Cryolithological Section of Ice-Rich Sediments of the Annual Heat Circulation Layer in Post-Pyrogenic Sections of the Kolyma Lowland North-East

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Abstract The article provides the results of cryolithological studies of ice-rich sediments in post-pyrogenic areas in the Nizhnekolymsky district of Sakha Republic (Yakutia) near Chersky village. Two boreholes were drilled, and a comprehensive analysis of core material was carried out. The results of the work reflect various cryogenic structure for relatively similar cryogenic landscapes.

1. Introduction

A phenomenon of forest fires causes catastrophic damage to the environment. Fires occur frequently and everywhere, they may be short-term or long-term, and cover small areas or big territories, reaching hundreds of hectares. Fires occur due to natural causes (lightning strikes, spontaneous combustion of peat crumbs, etc.) and due to human activities (agricultural burning, calamitous accidents and technological accidents. Fires annually destroy forest cover on large areas of the cryolitic zone [16]. In 2018, 641 forest fires on a total area of 3.4 million ha were recorded in Yakutia) [6].

The increased fire activity on the territory of the cryolitic zone primarily changes the conditions of heat transfer on the surface by reducing the surface albedo. It leads to a noticeable change in the soils’ thermal, water, and cryogenic regimes [23].

Studies of the forest fire effects in the cryolitic zone are conducted on a quite wide range of interdisciplinary issues. Many works study the response to forest biome fires [7, 19], cryogenic soils [22], carbon cycle transformation in boreal ecosystems [14] and post-fire dynamics of forest vegetation [12]. The issues of surface albedo changes after fires and consequences for the regional climate are examined separately by studying the data of the Earth remote sensing [9, 11]. A series of works devoted to the changes in the temperature regime of permafrost strata and parameters of cryogenic landscapes caused by fires was carried out by Melnikov Permafrost Institute of SB RAS (Siberian Branch, Russian Academy of Sciences) [2, 13, 17, 24]. As part of the implementation of international projects [10, 21], a comprehensive assessment of the cryogenic landscapes dynamics, the changes of seasonal thawing depth, the temperature of permafrost rock mass and the emission of
greenhouse gases was carried out. The Northeastern Federal University researches [3] demonstrated that noticeable changes in microclimatic and soil conditions in the burned areas occur during the first 10 years after the fire. It has been established that the soil temperature in young burned areas at a depth of 30 cm increases by 4.3–6.2 degrees Celsius in comparison with the forest. Over the course of succession period (20-25 years after the fire), the conditions changed by the fire stabilize.

It should be noted that the abovementioned works deal with issues related mainly to the biological component of cryogenic landscapes. Most of the study provide data of the thermal, water, and cryogenic regimes only for the several meters from the surface (seasonal thawing layer). Therefore, it still seems quite complicated to assess the role of forest fires in the cryolitic zone state change and the cryolitic landscapes dynamics. Undoubtedly, in order to solve this problem, the observations in the layer of annual heat rotations, i.e. up to depth of 10-20 m, are required.

The disturbed cryogenic landscapes of ice-rich permafrost layers are the most active. The sites considered in this article are located on the ice complex deposits and were affected by forest fires in the middle of the last century. The ice complex is understood to be syngenetically frozen sediments with a thickness of 40-60 m, mainly of silt content, including thick polygonal wedge ice (PWI) [8, 18, 20].

The aim of the study is to assess the influence of forest fires on the cryogenic structure of the upper horizons of the ice complex in the NizhneKolymsky region. The objects of the research are the soils of the annual heat rotations layer to a depth of 10 m.

2. Area of work and research methods
The climate of the Kolyma lowland is characterized as sharply continental. The annual amplitude of average monthly temperatures is 45.7 °C. The average temperature in July is +10.9 °C, and -34.8 °C in January. The duration of the period with an average daily temperature above 0 °C is 122 days. Snow cover in the coastal area stays for 270-290 days, snow thickness increases from 20-30 cm in the coastal area to 60-70 cm in the south [4, 25]. In the frames of geocryological terms, the territory is characterized by the continuous distribution of permafrost rock, and according to field observations, the soil temperature at a depth of zero heat rotation (10-15 m) varies in the range of -2 - -5 °C. The thickness of the seasonal thawing layer in the region varies from 60 to 100 cm [1].

Figure 1. A – Map of the area of work in the vicinity of Chersky village; Б – location of 18/3 borehole; В – location of the borehole 18/2. Satellite images. Bing Map- satellite.

