The transient layer of permafrost of the Eastern Chukotka coastal plains, NE Russia

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ABSTRACT

The paper presents the results of field and laboratory studies of permafrost transient layer characteristics within key study polygon of Eastern Chukotka coastal plains. The transient layer underlies the active layer and is characterized by an increased ice content, which determines its protective characteristics under conditions of short-period fluctuations in air temperature. Transient layer plays key role in thermokarst and thermal erosion, which are one of the most widespread dangerous processes for engineering facilities and infrastructure in the Arctic. Within the key area, the relief and Quaternary sediments were studied, surficial drilling was conducted, and the isotopic composition of the ice exposed in the boreholes was analyzed. As a result, variations in the transient layer thickness, its cryolithological structure, and the composition of stable oxygen isotopes were determined. Depending on the geomorphological conditions and lithological composition of the sediments, the transient layer thickness reaches 1.2 meters, while its gravimetric moisture content varies within wide range: from 70-150% in loamy sediments to over 1000% in peat. The stable oxygen isotopes composition ($\delta^{18}O$) in the transient layer is identical for all cores and varies from –11.4 to –14.0‰ that may be considered as diagnostic feature of this object in further studies.

KEY WORDS: Chukotka; Permafrost; Active Layer; Transient Layer; Climate Change

INTRODUCTION

Contemporary climate changes inevitably affect the state of permafrost. First of all, this concerns an increase in the mean annual ground temperature (MAGT) and the active layer thickness (Romanovskiy et al., 2017; Biskaborn et al., 2019) in different permafrost regions, including northeastern Russia (Abramov et al., 2019). An important role in the heat exchange between the permafrost and the atmosphere is played by the so-called transient layer (TL), a horizon within the uppermost part of the permafrost, passing into a thawed state under conditions that are most favorable for thawing (Shur, 1988). The TL of permafrost is quite complex in composition and cryogenic structure part of the ground strata both in the vertical section and in the lateral extent. It plays an exceptional role in a majority of exogenous processes occurring in the upper permafrost (Romanovsky, 1993; Shur et al., 2005; Lupachev and Gubin, 2008). Along with layer it forms a buffer system, which determines quite broad conditions for the permafrost existence. That’s why some researchers (Konishchev, 2009) call it a protective layer. Numerous studies have shown that the TL is characterized by high ice content, therefore it prevents excessive thawing of the upper part of the permafrost and contributes to the preservation of its thermal stability (Shur et al., 2005). Climatic trends of recent decades have led to partial or complete TL degradation, which is reflected in the activation of exogenous processes: thermokarst, thermal erosion and cryogenic landslides, recorded in large numbers in different permafrost regions (Nitze et al., 2019), including areas of low-temperature permafrost (Farquharson et al., 2019). For the territory of Eastern Chukotka, the predicted rates of permafrost degradation in the 21st century will lead to a significant soil surface lowering due to ground ice melt and subsequent activation of exogenous processes (Maslakov et al., 2019).

The purpose of this paper is to determine the current parameters (thickness, ice content, cryogenic structure, stable isotopic composition and distribution) of the transient layer within the key study area of Eastern Chukotka located within coastal plains of quaternary age. In our opinion, besides obvious cryostratigraphic features, the lightest $\delta^{18}O$ values may also indicate the transition of TL into permafrost deposits, which did not thaw for historic timescale and thus, the $\delta^{18}O$ variations may serve as indicator of TL foot marking. The research is based on long-term monitoring observations of the seasonal thawing depth and subsidence of the soil surface, data from drilling shallow boreholes in 2019-2020, as well as the results of field landscape studies.

Study area

The key study area (Fig. 1, yellow outline) has an area of 172 km^2. It is located within the coastal plains of the eastern part of the Chukotka Peninsula and the adjacent foothills and slopes of the Genkany (Teniany) ridge, composed of Precambrian rocks and Early Devonian shales, broken by Early Cretaceous granite intrusions.

