RESEARCH PAPER

# SOIL-CRYOGENIC COMPLEXES OF WEST SIBERIAN TUNDRA

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ABSTRACT. Soil-cryogenic complexes (the system of "permafrost-affected soils – upper permafrost"), located at the interaction hotspot of the biosphere and the cryosphere, were studied at five key sites in Northwestern Siberia situated on geomorphological terraces of different origin – from marine to fluvial and lacustrine – and age (Late Pleistocene and Holocene). In the context of the present-day permafrost zone transformation under global climate change and local anthropogenic impact, they are of considerable ecosystem significance. Based on the geomorphological and cryolithological studies, it was concluded that fully developed soil-cryogenic complexes (SCCs), comprising the active layer (AL), transient layer (TL), and intermediate layer (IL), are spatially limited in the study area due to lithogenic and ecosystem factors. Due to the wide distribution of deeply thawing sandy, ice-poor sediments where continuous and thick vegetation cover is unable to develop, morphologically expressed TL was absent, having already fully thawed. Modern soil formation most often occurs directly above the degrading IL or even Late Pleistocene frozen sediments containing fragments of ground ice. Relatively stable permafrost conditions and full-profile SCCs were observed in the thick peat massifs only where the presence of thick organic horizons reduces the heat flux and limits the active layer thickness (ALT). Furthermore, a number of hazardous geomorphological cryogenic processes – including thaw ground subsidence, thermal denudation, and thermal abrasion in coastal areas – contribute to the degradation of SCCs, thereby diminishing their protective role in permafrost preservation. A comprehensive approach to the assessment and forecasting of the ecological state and dynamics of fragile Arctic ecosystems, based on SCC research, could provide a deeper understanding of both natural and anthropogenic processes.

KEYWORDS: permafrost-affected soils, soil-permafrost coevolution, cryostructures, transient layer, intermediate layer, Arctic

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## INTRODUCTION

Nowadays, the Russian Arctic is one of the most promising regions, where major governmental projects are being implemented. The most dynamically developing region here (not only in Russia but in the global Arctic) is the northern part of West Siberia (Cordier et al. 2025), which is administratively part of the Yamal-Nenets Autonomous Okrug. Firstly, the active exploration of this territory in the 20th–21st centuries is linked to its high mineral resource potential: more than 130 hydrocarbon fields are located there (Khimenkov et al. 2020). Secondly, the ice navigation regime of the Arctic seas has changed during the last few decades and has significantly prolonged the period of the Northern Sea Route availability for the cargo sea transportation from Asian countries to Russia and Europe. The most important terrestrial aim, consequently, is the development of transport and economic infrastructure along this route to provide fast and safe transportation. Thirdly, there are several initiatives of the local authorities to improve citizens' living comfort, including increasing the transport availability of its remote regions. Anthropogenic activity on these territories, a major part of which is located in the permafrost zone, comprehensively influences the regional environment, especially permafrost conditions and terrestrial ecosystems. This influence mostly impacts the system of "permafrost-affected soils – upper horizons of permafrost" located in the interaction hotspot of the biosphere and cryosphere, and responds to changes in both of them.

Lupachev and Gubin (2023) proposed considering modern permafrost-affected soils and the upper permafrost horizons as the unified system – the soil-cryogenic complex (SCC). The SCC includes three main structural elements: a modern soil profile (mostly limited by the active layer thickness (ALT)), the transient layer (TL), and the intermediate layer (IL) of permafrost. TL and IL are characterized by specific ice-rich cryogenic structures – ataxitic, lenticular, layered, etc., as well as pure ice inclusions (Shur 1988). The SCC structural elements are relict formations of the earlier warmer periods of the Holocene in the permafrost zone of the Arctic and subarctic (Shur 1988; Shur et al. 2005; Bockheim, Hinkel 2005). They thaw at different frequencies; therefore, they could be incorporated into the soil formation sphere and biogeochemical cycles, and accumulate various soil formation products – soil organic matter (SOM), pedogenic metal oxides, soluble substances, etc. TL formed as a result of the recent average ALT dynamics (Shur 1988); its ice-rich cryostructures may have derived from ice segregation at the base of the active layer. IL has been inherited from the Holocene climatic optimum (Shur 1988) – the Early to Mid-Holocene warm period that ended around 5–4 ka (Borisova 2014). This layer could also be enriched with ice due to the gradual decrease of the ALT from the Mid to Late Holocene.

Pedogenesis was permanent throughout the Holocene in a major part of Northwestern Siberia; thus, the interaction between soils and underlying permafrost was constant. The Holocene climatic optimum is associated with significant air temperature increase (up to 12–14°C higher than the late glacial maximum, and 2–4°C higher than modern values), a series of synchronous tundra-taiga borderline shifts (Khotinskiy 1977; Borisova 2014), and different-scale Kara Sea level fluctuations (Fotiev 2005). The highest Holocene sea level rise occurred during the Boreal period, reaching 8–10 m (up to 12 m) above the modern level, corresponding to the geomorphological levels of the floodplain complex and the first terrace. During this period, pedogenesis was replaced by marine sedimentation. Atlantic and Sub-Atlantic periods were associated with less pronounced sea level rises, and during the Sub-Atlantic period, starting 4–3 ka, the 1–3°C cooling caused the tundra–taiga borderline retreat southwards to the Polar Circle (Vasil'chuk et al. 1983). Thus, alternation of warming and cooling stages and associated environmental shifts in Northwestern Siberia during the Holocene led to significant variations in the ALT in the past. However, according to Fotiev (2005), the total degradation of the upper permafrost layers did not happen there even in the Holocene climatic optimum.

In the context of permafrost zone transformation under global climate change and local anthropogenic impact, SCC is of considerable ecosystem significance. Firstly, thawing of the ice-rich TL and IL can trigger hazardous processes (thermokarst, thermal erosion, etc.) that negatively affect infrastructure stability and constrain the feasibility of engineering exploration of these territories (Shur 1988; Kanevskiy et al. 2014). Secondly, along with biochemical decomposition of SOM contained in permafrost, greenhouse gas emissions ($CO_2$, $CH_4$, $NO_x$, etc.) into the atmosphere may increase as a result of permafrost thawing (Shur et al. 2005; Ping et al. 2015; Oblogov et al. 2020). Thirdly, TL and IL thawing can activate geochemical fluxes in ecosystems. In the modern industrial era, uppermost permafrost horizons can be contaminated by accumulated anthropogenic pollutants migrating in soils as a result of local pollution or long-distance atmospheric transport (Lupachev et al. 2022; Gulfam-E-Jannat et al. 2025). Soluble ions, biogenic (metal-organic compounds, bioavailable element forms, soluble phosphates) and potentially toxic (heavy metals, anthropogenic hydrocarbons, pesticides, radionuclides, etc.) matters can be released from the thawing permafrost and then influence the biogeochemical cycles in adjacent ecosystems (Ji et al. 2019; O'Donnell et al. 2024). Disruption of the matter balance in terrestrial and aquatic ecosystems could irreversibly impact their functioning, potentially leading to ecosystem collapse. It is also important to mention that permafrost degradation always affects the traditional living and land use practices of the Arctic indigenous communities – reindeer herders, hunters and fishermen, – due to changing commercial animal resources ecology and traditional animal migration routes (Allard et al. 2023).

