Temperature Field of the Permafrost Zone in Northeastern Siberia

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Abstract. The Northeastern Siberia includes the coasts of the Sea of Okhotsk, part of the North Siberian Lowland, the Central Siberian Plateau and the Lena Delta. Based on field measurements and calculations, this study characterizes the regional distribution of permafrost temperature in the layer of zero annual amplitude (ZAA). Permafrost temperatures vary over a wide range from -2 to -13°C. Analysis of ZAA temperatures indicates that permafrost is transient in much of the study region. In its northern part, especially where diluvial deposits are present, temperature profiles are isothermal or have inverse (negative) gradients. The temperature field in the areas of pre-Quaternary carbonate rocks is characterized by wide scatter of the values and often by higher ZAA temperatures. This is due to the karst process in carbonate rocks which is associated with heat release. This process likely occurred below the bottom of post-catastrophic basins, resulting in greater heat flow and disturbance of the equilibrium state of permafrost. The layers of dolomite flour over the pre-Quaternary carbonate rocks provide additional evidence of the high water contents in upper permafrost during deposition of the diluvial sequence. Temperatures below ZAA in these areas may reach -4°C, while similar settings without carbonate rocks have temperatures below ZAA as low as -8 to -11°C. This study has confirmed the high variability of ZAA temperatures in the region.

1. Introduction

The study area is bordered on the south by the Arctic Circle, on the north by the shoreline of the Laptev Sea, on the west by the 112°N meridian, and on the east by the Lena river bed at the foot of the Verkhoyanski Range. The major geomorphological elements here are the Central Siberian Plateau (the summit plain 400-600 m, max. 900 m), the North Siberian and Central Yakutian Plain (100-400 m), the Primorskaia Lowland (up to 100 m). The Primorskaia Lowland and the Lena River delta are separated from the North Siberian Plain by the low (up to 300-500 m) Pronchishchev Ridge and the Czekenowski Mountain Range. Mean annual air-ground interface temperatures in the study area increase from the Laptev Sea shore (-15°) to the Arctic Circle latitude (-11°) according to the mid-1980s observations [1]. Present mean annual temperatures are approximately 2° higher according to the weather stations in the area (long-term average annual for 2010-2015). A rapid increase of air-ground interface temperature in the Arctic zone of the Russian East in recent decades may result in degradation of the permafrost zone and increasing probability of natural disasters associated with periglacial processes.
2. Methods
The study uses temperature data of the permafrost zone given in published and handwritten reports from the collection of the Ministry of Industry and Geology of the Sakha Republic (Yakutia): S.V. Aldakushkin et al. 1979, A.Yu. Derebiagin et al. 1983, S.N. Buldovich, S.F. Khrutskiy 1990, S.F. Khrutskiy, S.V. Aldakushkin 1976, etc. Also, we used data from the “Geocryological Database” by M.N. Zheleznjak, in preparation, be permission of the author. Data on stratigraphy, lithological composition, and distribution of Quaternary sediments as well as structure of the permafrost zone are obtained from published studies, including those of the Russian-German expedition [2, 3, etc.], and our own observations.

3. Results and discussion
V.T. Balobaev [4] showed that both the equilibrium and disequilibrium permafrost zone is found in Northeastern Asia. Equilibrium permafrost is in thermal equilibrium with underlying rock that is expressed by the heat flux equilibrium at both sides of the interface. Disequilibrium permafrost is characterized by a lower heat flux than equilibrium. Disequilibrium permafrost results from hysteresis between freezing-thawing process and a change of thermal regime following climate fluctuations. V.T. Balobaev suggests that low heat flux in disequilibrium permafrost is caused by composition of deposits constituting a particular permafrost zone. Upper disequilibrium permafrost is formed by disperse rock with high moisture capacity. The higher the moisture capacity, the higher the phase heat generation and absorption, the lower the phase boundary moves.

The survey of the study area enabled us to define the limits of development of the two permafrost thermodynamic characteristics, to specify genetic varieties and thickness of Quaternary syngenetic permafrost, lithology, their limits, the age of the pre-Quaternary bed, to characterize parameters of permafrost table in more detail: the depth of zero annual amplitude (DZAA) and the temperature at its base.

Clarifying the genesis of syngenetic permafrost allowed reconstruction of sediment deposition conditions, thus addressing the problem of the origin of disequilibrium permafrost.

Disequilibrium permafrost occurs in the study area within the following morphostructures: the North-Siberian Lowland, the Primorskaia Lowland, and in certain sections of the presented part of the Central Yakutian Plain. The rest of the area, the Central Siberian Plateau (the Anabar Plateau, the Olenek Plateau (the Kystyk Plateau), the Vilyuy Plateau) is dominated by equilibrium permafrost.

The areas of disequilibrium permafrost are dominated by surface syngenetic permafrost Quaternary sediments: ice complex, deposits of catastrophic outbursts (diluvium), glacial deposits, eluvial and slope deposits.

