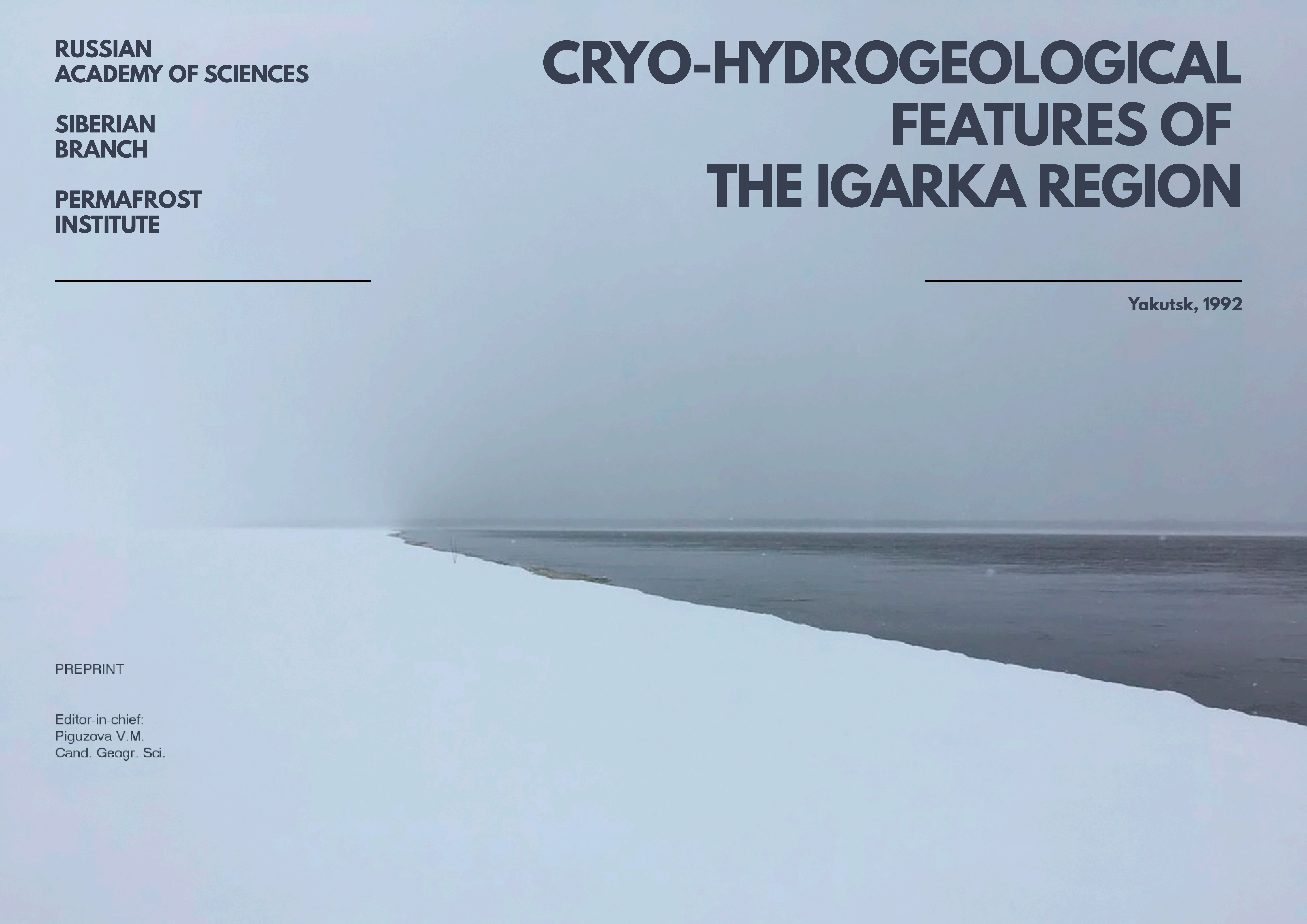

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CRYO-HYDROGEOLOGICAL FEATURES OF THE IGARKA REGION

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Piguzova V.M.
Cand. Geogr. Sci.

IGARKA REGION

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THIS PREPRINT

provides an overview of the regional occurrence of groundwaters and talik zones, separating permafrost patches with azonally low thickness and high negative temperature. The paragenetic relations between groundwater and frozen ground are outlined. This brochure is addressed to permafrost researchers, hydrogeologists, and geographers.

Reviewers:

Klimovsky I.V., Cand. Geogr. Sci.

Konstantinov I.P., Cand. Tech. Sci.

Grigoriev N.F.
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PREFACE

To the north of the Arctic Circle, in the vicinity of the city of Igarka, construction of new residential quarters and industrial facilities has been rapidly advancing over the last quarter of the century.
The complexity of local geocryological conditions complicates this development. This can be in large part explained by the absence of summary publications consolidating the outputs and conclusions of numerous geocryologic and hydrothermic studies undertaken by the staff of Igarka Permafrost Research Station, SB AS USSR, along with multiple departmental bodies.

This manuscript aims at generalizing the vast field observation data.
It puts an effort in explaining and discussing the origin and specific aspects of patchy permafrost distribution and the presence of highly water-saturated talik zones, based on the author's vision of the importance of hydrogeology and other local factors influencing permafrost distribution.
It also outlines paragenetic interactions between groundwater and permafrost.

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INTRODUCTION

The area surrounding the city of Igarka is in itself a peculiar permafrost 'oasis', where uniform permafrost conditions correlated with zonal climate are found along with azonal permafrost patches, featuring relatively warm negative temperatures, significantly reduced permafrost thickness and the abundance of talik zones, maintaining positive ground temperatures throughout the year. Particular relevance of azonal geocryological and hydrothermic conditions and the importance of its studies was underlined by P.F. Shvetsov (1950) and S.M. Fotiyev (1978).

Igarka Permafrost Research Station (IPRS) has accumulated important field data, characterizing hydrothermal regime of permafrost in the region. Between 1930 and 1933, numerous boreholes were drilled within the city limits, one of them reaching 61m depth. Thus, initial data on the local cryological and hydrogeological conditions were obtained, summarized later by N.I. Bykov (1934).
After 1935, when IPRS was transferred from Komseverostroy (Northern Construction Committee) to the Committee of Permafrost Research of the Soviet Academy of Sciences, permafrost studies in the region were expanded and became systematic, not only in the Igarka region, but also at a larger scale. During 1935-1939, along with regional permafrost studies, hydrogeological surveys were organized, including observations in wells (Meister, 1946).

Detailed permafrost studies along with geocryological surveys and mapping were continued in 1941-1944 by V.F. Tumel' and L.S. Khomichevskaya, enhancing our understanding of permafrost conditions in the Igarka region.

In 1949-1951, Northern Design & Exploration Expedition (NDEE), a large scientific expedition of Glavsevmorput' (Chief Directorate of the Northern Sea Route) conducted long-term research in Igarka for construction of a maritime port. This expedition drilled over 100 boreholes in various physiographical settings. Notably, a number of survey wells on the banks and within the channel of the Igarka Branch of the Yenisey River were drilled. Geological and hydrogeological transects and maps, predominantly of 1:10 000 scale, were drafted for several parts of the Igarka district. These survey wells also served to study thermal regime of both frozen and non-frozen soils. The bulk of fieldwork was carried out jointly with IPRS; expedition reports can be partially found in the station's archives.

In 1951, V.N. Saks published his description of the Igarka region paleoenvironment, including a draft stratigraphy of Quaternary deposits, and underlined the importance of glacial influence on the landform development in the region.

Valuable works of S.G. Tsvetkova (1961) were the first to mention the leading role of groundwater in development of taliks that define azonality of local permafrost conditions.

In 1952-1958, N.S. Shevelyova studied geology and permafrost in the Northern Yenisey region, and later summarized field data on the spatial distribution, temperature, and origin of perennially frozen Quaternary deposits (Shevelyova, 1964).
An overview of geocryological conditions of the region was compiled by N.S. Shevelyova and L.S. Khomichevskaya (1967).

Highly valuable data on the role of snow cover in permafrost development were collected by G.Ya. Shamshura in the adjacent Norilsk region, sharing common physiographic features with the vicinities of Igarka (Shamshura, 1959).

Studies of permafrost transformation in post-glacial time and the impact of snow cover on the dynamics of seasonally and perennially frozen grounds were published by G.S. Konstantinova (1961, 1962), who assumed an important role of snow cover in the development of azonal geocryological conditions. At the same time, A.P. Tyrtikov (1952, 1966) studied the influence of vegetation on permafrost dynamics.

For the region in question, considerable interest yields the research of G.F. Odinets, who performed drilling of hydrogeological boreholes. Based on these field observations, he established paragenetic links between permafrost and confined fracture waters in the Igarka region (Odinets, 1964).

From 1954 to 1968, and later from in 1970 to 1985, the present author participated in permafrost and hydrogeology studies at various sites within Igarka region. The author's observations, concerning distinctive features of hydrology and permafrost thermal regime in the region, as well as the role of local hydrogeology in the development of taliks, were partially published previously (Grigoriev, 1976a,b, 1980).

Concluding this general overview of preceding studies, it should be noted, that apart from published works, abundant archived data stored at Igarka Permafrost Research Station were used for drawing-up this booklet.

1. PHYSIOGRAPHY

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TOPOGRAPHY.

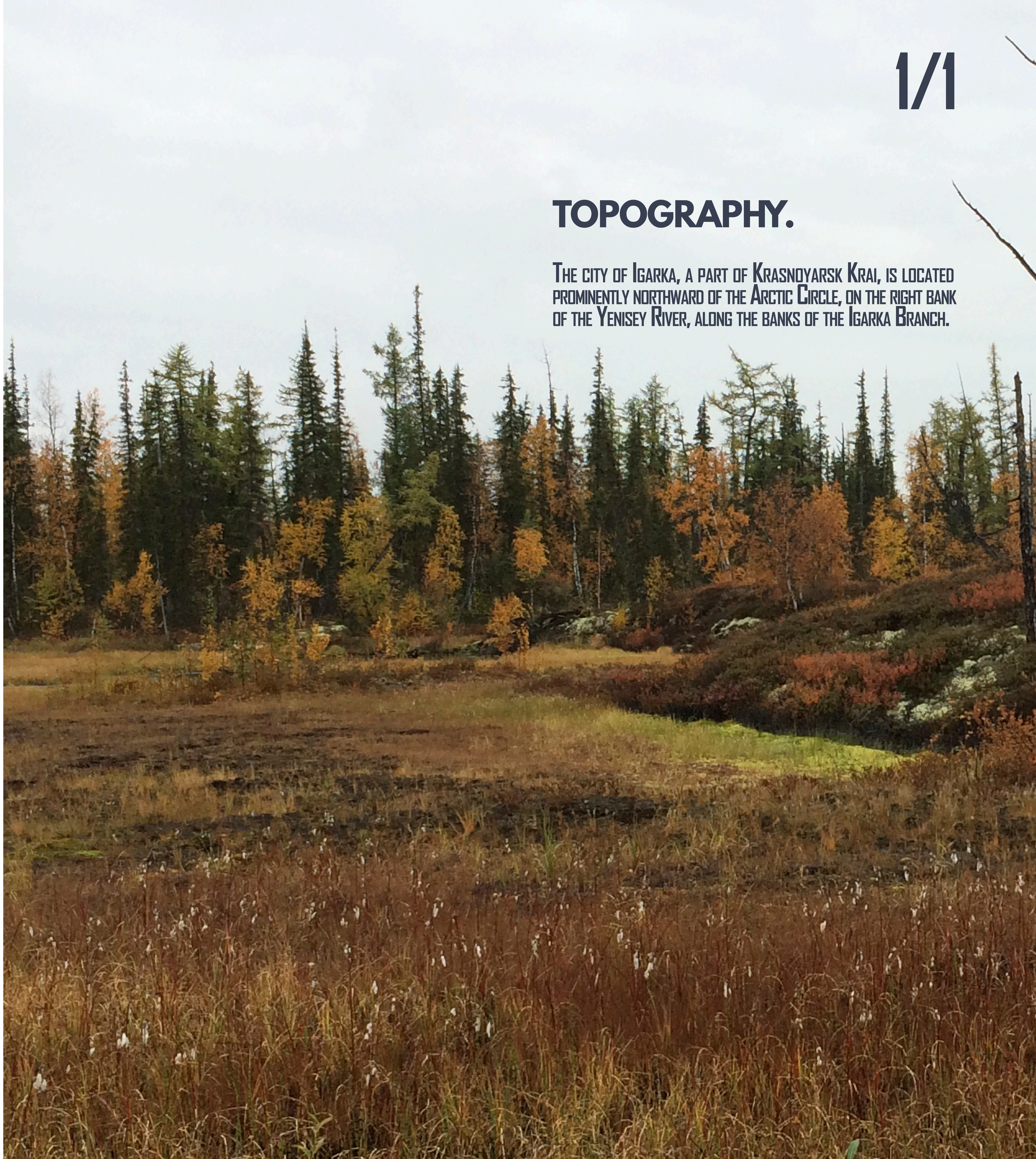
THE CITY OF IGARKA, A PART OF KRASNOYARSK KRAI, IS LOCATED PROMINENTLY NORTHWARD OF THE ARCTIC CIRCLE, ON THE RIGHT BANK OF THE YENISEY RIVER, ALONG THE BANKS OF THE IGARKA BRANCH.

Basic topography includes several floodplain and terrace surfaces. The elevation of the floodplain surface reaches 20 to 21 m above the reference (low-flow) level of the Yenisey River, and its width varies from 50 to 1 200 m. Transition between floodplain and terrace surfaces is poorly marked. The floodplain is contoured by a beachline about 50 m wide and elevated about 5 m above the reference level. Inundated lands include low and high floodplain levels. The low floodplain, including a beach-line, has an elevation of up to 15 m, and is 10 to 150 m wide. It is inundated annually. The high floodplain has elevations between 15 and 21 m. Its surface shows smooth transition toward terrace surface and is inundated only during extremely high spring flood events. Its surface is dissected by small gullies, and larger gullies even cut into its outer marginal part. Its surface is mostly covered with wetlands, and depressions accommodate cut-off lakes.

Fluvial (Karga[i]) terrace surface is transformed by both erosion and accumulation. Its elevation above the reference level varies from 21 to 45 m, and its width locally reaches 2.5 km. Most of the city infrastructure is situated within this surface, which, alike the floodplain surface, is dissected by variably-sized gullies. The valleys of Volchiy Log and Medvezhiy Log creeks have wide and flat thalwegs, and locally very sharp slopes. Toward its inner margin, the terrace surface smoothly evolves into a highly dissected plateau, up to 60 m of elevation, where separate uplifted patches are divided by deeply incised lakes and wetland bowls.