A comprehensive approach to the evaluation and forecasting perspectives of the ecological state and dynamics of cryogenic processes of the fragile Arctic ecosystems, based on SCC research, could provide a deeper understanding of natural and anthropogenic processes. However, data on the structure and current state of SCCs across different permafrost regions remain sparse. Systematic studies of SCC in the Russian Arctic have been carried out only in two regions – the Kolyma lowland, Northeastern Yakutia (Lupachev, Gubin 2008, 2023), and in the South-East of Bolshezemelskaya tundra near Vorkuta, northeastern European Russia (Kaverin et al. 2012). Few studies of SCC are known for the North American Arctic – North Slope region, Northern Alaska, and Yukon River Valley, Central Alaska, and the Canadian Northwest Territories (Bockheim, Hinkel 2005; Ping et al. 2013; 2015). In tundra environments of Northwestern Siberia, SCCs remain unstudied, and data on soil and geocryological research become obsolete.

The variety of ecological functions of SCC and its close connection with other cryogenic ecosystem compartments, especially under conditions of thin annual ALT, is the reason why SCC study is an important problem for the Russian Federation as the state where 2/3 of the territory is underlain by permafrost. Beyond their fundamental scientific value, spatial permafrost research in different regions is of the great social and economic significance as part of the "Basis for the Russian Federation government policies in the Arctic until 2035"[1]. Thus, comprehensive characterization of modern SCCs and projection of their probable development trajectories and associated ecosystem consequences represent pressing research objectives.

## MATERIALS AND METHODS

### *The study area*

Northwestern Siberia (Fig. 1) is located in the Arctic climate zone; mean annual air temperatures (MAAT) here vary from –4.5 to –10.4°C, and mean annual atmospheric precipitation (MAAP) varies between 250 and 600 mm/yr (Table 1). During the last few decades, the positive climate trend was observed: MAAT increased by 2.8°C for the period of 1970–2020 (0.56°C per decade), accompanied by a 5–10% annual increase in MAAP (Vasiliev et al. 2020). Long-term temperature monitoring indicates a gradual increase in permafrost temperature. From 1970 to 2020 (Vasiliev et al. 2020) it increased at average rates: 0.056°C/yr in typical tundra, 0.04–0.05°C/yr in southern tundra, and 0.035°C/yr in northern boreal forests. Since 2007, mean annual temperatures of the active layer have become positive; thus, the active phase of permafrost degradation has started. ALT deepening, which leads to the thawing of ice-rich permafrost layers, affects all landscape subzones of Western Siberia (Vasiliev et al. 2020; 2024). Consequences of the permafrost thawing in tundra zones are not so catastrophic yet. However, significant intensification of destructive cryogenic processes, associated with ice-rich permafrost degradation, is predicted for the 2030–2050 period (Kislov et al. 2023).

[1]The Decree of the Russian Federation President No. 164 (dated March 5, 2020) on the "Basis for the Russian Federation government policies in the Arctic until 2035". Kremlin, Russia. 2020. (in Russian).

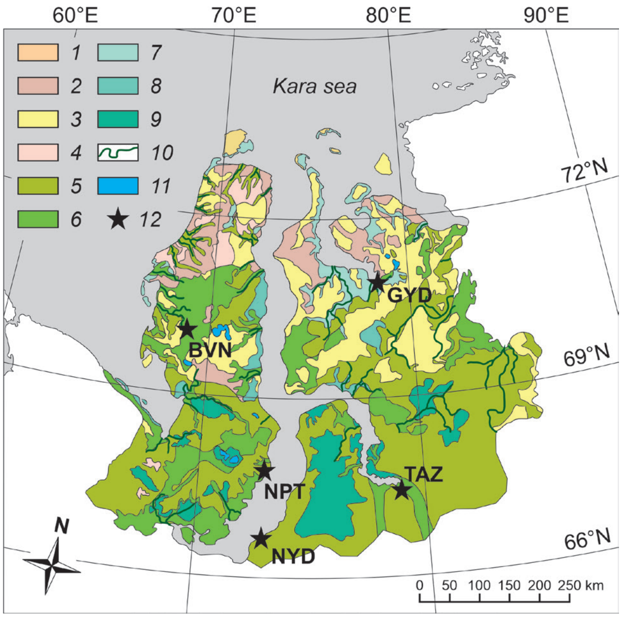


**Fig. 1. Tundra environments of the permafrost zone in Northwestern Siberia (based on[2]): 1 – Rush/grass, forb cryptogram (moist); 2 – Graminoid prostrate dwarf-shrub, forb (moist to dry); 3 – Nontussock sedge, dwarf-shrub, moss (moist); 4 – Prostrate dwarf-shrub, herb (dry); 5 – Erect dwarf-shrub (dry); 6 – Low-shrub (dry); 7 – Sedge/grass moss (wet); 8 – Sedge, moss, dwarf-shrub (wet); 9 – Sedge, moss, low-shrub (wet); 10 – Riparian corridors; 11 – Lakes; 12 – Key sites: BVN – Bovanenkovo; NYD – Nyda; NPT – Novy Port; TAZ – Tazovsky; GYD – Gyda**

Key sites were located on geomorphological terraces of different origin – from marine to fluvial and lacustrine ones. These terraces are of Late Pleistocene and Holocene age (Table 1). TAZ, BVN, and GYD sites were situated in the typical tundra subzone; NPT and NYD – in the southern tundra subzone. Two landscape subzones differ in permafrost conditions: in typical tundra permafrost is distributed continuously and mean annual ground temperature (MAGT) ranges from -2 to -6 °C, and in southern tundra it is located discontinuously and MAGT varies between -1.3 and -4.7 °C (Table 1). ALTs differ significantly between subzones and within key sites in different-textured soils. Various cryogenic processes are widespread across the study area – thermal abrasion, thermal erosion, thermokarst, frost heaving, frost cracking, etc.