Ice complex deposits in the study area are found in the Primorskaia Lowland, in the coastal zone between the Anabar and Olenek bays and in the Lena River delta. The complex is formed by loess loam up to 50-60 m thick with high iciness (up to 60-80 volume percent) and thick (up to 20 m) vertical ice wedges. The origin of the complex is still controversial. Many researchers following E.M. Katasonov [5, 6, etc.] suggest their floodplain genesis, others, supporting S.V. Tomirdiaro [7], consider their cryogenic-aeolian genesis. In our opinion, the origin of the ice complex is associated with formation of the shallow periglacial basin of the ice shelf of the Laptev and the East Siberian Sea [8, 9, etc.]. The age of the ice complex lies within 60 to 15 thousand years ago [10]. The investigated deposits were opened up approximately 68 m deep in the northern section at the Mamontov Klyk Cape near a coastal step about 24 m high [11, 12]. Temperature data were provided by M.N. Grigoriev [13]. At the depth of about 12 m, the seasonally active permafrost base was found, with temperature t°C= -12.8°C very close to the present air-ground interface temperature in this section of the Primorskaia Lowland. At the depth of 64 m the temperature is -12.6°C (see Table 1, No. 1). It means that the geothermal gradient is 0, while the temperature step is indefinable since it is very large.

Geothermy of the same deposits but somewhat farther East was investigated earlier by N.F. Grigoriev [14] in the Lena River delta at the Olenek Channel in the Chay-Tumus area. Geothermal characteristics of some wells investigated by him are presented in Table 1 (No. 2).
Received data show a low heat flux from the lower limit of the phase boundary (low values of the geothermal gradient and high ones of the geothermal gradient). In the permafrost table up to 60 m the temperature is practically equal to the present mean annual air-ground interface temperature (-11°C).

**Deposits of catastrophic outbursts (diluvium)** are discussed for the given study area for the first time. Diluvium (from Latin diluvium “flood”) is a genetic type of loose continental deposits resulting from accumulation of catastrophic outbursts of Pleistocene glacier-dammed lakes in discharge basins. Identifying the Quaternary deposits within the study area as those of diluvial genetic type differs from the views of most researchers suggesting that it is either an area of accumulation of glacial deposits [15, 16], a region of marine deposits [17], or an area of modern alluvial deposits. Formation of diluvium was caused by the break-up of the ice shelf of East Arctic seas, with the pre-ice age freshwater basin discharging onto adjacent land [8, 18, 19]. Peak flows could be as high as 200 m above the modern sea level.

We identified three lithological types of accumulative diluvium within the study area: sandstone, siltstone-sand-pebble and sand-siltstone conglomerate. **Sand lithofacies of diluvial-accumulative deposits** are most prevalent in the Lena River delta, forming the Argaa-Muora-Sise Island (100x80 km). Exposed thickness of deposits is about 30 m. Instrumental data on permafrost geothermy of these syngenetic permafrost deposits are not available. Mean annual temperature according to circumstantial evidence defined using the cartogram method [19] is close to t°C=−12°C which corresponds to present mean annual air-ground interface temperatures or is somewhat lower.

**Siltstone-sand-pebble diluvium** (referred to as SSP in Table) comprise the central part of the North Siberian Plain (between the Lena and Anabar River). Full thickness, about 80m [20], of this deposit facies was opened up in the mouth of the Tigyan River flowing into the Kozhevnikova Bay (the Khatanga Gulf). Geothermal data are given for wells in the North Siberian Lowland also, but somewhat to the west of the area under consideration (Table 1, No. 3): section 146 72°52′36.49″N 105°23′20.12″E, section 147 73°01′18.40″N 110°10′49.38″E, section 144 71°55′50.34″N 97°27′09.33″E (data by M.N. Zheleznyak).

Negative gradients (No. 146, 144) indicate a low isolated heat flux. A higher temperature gradient (No. 147) and a sharply negative one with a low value of the geothermal gradient (No. 146) at low temperature of the SSP base rather suggest local heat migration to supercooling areas.

**Sand-siltstone diluvium facies** (Table 1, SS, No. 4) occur on edges of the North Siberian Lowland and, likely, on the presented section of the Central Yakutian Plain. On the northern edge, these deposits overlie sedimentary semi-rock forming the Pronchishchev and the Czekanowski Ridge, while on the southern edge overlying mostly carbonate rocks forming sides of the Anabar Plateau.

Geothermal description of syngenetic permafrost siltstone-sand-diluvial deposits is made using wells in the basin of the right tributary of the Anabar River Ebelyakh (A.Yu. Dereviagin et al., Moscow State University, 1983).

The opened deposits of this facies are 2.5 to 17 m thick. The depth of zero annual amplitude lies in Cambrian carbonate rocks underlying these facies. Non-gradient temperature curve continues into pre-Quaternary rocks without noticeable change of shape. The temperature at the depth of zero annual amplitude is significantly higher than in other Quaternary sheets overlapping terrigenous deposits. In our view, it is related to the exothermic reaction of solution of underlying Cambrian carbonate rocks.

