, and alas basins also.

The erosional activity of streams and magnitude of the subaqueous accumulation were significantly decreasing. Thick alluvium was forming in the valleys of large rivers; the valleys of small rivers and creeks and alas depressions were filling with slope and proluvial sediments; terraces were transforming into terrace-ridges [Gravis, 1981; Konishchev, 1981]. Depending on the geomorphological conditions, at least three types of environment of the IC accumulation can be identified. The first corresponds to the terrace-ridges conditions. Terrace-ridges have accumulated the mantle of aleurite material; it formed as a result of cryogenic processing of alluvial deposits on the slopes and the formation of thick (up to 20 m) fans of loess slope deposits intersected by the polygonal grid of repeated vein ice sometimes deformed in the direction of sloping surface [Gravis 1969] and filling small valleys in the foothills and lowlands. The IC of this type is usually underlain by coarse alluvial deposits. Its mineralogical parameters are typical cryogenic [Konishchev, 1981]. The second situation corresponds to the valleys of rather large stable watercourses and their deltas. There, alluvial deposits, quite diverse in composition, have accumulated: sandy aleurites, medium- and fine-grained sand, and sometimes silty and interbedded with gravel. In these deposits, thick syngenetic ice wedges, sometimes as several horizons, were also forming. Deposits of this type are also the IC facies and are characterized by the cryogenic-sedimentogeneous type of differentiation of mineralogical parameters within the granulometric range [Konishchev, 1981].

The third and the most typical and common situation was occurring in the alas valleys, alas themselves, and small valleys and streams on the coastal plain. There, the IC is often underlain by lacustrine loam, peat, or alluvial sand deposits, whose age dates to the beginning of the Karga period (40 thousand years or more) that had relatively warm climate with development of taiga vegetation [Zanina, 2006]. These deposits were overlain by quite a diverse range of facies. Climatic fluctuations of the period are manifested in their alternation – from water-rich ridge to flat ridge-free

polygons. The average annual ground temperature during the accumulation of the horizon of icy and highly deformed yellow-green aleurites, separated by layers of brownish-gray non-icy and undeformed aleurites, ranged from -10°C to $-2 \div -3^{\circ}\text{C}$ [Konishchev, 2002], and this specifically was the reason for the cyclic structure of this section. The products of cryogenic weathering that filled alas basins and small valleys and that moved from the slopes with melt water and by solifluction processes, even at this stage, have been already subjected to sorting impact of the aquatic environment.

This is manifested in the cryogenic sedimentation type of the distribution of the mineralogical parameters within the size fractions (Fig. 10).

The brown aleuties with fine schlieren and massive cryotextures and undeformed layers at contact with ice veins were accumulating at the final stage of filling of the alas depressions and valleys under very harsh and relatively

dry climate of the Sartan period when the average annual soil temperature reached $28 \div -30^{\circ}\text{C}$ [Konischev, 2002]. This IC type has thick (up to 8 m wide) transit syngenetic ice veins that intersect, as solid wedges, all facies and horizons of the IC.

CONCLUSION

Thus, at all levels of structure of the IC deposits – from the most general (lower Karga and upper Karga - Sartan horizons) to different types of cycles - the determining factor of the accumulation of deposits was multi-scale fluctuations of cryogenic-climatic conditions. The facies and genetic structure of different types of the IC is a derivative of the permafrost-climatic characteristics. Cryogenic weathering, the character of slope processes, and frost cracking were most responsive to climate change. Climate impact on other processes of morpholithogenesis in the cryolithozone (erosion, thermokarst) was more complex and indirect. Precisely this has determined the accumulation of the IC deposits. ■

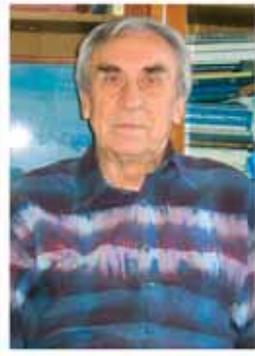
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