A plain is composed of gently sloping and hilly surfaces that makes up a system of terraces of various ages and genesis. There is a fluvioglacial plain located in the eastern part of the polygon, on the southern coast of the St. Lawrence Bay, It is composed of moraine deposits of the Lower Pleistocene and reaching an altitude of 60-80 m above sea level. The surface is hilly, slightly sloping. On the coast of the St. Lawrence Bay it emerges in the form of numerous thermocirques and marine abrasion scarps up to 20 m high. The deposits are represented by gray and bluish loam, with the inclusion of unsorted low-rounded debris up to 2 meters in diameter; in marine outcrops, there are inserts of medium-grained sand with the inclusion of pebbles. Moraine deposits are fragmentarily overlain by Holocene peatlands containing ice wedges (Vasil'chuk et al., 2018).

The central and western parts of the polygon are represented by the 4th marine and glacial-marine terrace of Early and Middle Pleistocene. It is 40-80 m above sea level and is composed of gray loams with the inclusion of boulders and yellow and pale sands with the inclusion of pebbles of marine genesis. The surface of the terrace is flat, has a slight slope towards the sea, on the coast it is complicated by ravines and gullies.

The 3rd marine terrace is Middle and Late Pleistocene age and has absolute heights of 15-30 m and composed of sands with the inclusion of pebbles. Within the polygon, the terrace is found in the western part; it also forms erosional remnants in the valley of the Lorinka River.

In the western part, the polygon is represented by the valley complex of the Lorinka River. (see Fig. 1). The floodplain terrace of the river has a height of 10-15 m and is composed of sands, sandy loams and loams of the Holocene age. The floodplain of the river, like other rivers within the polygon, is narrow, composed of loams and sandy loams. The riverbed is paved by alluvium of pebbles and rounded boulders.

The territory of Eastern Chukotka is characterized by a combination of the arctic and subarctic climate, which is caused by the significant influence of sea air masses. Summer is cloudy and cool; winter is long, with frequent and prolonged snowstorms. The average annual rainfall in the east of Chukotka grows from north to south from 230 (Uelen) to 690 mm (Provideniya); the mean annual air temperature for the last decades is –6.1ºC (Kobysheva, 2001).