Local interactions of lithological, geomorphological, and hydrothermal conditions explain variations in thawing depth of permafrost-affected soils (WRB 2022): Cryosols have an annual thaw depth of up to 100 cm, and Gleysols and Podzols are characterized by 100–150 cm ALT. Sandy Arenosols, commonly developed in well-drained ecosystems with discontinuous or totally absent vegetation cover (e.g. non-vegetated hill shoulders or watersheds with aeolian deflation hollows), thaw annually to depths of several meters. In some cases, there are taliks developed under low-lying sandy floodplains. Histosols are also widely distributed on key sites. They are mostly characterized by the lowest ALT, which has not demonstrated significant deepening during the last few years (Khomutov et al. 2024).

*Methods*

SCCs were studied in natural outcrops and drilling boreholes. Drilling was carried out using a motor-holster Hüter GGD-52 and a 59-mm diameter core sampler. Soil profiles were described according to the WRB Soil Taxonomic System (2022). The cryogenic structure of permafrost cores was classified according to (Kanevskiy et al. 2014). Soil pits and boreholes were made during field seasons 2023–2025; from late August to late October, when the observed ALT was closest to its maximum annual depth.

RESULTS

*NYD key site*

Soils at the NYD key site included Gleyic Turbic Cryosols and Gelic Gleysols. They developed in silty and clayey lacustrine loams overlying a thick alluvial sandy layer in the structure of a gentle slope of a fluvial-lacustrine terrace. Fine particles of plant residues occurred buried during cryoturbation in Cryosol profiles (Fig. 2 – sections BVN-24-03/04/08, GYD-25-01/03/05). The territory of this key site was previously affected by solifluction. Signs of lateral matter redistribution along slopes were especially obvious at hilltops. These terrain positions were not influenced by peripheral thawing, so ALT was minimal there and did not exceed 90 cm. A well-expressed system of TL and IL was observed there. Its total thickness was between 32 and 47 cm in silty loam soils. TL and IL were characterized by greater ice content in loamy Gleysol profiles because of the finer sediment textures and flatter mesorelief that determine wetter and colder local hydrothermal conditions. For that reason, more ice segregated at the bottom of the AL.

Upper permafrost horizons included several layers with various cryogenic structures from reticulate to lenticular and porphyritic, i.e., with ataxitic sublayers. Among the pedogenic features observed in upper permafrost horizons, oxidized $Fe^{3+}$ neoformations were visually distinct. They were associated with core sections of maximal ice content and were located at the contact between the mineral matrix and ice inclusions. There were no signs of gleyic metamorphism in permafrost in comparison with modern soils within AL. In the upper parts of hillslopes where the peripheral thawing influence was significant, TL and IL were absent in the SCC. It is likely that they have been completely thawed in recent years.

*NPT key site*

Soils at the NPT key site were classified as Arenosols, developed on sandy deposits subject to active aeolian redistribution of mineral material. Organic horizons

[2]CAVM Team (2003). Circumpolar Arctic Vegetation Map. Scale 1:7,500,000. Conservation of Arctic Flora and Fauna (CAFF) Map No. 1. U.S. Fish and Wildlife Service, Anchorage, Alaska.

**Table 1. Natural factors of tundra environments at studied key sites in Northwestern Siberia**

| Factor | Parameter | | NYD | NPT | BVN | TAZ | GYD |
|---|---|---|---|---|---|---|---|
| Climate | MAAT, °C[1] | | –4.5 | –7.1 | –6.7 | –7.3 | –10.4 |
| | MAAP, mm[1] | | 379 | 263 | 328 | 577 | 309 |
| Permafrost | Distribution | | Discontinuous | | Continuous | | |
| | MAGT, °C | | –2.2/–1.9[2] | –3.9/–1.3[2] | –6.0/–3.0[3] | –3.5/–2.0[3] | –6.0/–5.0[4] |
| | Mean ALT, cm | Sand | 187[2] | 164[2] | 105[3] | 137[3] | 128[3] |
| | | Loam | 120[2] | 57[2] | 70[3] | 58[3] | 65[3] |
| | | Peat | 43[2] | 35[2] | 43[3] | 47[3] | 46[3] |
| | Cryogenic processes | | Deflation, solifluction | Thermal abrasion, thermal erosion, frost cracking, deflation | Thermal denudation, thermokarst, thermal erosion, frost cracking, frost heaving, deflation, solifluction | Thermo-karst, thermal erosion, frost heaving, frost cracking, deflation | Thermal abrasion, thermokarst, solifluction, frost heaving |
| Geomorphology | Terrain forms | | Terraces | | | | |
| | Genesis | | Fluvial-lacustrine | Fluvial | Marine | Fluvial Fluvial-lacustrine | Marine, Fluvial-marine Fluvial-lacustrine |
| | Age | | Late Neopleistocene | Upper Neopleistocene-Holocene | Upper Neopleistocene | | Upper Neopleistocene-Holocene |
| | | | Ermakovo | Sartan | Ermakovo | Kargin | Kargin – Sartan |

Notes: [1] – data from[3] (Bulygina et al. 2025); 2 – data from; [3] – data from[4] (Khomutov et al. 2024); [4] – data from (Obu et al. 2019).

of such soils were thin (less than 5 cm) and poorly decomposed (Fig. 2 – sections NYD). Immobilization and crystallization of Fe compounds in the suprapermafrost soil horizons were, probably, connected to the presence of a contrasting mechanical barrier at 50–60 cm depth. It was well-expressed visually in soils on fluvial terraces. There were layers of alluvial and aeolian sand that gave way to bluish-gray marine clay at this depth, and the AL bottom often matches this lithological contact. On a modern floodplain, where there was no such contact observed, the Arenosol profile differed poorly horizontally by texture and morphological reflections of mineral mass pedogenic metamorphism degree.

At depths of 115–140 cm in SCC profiles on the fluvial terrace, the ice-rich permafrost layers were observed. They were characterized by lenticular cryogenic structures. Their thickness varied between 20 and 35 cm, and it decreased along as it got closer to the slope's shoulder. In the underlying permafrost horizons, cryogenic textures were massive and, less commonly, thin-layered. No gleyic or oxic Fe metamorphism was observed along the clayey layer cores, and their bluish-gray color is, most likely, the original.