Glacial processes also left their imprint onto contemporary topography of the Igarka region. According to S.A. Arkhipov (1971), under Zyryan glaciation, an essentially morainic relief formed in the plateau zone. Closer to the Yenisey River, within the Karga terrace, this morainic relief changes to an alluvial lacustrine plain.

[i] Karga interglacial = MIS3, 57-29 ka



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CLIMATE.

General circulation defines the key features of the regional climate, pertaining to subarctic climatic zone, with long and cold winters and relatively short and warm summers.

Cyclonic activity is driven by the transfer of Arctic air masses from the Kara Sea and their transformation into continental air masses. In summers these air masses warm up to a degree that mean monthly temperature in July reaches 14°C, while the highest daily air temperature periodically attains 35°C to 40°C. In winter, the air intensively loses heat, causing extremely low negative temperatures. Mean annual air temperature is -9.3°C, while mean monthly lowest in January reaches -26.5°C, and the absolute low is -56.5°C.

Strong continentality of the local climate is illustrated by a significant temperature range between the coldest and the warmest months. Cold period with negative temperatures lasts for 225 days. The date of transition to positive temperatures in spring is May 20, and mean annual air temperatures vary between -6.6°C and -10.4°C. Cyclonic activity explains the prevalence of north-western winds during winter months, while in summer south-eastern winds dominate.

Annual precipitation totals *ca.* 460 mm. November to March, its amount stays below 130 mm, and during warm period it exceeds 320 mm. Stable snow cover is established between 4 and 20 October. Depending on topography, vegetation, and wind direction, snow thickness varies from 0.2 m on open hilltops to 3.5 m at the bottoms of forestated gullies. Meltdown and complete snow cover loss advance rapidly in the second half of May, which procures a rapid meltwater via the seasonally thawed layer surface.

According to observations by G.S. Konstantinova (1961), snow density varies from top to bottom in a vertical cross-section. In November, it equals 0.10 to 0.19 $kg.m^{-3}$ in top layers and 0.23 to 0.24 $kg.m^{-3}$ in bottom layers; in the second half of winter, snow density increases to 0.20 to 0.30 $kg.m^{-3}$ on top, and up to 0.35 $kg.m^{-3}$ near the ground surface.

Radiative balance is an important climatic variable for open non-forested land patches. According to calculations by M.K. Gavrilova (1963), total monthly solar radiation input on such surfaces varies from 4.1 $MJ.m^{-2}$ in January to 611.8 $MJ.m^{-2}$ in June.

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Table 1

Typical water stages of the Yenisey R. in Igarka

Stage feature	Mean stage, m	Date
Highest, annual	16.83	1.Jun
Winter lowest	0.46	7.Feb
First ice movement	5.23	23.May
Ice breakup	12.22	29.May
Highest, spring flood	16.75	1.Jun
Highest, first ice-free date	13.94	8.Jun

HYDROLOGY.

Hydrological conditions of the region are governed by water regime of the Yenisey River and its right tributaries, the Graviyka and the Chernaya Rivers, as well as of numerous lakes in the vicinity of Igarka.

Main channel width of the Yenisey River in Igarka is 3.5 km, with water depth reaching 40 m. The main channel is separated from the valley side by the Igarka Branch, which is 12 km long and up to 395 m wide. Water depth in this branch varies from 7 to 20 m.

The Graviyka River delineates the Igarka city area from the north, and the Chernaya River - from the south and south-east. The former discharges into the Yenisey R. *ca.* 15 km downstream from Igarka, while the latter drains into the Igarka Branch about 5 km upstream from the Old City quarter. The Graviyka R. channel in the estuarine part is 15 to 20 m wide, while the Chernaya R. width at its mouth hardly exceeds 12 to 15 m. A number of smaller and shorter creeks, such as Severny, Volchiy Log, Medvezhiy Log, Nezametny, and others also flow into the Igarka Branch.

During the spring flood, water level in the Yenisey R. normally rises by 15 m to 17 m, and, exceptionally, up to 22 m in occasional years (Table 1). The near-surface water temperature in the Yenisey R. varies from 10 to 12°C, decreasing to 6-8°C toward the bottom. River ice builds up on most streams starting from mid-October. The ice thickness on the Yenisey R. reaches its maximum values, ranging from 1.3 m to 1.4 m, in April. In the Igarka Branch, the flow velocity is lower, compared to the main channel, and the ice thickness increases to 1.5 m to 1.6 m. Ice breakup on rivers occurs by the end of May, and by mid-June they are completely ice-free.

The Igarka region hosts numerous lakes of various form, size, and origin. Floodplain lakes are mostly shallow and pertain to cut-off type of lakes that are remnants of the abandoned channels of the former Yenisey R. minor branches, gradually reoccupied by wetland vegetation.

At the outer margin of the dissected plateau, lakes of thermokarst origin are the most abundant. Their contours are highly irregular, and only on rare occasions they have a rounded shape. Half-drowned dry forest by the lake banks evidences the ongoing lake bottom subsidence and its gradual inundation. Some thermokarst lakes have elongated forms, with lengths between 1.0 and 1.5 km. The lakes of this type are mostly shallow, and their depth rarely exceeds 3 m.

Water temperature data for the lakes of the region are presented in the following sections addressing the development of sub-lacustrine taliks.

VEGETATION.

The Igarka region vegetation is of tundra forest type, where certain landforms accommodate specific vegetation community types.

On the right bank of the Yenisey R., the following communities are widely present:
1) spruce and larch forest with continuous moss cover (green mosses prevail) and organic-rich peat topsoil horizon, 5 to 15 cm thick;
2) swamped open larch forest with continuous peat cover;
3) tussock bogs with subshrubs;
4) open forest on sphagnum wetland.

The Karga terrace is mainly occupied by:
1) closed spruce forest;
2) open mixed forest - spruce, larch, and birch;
3) open forest on sphagnum wetland (Tyrtikov, 1952, 1966).

It is well known that vegetation cover regulates the rate of absorbed and reflected solar radiation and controls the pattern of soil layer cooling and heating.

GEOLOGY.

Pre-Quaternary geologic history of the region has its characteristic features. According to A.A. Mezhvilk (1964), a regional fault network can be traced along the right bank of the Yenisey R., 10 to 15 km away from the river, with predominant N-S orientation. These fault lines densify and intersect locally. These neotectonic shifts define the block structure of the region. The most intense rock fragmentation is observed in the Igarka-Rybinsk fault zone (Figure 1).

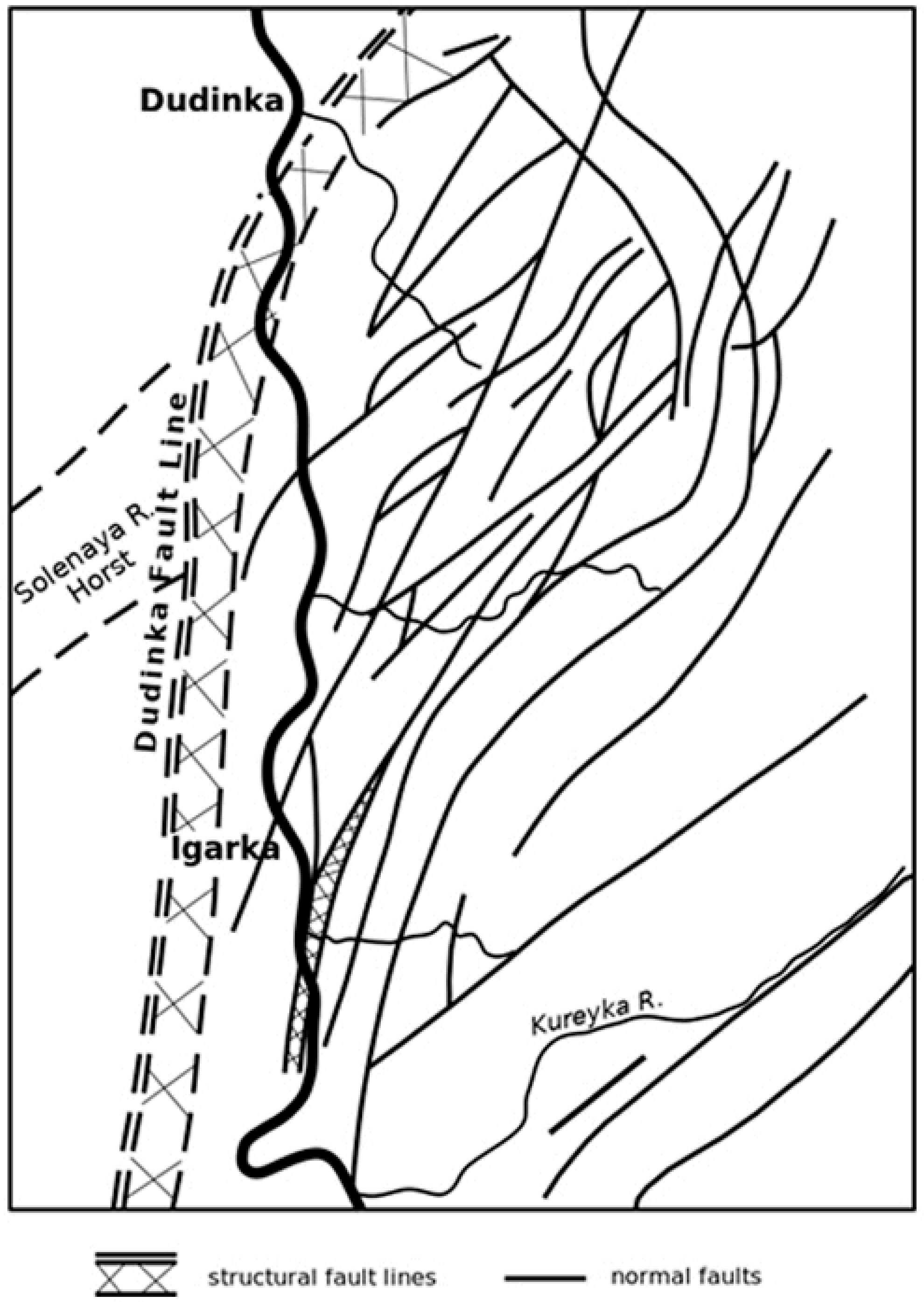

Figure 1. Tectonic faults of N-W margin of the Siberian Platform (Mezhvilk, 1964)

Emergence of this faultline occurred along with formation of effusive rocks and tuffs of the Igarka stratum. The very fact of the faulting process is illustrative of active disjunctive tectonics, which most probably also promotes an increased activity of deep groundwater (Odinets, 1964).

The most detailed description of the Quaternary sediments and underlying rock strata is given in the article by V.N. Saks (1951), which makes use of multiple field data sources, including those obtained by Igarka Permafrost Research Station.

The oldest bedrocks are represented by a complex of Proterozoic and Paleozoic sedimentary and effusive rocks, including chlorite shales, silicified limestones, and sandstones, locally heavily sheared. Tuff-breccias, tuffs, diabase and dolerite transverse dykes are among the most well-represented tuff-effusive rocks (bedrock exposures are traced along the northern limit of the new city of Igarka, and in the Bezymyanny Creek valley thalweg). The top of bedrock depth varies from 0 to 30 m and more.

According to V.N. Saks (1951), the oldest Quaternary deposits overlying the bedrock are Santchugovsky marine clays and silts, interbedded with silty sands and containing gravels. Total thickness of this layer is about 13 m. Santchugovsky stratum is overlaid by sands and silty sands with thin gravel layers, comprising the Kazantsev stratum.

Kazantsev sands, in their turn, are covered by fluvio-glacial deposits of non-sorted silty sands and silts with gravels and boulders, with overall thickness ranging from 1 to 12 m. Their deposition presumably occurred during the upper Zyryan glacial period. The layer of gravels and boulders, contacting the uniform fine sand layer at a steep angle, are exposed between the eastern limit of the Igarka city and the Graviyka River channel. These morainic deposits are overlaid by a sequence of varved clays and silts, presumably deposited in the periglacial environment of the glacial basin. These sediments are well exposed in the Igarka Permafrost Tunnel and described in detail by Kuznetsova et al. (1985). In this profile, the upper part demonstrates sandy silts with indistinct varved-like lamination, replaced horizontally by very fine sands with abundant plant remains and exceptionally well-preserved timber, mostly larch. Total thickness of glacio-lacustrine deposits, according to the data from borehole No. 2043 (NDEE), locally exceeds 60 m. Absolute ages of larch timber samples are *ca.* 30 to 31 ka BP (Kind, 1974).

Farther down the cross-section, varved-like silts and silty sands are replaced by a layer of varved clays, *ca.* 20 m thick. The varved clays show a thin lamination, where thin, *ca.* 1 mm, light-grey finer layers interchange with thicker layers, from 8 to 50 mm and more.

Lacustrine sediments are covered by Karga deposits, comprising the surficial strata of the Karga terrace, where the city of Igarka is located. Karga deposits are silty sands and silts, with inclusions of gravel, sand, and plant remains. According to V.N. Saks (1951), Karga deposits represent floodplain deposits of the Yenisey R.; their thickness within the city limits varies from 4 to 15 m.

Contemporary deposits are represented by alluvium of both upper and lower floodplain levels of the Yenisey R., and are mostly silty clays, silty sands with layers of gravels, and coarse sand. Alluvial deposits of the lower

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floodplain level are mostly represented by light and heavy silty clays, with bands of gravels and boulders. Thickness of floodplain deposits layer ranges from 1-2 to 6-7 m. Beachside alluvium is mostly heavy and light silty sands and silty clays, as well as boulders on the banks of the Yenisey River. Its thickness varies from 1 to 2 m.

These deposits also include the upper layers of peat in various decomposition states, from 1 to 3 m thick, found in depressions and on hilltops along the eastern margin of Igarka. According to the data from G.M. Levkovskaya et al. (1970), their absolute age is between 7.5 and 9.5 ka BP.

The most recent deposits are comprised of a surficial layer of fine grey silty clays overlain by tundra Gleysols. The thickness of surficial silty clays varies, as a rule, from 0.6 to 1.0 m, and their lower part is occasionally frozen.

Along with the stratigraphy of the Igarka region proposed by V.N. Saks (1951), the most recent assessment proposed by S.A. Arkhipov should be mentioned. In Quaternary deposits Arkhipov identifies a periglacial complex dominated by varved clays of moraine-dammed lakes, and stratified sands and silty clays of glacio-lacustrine origin.