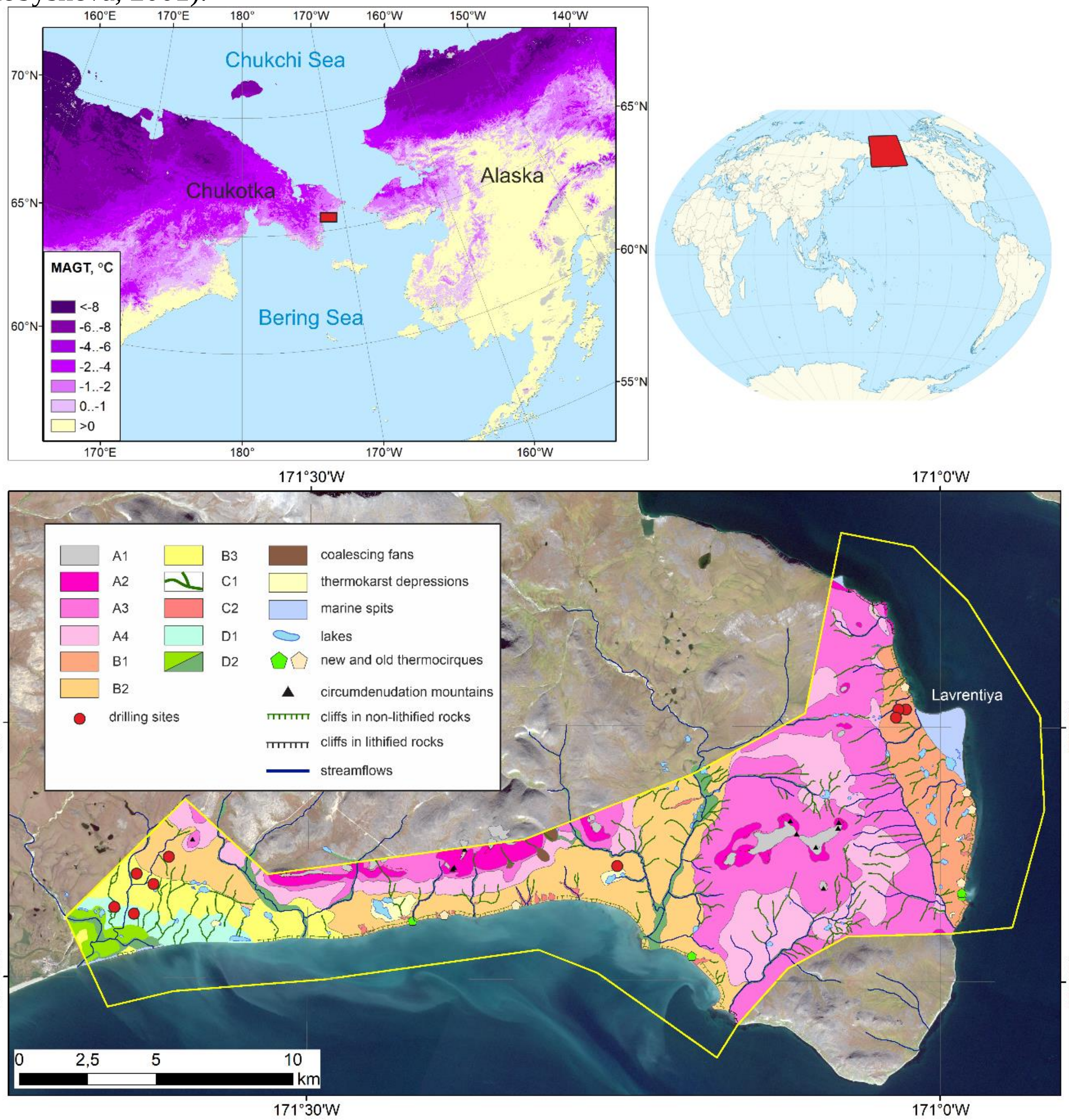

Figure 1. Study polygon. Mean Annual Ground Temperature (MAGT) is from Obu et al. (2019). A1 – summit plains; A2 and A3 – steep (> 15°) and medium (5-15°) mountain slopes; A4 – mountain foothills (<5°); B1 – fluvioglacial plain; B2 – the 4th marine and glacial-marine terrace of the coastal plains; B3 – the 3rd marine terrace; C1 – upper elements of the hydrographic network (runoff troughs and dells), C2 – ravines; D1 – the 1st floodplain terrace of the Lorinka River; D2 – deltas and floodplains of small rivers.

Permafrost has continuous extent within the study polygon. Taliks are open and confined to Lorinka and Akkani Rivers as well as to large lakes. In low-lying coastal areas, the

permafrost thickness is 100-200 m with the MAGT of –2 to – 4 °C (Gasanov, 1969; Maslakov et al., 2019), on the slopes and the summits of the Genkanyi Ridge the thickness in permafrost increasing. Active layer thickness varies from 0.3 to 3.0-4.0 m depending on landscape conditions. Thermokarst and thermoerosive landforms, ice complex and massive ice beds are widespread here (Gasanov, 1969; Maslakov et al., 2018; Vasil'chuk et al., 2018). The air temperature has been increasing in the region since 1970s (Maslakov et al., 2020a) that affects to permafrost conditions and triggers thermal erosion ravines and retrogressive slumps formation.
The study area is attributed to typical polar tundra (ET) climate type according to the Köppen-Geiger updated classification system (Kottek et al. 2006). Rocky summits and slopes and occupied by barrens, stone deserts and curtain tundra of various grasses on primitive soils. In the most favorable sites, alpine meadows appear. Starting from an altitude of 150-200 m a.s.l. typical tundra soil-plant associations are found. These are low-shrub, sedge-moss and hummocky tundra and sedge swamps and meadows on tundra gley, peaty boggy soils. Intrazonal types of soil and plant communities are confined to floodplains and river deltas and characterized by seasonal moisture regime. Sedge-moss meadows with creeping willows on alluvial soils cover these surfaces. Stony riverbeds, sea pebble beaches, and spit areas are usually without any vegetation.