### *TAZ key site*

Soils at the TAZ key site were represented by two deeply thawed (down to 150 cm) Arenosol profiles, and one far shallower thawed Histic Cryosol. Arenosols were characterized by thin (2–3 cm) organic horizons with a low plant residue decomposition degree. Histic Cryosols, oppositely, differ in low ALT (66 cm) despite the same texture due to the 30-cm thick organic horizon that limits thawing (Fig. 2 – section TAZ-24-02). The mineral part of soil profiles did not include visually well-expressed Fe neoformations, except thin so-called pseudo-fibers. Their formation is associated with gradual soil thawing and suprapermafrost oxidized groundwaters standing during the spring season. Cryoturbation process signs, such as irregular horizon boundaries, buried plant residues, and frost boil microrelief of the surface, were widely distributed across different terrain forms at the TAZ key site.

Upper permafrost in deeply thawed SCC had low ice content and massive cryogenic structures. Ice-rich layers, even if they existed, probably had thawed completely in recent years (Fig. 2 – TAZ-24-01, 25-01 sections). Despite the same mineral soil texture, in SCC on low lacustrine terraces the ice-rich TL and IL still remain due to the heat-insulating role of thick organic horizons (Fig. 2 – TAZ-24-02 section). Upper permafrost layers were of the braided cryogenic structure; the thickness of ice inclusions varied from 3 to 5–6 cm, and the distance between them was 4–7 cm. In contact with the mineral matrix and ice inclusions, the oxidized Fe concretions were observed, despite the fact that the main matrix was gleyic.

[3]Bulygina O.N. Razuvaev V.N. Korshunova N.N. and Shvets N.V. (2015). Climate Characteristics in North-Western Siberian Weather Stations. [online] Meteo.ru. Available at: http://meteo.ru/data [Accessed 20 Oct. 2025].
[4]System of Automatized Geocryological Monitoring of the Yamal-Nenets Autonomous Okrug. [online]. Monitoring.arctic.yanao.ru. Available at: https://monitoring.arctic.yanao.ru/ (Accessed 20 Oct. 2025).

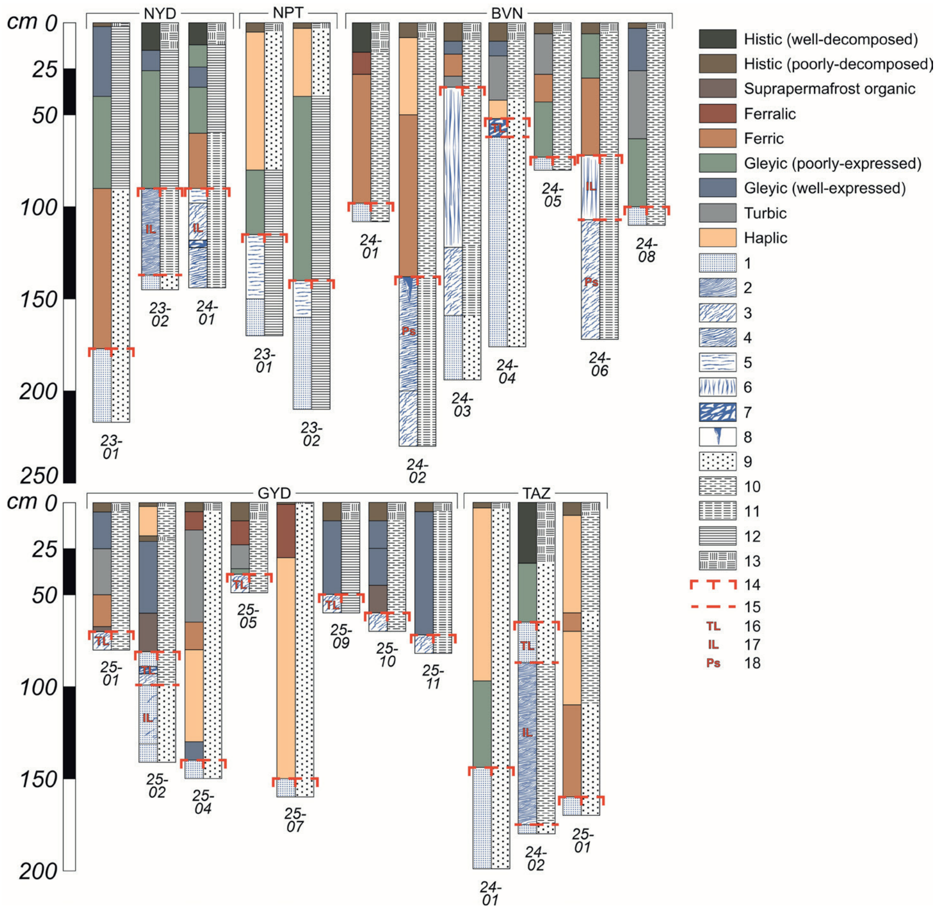


**Fig. 2. Structure of the studied SCC. Soil horizons are given according to (IUSS… 2022). Cryostructures (by (Kanevskiy et al. 2014)): 1 – massive; 2 – reticulate; 3 – braided; 4 – thin-braided; 5 – lenticular; 6 – vein; 7 – ataxitic; 8 – ice wedges. Soil texture classes: 9 – sand; 10 – sandy loam; 11 – sandy loam to loam; 12 – loam (incl. silty loam); 13 – peat. 14 – actual AL depth; 15 – estimated borders of TL and IL; 16 – transient layer; 17 – intermediate layer; 18 – Late Pleistocene permafrost. Detailed information in Table 2.**

*BVN key site*

At the BVN key site, the variety of soil types included Turbic Gelic Podzols, Turbic Gelic Gleysols, and Cryosols. The number of soil formation processes in each soil type was specific; thus, the morphological structure of their profiles significantly varied. ALT varied from 54 to 140 cm depending on soil texture, organic horizon thickness, terrain, etc. (Fig. 2 – sections BVN). In some cases, ice-rich TL and IL were completely thawed, especially as a result of lateral thawing. In SCC with lower ALT, such signs of cryoturbation processes as vortex horizon structure and the presence of buried organic horizon fragments and plant residues were clearly expressed visually. These processes were most intense in SCC on flat hilltops. In some soil profiles there were subsurface gleyic mineral horizons.

TL and IL, visually expressed in some SCC sections, were moderate and ice-rich and characterized by vein, braided, and ataxitic cryogenic structure (>50% by visible volume), the occurrence of which depended on the sediment lithological properties. Some TL and IL contained plant residues of moderate and high decomposition degrees, thin 2–3 mm layers of which alternated with mineral layers, and ice-rich zones were associated with these organic layers. The mineral matrix of permafrost in TL and IL was predominantly gleyic.