The loose strata in the region are represented by sandy pebbles and sands of the Begun suite of the late Pliocene, eopleistocene sandy loam and loam of the Olerian suprahorizon, icy siltly loam, and sandy loam of the late Neopleistocene ice complex, a transitional horizon (cover layer) formed in the Holocene optimum era, tabular alas and lake-bog sediments, modern alluvium of rivers and streams, the channel of the Kolyma river valley and slope deposits [26].
The studied sites are located on the piedmont of the right bank of the lower Kolyma river, on a drive-separated yedoma surface with a different stage of post-fire vegetation development (Fig. 1). Boreholes in a depth of 10 m were drilled at each site (Fig. 1). The age of post-pyrogenic succession at each site was determined using the dendrochronological method, it is 70 years for the first site, and 30 years for the second site. Geobotanical survey of the area was carried out. The cryogenic structure of the deposits was studied, based on core material; moisture weight was determined by drying to constant weight; composition of water-soluble salts; volumetric weight was determined by weighing frozen samples in a neutral liquid and the total organic matter content obtained by calcining dry samples at a temperature of 450 °C. Granulometric composition of the soil is determined according to GOST 125336-2014 by the areometric method. The mineralogical composition in the particle-size fractions of 0.05 - 0.1 and 0.01 - 0.05 was determined by the immersion method.

3. Results of the works
The borehole at the first site is numbered 18/2K; an intense fire occurred at this site 70 years ago. The borehole at the second site is numbered 18/3K, a fire occurred 35 years ago. The section is represented by brown, grayish-brown, gray, sandy, and clayey siltstones containing the PWI. The deposits are characterized by a high ice content of micro- fine-, thick-schlieren, ataxitic, and massive cryotexture [5] (Fig. 2). The rocks are penetrated by a network of filamentary roots and plant macro-residues in the form of wood fragments with various degrees of decomposition; there are unevenly distributed gleying and ironing spots (Fig. 2 d, h).

The borehole 18/2K (68,75602° N; 161,45439° E) is located on the slope of the northern exposition (absolute elevation 34 m). The surface is horizontal, slightly inclined, slightly tuberous, frost cracks can be found at the site. The vegetation is at the stage of undergrowth and is a post-fire larch-shrub-moss forest with lichens and mixed herbs. In general, 4 layers can be distinguished in the section:

1) seasonal thawing layer to a depth of 0.8 m;
2) transitional layer in the range of 0.8-1.7 m. These horizons are represented by brown clay siltstones of a homogeneous composition, with a dust fraction (0.002-0.05 mm) up to 75%; the rocks are penetrated by filamentous roots of vegetation; the signs of ironing is noted; the organic matter content varies from 1.9 to 3.8%. The interval of 0.4 – 1.7 m is characterized by ataxitic, netted, “complex belt”, thick-schlieren cryotextures (Fig. 2). Moisture weight indicators vary in the range of 0.5 - 3.9 units. There are weakly moistened and compacted (dried up due to moisture migration to the freezing front) aleurites with massive cryotexture (humidity 0.3 and 0.19 units) at depths of 1.2 m and 1.7 m,

3) the PWI selvedge have been naked in the range of 1.7-5.9 m. The ice is cloudy, transparent, the isometric gas bubbles are traced inside (Fig. 2 i). The ice has cracks filled with mineral matter.

4) the grayish-brown sandy siltstones with a large number of unevenly distributed gleying spots have been naked from a depth of 5.9 to 10.0 m. Plant inclusions in this part of the section are presented in the form of semi-decomposed and borehole-preserved elements of the roots of herbaceous plants and the fragments of shrubs branches. The cryotextures are micro-schlieren, inclined and folded, some cyclicity of deformation is traced, which is specific to the mineral part of the ice complex between the veins (Fig. 2).