MATERIALS AND METHODS

The study of Quaternary sediments within the polygon was carried out by analyzing the previously published studies (Gasanov, 1969; Ivanov, 1986), as well as using the State Geological Map at a scale of 1: 200,000 (sheet Q-2-XXI, XXII, XXIII). The studied materials were compared with the results of field observations of natural outcrops and drilling of shallow boreholes.
Drilling and coring of the active layer and the upper horizons of the permafrost (down to 2.7 m) was carried out mainly near the active layer monitoring sites within CALM (Circumpolar Active Layer Monitoring) program (Maslakov et al., 2019) with an ADA GroundDrill 15 motor-drill. The drilling was performed in late August, when the active layer reached approximately 70-80% of its maximal thickness. The extracted core was described, visual ice content was assessed, ice was sampled for stable oxygen isotopes composition ($\delta^{18}O$), and gravimetric water content. The drilling sites had landscape descriptions and measurements of active layer thickness, vegetation cover parameters and ground water level. The sites are shown in Fig. 1.
Water samples were analyzed in the stable isotope laboratory of the Geography Faculty at Lomonosov Moscow State University (Prof. Yu. Vasil'chuk and Dr. N. Budantseva) using a Finnigan Delta-V Plus mass spectrometer applying equilibration techniques. The method details and measurements accuracy were described in Vasil’chuk et al (2018). The recent studies in the region (Maslakov et al., 2020b) revealed that the $\delta^{18}O$ values for ice from TL here vary from –11.5 to –14.0‰ that is different from ice of wedges (–14.3 to –18.0‰) and massive beds (–16.2 to –22.4‰). These findings allow us to establish lower boundary of TL as –14.0‰ and differ it from the rest permafrost using stable oxygen isotope data.

RESULTS

Analysis of the relief, vegetation and Quaternary deposits of the polygon showed a motley combination of landscape and lithological conditions. Frozen ground exposed in boreholes allow assessing the state of the transient horizon and its characteristics.

The Early Pleistocene fluvioglacial plain in the east of the polygon is composed from the surface by loams with gravel and boulders inclusion, while the upper permafrost layer has a layered cryostructure. The average moisture content of the transient layer (W_{tot}) varies within range of 70-110% in loams and 200-600% in lenses of peat. According to the data from 5 boreholes within this plain, the thickness of the TL was determined by the higher moisture content and is 50-70 cm. The stable water isotope composition ($\delta^{18}O$) of ice in the layer varies within –11.5 ‰ to –13.5 ‰.
The sediments of the 4th marine and glacial-marine terrace were drilled by 2 boreholes in the central and western parts of the key polygon (Fig. 1). The core of the borehole 2020-01, drilled closer to the rear part of the terrace (see Fig. 1), contains loam, sandy loam and interlayers of peat with the inclusion of crushed stone and gravel. The cryogenic structure for loamy-sandy loam deposits is massive (W_{tot} = 25-120%), for peat it is lenticular (W_{tot} = 150-200%). Apparently, TL is strongly reduced here. The borehole 2020-05, exposing the terrace deposits in the center of the polygon (Fig. 2), has a well-defined TL 1 m thick with a lattice cryogenic texture. As the depth increases, the $\delta^{18}O$ of ice decreases from -12.5 ‰ to -18 ‰, capturing the sediments of the permafrost underlying the TL.
Sediments of the 3rd marine terrace from the surface are loamy without inclusions, interbedded by peat lenses or peat of peatlands (boreholes 2019-04 and 2020-02). The exposed thickness of the TL is 50 cm; its foot was not exposed by the borehole. The moisture content of TL deposits here is 100%; the cryogenic structures are layered, lenticular, with often interlayers of pure ice layers of 3-8 cm thick. The $\delta^{18}O$ variations in ice are –11.4 to –13.4 ‰ without a clear trend in depth.
The boreholes drilled on the floodplain terrace of the Lorinka River exposed a peatland (borehole 2020-03) and a loam with the inclusion of rock waste (borehole 2020-04, see Fig. 2). The moisture content of peat exceeds 1000% near the TL roof (depth of 70 cm below surface level) and decreases with depth to 400% (160 cm). The cryogenic structure is lattice and ataxitic; the isotopic composition of ice varies from –12.4 to –16.8 ‰. Loamy deposits have layered, less often reticular, ataxitic and lattice cryogenic structures and the moisture content of 120-150%, without a gradient in depth (see Fig. 2). Apparently, the TL starts from a depth of 70 cm and smoothly transforms into permafrost with a small shift in ice content and a change in the structure at a depth of 185 cm.
The deposits of floodplains, riverbeds, beaches and marine spits, as well as sedimentary cover of the Teniani Ridge, were not exposed by drilling.