According to S.A. Arkhipov, the glaciation of the Yenisey Plain had caused glacioisostatic rebound in the Igarka region, evidenced by floor depth of Kazantsev sediments some 20 to 35 m below the contemporary Yenisey R. level.

2. PERMAFROST

It is believed that permafrost formed in the late upper Quaternary to middle Quaternary (within the plateau zone) and has been uninterruptedly existing since that time. However, outside the Yenisey R. valley, at the water divide plateau, it is presumably older (Sheveleva, 1964).

A characteristic feature of the Yenisey right bank area is the absence of frozen sediments under the Yenisey River channel, the Igarka Branch, and under the channels of right-hand tributaries - the Graviyka and Chernaya Rivers, as well as under certain creeks flowing into the Igarka branch.

A basic feature of permafrost distribution in the region is its discontinuous or patchy character, accompanied by hydrothermal taliks.

The Yenisey River separates two distinct geocryological zones - the left-bank and the right-bank zones. To the west from Igarka, on the right bank, a geocryological zone is traced that formed during Zyryan glaciation, when permafrost developed within ice-free regions under cold climate. The left-bank platform zone is dominated by continuous, thick (down to 540 m) and cold (down to -7°C) permafrost.

The right-bank geocryological zone was formed in the Karga times, and its permafrost is discontinuous, even patchy, in thin layers (from 10 to 30 m) with relatively warm temperatures, from -0.2 to -0.3°C. This zone hosts a large number of hydrothermal taliks confined to the Igarka-Rybinsk fault zone.

The Karga deposits became frozen around 30 to 31 ka BP, according to a date obtained from wood remains found in the Igarka Permafrost Tunnel ca. 8 m from the surface (Kind, 1974). If these wood remains had not been washed out from older sediments, then the Karga alluvium freezing occurred not earlier than 31 ka BP.

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PERMAFROST

The development of a perennially frozen layer in the Igarka region and its vicinity occurred differently and at different timeframes, depending on paleogeographic, geologic, and climatic conditions.

On the surface of permafrost patches around Igarka, complex thermophysical processes occur, leading to annual seasonal thawing and freezing of the surficial ground layers.

Ground thaw on open surfaces starts in the second half of May, and by early June, the zero isotherm descends to about 1 m depth. The maximum thawing is observed by the end of August, and in the second half of September, a seasonally-frozen layer starts do develop, with maximum thickness observed in April-May.

Analysing the observation data on distinctive features of active layer behaviour in the Igarka region, an extreme spatial variability of the seasonal freezing and thawing depth can be observed, which is directly related to physiographical conditions. In clays and silty clays, the active layer depth can reach 1.2 to 1.4 m, in sands - 1.6 to 1.8 m, and in peats -0.3 to 0.6 m. Observations evidence the protective role of vegetation, controlling the amount of absorbed and reflected solar radiation, which shields the ground surface from rapid temperature fluctuations and defines, to a large extent, the seasonal thawing depth. As shown by observations by A.P. Tyrtikov (1966), the active layer depth under thick Labrador tea cover is ca. 1.5 times less than on open surfaces.

The seasonal freezing depth reaches 2.5 to 3.5 m over the open and closed taliks, and 4 m over the bedrock. Seasonal thawing depths increase with increased thickness and water abundance of suprapermafrost aquifers, if such are present. The same pattern is observed in rough hilly terrains, where shallow groundwater flow occurs.

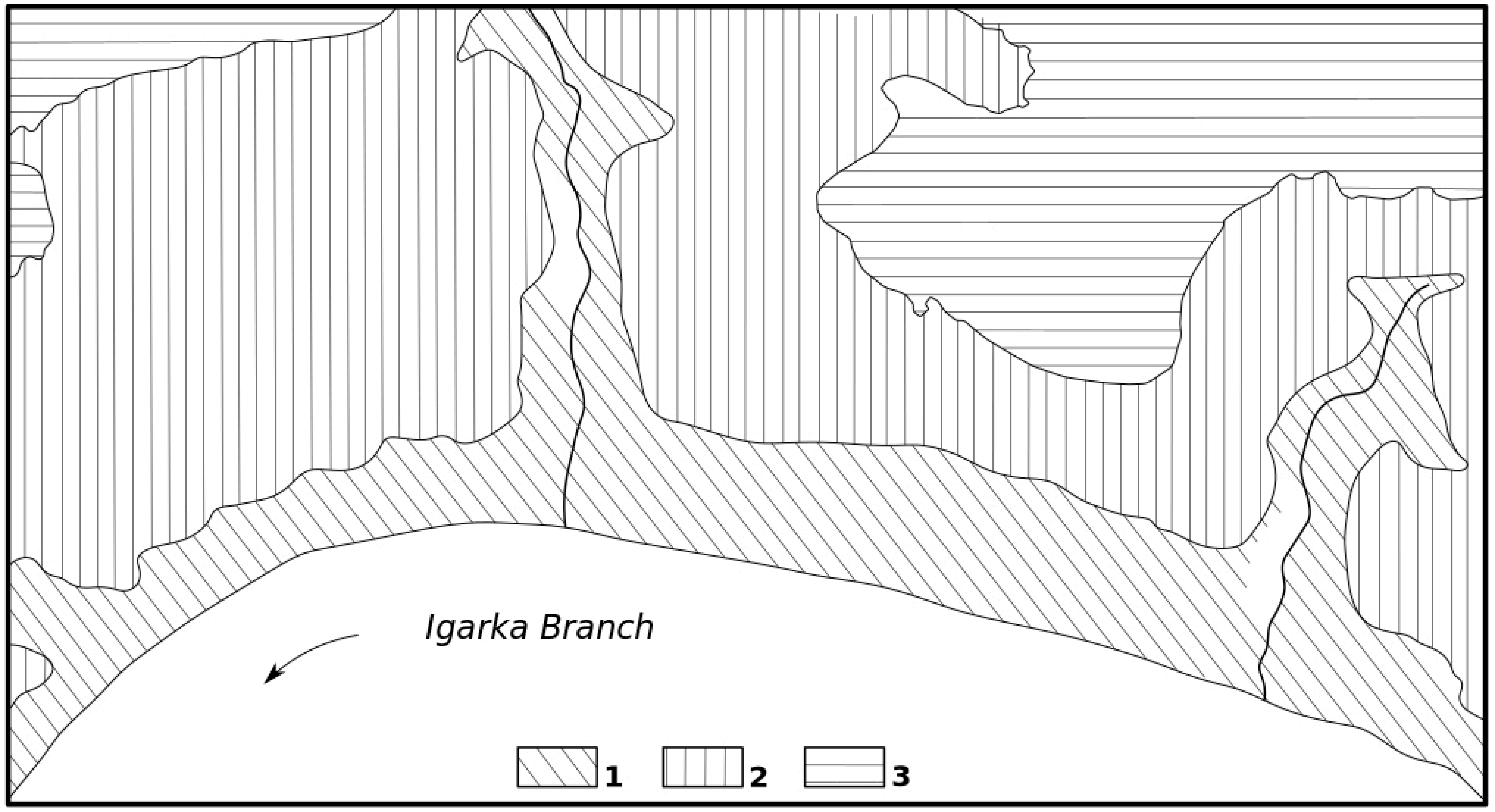

Figure 2. Spatial extent of geocryological subzones within the city of Igarka. Subzones: 1 - floodplain; 2 - terrace; 3 - plateau.

Review and analysis of published and field data allow to identify several morphotypical subzones, usually in conjunction with landforms, differing in age and conditions of freezing. Within the right-bank geocryological zone of the Igarka region, the following subzones exist: (a) floodplain surface; (b) terrace surface; (c) hilly lake-abundant plateau (Figure 2).

Within all subzones, the distribution of frozen and non-frozen grounds is patchy and mosaic. Separated permafrost islands exist locally, alternating with both open taliks (mostly under the river channels and lakes) and closed taliks (pseudotaliks), where seasonally frozen layer is separated from the top of permafrost by a non-frozen layer of variable thickness.

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FLOODPLAIN SUBZONE

Floodplain subzone is traced as a narrow stripe along the right bank of the Igarka Branch of the Yenisey R., also embracing the valleys of smaller creeks, opening to the Igarka Branch.

In the alluvial deposits of the low floodplain, comprised of sands and silts with inclusion of gravels, permafrost was not detected by drilling. Nonetheless, at the high floodplain level, permafrost patches were observed, which developed mostly syngenetically during the Holocene. The boreholes drilled on the inner margin of this high floodplain (No. 2408 and others), intersected permafrost with lowest temperatures around -0.5°C (Figure 3).

Permafrost thickness reached 20 m in some points.
Observed cryostructure in these deposits was massive or thin-layered.

It is worth nothing, that the frozen state was persisting even though this high floodplain margin was inundated periodically during spring floods.

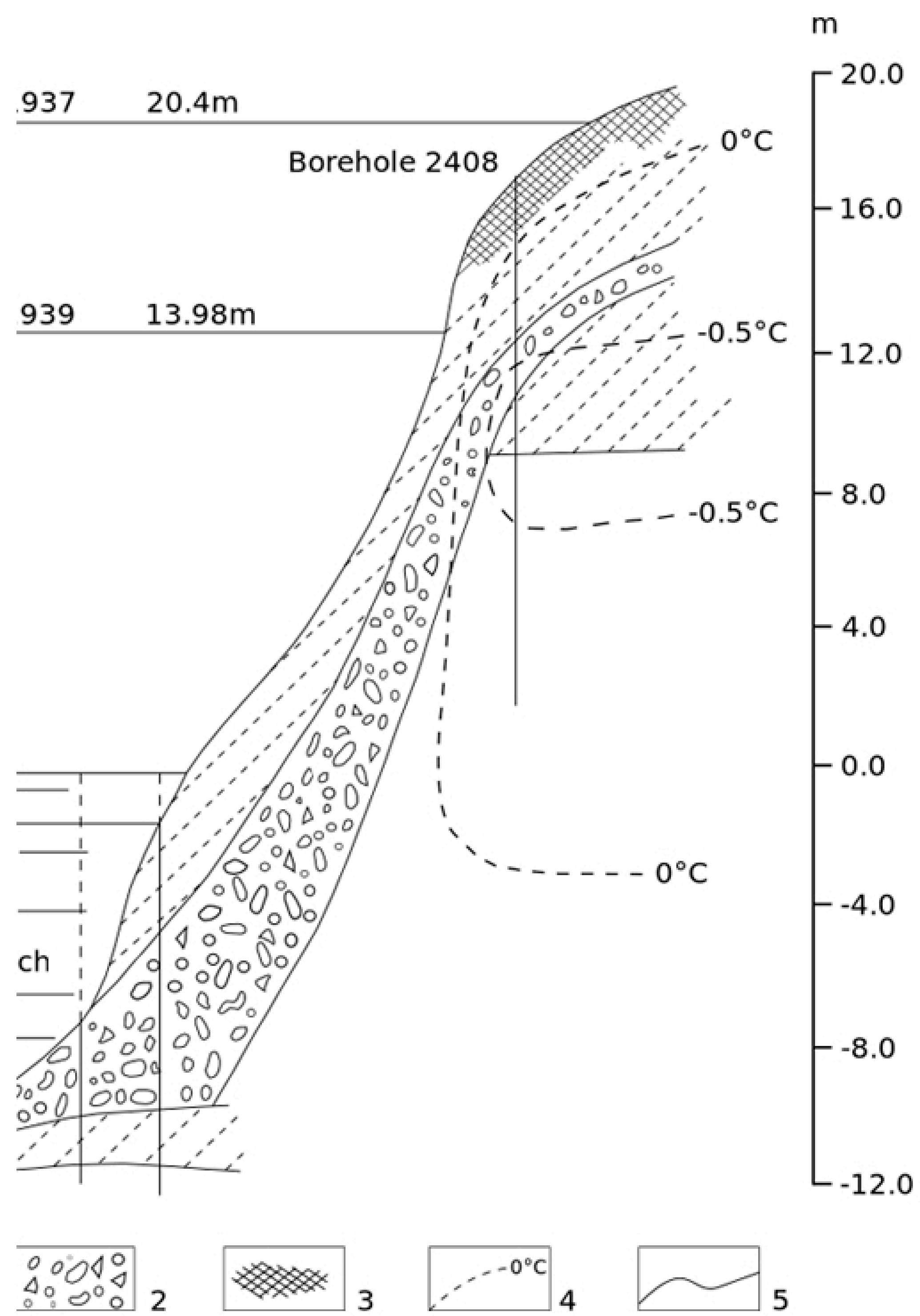


Figure 3. Cryo-geological cross-section of the inner margin of high floodplain adjacent to Borehole No. 2048; 1 - silts; 2 - gravels with sand; 3 - peat; 4 - isotherm; 5 - layer boundaries.

TERRACE SUBZONE

Terrace subzone, as a morphotype, is characterized by a unified complex of physiographic and geocryologic conditions.

The terrace surface is relatively plane, though occasionally segmented by creek valleys and gullies, and accommodates numerous lake basins and marshy depressions. Quaternary deposits of the terrace host permafrost layer, developed in the upper Quaternary, with thickness varying from 3-5 to 35 m and more, depending on endogenous and exogenous factors. Permafrost layer is fragmented by taliks, occupying roughly 60% of the terrace surface and resulting from thermal impact of surface waters and groundwater, along with increased snow cover depth.

Based on the seasonal freezing and thawing parameters, top of permafrost depth, and thermal regime, G.S. Konstantinova (1962) identified three permafrost zones: (a) degradational, (b) unstable, (c) stable, with aggradation trends. Degradational type has ground temperatures around -0.1°C, and thickness ca. 10 m, and is typical for surface depressions with increased snow accumulation. Unstable permafrost type has uniform vertical ground temperature distribution, with values varying from -0.1 to -0.3°C, and closed taliks (pseudotaliks) are virtually omnipresent. Pseudotaliks could be locally overlaid by contemporary frozen ground layers persisting over several consecutive summers. Stable permafrost type features complete freezing of seasonally thawed layer, the lowest average ground temperature across subzone, down to ca. -1.0°C, and increased ice content, mainly as layers that become thicker with increasing depth. Ground ice distribution pattern evidences the epigenetic freezing. Taliks, where present, comprise not only surficial deposits, but also the bedrock.

Long-term temperature observations were undertaken in the Borehole No. 1159 from November 1949 to May 1950 (see Table 2, p.43). These 6-months observations, in line with previous punctual measurements, confirmed the uniform vertical temperature distribution between 2 m and 17 m, with mean annual temperature -0.2°C.