There are 98.7 - 98.9% of light fraction minerals in the studied samples. Minerals of the group of clay-micaceous aggregates (41–63%) and quartz (24–41%) prevail. The feldspars content is 10-16%. The mineralogical composition of the heavy fraction is quite diverse. Among the minerals, micaceous aggregates (22–46%) and amphiboles (39–50%) prevail. A significant (2.9-14.6%) content of iron and epidote hydroxides (4.4-16.3%) is noted (Fig. 3). There are pyroxenes, garnet, biotite, and chlorite throughout the section. Zircon, apatite, tourmaline, and carbonates were sporadically found (Fig. 3).
Figure 2. Fragments of core from boreholes 18/2K, 18/3K. Values on the measuring tape are indicated in cm: a-i – borehole. 18/2K: a - ataxitic cryotexture in the active layer (interval 0.4-0.5 m); b – ataxitic cryotexture in the transitional layer (interval 0.8-0.9 m); c – horizontal fine-schlieren cryotexture (interval 1.5-1.6 m); - cleavage at a depth of 2.25 m; e – netted micro-schlieren cryotexture (interval 5.80-5.90 m); f – inclined micro-schlieren cryotexture (interval 5.97-6.07 m); g – oblique fine-schlieren cryotexture, inclusions of plant exist (interval 7.1-7.2 m): h – massive cryotexture, gleization spots, inclusion of plant residues (interval 7.64-7.73 m); i – horizontal PWI cleavage (depth 3.7 m); j – 1 borehole. 18/3K: j - horizontal fine-schlieren cryotexture (interval 0.95-1.05 m); k – massive cryotexture, with an organically saturated interlayer (interval 1.15-1.25 m); l – contact of the mineral part with the PWI (interval 1.6-1.7 m).

Chemical analysis of soluble components revealed a hydrocarbonate magnesium-calcium composition, the same results were for vein ice; the mineralization is ultra-fresh. The pH index varies from 6.09 to 7.49, in general, characterizing a neutral and mildly alkaline environment, which is typical for surface waters. However, a slight increase in mineralization is observed at the depth of the contact between vein ice and soils, which may occur due to squeezing of unfrozen water enriched with soluble compounds from frozen soils and its rapid freezing (Tables 1, 2).

The borehole 18/3K (68.761750° N 161.386333° E) is located on a dividing surface. The surface is relatively flat with a slight slope. The thickness of the seasonal thawing layer is 1.0 m. The vegetation is at the stage of undergrowth and is a post-fire larch brush-shrub-moss forest with lichens and mixed herbs.

The borehole naked an ice core of a depth of 1.65 m to the borehole’s bottom-hole (10 m). The upper horizon is represented by monotonous sandy grayish-brownish siltstone with massive and micro, fine-schlieren cryotextures; the thickness is relatively small-iced, the weight humidity varies from 10% to 60%. A dry frost horizon can be traced in the interval from 0.4 to 0.9 m. A horizontal
micro-schlieren cryotexture is traced in the interval of 0.97 - 1.15 m. Probably, the icy part of the stratum degraded after the fire, and the location of the site on the slope contributed to the drainage.

The average organic matter content in the section is 2.52%. Micaceous aggregates (22–46%) and amphiboles (39–50%) predominate among heavy minerals. A significant (2.9-14.6%) content of iron and epidote hydroxides (4.4-16.3%) is noted (Fig. 3). The light fraction is mainly characterized by quartz (24–41%) aggregate-micaceous (26–48%) composition.

![Figure 3](image-url)

**Figure 3.** The results of comprehensive studies on boreholes 18/2K, 18/3K. Legend: 1 - soil; 2 - aleuritis; 3 - filamentary roots; 4 - a - plant macro-residues, b - branches; 5 - a - ironization, b - gleying; 6 - ice vein; 7 - border of frozen rocks; 8 - massive cryotexture; 9 - netted cryotexture / inclined schlierened cryotexture; 10 - micro-, fine- and thick-schlieren cryotextures; 11 - ataxitic cryotexture; 12-vein ice; 13-18 the diagram of granulometric fractions distribution in the section (mm): 13- 1.0-0.5; 14- 0.5-0.25; 15- 0.25-0.1; 16- 0.1-0.05; 17- 0.05-0.01; 18- 0.01-0.002; 19-30 the diagram of mineralogical composition: 19 – epidote; 20 - pyroxene; 21 - amphiboles; 22 - zircon; 23 - micaceous aggregates; 24 - clay aggregates; 25 - biotite; 26 - chlorite; 27 - pomegranate; 28 - carbonates; 29 - quartz; 30 – feldspars.
Table 1