*GYD key site*

At the GYD key site, the studied soils mostly were classified as Gleyic Cryosols, Gelic Gleysols, and Podzols, profiles of which were often partly or totally gleyic, especially in the subsurface layers (Fig. 2 – sections GYD-25-01–04/09–11). Gleyization was observed in soils on elevated sandy and loamy terraces that were characterized by the coldest hydrothermal conditions within this key site, and ALT was lower there, ranging from 44 to 71 cm. The expression of cryogenic disturbances of the soil profiles was commonly low; however in some Cryosol profiles the cryoturbation features – "drops" and "tongues" – were clearly expressed. In contrast, Gleysol profiles demonstrated undisturbed horizontal profile structures and equal gley distribution. In the warmest terrain positions on slopes, the ALT reached depths of 140–150 cm. Upper parts of these profiles, and in some cases all the profiles, were disturbed by solifluction processes that were further intensified by cryoturbation.

Upper permafrost horizons on the GYD key site were moderate and ice-rich. Cryogenic textures in them were predominantly ataxitic and braided, and maximal ice content was observed in the uppermost permafrost layer, right under the ALT bottom. Lowermost permafrost horizons were ice-poor and of the massive cryogenic structure. TL and IL had a predominantly gleyic mineral matrix with rare sulfide patches. Other pedogenic signs that enrich the system of TL and IL were Fe oxides and different-sized fine-grained organic matter patches. All these signs accumulated there as a result of cryoturbation and vertical migration processes.

## DISCUSSION

According to Shur (1988), the system of TL and IL develops in frozen loose sediments despite the differences in genesis and texture. Thus, these natural-historical bodies are

**Table 2. Environmental conditions around the studied SCC sections in Northwestern Siberia**

<table>
<tr><th rowspan="2">SCC</th><th rowspan="2">Landform</th><th rowspan="2">Soil type</th><th rowspan="2">Soil texture</th><th rowspan="2">Cryogenic microrelief</th><th colspan="2">Vegetation cover</th><th rowspan="2">ALT, cm</th></tr>
<tr><th>Type</th><th>Density, moisture</th></tr>
<tr><td colspan="8">BVN key site</td></tr>
<tr><td>BVN-24-01</td><td>Marine terrace slope</td><td>Spodic Cambic Cryosol (Arenic)</td><td rowspan="7">Sandy loam to loam, incl. underlain by sand</td><td rowspan="3">Mounds</td><td rowspan="2">Grass dwarf-shrub moss</td><td>H, D</td><td>98</td></tr>
<tr><td>BVN-24-02</td><td>RTS outcrop</td><td>Protic Arenosol (Arenic, Abruptic, Turbic)</td><td>M, D</td><td>138</td></tr>
<tr><td>BVN-24-03</td><td>Marine terrace summit</td><td rowspan="2">Turbic Cryosol (Arenic, Limnic)</td><td>Grass dwarf-shrub moss lichen</td><td>H, D</td><td>54</td></tr>
<tr><td>BVN-24-04</td><td>Marine terrace slope</td><td>Solifluction terraces</td><td>Shrub grass moss lichen</td><td></td><td>52</td></tr>
<tr><td>BVN-24-05</td><td>Marine terrace summit</td><td>Spodic Cambic Cryosol (Arenic)</td><td>-</td><td rowspan="2">Grass dwarf-shrub moss</td><td></td><td>75</td></tr>
<tr><td>BVN-24-06</td><td>RTS outcrop</td><td>Turbic Cryosol (Loamic, Abruptic)</td><td>Mounds</td><td></td><td>80</td></tr>
<tr><td>BVN-24-08</td><td>Marine terrace slope</td><td>Reductigleyic Gleysol (Loamic, Turbic)</td><td>Patches (frost boils)</td><td>Grass dwarf-shrub moss lichen</td><td>L, D</td><td>105</td></tr>
<tr><td colspan="8">TAZ key site</td></tr>
<tr><td>TAZ-24-01</td><td>Alluvial terrace summit</td><td>Protic Arenosol (Ferralic)</td><td rowspan="3">Sand to sandy loam</td><td>Patches (frost boils)</td><td>Moss lichen</td><td>L, D</td><td>145</td></tr>
<tr><td>TAZ-24-02</td><td>Lacustrine lowland</td><td>Turbic Histic Cryosol (Arenic, Limnic, Thixotropic)</td><td>-</td><td>Dwarf-shrub moss lichen</td><td>H, M</td><td>66</td></tr>
<tr><td>TAZ-25-01</td><td>Alluvial terrace slope</td><td>Protic Arenosol (Ferralic, Turbic)</td><td>Patches (frost boils)</td><td>Moss lichen</td><td>L, D</td><td>160</td></tr>
<tr><td colspan="8">GYD key site</td></tr>
<tr><td>GYD-25-01</td><td>Marine terrace slope</td><td rowspan="2">Turbic Cambic Cryosol (Arenic)</td><td rowspan="5">Sandy loam</td><td>Mounds, frost cracks</td><td>Grass dwarf-shrub moss lichen</td><td>H, M</td><td>71</td></tr>
<tr><td>GYD-25-02</td><td>Marine terrace summit</td><td>-</td><td>Grass (disturbed)</td><td>H, D</td><td>81</td></tr>
<tr><td>GYD-25-04</td><td>Lacustrine lowland outcrop</td><td>Albic Podzol (Arenic, Turbic)</td><td>Frost cracks</td><td>Grass dwarf-shrub moss</td><td>M, D</td><td>140</td></tr>
<tr><td>GYD-25-05</td><td>Lacustrine lowland</td><td>Spodic Cambic Cryosol (Arenic)</td><td>Mounds</td><td>Dwarf-shrub moss lichen</td><td>H, M</td><td>48</td></tr>
<tr><td>GYD-25-07</td><td>Alluvial terrace slope</td><td>Yermic Arenosol (Fluvic)</td><td>Solifluction terraces</td><td>Shrub horsetail</td><td>M, D</td><td>150</td></tr>
</table>