Glacio-lacustrine deposits of the terrace subzone are best described and studied in the profile at Igarka Permafrost Tunnel. According to descriptions of T.P. Kuznetsova et al. (1985), 6 to 8 m thick upper layers of silty clays are replaced, in the deeper layers, by silty sands and sands containing plant detritus and large tree trunks.

The presence of all three permafrost types within a single terrace subzone evidences the complexity of development of cryogenic processes, resulting in a strong azonality of local hydrothermal conditions. In this case a crucial role is played by hydrogeologic factor - occurrence of aquifers and hydrothermal taliks in permafrost layers (sub-lacustrine, sub-channel, and others), governing a discontinuous or patchy permafrost distribution. Interaction of groundwater with permafrost is reviewed in the following sections.

Let us review field data evidencing the key aspects of geocryologic conditions in the terrace subzone.

During a geologic survey at the Igarka Timber Factory facilities in 1973, numerous thermic boreholes up to 15 m deep were drilled; the Igarka Permafrost Research Station staff took part in logging and geothermic observations (Table 3, p.44). The lowest temperatures, ranging from -1.8 to -1.9°C, were observed in the upper layers of permafrost, between 8 and 9 m. In the majority of boreholes, a weak temperature gradient was observed, and the temperature at zero annual amplitude depth was around -0.2°C. Thermic data show important variation in permafrost thickness within the industrial facility - from 7 m (No. 863) to 12-15 m and more in other boreholes.

Upper layers of the Karga alluvial suite are underlain by varved clays of the Zyryan age, typically having layered cryostructure.

Accordind to T.P. Kuznetsova et al. (1985), ground ice accumulation in this clayey horizon occurred via segregation, while ice distribution pattern evidences the epigenetic freezing of these fine deposits. Radiocarbon age of woody remains suggests the terrace level sediments were deposited around 33 ka.

PLATEAU SUBZONE.

THE PLATEAU SUBZONE FLANKS THE TERRACE SURFACE FROM THE NORTH AND IS CHARACTERIZED BY INCREASED ELEVATIONS OF UP TO 65 M AND MORE, AND MOSTLY HILLY TERRAIN WITH HUMMOCKY HOLLOWS AND LAKES.

This plateau subzone is the least studied of all three subzones. Its most complete and detailed geocryological section was obtained from a borehole No. 295/417, drilled on the plateau surface to the north from the Igarka Branch. This borehole is 31 m deep, and thermal monitoring was being implemented there from 1938 to 1941 (Table 4, p.45). The period given was sufficient for the thermal imprint of drilling to fade out. Seasonal fluctuations observed at different depths, ranged significantly only in the upper part of the frozen ground layer. In deeper layers, ground temperature varied only slightly. Mean annual frozen ground temperature in the plateau subzone was found to be several times lower, than in other subzones. At the bottom of the annual turnover layer (12 to 14 m) the ground temperature was about -1.7°C.

Cryogenic structure of fluvioglacial deposits of the plateau is highly variable depending on grain size distribution. Massive cryostructure is typical for sands and sandy silts; it is reticular in silts and clays, and basal-layered in peatlands.

In peats and lacustrine deposits, infilling both waterlogged and dry depressions of the plateau surface, polygonal features are observed, responsible for ice wedge growth.

In 1973, during fieldwork carried out by the present author jointly with E.G. Karpov, a frost crack was observed *ca.* 4 km to the north-east from Igarka, on the open hill surface. An ice wedge approx. 1.5 m wide was found right under peat layer, its width decreasing to 0.25 m at 2 m depth.

In his book *Ground Ice of the Northern Yenisey Region* (1986), E.G. Karpov describes frost heave processes related to refreezing of relict sub-lacustrine taliks under surface depressions, and caused by ice accumulation either in form of separate layers (segregational ice) or wedges.

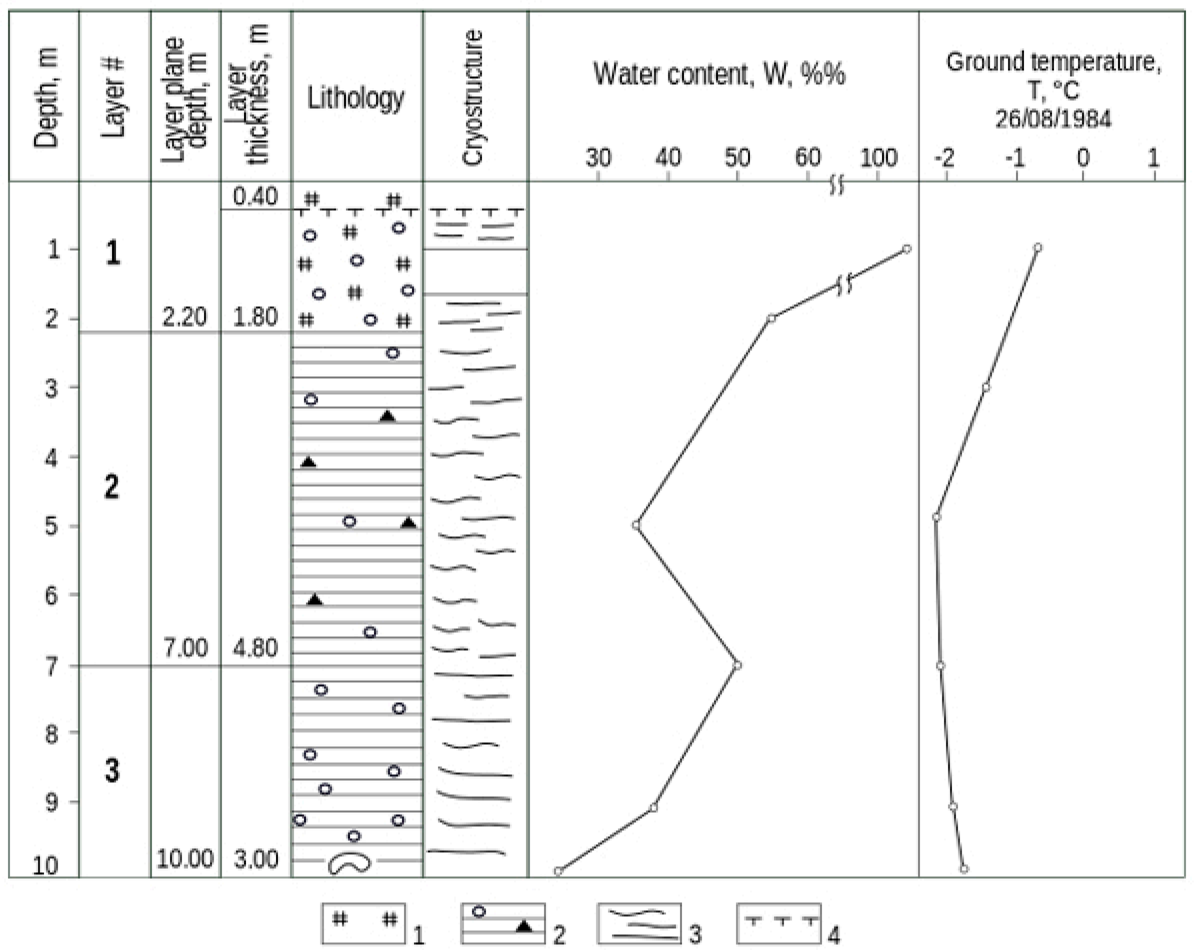


Figure 4 Geological cross-section with permafrost description, Borehole #13
1 - peat, 2 - clay, 3 - layered cryostructure, 4 - top of permafrost

Geocryological conditions of the plateau subzone can be further illustrated by a geological section from Borehole No. 13, located in about 30 km from Igarka. This borehole was drilled at an open hill surface (Figure 4). Here, under a 2.2 m thick peat layer fluvio-glacial deposits were found, comprised of clays with boulders. Permafrost has layered, or veined cryostructure and low (-2.0°C) mean annual temperatures at zero annual amplitude depth. Temperature distribution in this borehole at the outer margin of the subzone resembles that, observed in Borehole No. 295/417 located at its inner margin.
Hilly surface of the plateau accommodates waterlogged, marshy depressions. Test drilling at the bottom of a selected hollow revealed non-frozen ground down to 4-5 m.

Thus, in contrast to the terrace subzone, the permafrost of the plateau subzone was formed in middle Quaternary by epigenetic freezing, under weak hydrogeological influence, and is relatively monolithic, only locally interrupted by sub-lacustrine and sub-channel taliks.

3. GROUNDWATER

3

GROUNDWATER.

According to the Map of Cryo-Hydrogeological Regions of Eastern Siberia (1984), Igarka region is a part of the Turukhan-Norilsk admassif, predominantly represented by fissure ground waters (Figure 5).

The aquifers of the region are mostly confined to upper Quaternary deposits and to underlying bedrock, such as sandstones, limestones, and tuffs. Here, permafrost accommodates various groundwater types (supra-, intra- and sub-permafrost), making way through hydrothermal taliks of differing origin.

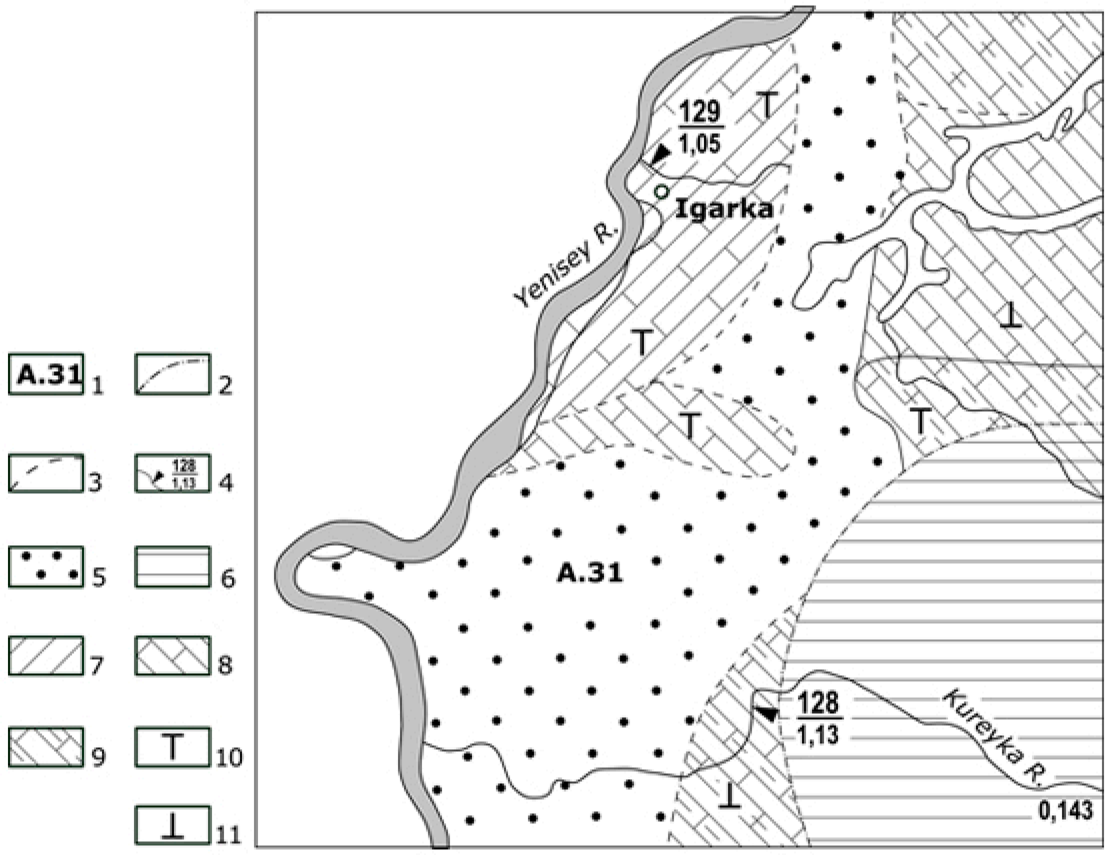


Figure 5 Groundwater classes and water-bearing rocks, according to (Zonation map…, 1984)
1 – cryo-hydrogeological zone, 2 – boundaries of second order hydrogeological regions, 3 – boundaries of groundwater classes occurrence, 4 – gauging site, above – gauge number, below – groundwater discharge, m3 s-1, 5-9 – groundwater classes and water-bearing rocks: 5 – porous formation waters in loose terrigenous sediments, 6 – fissured formation waters in terrigenous rocks, 7 – fissure waters in carbonate rocks, 8 – fissure waters in terrigenous rocks, 9 – fissure-karstic waters in carbonate and terrigenous rocks, 10-11 – groundwater salinity, g L-1 : 10 – 1…10, 11 – 10…35.
(Zonation map…, 1984): Zonation map of cryogenic hydrogeology, Eastern Siberia, scale 1:2500000

3/1

SUPRA-PERMAFROST GROUND WATERS.

Supra-permafrost ground waters are the most frequently observed in the Igarka region.

Prospective surveys with drilling revealed that aquifers of varying thickness and water content were present at the top of permafrost on numerous occasions. Water-holding layers are built with silts, silty sands, and silty clays. Supra-permafrost waters are observed within all major landforms, excluding open palsa surfaces.

Supra-permafrost waters could be divided into (a) seasonally freezing and (b) non-freezing; the latter being widely present within pseudotaliks. Origin, period of activity, and overall thickness of a seasonally freezing aquifer depend on seasonality of freeze-thaw processes, controlled, in its turn, by landcover type and climate, as well as by topography, lithology, and snow cover features; thickness ranges between 0.3 and 2 m.

Water supply to supra-permafrost aquifers occurs by infiltration of rainfall and meltwater from the active layer thawing. The active layer depth controls the aquifer thickness, which varies from 0.05 m to 0.1 m and can exceed 0.5 m in individual cases. Small isolated depressions at the top of permafrost can accumulate and store supra-permafrost waters, limiting their discharge to fluvial network. Period of existence of a supra-permafrost flow depends on the active layer dynamics, and is relatively short: it exists, on average, from mid-May to late October - early November, when the active layer refreezes completely.

We shall further review the data on supra-permafrost waters, observed in surface depressions of the fluvial terrace and under dried oxbow lakes in alluvial deposits, at the depths from 1.5 to 3.2 m below the surface. Hydraulic head up to 1.5-2.0 m high was observed in Borehole No. 1439 and others. Pumping tests showed a well yield of 0.13 L/s. Water chemistry analyses showed presence of HCO_3 - 868.2 mg/L, Cl - 4.8 mg/L, SO_4 - 10 mg/L. Water hardness was 38.3 German degrees. Early summer water temperature varied from 0.6 to 1.5°C. Prospective drilling in the Volchiy Log creek valley discovered an aquifer at depths from 1.5 to 3.0 m, with well yield varying from 0.13 to 0.3 L/s.