| Depth, m | Ion content, mg-eq/100g |
|----------|-------------------------|
|          | Ca         | Mg         | Na         | K          | NH₄        | HCO₃       | SO₄       | Cl        | NO₂       | NO₃       |
| Borehole 18/2 K |
| 1,1      | 0,132      | 0,110      | 0,022      | 0,005      | 0,006      | 0,190      | 0,010      | 0,039      | 0,000      | 0,004      |
| 1,6      | 0,269      | 0,134      | 0,035      | 0,005      | 0,006      | 0,379      | 0,021      | 0,055      | 0,000      | 0,002      |
| 6,1      | 0,376      | 0,376      | 0,326      | 0,006      | 0,008      | 0,000      | 0,503      | 0,219      | 0,442      | 0,000      |
| 6,7      | 0,586      | 0,578      | 0,435      | 0,006      | 0,014      | 0,483      | 0,833      | 0,387      | 0,000      | 0,005      |
| 9,3      | 0,358      | 0,460      | 0,217      | 0,008      | 0,014      | 0,414      | 0,260      | 0,359      | 0,000      | 0,001      |
| Borehole 18/3 K |
| 0,6      | 0,124      | 0,099      | 0,043      | 0,004      | 0,003      | 0,224      | 0,024      | 0,036      | 0,0001     | 0,0056     |
| 1,3      | 0,323      | 0,242      | 0,074      | 0,008      | 0,003      | 0,414      | 0,156      | 0,083      | 0,0001     | 0,0037     |

Table 2

| Depth, m | Ion content, mg-eq/l |
|----------|----------------------|
|          | Ca         | Mg         | Na         | K          | NH₄        | HCO₃       | SO₄       | Cl        | NO₂       | NO₃       |
| Borehole 18/2 K |
| 1,9      | 0,3817     | 0,2903     | 0,1392     | 0,0230     | 0,0021     | 0,6206     | 0,0583    | 0,0608    | 0,0002     | 0,0903     |
| 2,8      | 0,2903     | 0,1935     | 0,0435     | 0,0179     | 0,0571     | 0,4827     | 0,0377    | 0,0552    | 0,0002     | 0,0048     |
| 3,7      | 0,3656     | 0,1989     | 0,0870     | 0,0256     | 0,1071     | 0,6206     | 0,0823    | 0,0773    | 0,0002     | 0,0030     |
| 4,7      | 0,5053     | 0,3011     | 0,1479     | 0,0230     | 0,1071     | 0,7930     | 0,0891    | 0,1657    | 0,0002     | 0,0042     |
| 5,7      | 0,6989     | 0,3978     | 0,1653     | 0,0997     | 0,0036     | 0,8965     | 0,0720    | 0,1878    | 0,0004     | 0,4032     |
| Borehole 18/3 K |
| 2,2      | 0,4140     | 0,3118     | 0,0870     | 0,0205     | 0,0357     | 0,7586     | 0,0617    | 0,1491    | 0,0002     | 0,0016     |
| 3,2      | 0,4301     | 0,2957     | 0,1000     | 0,0153     | 0,0643     | 0,7586     | 0,0651    | 0,0773    | 0,0002     | 0,0016     |
| 4,0      | 0,4032     | 0,2957     | 0,1044     | 0,0179     | 0,0500     | 0,6896     | 0,0583    | 0,0552    | 0,0002     | 0,0016     |
| 5,7      | 1,2419     | 0,4516     | 0,0565     | 0,0205     | 0,0286     | 1,3792     | 0,0446    | 0,0939    | 0,0009     | 0,1290     |
| 6,4      | 0,6989     | 0,3333     | 0,0870     | 0,0179     | 0,0714     | 0,9516     | 0,0572    | 0,0552    | 0,0002     | 0,0129     |
| 8,4      | 1,9999     | 0,9569     | 0,2740     | 0,0358     | 0,0143     | 2,7584     | 0,2400    | 0,1105    | 0,0004     | 0,1452     |
| 9,7      | 1,3440     | 0,6989     | 0,1566     | 0,0230     | 0,0036     | 1,8688     | 0,0446    | 0,1326    | 0,0002     | 0,1452     |

4. Conclusion

The boreholes 18/2K and 18/3K were drilled in areas with relatively similar conditions and in relative proximity to each other (600 m), but they reveal different cryolithological structures in the section within the intervals from the lower boundary of the seasonal thawing layer to the roof of the PWI. The surface conditions of the second site degraded after the last fire so much that it affected the cryotextural structure of the deposits from the surface to the roof of the PWI. The moisture, which formed within the seasonal thawing layer due to melting of texture-forming ice, have probably shifted down the slope, since the area under consideration has a slight slope. At the same time, there were no signs of any occurred negative cryogenic processes. The section of the first site withstood less pronounced changes, the fire probably affected the environment to a lesser extent, and the vegetation cover quickly recovered. The cryogenic structure of deposits in the interval from the lower boundary of the seasonal thawing layer to the roof of vein ice did not undergo significant transformations.
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