CONCLUSIONS

The conducted studies revealed significant variations in the TL parameters within relatively compact key study polygon in Eastern Chukotka. Depending on the geomorphological level and composition of the sediments, the thickness of the transient layer is from 0.0 to 1.2 meters; its gravimetric moisture content varies within wide range: from 70-150% in loams to over 1000% in peat. It's noticeable that the deposits moisture content decreases along with increasing depth. The stable oxygen isotopes composition in the TL is identical for all cores and varies from –11.4 to –14.0‰ that corresponds with the previous studies (Maslakov et al., 2020b).

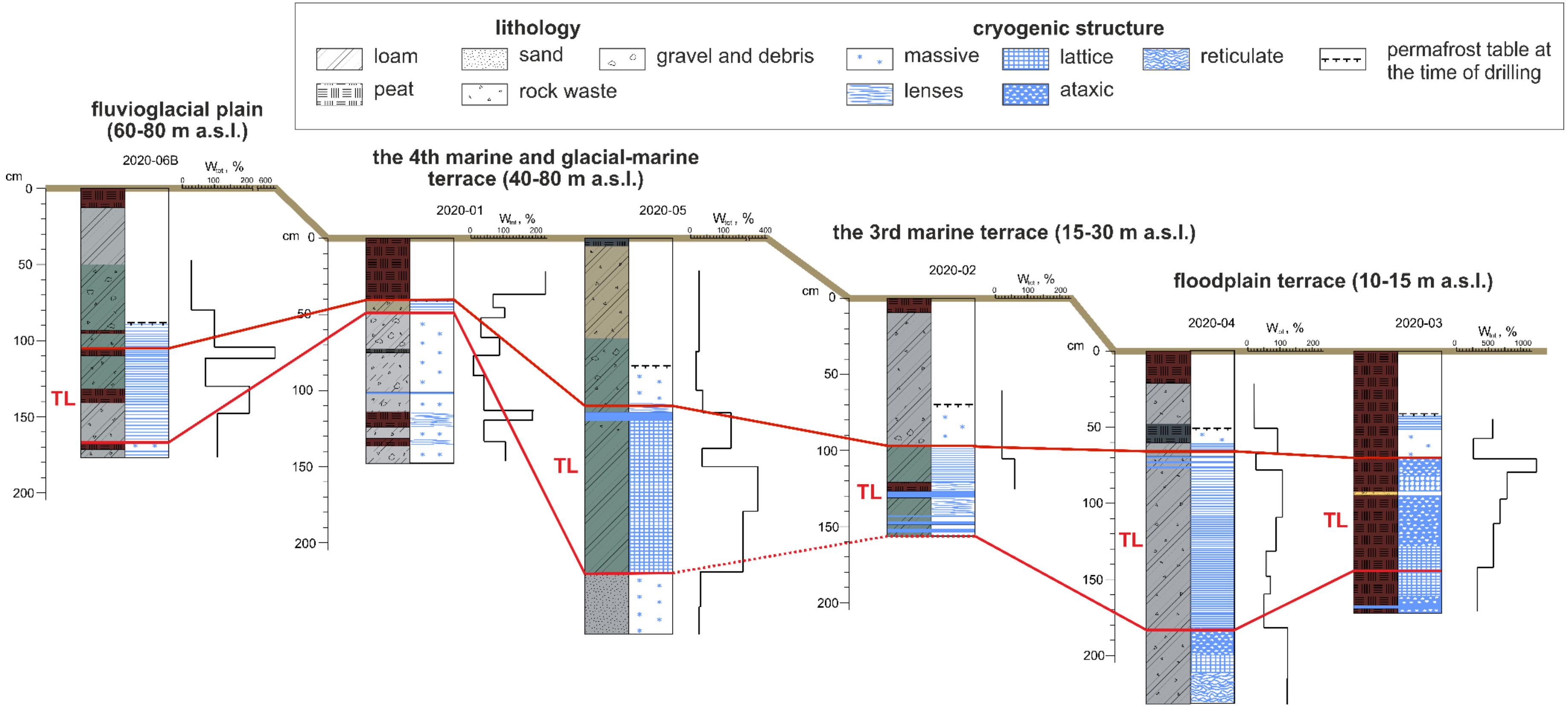

Figure 2. Summary scheme of lithology, cryogenic structure, and TL thickness for the coastal plains of the Eastern Chukotka

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