Significant variation of supra-permafrost water chemistry depends on the source and the availability of natural drainage. According to L.A. Meister (1946), in the latter case their total dissolved solids (TDS) content is insignificant. Chemical composition is dominated by HCO3 and Ca; HCO3 content can reach up to 200 mg/L.

In numerous boreholes, the supra-permafrost waters were observed in summer, and intra- and subpermafrost waters in other seasons. All groundwater types were found in confined aquifers and had a hydraulic head.

ICINGS (NALED').

OCCURRENCE OF ICINGS IN IGARKA IS AN INDICATOR OF GROUNDWATER DISCHARGE DURING WINTER AND IS OFTEN RELATED TO SUPRA-PERMAFROST WATERS.

Icings can be divided into two groups, occurring: (a) under natural conditions, (b) under technogenic impact. Both types are congelation ice phenomena, developing on the Earth's surface periodically. They originate from forced water migration resulting from seasonal freezing of groundwater aquifers. The Igarka icings are hydrogeogenic, according to V.V. Shepelev's (1974) generic classification.

In the studied region, icings occur on the terrace surface, along the Yenisey valley margin, and the valley sides of small creeks running into the Igarka Branch.

A review of some of the Igarka region icings will follow; some of them were partially described by the author previously (Grigoriev, 1976b). In March 1985, on the terrace surface with altitudes from 30 to 35 m (Barbashova Street), a 250 m2 icing was observed. Icing thickness varied from 0.2 m to 0.6 m. The icing surface was rough, slightly inclined, with water flow signs. The icing ceased to exist during the spring snowmelt. A similar phenomenon was observed on the terrace surface in 1987. An icing with a surface of 150 m2 was observed on the Papanina Street. An icy snow layer was found under the icing locally.

An icing with the largest area (over 500 m2), was observed in the Volchiy Log creek valley near its mouth. Originating from the valley side, at 3 to 5 m above the thalweg, this icing overran the creek valley and covered the beach side of the Igarka Branch and its ice cover. The icing thickness varied from 0.2 to 0.4 m on the bank, and 0.5 m on the branch ice cover. This icing had a bumpy, ribbed, flow-like surface on the brooksides of the Volchiy Log creek, and a smooth surface over the creek

Supra-permafrost waters were observed in boreholes adjacent to observed icings. Groundwater outpouring in winters appears to be in direct relation to refreezing of the supraperma-frost aquifer. Closed non-frozen 'pockets' with increased hydraulic head were possibly forming during the active layer refreezing. That be the case, supra-permafrost waters could outpour through cracks in the upper frozen layer to the surface, where it was freezing layer by layer. During the icing development period, air temperature reached -40°C.

Icings formed under technogenic impact were found near buildings of the Igarka city and in the outskirts of the Old City district. One such icing, developed during winter 1975, was observed in the mouth of the Medvezhiy Log creek valley. Aquifers were exposed during dredging works aimed at creating a winter lay-up basin for river fleet. Groundwater discharge along the steep valley side created a tail-like icing with an area of several hundred square meters, and ice thickness at the slope foot exceeding 1.0 m.

Numerous icings occurred on the city streets by the end of March in several consecutive years, varying from several to dozens of square meters in extent, and having an average ice thickness around 0.3 m. Icings surface was smooth, ice colour was greyish to pale-brown. The origin of those icings is apparently related to refreezing of supra-permafrost groundwater stored in closed non-frozen pockets under previously built roads, where snow layer was the thinnest.

Icings related to human activity are also those formed during the refreezing of thawed basins under single-storey wooden barracks without ventilated basements, after suspension of heating, or under brick-laid multi-storey apartment blocks with ventilated basements upon aquifer freezing.

3/2

INTRA-PERMAFROST GROUNDWATER

Intra-permafrost aquifers of varying thickness were encountered on multiple occasions within perennially frozen ground patches during borehole drilling, implemented by Igarka Permafrost Research Station and other survey groups.

As a rule, these non-frozen aquifers in talik zones were confined to interbeds of highly permeable soils. Weakly permeable frozen clays and loams served as side contacts of these saturated talik layers.

Two thin intra-permafrost aquifers were intersected in 17.5 m thick frozen silt during drilling of Borehole No. 88 in the Old City district, at the intervals from 8.6 to 8.8 m, and from 11.6 to 11.8 m in grey quartz sand. Ground waters were confined, and the piezometric level finally stabilized at 4 m below the wellhead. A deep borehole, drilled in 31 m thick permafrost section 200 m aside from the Igarka Permafrost Research Station facility, intersected four non-frozen aquifers confined to sandy interbeds. According to N.I. Bykov (1934), the aquifers were observed at intervals from 4.0 to 4.2 m, from 5.8 to 6.3 m, from 15 to 16 m, and from 18.0 to 18.6 m accordingly. No data is available on either aquifer head or water temperature.

The presence of four intra-permafrost aquifers interlaid by relatively thin frozen layers evidences a significant hydrostatic head, which permits their persistence in frozen medium even at low groundwater temperatures. Borehole No. 144O, drilled within the terrace subzone at the north-eastern limit of the Igarka city, provides more detailed data on the intra-permafrost groundwater features.

Two talik aquifers were encountered in frozen loams, at intervals from 3.0 to 4.5 m, and from 5.0 to 7.8 m. The upper aquifer was presumably fed by infiltration of surface waters, notably precipitation, and swamp water: bicarbonate ion content varied from 342 to 519 g/m^{-3}, and water temperature ranged from 2.4 to 3.3°C. The lower aquifer water temperature was *ca.* 1°C; its water chemistry differed slightly from that of the upper aquifer: bicarbonate ion content was 940 g.m-3. Groundwater chemistry was dominated by HCO3- and Ca, with medium TDS content.

Intra-permafrost groundwater persistence in frozen medium has several explanations. The most probable one is existence of highly permeable interbeds divided by massive frozen aquitard layers, so called cryogenic aquitards, with pores filled with ice. Confined character of water-saturated layers can also promote cross-layer water flow. Relatively low water temperature prevents thawing of frozen strata separating the aquifers. And, finally, high filtration rates in intra-permafrost aquifers might be supported by constant groundwater discharge either to the Igarka Branch or to the valley bottoms of nearby creeks.

3/3

SUB-PERMAFROST GROUNDWATER

Confined sub-permafrost aquifers are often found in the Igarka region under patchy permafrost, below the permafrost base. Sub-permafrost groundwater table depth is generally constrained by the depth of permafrost base.

Sub-permafrost groundwater is mostly confined to alluvial sands and sandy loams, and on rare occasions, to quasi-impermeable clay loams. These aquifers are fed by infiltration of lake and riverine waters through open taliks. Some groundwater inflow appears to come from deep confined waters in dislocated and fissured rocks.

From 1938 to 1940, Igarka Permafrost Research Station conducted drilling operations to prospect water sources for the Igarka city. In the lower reaches of the Medvezhiy Log creek, in Borehole No. 303, a sub-permafrost aquifer was intersected at 16.65 to 21.56 m interval, in the nearby Borehole No. 310 - at 8.65 m depth. The aquifers were confined, and groundwater level has settled at 4 m below surface at Borehole No. 303, while outpouring was observed at Borehole No. 310 with discharge rate of 0.8 L.s. Outpouring water temperature was 0.6°C. In 1940, a new Borehole No. 418 was drilled close to the Borehole No. 310. This new borehole 75 mm casing with filter section was installed within the sandy-gravelly aquifer layer. Maximum rate of discharge from this borehole reached 1.9 L.s at 5 m drawdown. In May 1941, after a long-term pumping test, the discharge rate from this borehole stabilized at 2 L.s, and water was supplied to the households in the Old City (Grigoriev, 1976a).

Besides the right-bank terrace subzone sub-permafrost groundwaters were also encountered at the Igarsky Island during a survey led by Igarka Permafrost Research Station. Artesian groundwaters were observed at various depths under a permafrost patch, in highly conductive sandy deposits. Piezometric water level exceeded the low-flow level of the Yenisey R. by 7 to 12 m.

Two deep boreholes were drilled at the Igarsky Island to supply water to the Igarka Airport in 1979. Borehole No. 5-134 intersected a confined sub-permafrost aquifer under a 20 m-thick layer of frozen sands and silts. Pumping test caused a rapid level drawdown. After that, the borehole was continued to 70 m, including 40 m in bedrock, consisting of highly fissured sandstones and tuff-breccias (Fig. 6). Pumping level settled at 6 m upon completion of the well, with a discharge from 0.6 to 0.8 L.s, which was insufficient for technical and household needs.
A new Borehole No. 5-136 was drilled 300 m away from the previous one. Above the bedrock superface, intersected at 26 m, non-frozen loams and sands were encountered. The borehole was further drilled down to 100 m, intersecting confined aquifers in highly fissured sandstones. Water table has settled at 12 m from the wellhead. Pumping level varied from 26 to 36 m, and pumping discharge rate exceeded that in the previous well, reaching 3.3 L.s of fresh high quality drinking water.
Considering the potential linkage between this aquifer, crossed by the two boreholes on the Igarka Island, and the Yenisey River waters, it should be noted that water table in these boreholes settled at 6 and 12 m, while the relative wellhead elevation was *ca.* 22 m, hence water table level exceeded low flow water levels by 10 m. This fact counters the direct link between groundwaters of the Igarsky Island and the Yenisey R. water which is characterized by seasonal level fluctuations.

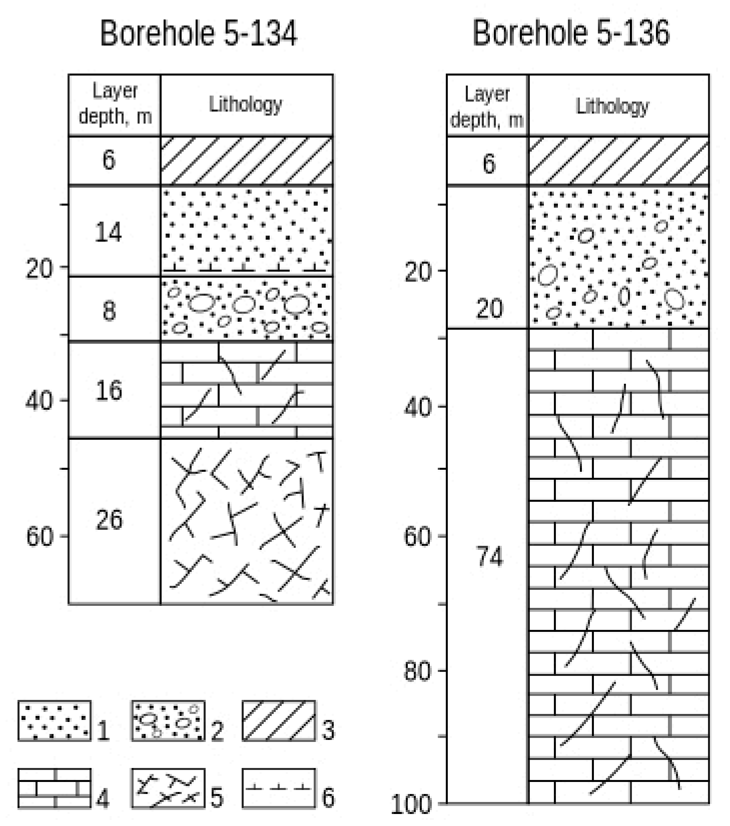


Figure 6 Geological cross-section with permafrost description. Boreholes ## 5-134 and 5-136 1 - sands, 2 - gravel with sand, 3 - loams, 4 - basal rock, 5 - fissured basal rock, 6 - permafrost limit

It is likely that the major sub-permafrost aquifer intersected by boreholes on the Igarka Island is linked to deep confined fissure water. This is supported both by variability of dynamic groundwater level in boreholes, and by aquifer discharge rate of *ca.* 3.3 L.s. Water pumping from production Borehole No. 5-136 was performed through filters in pipes installed at 45 to 60 m interval.

Water temperature in deep fissured bedrock layers varied from 2 to 2.3°C. High groundwater flow rates and associated upward transfer of geothermal heat have presumably allowed the existence of an open talik near this Borehole No. 5-136. A different situation was observed near the Borehole No. 5-134. This borehole intersected a permafrost layer with thickness of ca. 20 m, that persisted regardless of the presence of fissured bedrock containing deep groundwater. This can be explained by a lower hydraulic head of fissure waters and their weaker heat impact on the overlying permafrost layer.