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| GYD-25-09 | Alluvial terrace summit | Turbic Oxyaquic Cryosol (Loamic, Thixotropic) | Silty loam | Mounds | Grass dwarf-shrub moss lichen | H, M | 50 |
| GYD-25-10 | Alluvial terrace summit | Turbic Cryosol (Arenic, Fluvic) | Sandy loam | - | | H, D | 59 |
| GYD-25-11 | Marine terrace slope | Turbic Reductaquic Cryosol (Loamic, Sulfidic, Thixotropic) | Loam | - | Shrub grass moss | H, W | 72 |
| NYD key site | | | | | | | |
| NYD-23-01 | Lacustrine terrace shoulder | Reductigleyic Gleysol (Loamic, Limnic) | Loam to silty loam underlain by sand | Solifluction terraces, patches (frost boils) | Moss lichen | L, M | 180 |
| NYD-23-02 | Lacustrine terrace slope | Turbic Cryosol (Loamic, Limnic, Thixotropic) | | Solifluction terraces | Grass dwarf-shrub moss lichen | H, D | 90 |
| NYD-24-01 | Lacustrine terrace summit | Reductaquic Cryosol (Loamic, Limnic, Thixotropic) | | - | | H, W | 90 |
| NPT key site | | | | | | | |
| NPT-23-01 | Alluvial terrace summit | Aeolic Protic Arenosol (Fluvic) | Sand to sandy loam underlain by silty clay | Patches (frost boils) | Moss lichen | L, D | 120 |
| NPT-23-02 | Alluvial terrace shoulder | | | | | | 140 |

Notes: "-" stands for the absence of cryogenic microrelief. Vegetation cover density classes: L – low, M – middle, H – high. Moisture classes: D – dry, M – moist, W – wet. RTS – retrogressive thaw slump.

widely distributed in the Northern Hemisphere permafrost zone, especially in lowland coastal plains with tundra environments (Gubin, Veremeeva 2010; Mergelov, Targulian 2011; Kanevskiy et al. 2014; Lacelle et al. 2019; Lupachev, Gubin 2023). However, in several regions where environment development processes were more comprehensive (e.g., sources of the soil-forming materials changed each other or sharp environmental shifts occurred), it was shown that these diagnostic criteria do not easily allow distinguishing permafrost parts of SCC. In polar environments of the Western Russian Arctic (e.g., Bolshezemelskaya Tundra, North-Eastern European Russia) TL and IL could not be strongly identified using visual features only (Kaverin et al. 2012). During this study, we have also faced methodological problems with TL and IL distinguishing in the SCC research at the Yamal and Gydan peninsulas.

In this regard, we summarized ALT monitoring data that were accumulated over the periods of 3–32 years at 5 CALM polygons or long-term ALT measuring transects[5]. Despite their predominant location on automorphic landforms – terrace summits or slopes, including those covered with polygonal peatlands (Fig. 3) – presented data mostly demonstrate ALT dynamics in these regions. Accounting for the different exact ALT measuring days at each site, we used only a 50% interval (between quartiles 25 and 75%) to estimate the approximate TL thickness.

The main factor that determines ALT as well as vegetation cover density is the soil texture. The largest variation intervals and deepest thawing among all observed sites are typical for sandy soils and ALT decreases in a row: sands – sandy loam – loam – peat (Fig. 3). Polygonal peatlands demonstrate not only the lowest mean ALT but also the narrowest variations across observation periods. It determines the approximate TL thickness of 1.9–6.0 cm. Polygonal peatland showing no signs of ice wedge degradation exhibits an interquartile (Q25–Q75) interval approximately twice as wide (Fig. 3). At the BVN key site, approximate TL thicknesses varied from 6.5 to 16.2 cm, with the lowest values associated with sandy loam to loamy soils. Relatively low TL thickness under the sandy soils at the TAZ key site could be explained by the stable seasonal thawing conditions there for the relatively short observation period (Fig. 3). The attached data on ALT measurements at key sites in Northwestern Siberia demonstrate the great inter-landscape variability of mean ALT, multiannual ALT variation intervals, and approximate TL thicknesses. Thus, the relatively thin layer (likely no more than 15 cm) in the upper part of frozen sediments could be considered as the TL here. In some of the studied SCC sections the ice-rich ataxitic layers (approximately 10 cm-thick) were described in the uppermost part of permafrost (Fig. 3).

[5]https://www2.gwu.edu/~calm/data/north.htm

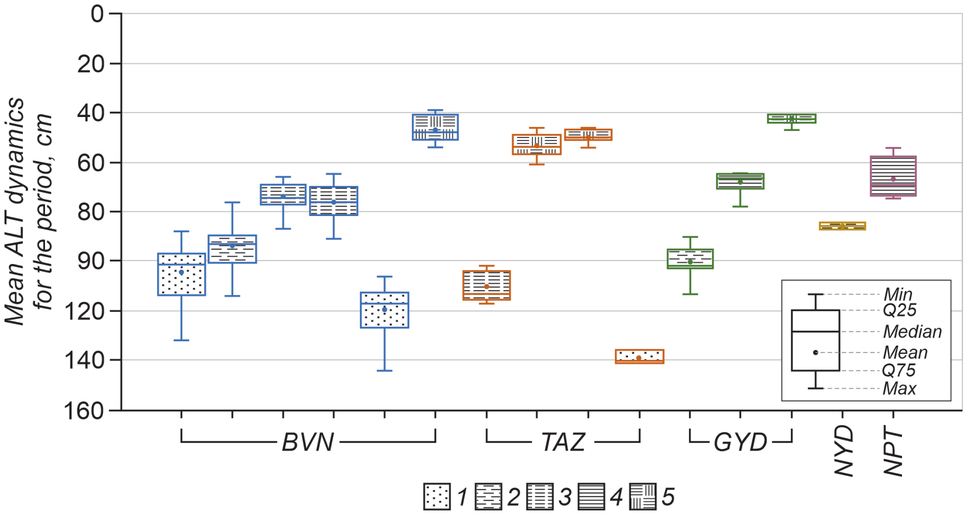


**Fig. 3. Mean ALT dynamics for the observation periods based on CALM sites[6] and ALT-monitoring transect data [Khomutov et al., 2024]. Soil texture classes: 1 – sand, 2 – sandy loam, 3 – sandy loam to loam, 4 – loam, 5 – peat. See all detailed information in the supplementary materials**

Since the majority of the studied SCC developed in automorphic conditions, most likely the development of TL was driven by exclusively climatic factors, i.e., interannual ALT variation. The presence of the IL was most often observed in the SCCs at the uppermost surfaces of terraces (Table 2).