**Glacial deposits** are restricted by the southern foot of the Anabar Plateau and the western foot of the Olenek Plateau. They are widely spread on the right bank of the Lena River beyond the study area. In the study area, they are represented by rudaceous sediments up to first tens of meters. They are not studied in terms of geothermy. The depth of zero annual amplitude at the foot of the Anabar Plateau is estimated to be -5°-6°C according to cartograms. This value is 2°C higher than present mean annual air-ground interface temperatures.

Within the **area of eluvial deposits** in the disequilibrium permafrost region (Table 1, EDP, No. 5), in the Ebelyakh River basin (A.Yu. Dereviagin et al., Moscow State University, 1983) as in the case of thin sheets of channel lag deposits, higher t’0 values, zero gradients, and large temperature steps are noted. Here, eluvium of dolomite powder(sand) also overlies carbonate base.
In the disequilibrium permafrost region, non-gradient temperature curves are observed at least as deep as 20 m on denudation surfaces (often diluvial-erosional) formed by semi-rock and rock. Areas of equilibrium permafrost are characterized by development of thin eluvium at certain watersheds and slope formations with predominant denudation surfaces of various origins.

Eluvial deposits in the study area (Table 1, EEP, No. 6) demonstrate various lithological composition: sandy loam and loam, often with peat, crushed stone of carbonate, volcanogenic, terrigenous, and crystalline rocks from 1 to 10 m thick.

In the areas of their occurrence the temperature at the depth of zero annual amplitude is $-1.5 \pm 6.5^\circ$C (Khrutskiy, 1979). The lowest values of this parameter are approximately 2°C higher than the air-ground interface temperatures of these regions. Relatively high permafrost temperatures may be related to the warming effect of ground cover, surface water filtration, exothermic reaction of base carbonate solution, and other factors.

Geothermal characteristics of eluvial areas was received from wells (data by M.N. Zhelezniak) at the left bank watershed of the Satykan River (well 69, 66°10'0.00''N 111°40'0.00''E, wellhead mark 737 m).

In the areas of slope deposits (Table 1, SDEP, No. 7), the following geothermal characteristics were obtained for the well 305, 66°26'0.00''N 112°17'60.00''E, wellhead mark 346 m (data by M.N. Zheleznyak).

Permafrost in the area of bedrock exposed by denudation and exaration (Table 1, ExEP), No. 8) at the Anabar Plateau is illustrated by the section Yryas, wells 11 and 7 (data by M.N. Zhelezniak). The wells are drilled several tens of kilometers to the west of the study area, well 11 coordinates 69°48'29,00''N 105°57'43,97''E, wellhead mark 604 m, well 7 coordinates 69°48'28,61''N 105°57'42,32''E, wellhead mark 604 m. The temperature profile of the permafrost table under denudation surface is typical for equilibrium permafrost: a positive temperature gradient and a relatively low temperature step.

4. Conclusions

The temperature field of the study area is characterized by mosaic structure. It is formed by sections (polygons) within which permafrost temperature has a relatively narrow range. A general feature of the temperature field is that the lowest temperature characteristics are within the limits of the equilibrium temperature field and cover the north-north-west part of the area. The temperature range at the depth of zero annual amplitude (DZAA) lies within $7^\circ - 1^\circ$C. The range of the disequilibrium temperature field is controlled by negative morphostructures. There is a possibility that cooling of the disequilibrium field might have resulted from gas hydrate dissociation at drastic pressure changes [21, 22, 23].
Table 1. Geothermal characteristics of Quaternary syngenetic frozen ground and denudation surfaces in Northeastern Siberia.

| Interval, m | Geothermal step | Geothermal gradient degrees/100 m | Source |
|-------------|-----------------|----------------------------------|--------|
| 1 1 12 -12.8 | 10-60 52 52 | 0 | [13] |
| 2 1 -8.7 10 | 52.5 52.5 | -1.2 | [14] |
| 4 -10.6 12 | 58 58 | +1.9 | |
| 5 -11.2 12 | 33.14 33.14 | +1.48 | |
| 9 -10 12 | 52 52 | +1 | |
| 3 146 -6 10 | 10-30 5.51 | -18.1 | data by |
| SSP 147 -11.07 10 | 10-30 32.25 | +3.2 | M.N. |
| SSP 144 -7.31 10 | 10-30 285.7 | -0.35 | Zhelezniak |
| 4 Ebelyakh -8 12 | 12-18 | - | data by |
| well 39 | | | A.Yu. |
| SSP 48 -4.5 17 | 3 | - | Dereviagin |
| SSP well 40a | -6.8 14 | - | et al, 1983 |
| EDP 5 Ebelyakh -5 14 | 12-19 | 0 | |
| well 49 | | | |
| EEP 6 69 | -6.91 10 | 7.8 | +12.82 | data by |
| SDEP 7 305 | -4.55 10 | 75 | +2.47 | M.N. |
| ExEP 8 11 | -7.66 10 | 19.23 | +5.2 | Zhelezniak |

SS - sand-siltstone; SSP - siltstone-sand-pebble; EDP - eluvial disequilibrium permafrost; EEP - eluvial equilibrium permafrost; SDEP - slope deposits of equilibrium permafrost; ExEP - exaration deposits of equilibrium permafrost.

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