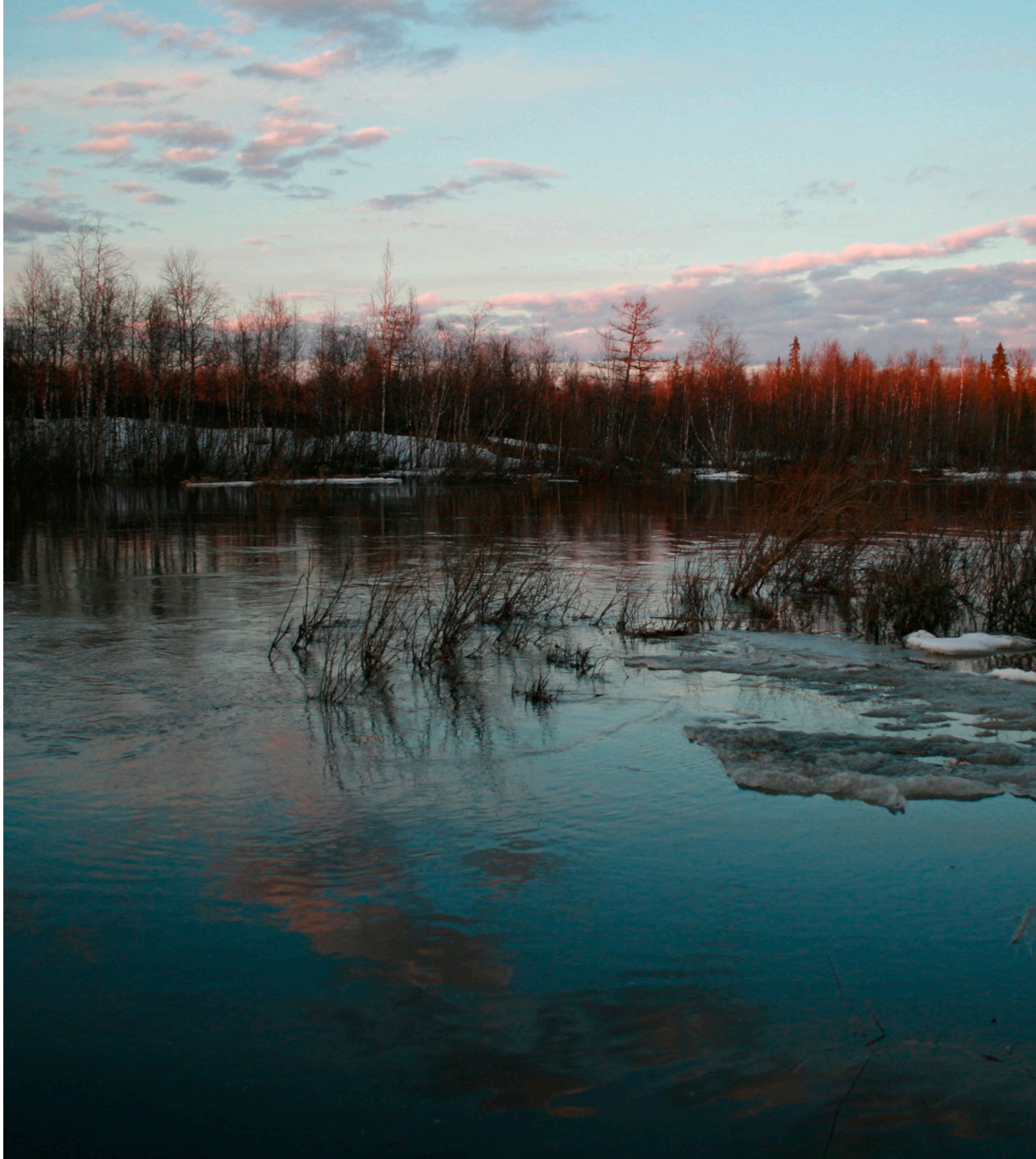
3/3

SUB-PERMAFROST GROUNDWATER

A similar picture was observed on the right bank of the Igarka Branch, within the terrace subzone, where numerous boreholes were drilled both in the Quaternary deposits and the underlying bedrock. Individual boreholes also encountered confined fissure waters with temperature around 5°C, and open taliks were observed around these boreholes.

The presence of permafrost in deposits underlain by bedrock, and its absence in neighbouring areas with geology similar to that where open taliks were present, can have several explanations. In areas with closed taliks, the underlying bedrock was less displaced (dislocated) and shattered, and consequently the groundwater head was smaller, with less heat imprint. At open talik sections, the bedrock was apparently more shattered, and groundwater flux through fissures and its warming effect on the reservoir rocks were more apparent.

Field observation data on the rock fissurization is currently absent. It is only known that the Igarka region is situated in the active tectonic area where the degree of fissurization and shattering of bedrock are varying throughout the region.



4. HYDROGENIC TALIKS (WATER-THERMAL)

Azonality of local hydrogeological conditions is predominantly related to the development of hydrogenic taliks of various classes. Overall, they are chaotically distributed across the Igarka region, occupying not less than 60% of its territory.

4/1

SUB-LACUSTRINE TALIKS

IN THE IGARKA REGION, SUB-LACUSTRINE WATER-THERMAL TALIKS ARE ABUNDANT.

They are found mostly on the lake-covered plateau surface, where they occupy 1/3 of the territory at least, as well as on the annually inundated floodplain level of the Yenisey R. right bank. It is noteworthy that the taliks are present not only under large lakes that do not freeze to the bottom, but also under smaller shallow lakes and swamps. Both open taliks and pseudotaliks are present; the latter are closed and underlain by permafrost at a certain depth.

Lakes and sub-lacustrine taliks were usually studied in course of transect surveys and included drilling of survey boreholes down to over 20 m. In winter boreholes were drilled on ice, and in summer - on lake shores. A total of more than 30 lakes were studied between 1931 and 1941.

In 1934, three survey boreholes were drilled, two within lakes and one in a swamp, down to 26.6 m depth. The Igarka Permafrost Research Station archives contain only brief description of surficial geology and permafrost in sub-lacustrine taliks, obtained from these boreholes (Table 5, p.46).

In 1941 the Igarka Station became the first to implement detailed observations on the thermal regime of lakes and lacustrine deposits in this region (Tsvetkova, 1961). Primary objects of these studies were the lakes situated at the plateau surface 3.0 to 3.5 km from the Igarka Branch.

Most observations were done at Lake 1, having an open surface area of *ca.* 2 000 m^2 and maximum depth in the center of the lake of about 2.4 m. Near the lake, three peat plateaus (palsas) were located, dissected by small linear depressions draining the lake toward the Medvezhiy creek headwaters. Two boreholes were drilled from ice - in the central part of the lake (No. 49-11 762), 13 m deep, and near the lake shore (No. 49-12 763), *ca.* 10 m deep. A third borehole, No. 49-13 764, was drilled 5 m from the shoreline.

Bottom lacustrine deposits are fine clays and silts, with local sand layers up to 0.5 m thick (at 6.5 m to 7.0 m interval). In summer, water temperature varied from 0°C to 12.2°C at the lake surface, from 0.4°C to 10.2°C at 1.0 m depth, and from 1.0°C to 5.2°C at the lake bottom. Ice thickness at Lake 1 was 0.3 to 0.5 m, thickness of snow over the ice - 0.6 to 0.7 m.

Temperature observations in lacustrine sediments in the borehole at the lake centre revealed that in mid-May the temperature in the upper sediment layer (1.4°C) was close to the water temperature near the bottom, 1.0°C.

Three to four meters below the lake bottom, ground temperature increased to 1.8°C, and was 1.2°C at the borehole bottom at 13 m depth; that is supposedly close to average temperature at the zero annual amplitude depth. Temperature observations in the same borehole at the end of summer (August 15), and early winter (September 15), showed only minor temperature fluctuations across the vertical profile, despite a significant increase of water temperature in the bottom layer, reaching 5.2°C. Relatively high temperature of non-frozen sediments (around 1.0°C) at 13 m depth evidences deep thawing of lacustrine sediments owing to existence of an open talik.

In course of drilling the borehole at Lake 1, confined aquifer was found with hydraulic head *ca.* 12 m from the borehole bottom at 13 m depth.

Frozen ground patches, *ca.* 5 m thick, were discovered by drilling in palsas, or peat hills, surrounding this Lake 1. The contact surface between the frozen grounds, maintaining temperatures from -0.2°C to -0.3°C, and a sub-lacustrine talik, was sub-vertical. Drilling in hollows or trenches between these palsas did not show any frozen ground above 6 m. Chemical analysis of samples collected from both the lake and the sub-lacustrine talik revealed a significant difference between the two. Lake waters had relatively higher mineralization and lower hardness.

Second water body where sub-lacustrine talik development was studied was Lake 2, with surface of *ca.* 250 m^2, relatively shallow (1.2 m), situated 100 m aside from Lake 1. According to Tsvetkova S.G., water temperature in the Lake 2 in mid-August 1949 varied from 12.6°C at the lake surface to 9.3°C at the lake bottom. The lake was not freezing to bottom in winter season. No boreholes were drilled at the lake center, but a survey borehole was drilled at the shoreline, exposing frozen ground between 0.7 m and 3.0 m depth, a continuation of a frozen massif of a nearby palsa. Drilling in the hollows, dissecting palsas and draining toward Lake 2, exposed non-frozen ground above at least 10.7 m. In a marshy terrain in the vicinity of Lake 2, a minor lake at the centre of this marsh was studied, with a diameter between 1 and 2 m, and depth from 1.0 m to 1.5 m. Drilling under the bottom of this lake discovered non-frozen sediments above at least 10.0 m, highly saturated with groundwater, with hydraulic head exceeding 9 m.

4/1

SUB-LACUSTRINE TALIKS

Thermokarstic hollows with drying lakes at their bottoms, widespread at the plateau surface, and the abundance of half-submerged dead tree trunks leaning in all directions by the lakes' shorelines evidence active thermokarst development within subsided zones with an increased snow cover thickness, where, according to S.G. Tsvetkova (1961), sub-lacustrine talik ground waters are formed.

As evidenced by the depth of relict permafrost layers, we can suppose that within these depressions and marshy hollows, the processes of permafrost degradation under warming influence of lake waters take place and their intensity varies under differing conditions. Talik development under marshes with significant thermokarst effect, also occurred at different rates depending on the thickness and depth of ice-rich layers.
The omnipresence of groundwater throughout the region, in open taliks, under large and small lakes, marshy hollows, as well as under permafrost patches, can be explained by existence of a single aquifer, fed by infiltration of surface waters of rivers and lakes through open taliks by downward water fluxes, that presumably exist all year round (Tsvetkova, 1961).

In the author's opinion, existence and widespread occurrence of open sub-lacustrine taliks is also explained by the presence of confined aquifers fed by deep fissure waters.

4/2

SUB-CHANNEL TALIKS

Water-thermal (hydrogenic) taliks, widespread in the Igarka region, include open and closed subchannel taliks under both freezing and non-freezing streams.

The largest stream in the studied region is the Igarka Branch of the Yenisey River. Several borehole lines were drilled from ice in the Igarka Branch channel during geologic surveys performed by Northern Development & Exploration Expedition (NDEE).

Boreholes were drilled down to a depth from 5 to 15 m below the bottomline. One borehole, No. 1246, near the right bank channel zone, was drilled down to 32 m and exposed metamorphic bedrock, marl and tuff-brecchia, along with overlying silty sands, sands, and gravels (Figure 7). All intersected deposits, including bedrock, are lying under a 15 m thick layer of water, maintaining its temperature around 1.0°C throughout the year.

Positive mean annual ground temperature under the Igarka Branch channel evidences the existence of an open talik contoured by frozen ground patches ('islands'). This talik might be connected to intra- and sub-permafrost aquifers, the free surfaces of which are above the water level in the branch. These aquifers, apparently, discharge to the Igarka Branch channel leading to increased temperatures in the surrounding frozen sediments in the channel banks. The heat exchange is promoted by the presence of highly hydraulically conductive layers (sands and light silts) in the channel banks and bottom.

Open sub-channel taliks of filtration class under the Igarka Branch and, surely, under the Yenisei R. main channel are likely to have existed for a long time. On the right bank of the Igarka Branch, under the channels and in the valleys of minor creeks draining into the branch, open taliks of infiltration class were found in numerous boreholes, e.g. in the Medvezhiy Log creek valley.

In the development of sub-channel taliks, sub-channel groundwater flow is mixed with the infiltration flow, hence these taliks are both water-supplying and water-consuming. Groundwater temperature in such open taliks depends not only on the surface water temperature, but also on the convective heat flux within a talik.

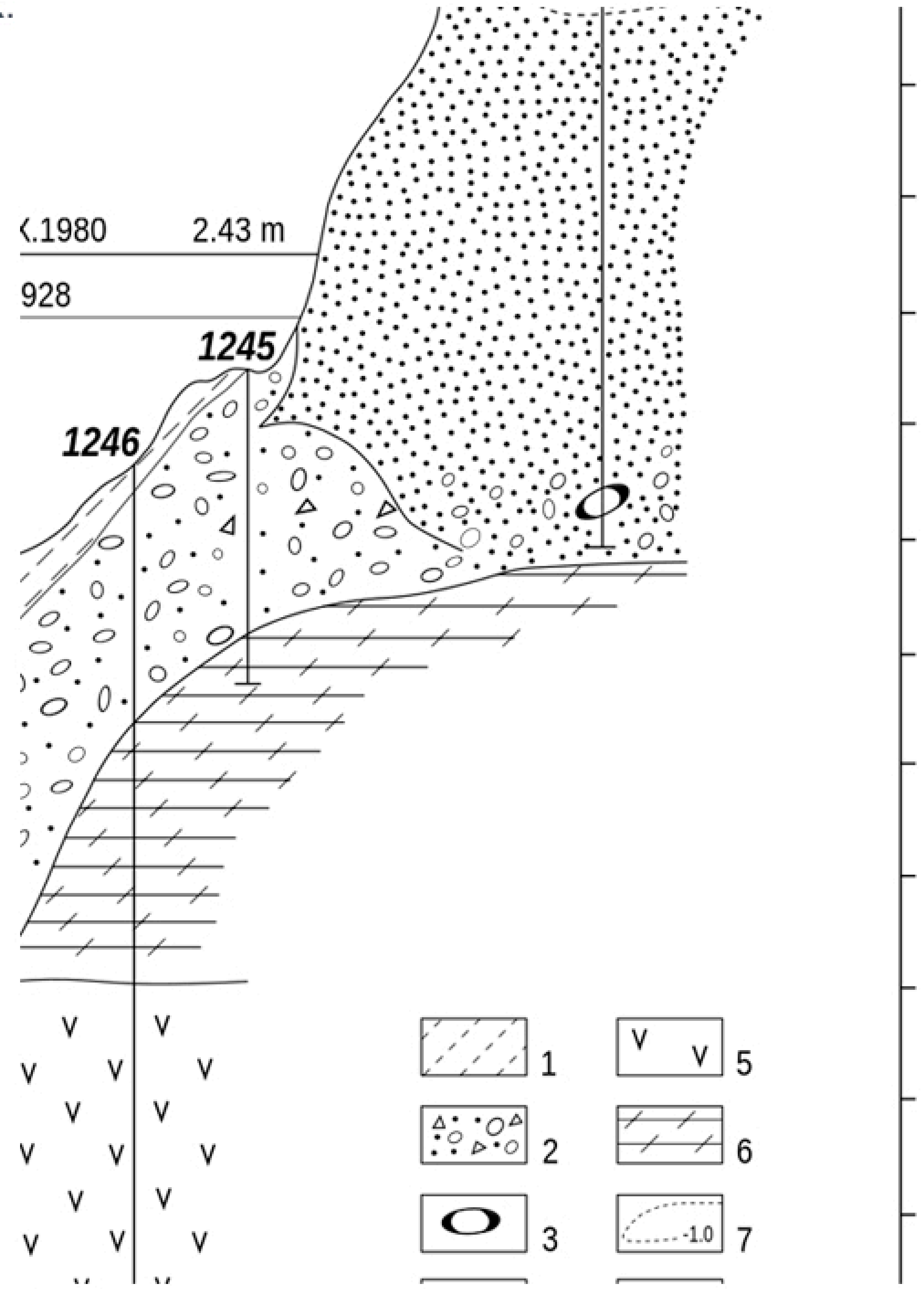


Figure 7 Geological cross-section with permafrost description, Boreholes 1241-1247
1 - sandy loams, 2 - boulders and gravel, 3 - single boulder, 4 - sands, 5 - tuff breccias, 6 - marls, 7 - isotherms, 8 - lithological boundaries, 9 - borehole number

4/3

PSEUDOTALIKS.