Processes of mineral material sedimentation in Northwestern Siberia were associated predominantly with marine and fluvial accumulation. That is why light-textured sediments occupy a major part of the region. This has resulted in the specificity of sediment cryogenic structures. In the outcrop of sandy-loamy marine terrace at Beliy Island, Slagoda and co-authors (2013) identified a TL with latticed cryostructure at the depth of 30–40 cm. That could be explained by relatively shallow average ALT at Beliy Island, even in sand (Khitun et al. 2011). Central and southern parts of Northwestern Siberian tundra, covered with sandy sediments, are characterized by relatively high ALT in comparison with other more heavily textured soil-forming materials (Khomutov et al. 2024). For that reason, the cryogenic structure of frozen sands could not be confidently used as diagnostic criteria for TL and IL subdivision without considering any other features. More than 70% of the studied SCCs were from fine sand to sandy loam, and cryogenic structures of their TL were massive, layered, and (far less commonly) braided (Fig. 2). The absence of ataxitic cryogenic structures in the studied SCC could be explained by the gradual AL deepening due to the fact that the ice-rich TL probably has already thawed.

Abakumov et al. (2017), based on geoelectrical research at the northern Gydan Peninsula and Belyi Island, showed that the deeper the thawing, the smoother the rise of the specific electrical resistance at the boundary between the AL and the underlying permafrost. This change of the resistance was highest in the ice-rich TL and IL, especially under the thick uppermost peat horizon of the soils. Thus, the thicker the peat cover, the higher the probability of the full three-element composition of the SCC existing beneath it. Kanevskiy et al. (2005) showed that at Marre-Sale Cape the ice-rich TL of nearly 20 cm thickness was preserved only under the mossy-peaty cover of at least 30 cm depth. Oblogov et al. (2023) also demonstrated that this uppermost permafrost layer is the most ice-rich within the entire 10-m permafrost exposure at Marre-Sale Cape. They suggest that the relatively shallow ALT (~40 cm) remains stable solely due to the thick peat cover, noting that ALT in wet polygonal tundra has remained stable over the past ~40 years, while neighboring drained tundra has experienced a marked ALT increase. Tikhonravova et al. (2019) and Opokina et al. (2024) demonstrated that thick peat cover preserves not only the ice-rich cryogenic texture but even the small rejuvenated Holocene ice wedges in the IL of permafrost, which can be interpreted as its strong diagnostic feature (Koroleva et al. 2021). We observed a similar structure of the soil-cryogenic complexes in the northern part of the Pur-Taz interfluve, where peat cover was about 30 cm thick, the total ALT was around 65 cm, and the system of the TL and IL of permafrost comprised a nearly 1-meter-thick ice-rich mass with the braided and ataxitic cryogenic structure. Thus, the main factor that protects SCCs of Northwestern Siberia from degradation under the current climatic trends of rising air temperatures is the local environmental conditions of soils (the degree of hydromorphic expression and the moss-peat cover thickness).

Limited suprapermafrost and intrapermafrost SOM accumulation is rarely expressed in SCC cores and outcrops in the tundra zone of West Siberia, which also complicates its morphological identification. Cryoturbation is observed as one of the most important processes of the TL-IL system enrichment with SOM (including coarse and fine SOM fragments) (Kaiser et al. 2007; Gentsch et al. 2015; Lupachev, Gubin 2023). In the northeastern part of Siberia strongly cryoturbated soils occupy the majority of automorphic surfaces in the coastal lowland areas (Gubin, Lupachev 2020). A combination of cryoturbation and shallow ALT in loamy sediments leads to great variability of organic-rich patches and layers in cryogenic soils and upper permafrost (Gubin, Lupachev 2018). However, according to Gerasimova (2007), cryoturbated soils (Turbic Cryosols) occupy a far smaller percentage of the total area in Northwestern Siberia in comparison with Middle and North-East Siberia. Another reason why suprapermafrost and upper permafrost layers of the West-Siberian SCC are depleted by SOM refers to the light (e.g., sandy) texture of soils. Sandy permafrost-affected soils (Sandy Podzols, Arenosols etc.) in Northwestern Siberia are rarely affected by intensive cryoturbation in their middle and lowermost parts (Walker et al. 2009).

For that reason, the pressing challenge is to identify alternative indicators that could be used to distinguish

[6]CALM North Summary Data Table [online] (2026). www2.gwu.edu. Available at: https://www2.gwu.edu/~calm/data/north.htm (Accessed 10 Feb. 2026).

the TL and IL. Based on the consideration that pedogenic processes take an important part in the formation of TL and IL structure and composition (Lupachev, Gubin 2008; 2023), we can suggest that several biogeochemical properties could be interpreted as the result of organic and mineral matter interactions between the soil profile and upper permafrost horizons. The C:N ratio is widely used in soil science and biogeochemistry as the degree of SOM decomposition. Lacelle et al. (2019) showed that in the Canadian Arctic coastal lowlands, the C:N ratio in the AL exceeds that in the TL by more than 25% in some cases. The reason is, probably, that modern AL (including its suprapermafrost part) is enriched with raw organic matter of relatively low decomposition degree, transferred into it through cryoturbation processes. The same authors demonstrate that TL is almost indistinguishable from the underlying permafrost by C and N total concentrations and C:N ratio values. At the same time, total S concentration marks the TL-IL transition quite well. In the TL it is characterized by the widest range and higher values in comparison with the AL and lower permafrost layers as well. Perhaps the reason is that the permafrost formed under predominantly reductive conditions, where S crystallized in the form of sulfide minerals (Lacelle et al. 2019). Similar features were observed in permafrost cores from the SCCs of the GYD and BVN key sites, where the gleyic mineral matrices contained abundant small sulfide spots. Lupachev and Gubin (2023) interpreted them as the sign of the reductive hydromorphic SCC development stage of the soil formation processes on the Kolyma lowland in the Mid-Holocene.

It has also been noted that among all biogenic compounds enriching the permafrost TL, methane plays an important role (Oblogov et al. 2020; Kim et al. 2025). The biogenic $CH_4$ content in the TL of permafrost in the Marre-Sale Cape, western Yamal, is slightly higher compared to the overlying AL and underlying permafrost. The mechanism of the TL enrichment with biogenic gases ($CH_4$ and $CO_2$) can be commonly explained by the blocking role of downward freezing at the start of winter that presses the gases from the AL and preserves them in the upper permafrost layers (Kraev et al. 2017; Oblogov et al. 2020; Kim et al. 2025). Besides, another way of upper ice-rich permafrost enrichment with gases is possible in a number of permafrost regions – upward filtration and accumulation below the TL-IL system bottom. This way could be especially typical for the West Siberian permafrost zone, where deposits contain large amounts of hydrocarbon gases and gas hydrates (Khimenkov et al. 2020). Via gas-hydrate dissociation gases filter through the permafrost, and TL-IL systems can become natural barriers on the migration way because of their high ice volume. The results of the laboratory experiments held by Chuvilin and co-authors were that ice-rich frozen sediments are approximately impenetrable for fluids under the low negative temperatures. As temperatures rise, the gas permeability increases significantly even before thawing (Chuvilin et al. 2024).