Geocryologic and geologic surveys in the Igarka region have revealed a widespread occurrence of pseudotaliks, *i.e.* non-frozen layers between the seasonally freezing layer bottom and the top of permafrost, retaining positive temperatures throughout the year. Some researchers link the development of pseudotaliks to an increased snow cover thickness (Sukhodol'sky, 1982).

The snow cover depth in the Igarka region varies from 0.1 m to 3.0-3.5 m as per terrain topography and vegetation cover. Snow cover serves as an effective insulation reducing heat loss from the ground surface. In winter, it strongly reduces the range of near-surface ground temperature fluctuations and, depending on its thickness, reduces heat exchange between ground surface and atmosphere. Observations from the neighbouring Norilsk region show that zero isotherm could be traced under 2 m thick snow cover in winter. Across 8% of the tundra surfaces and 19% of the piedmont areas around Norilsk, an increased snow cover depth sustained positive mean annual ground temperatures in the near-surface ground layer, and prevented freezing of 37% of the total area (Shamshura, 1957).

Igarka Permafrost Research Station was observing temporal variations of the top of permafrost depth, highest snow depth, and seasonally frozen layer thickness in the Kladbishchensky Creek valley from 1946 to 1949, by means of shallow drilling (Table 6, p.47). Obtained data show only minor interannual variations in the observed parameters of the top of permafrost depth or pseudotalik thickness during three years of study.

Depending on the topography and vegetation cover, given 0.5 to 0.8 m snow depth, the top of permafrost depth varied from 5 to 7 m. Permafrost persisted with the snow depth increase from 0.8 m to 1.14 m, but its top subsided to 9.0 m and, in one case, even to 11.2 m.

Long-term regime observations of snow cover insulation capacity and its influence on soil thermal regime, performed by the Igarka Permafrost Research Station, were continued in 1971-1974. Experimental plots were set up at the outer edge of the terrace permafrost subzone, where snow cover depth and temperature were observed (**Table 7**, p.48), and geothermic boreholes were drilled for observation purposes. These data show that at a monthly scale the air temperature roughly equals the snow surface temperature (**Table 8**, p.49), though rapid temperature fluctuations in the snow layer were also observed.

A crucial part in pseudotalik development, along with the insulating snow cover effect, is often played by groundwater. Observation data confirming groundwater presence in pseudotaliks were obtained in boreholes No. 1440, 1441, and 1444 at the terrace subzone, where the top of permafrost was found at depths varying from 4 to 8 m.

As noted previously, two aquifers were observed in the non-frozen layer: the first between 3.0 m and 4.5 m, and the second between 5.0 m and 7.8 m. Presence of groundwater in pseudotalik (with temperatures from 1.0°C to 3.4°C) contributes to the pseudotalik's increased thickness and higher temperatures of the underlying frozen soils via both convective and conductive heat transfer. Moreover, these aquifers serve as insulating layers that limit the influence of seasonal air temperature variations on ground temperatures.

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FISSURE WATER-THERMAL TALIKS

FISSURE WATER-THERMAL TALIKS ARE TIGHTLY LINKED TO TECTONICS AND HYDROGEOLOGY OF THE IGARKA REGION.

They originate and exist owing to local heat transfer by fissure water. These taliks are azonal in respect to spatial distribution, origin, and relation to major tectonic structures. Igarka region completely falls within the Yenisei hydrogeologic zone with disjunctive dislocations.

The longest and the most fragmented is the Igarka-Rybinsk fault line, surrounded by minor Norilsk, Khantayka, and Kulyumba fault lines (see Fig. 1). The width of each crush zone varies from first hundred meters to first kilometers.

Widespread fault tectonics in the region governs the complexity of hydrogeological conditions, since groundwater discharge areas strongly correlate with fault zones. Thus, water-bearing tectonic faults are not only core discharge areas but also secure the connectivity between groundwaters and surface waters.

Circulation of thermal confined groundwater in fissure zones is a permanent driver that provides favourable conditions for convective heat transfer - warming of the surrounding rocks and formation of saturated taliks with annually positive temperature.

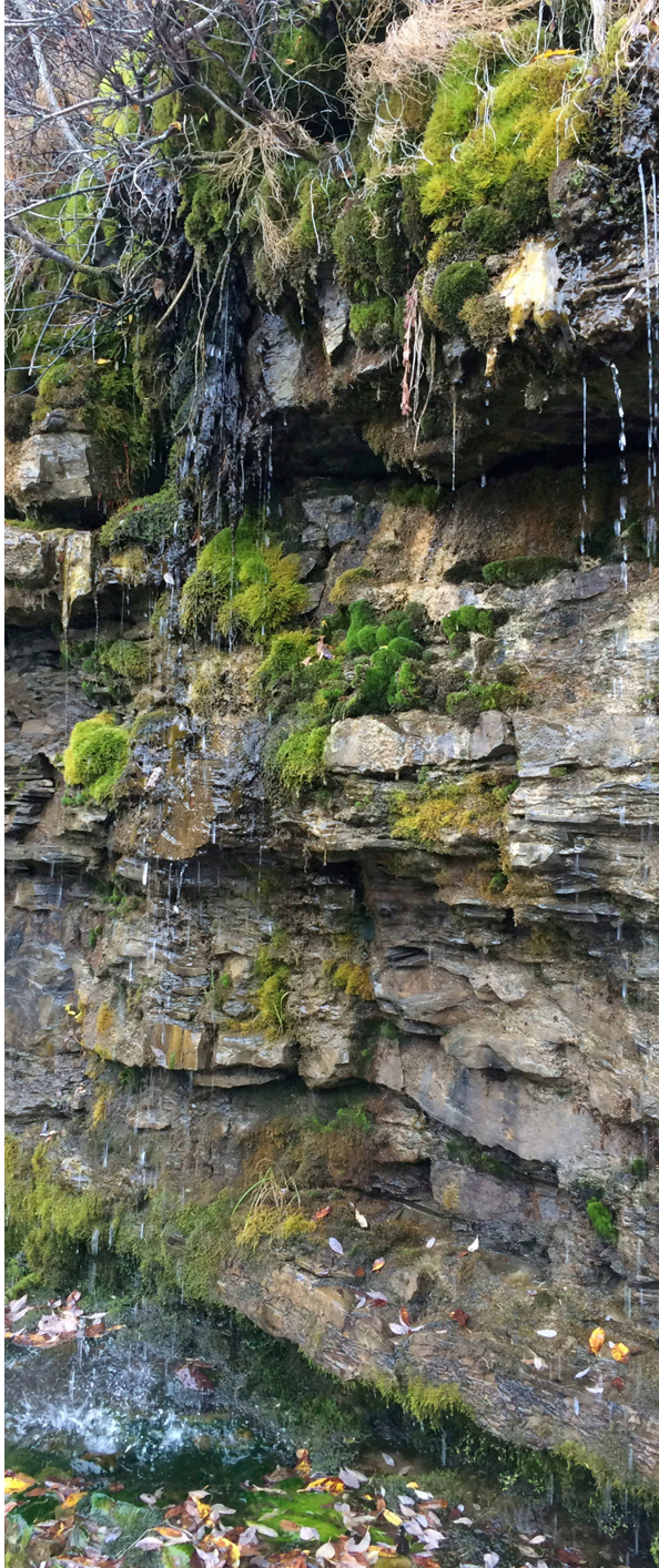
A number of boreholes in Igarka was drilled in base rock: primarily effusives and brecciated tuffs, and sedimentary rocks to a lesser extent. The majority of boreholes intersected confined aquifers. According to G.F. Odinets (1964), test pumping from individual boreholes (11-k, 53-k, 17-k) allowed estimating the specific yield of fissure waters and the hydraulic conductivity of effusive rocks. The highest specific yield, 0.087 L/s, was registered in Borehole No. 11-k, where the aquifer thickness was 18.05 m and the top of aquifer was located at at 5.1 m. The lowest specific yield, 0.0017 L/s, was observed in Borehole No. 29-k, where the top of aquifer was found at 10.0 m and the aquifer thickness varied from 20 to 25 m. Hydraulic conductivity of the bedrock vary from 0.02 m/day in Borehole No. 29-k to 0.78 m/day in borehole No. 53-k.

Observed piezometric level was always above the bedrock layer top, and in the Borehole No. 11-k it was 0.35 m above the well-head. Fissure water temperature and chemical composition were measured. According to G.F. Odinets (1964), the temperature of the fissure waters varied from 0.4°C at 17 m to 5°C at 12 m depths.

Water temperature observations were done in January and February. Fissure waters had a high TDS content, dominated by chlorides and natrium.

A stable piezometric level would set at various depths and, in most cases, above the bedrock top. Often it was higher than the water level in the Igarka Branch and in nearby lakes.
The fissure pressure waters have the highest thermal imprint in fault zones where geothermal flux is the greatest and where, as borehole geothermic observations show, frozen ground is continuously warmed and convective taliks are formed.

Highly valuable observation data were obtained when the pressure water temperature was measured in boreholes at 2 m to 40 m interval (Odinets, 1964). They evidence positive water temperatures throughout the entire water column in boreholes. Thus, relatively high temperatures, ranging from 2.4°C to 3.3°C, were observed in boreholes No. 11-k, 12-k, and 1231.



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Positive water temperatures in shallow aquifers in winter confirm the existence of open taliks. Based on average groundwater discharge ca. 30 L.s (test pumping data from boreholes Nos. 17-k and 53-k) and mean water temperature around 2.1°C, G.F. Odinets did a preliminary calculation of heat flux carried by groundwater from the Igarka effusive rocks in winter for a section between the Karmakuly Cape and the Medvezhiy creek mouth (1964).

Among areas occupied by fissure water-thermal taliks are not only those locations where effusive rocks are exposed (the Karmakuly Cape area), but also those where they are covered with Quaternary sediments of

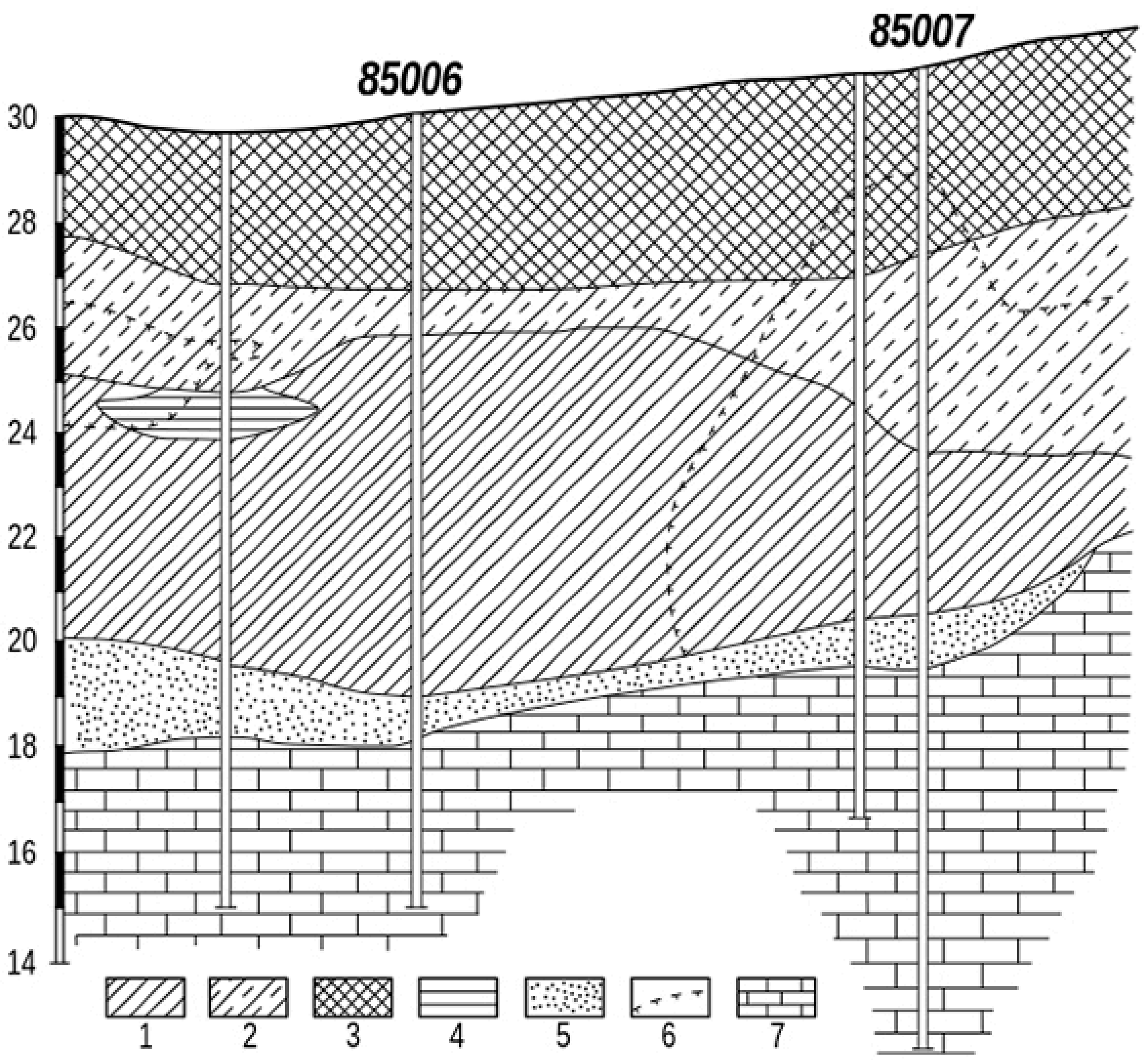

Figure 8 Geological cross-section with permafrost description, Boreholes ## 85006 & 85007
1 - loams & silty loams, 2 - sandy loams, 3 - bulk fill soil, 4 - clays, 5 - sands, 6 - permafrost boundary, 7 - basal rock

varying thickness (sections of First and Second Districts of the Igarka city). Confined aquifers are often found in underlying bedrock. Some reports by the Krasnoyarsk Trust of Geological

Surveys even suggested that at certain locations bedrock serves as a 'heating element' for the overlying frozen Quaternary deposits, where open taliks developed.