As a result of downward vertical migration, the reactive chemical compounds ($K_2O$, $P_2O_5$, $Fe_2O_3$, MnO, etc.) can accumulate in the suprapermafrost parts of soil profiles and be preserved in the upper permafrost layers (Jones et al. 2020). Some of them could be considered exclusively pedogenic, formed via biochemical processes in soils, e.g., non-silicate Fe compounds (Zonn 1982).

The most commonly used approach to diagnose the TL and IL is the cryolithological differentiation of layers based on their cryostructure (Shur 1988). TL is often considered the most ice-rich layer in the upper section of permafrost underlying AL. The IL is also characterized by relatively high ice content compared with underlying Late Pleistocene deposits. This feature is typical of regions such as the Northeastern Yakutia coastal plains, where SCCs were mainly described (Lupachev, Gubin 2023). In other regions where the upper permafrost contains ice-rich sequences (like Northwestern Siberia) (Streletskaya et al. 2021), distinguishing TL and especially IL meets certain difficulties.

In some studies, it was stated that TL of permafrost contains large amounts of SOM, both its fine and coarse fractions (Kaiser et al. 2007; Mergelov, Targulian 2011; Gentsch et al. 2015; Lupachev, Gubin 2023; Cherepanova, Shepelev 2023) via processes of cryogenic mass exchange within the AL. Alekseev and co-authors (2003) discovered the possibility for the colored Fe mineral lepidocrocite to accumulate at the bottom of the AL, which also could be considered as a diagnostic criterion for AL depth. Maslakov and colleagues (2020) applied the isotopic analysis of textural ice showing that $\delta^{18}O$ values in the TL vary within the narrow interval between −14 and −11‰, indicating periodic TL thawing and enrichment with atmospheric waters with "heavier" isotopes. Observing the TL and IL system in frozen polygonal peatlands with ice wedges, Koroleva and co-authors (2021) noted that in some cases the so-called "wedge sprouts" can penetrate the IL indicating the modern stage of frost cracking process.

At present, a major part of Northwestern Siberia is characterized by a pronounced trend of permafrost zone area and vertical thickness reduction against the backdrop of warming and humidifying climatic shifts (Vasiliev et al. 2024). Consequently, the number of geomorphological cryogenic processes is conditioned by the upper ice-rich permafrost layer dynamics via thaw ground subsidence (Streletskiy et al. 2025), thermal denudation (Nesterova et al. 2025), thermal abrasion in the coastal areas (Isaev et al. 2018). Until 2050, the significant expansion of the area exposed to various destructive cryogenic processes is projected (Kislov et al. 2023). SCCs of Western Siberian tundra are extremely unstable to modern climate change. The areas with full-profile SCCs, where the TL-IL system plays the shielding role and protects underlying permafrost and massive ground ice, are relatively limited in spatial distribution. The SCC sections with partially or totally thawed TL occur the most often, and the ALT there reaches the IL. The NYD-24-01 SCC section was presumably of such type: its frozen part differed markedly from the thawed soil profile – it consisted of an ochric-gray-colored mineral matrix where the modern AL was dominantly gleyic. The TL forms under the influence of cryogenic mass-exchange processes, and the lowermost part of the AL can not differ markedly from it; thus, the TL presumably degraded completely here. Soils on light-textured sediments of the southern part of the Yamal and Gydan peninsulas and northern Pur-Taz interfluve are often characterized by the full absence of the TL and IL in the system of SCC. Probably, the sharp transition from the active layer to the underlying permafrost shows the physico-chemical features of the shift of the environmental conditions here in the Early Holocene. BVN-24-02 section had an AL of nearly 140 cm depth due to the lateral heating of the thaw slump wall. The isotopic composition of the ground ice wedge head in the uppermost permafrost layer was similar to the earlier studied Late Pleistocene ones in the region (Vasil'chuk 2025 – personal communication), thus we conclude that the TL and IL fully degraded because rejuvenated ice wedges in the IL can possibly be of Holocene age only.

## CONCLUSIONS

During the first stage of detailed SCC research in Northwestern Siberian tundra environments, we obtained initial results on the morphological and cryogenic structure of thawed and frozen parts of the SCC and attempted to broaden the approaches to TL and IL diagnostics in the upper part of permafrost in different landscapes.

Regardless of the geomorphological level, SCCs of the permafrost zone of Western Siberia share a common characteristic: their full-profile variants, comprising two main structural elements – TL and IL – are spatially limited due to lithogenic and ecosystem factors. The widest distribution of deeply thawing sandy sediments where continuous and thick vegetation cover is unable to develop due to its depletion in nutrients and active wind erosion that destroys the root layer prevents the full-profile SCC development in modern conditions. Among all studied SCCs, the ALT was the highest in sandy soils, and morphologically expressed TL was absent. Modern soil formation took place in the seasonally thawed layer that overlies the degrading IL or Late Pleistocene permafrost, containing fragments of ground ice (massive or wedge). Besides, relatively low ice content in sands rarely allows one to confidently differentiate TL and IL by visual cryolithological signs (ice volume and inclusions), and such features as organic concentration zones (with raw poorly-decomposed plant residues) typical for some permafrost regions (Kolyma, European North-East Russia, Alaska), were observed here only in individual SCC sections where average ALT was below 40–60 cm. The intra-annual temperature gradients in such soils were highest, and that is why cryogenic mass exchange properties were most intensive. It was also a methodological challenge to distinguish the TL and IL in the complex polygenetic structure of some SCC frozen parts. In some of them periods of deepened thaw were accompanied by sediment redistribution, burying organic layers and exposing mineral material. Transition from synlithogenic soil formation to postlithogenic introduces several characteristics that complicate the morphological identification of TL and IL in the SCC.

For a major part of the studied key sites, the Holocene was probably a period of variable-intensity soil-permafrost cryogenic mass exchange. These fluctuations were explained by the wide intervals of soil thawing, especially on sandy sediments. Relatively stable permafrost conditions were in the thick peat massifs only. The presence of thick organic horizons on the soil surface that reduces the heat fluxes into soils and limits the ALT is the leading factor of the thawing stabilization. Only in such cases, the full-profile SCCs still remain even in mineral sediments.

Developing the diagnostic criteria to raise the confidence of TL and IL diagnostics (or assessment of their partial or complete thawing) in permafrost layers is under future consideration. Biogeochemical parameters, micromorphological indicators of pedogenesis, and the chemical composition of textural ice are among the candidates for such diagnostic criteria. ■

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