Complex water-thermal taliks connected to pressure waters in bedrock include non-frozen sections in sediments, which were found during permafrost and geology surveying at construction site for the Igarka Timber Factory workers supply department warehouse, located at the first terrace in Igarka. In 1984, Igarka Permafrost Research Station was involved in these surveys. Drilling data provided information on the distribution and thickness of both frozen and non-frozen sediments overlying bedrock. In 1985, additional boreholes were drilled in lacustrine and fluvio-glacial deposits, and in the underlying bedrock down to 9 m below its top. The top of highly fissured limestone bedrock was rough and was found at 10 m below surface and deeper.

In course of drilling, a confined aquifer was found and its level settled at depths ranging from 1.25 m to 1.35 m below well-head, while well bottom depths varied from 14 m to 20 m. Groundwaters were fresh, and bicarbonate ions prevailed in chemical composition. Borehole data was used to plot a permafrost geology cross-section (Figure 8). Its analysis shows that there is an open talik at the location of Borehole No. 85006, while Borehole No. 85007, *ca.* 50 m aside, was drilled in a frozen massif having a steep wall contact with non-frozen ground. Geothermic observations revealed a uniform temperature distribution around +0.8...+0.9°C within the talik (Borehole No. 85006).

Upon completion of both boreholes, before thermometric casing was installed, an increase of groundwater level was observed.

Groundwater was discharging from a confined aquifer in non-frozen sandy stratum, *ca.* 1 m thick, overlying the bedrock. Drowning of a borehole was also observed at bedrock interval, and the groundwater level settled at a depth from 15 m to 17 m above the low-flow stage at Igarka Branch.

Groundwaters from both the Quaternary deposits and the underlying fissured bedrock presumably discharge into this branch.
In the neighbouring Borehole No. 85007, where the top of permafrost was observed at 2 m, and its bottom at 10 m, mean temperature was -0.1°C. The temperature of the underlying non-frozen layer at 10 m to 13.9 m interval was *ca.* 0.2°C.

G.F. Odinets (1964), describing conditions of talik development under influence of pressure groundwater, underscores a positive correlation between frozen ground thickness and hydraulic properties of sediments.
As permafrost geology profile of Boreholes Nos. 85006 and 85007 shows, the top of bedrock is overlaid by a *ca.* 1 m thick layer of coarse-grained sand. High hydraulic conductivity of this sandy layer given fissure groundwater presence in bedrock, was likely to cause the development of a two-layered water-thermal talik, which was found while drilling at this construction site section.
Hydraulic head in groundwater in both sedimentary and bedrock aquifers evidences their abundance, and positive temperatures (up to +5.0°C) confirm their measurable thermal imprint on the ground.
Groundwater transit from various aquifers is accompanied by heat transfer toward discharge zones, located below the static groundwater level. It is these circumstances that lead to a wide areal development of taliks (their extensive network) and azonal patchy distribution of permafrost in the Igarka region.

CONCLUSION

CONCLUSION

KEY FEATURE OF GEOCRYOLOGICAL CONDITIONS IN THE IGARKA REGION IS A DISCONTINUOUS, PATCHY DISTRIBUTION OF PERMAFROST, SEPARATED BY WATER-THERMAL TALIKS.

Furthermore, the thickness of permafrost varies from 5 m to 35 m.

Permafrost development in the region occurred at different time periods. In the oldest terrain elements within the plateau, frozen layers developed in the middle Quaternary, within the Karga terrace - in the upper Quaternary, and on the youngest terrain elements - in Holocene. Rocks of different origin (fluvioglacial, lacustrine-alluvial, etc.) were mostly freezing epigenetically, and to a lesser extent, syngenetically.

Regional hydrogeology has a major impact on the development of geocryological conditions in the region.

As a rule, permafrost develops in correlation with sub-permafrost groundwater. Hydraulic head, typical for the majority of the latter, procures their discharge to the Igarka Branch of the Yenisei River. When the piezometric surface rises above the thalwegs of local streams that drain into this branch, groundwater drainage occurs within this channel network.

Groundwaters pressure, their thermal state, and heat capacity created optimal conditions for the development of both open and closed taliks (pseudotaliks). The aquifer thickness in taliks of various types, located at the top or bottom of permafrost, ranged from 0.2 m to 2.5 m and more.

That being said, groundwater discharge rates depend mostly on their sources.
Water-thermal taliks are very unevenly distributed both across the region and in cross-section. Positioning of aquifers at various depths allows water migration and exchange between them. Open taliks are both discharging and consuming water, and the intensity of thermal imprint on permafrost increases with increasing water capacity, water temperature, and hydraulic head of an aquifer.

Groundwater acts as a heat-transfer agent, altering the temperature field within the talik. In the uppermost aquifer, conductive heat transfer prevails in some cases, and convective heat transfer in others. For example, in sub-lacustrine taliks, abundant in the region, their thermal regime is defined by the near-bottom water temperature, and ground thawing occurs under conductive pattern. When water transit exists within aquifers, convective heat transfer seems to be prevailing. Available data by G.F. Odinets (1964) evidence that faults promote confined fissure water transfer along tectonic fractures, releasing geothermal heat and thawing the ground. As a result of a permanent hydrodynamic action, maintaining groundwater movement and convective heat transfer, open taliks were formed in areas where fissured strata and water-abundant bedrock are found. But there are some sites, where frozen patches of loose deposits overlie bedrock. Notably, they are located close to open taliks not only in bedrock, but also in the overlying loose deposits, with steep side contacts.

Explanation of the rapid shift in permafrost geology conditions is to be looked for in the presence or absence of fissured bedrock below the Quaternary sediment cover, their water cut, hydraulic head, and heat content of deep groundwater.

At sites where bedrock is solid and deep waters do not have a direct thermal impact on loose deposits, frozen layers of varying thickness were preserved.

In open taliks, where bedrock and overlying loose deposits are in thawed state, the piezometric levels of deep fissure waters that are close to the ground surface, prevent freezing of loose deposits and development of permafrost, despite cold climatic conditions.

In open taliks, deep fissure groundwater in some cases feeds sub- and intra-permafrost groundwater connected to permafrost.

We can assume that free water and heat exchange zones exist across large areas of the region, where an integral aquifer is sustained by the action of fissure water. This aquifer is fed by deep groundwater and, through infiltration, by surface waters of riverine and lacustrine origin, the downwelling heat flux from which is effective year-around.

Azonality of local geocryological and hydrogeological conditions in Igarka complicates the choice of both construction sites for engineering structures and construction methods in given local conditions.

Taking into account the patchiness of local geocryological conditions is key to identify adequate design and construction practices in the Igarka region and adjacent territories.

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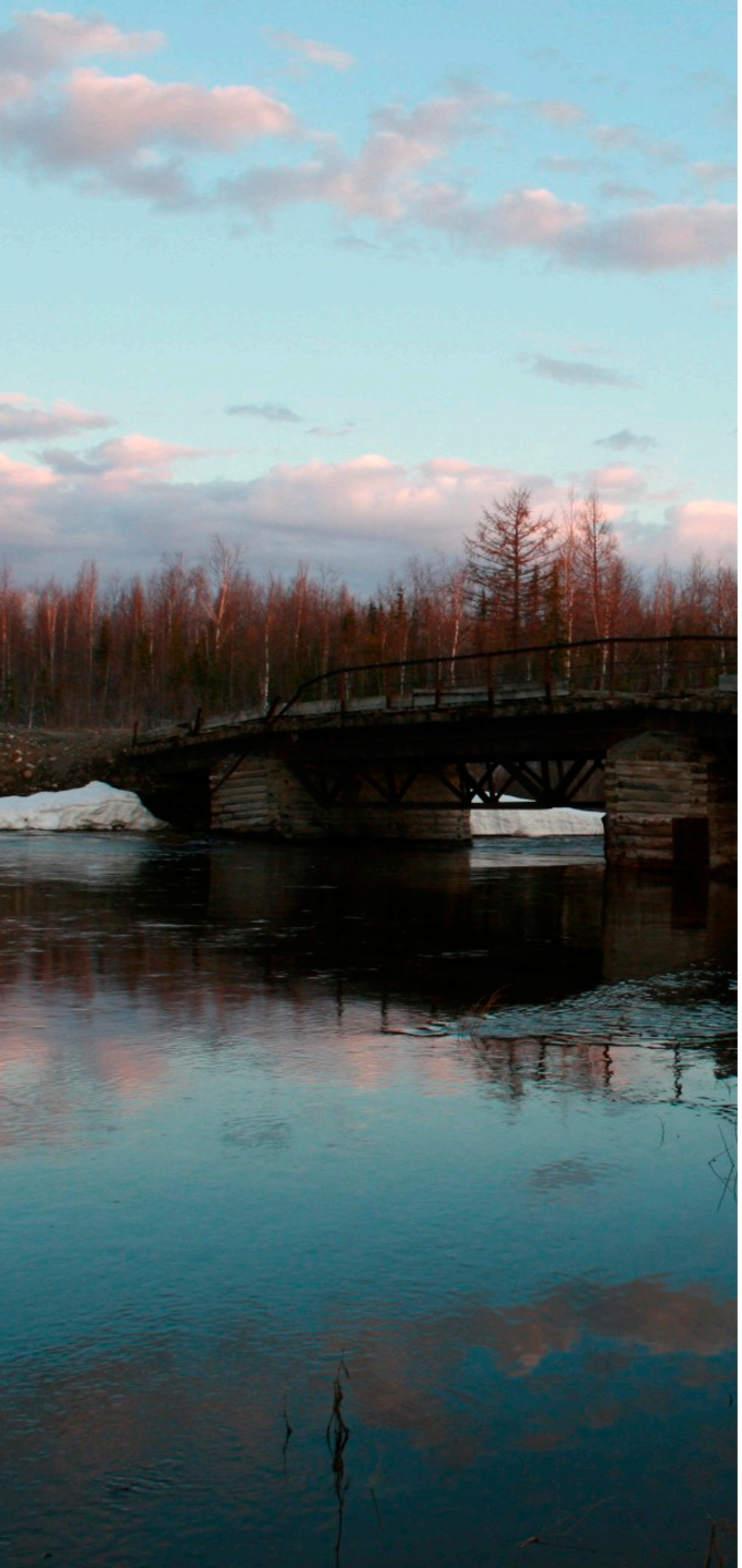
[i] Karga interglacial = MIS3, 57-29 ka
[ii] Zyryan glaciation = MIS4, 71-57 ka
[iii] Sanchugovsky glaciation = MIS6, 191-130 ka
[iv] Kazantsev interglacial = MIS5, 130-71 ka

AFTERWORD

BY DR. NIKITA I. TANANAEV



AFTERWORD

A SAD CONSTATATION: IGARKA, AS DESCRIBED BY NIKOLAY GRIGORIEV, HAVE CEASED TO EXIST IN ROUGHLY A DECADE FOLLOWING THE PUBLICATION OF HIS MANUSCRIPT.

The text you have just gone through has therefore a specific merit from the point of scientific palaeontology, since it relates at once to the inexistent location and lifestyle, and also to a particular, now-obsolete research medium and scientific tradition. In my translation, I have tried to stay close as possible to a specific style of academic writing, so typical for the old-school Soviet researchers.

The collapse of Igarka is a remarkable societal transition. The shrinking isolated community, surviving the economical storm of the post-USSR years, and its capacity to adapt, can be seen in a wider scope of a global *collapse & recovery* cycle, including certain physiographical implications. The emerging New Arctic with its milder climate, though promising more favourable living conditions to fellow Northerners, may also live through difficult times in the coming decades. Warmer climate scenarios are expected to drive vegetation changes, permafrost thaw, soil subsidence, alteration of hydrological pathways and biogeochemical fluxes, to limit winter transportation and to undermine infrastructure stability. Quantifying changes requires a baseline against which the assessment is drawn up, a set of historical scientific data resembling collective memory of previous generations, which this booklet somehow provides.

Russian Arctic has been extensively studied during the Soviet era, but only an insignificant fraction of collected data, descriptions and insights had passed the Iron Curtain. The rest is gathering dust in institutional archives mostly unknown to general public.

These data have been only partially treated and interpreted even in Soviet/Russian literature, and introducing them to the global research community is resembling of driving a time machine.

I count myself personally fortunate to live in Igarka over six years, from 2010 to 2017, and to observe its downfall just before it became an agony two years later. I still keep in me this pride of being part of the city history, and compassion toward all my Igarka friends and colleagues living through the decline of the city. I even feel this *nostalgia* for the former independence and free spirit, so typical for Igarka throughout its history. I owe much to Igarka, both personally and professionally, and I return the favour in the only way I am capable of.

This publication was made possible through collaboration and with support from my friends around the world, both in Igarka, where **Anna Usoltseva** was long the only person absolutely convinced in the importance of this effort, in Yakutsk, where **Kyunney Fillipova** proof-edited my English translation, in Moscow, where **Anna Zakharova** created this marvellous layout full of colour and style, and in Toulouse, where **Roman Teisserenc**, **Laure Gandois**, true Igarka friends, offered me endless support during my stays. To them all, and to many others, who have visited Igarka Permafrost Research Lab, and shared with me the Northern way of life and research, I extend my endless gratitude.

The following sections briefly compile some up-to-date information on the physiography of the Igarka region, from both published and unpublished sources. My hope is that this snapshot could provide a basic, yet concise reference for those interested in the Northern Yenisey region, attract scientific attention to this otherwise understudied region, and drive future studies.

CLIMATE

The Igarka climate is *Dfc*, Subarctic Continental or Boreal, according to Köppen classification, with seven to eight months below 0°C, and two to three months above 10°C. Its coldest month, January, averages -27.9°C (1936-2019), and the warmest, July, +15.4°C, and mean annual air temperature (MAAT) is -7.8 ± 1.5°C.

Mean annual precipitation (P) is 647 ± 99 mm, with an average snow/rain ratio close to 1.2, or 55/45, and only on rare occasions, annual rainfall exceeds snow precipitation. It should be noted that in the 1940s and 1950s, new precipitation gauges were installed at meteo stations in the USSR, and numerous changes to observation protocols were introduced in later years. Therefore, direct observation data are invalid until corrected, and this fact should be accounted for. Both corrected and uncorrected datasets are openly accessible via the RIHMI-WDC web-portal (http://aisori-m.meteo.ru/waisori/).

Recent decade was marked with several weather anomalies, both in winter and in summer. In 2014, January was the coldest on records, with mean monthly air temperature below -40.1°C, caused by the Polar Vortex breakdown, preceded by Ural Blocking event and sudden stratospheric warming. In the 2010s, June was on two occasions, in 2011 and 2018, the warmest month of the year, which before had only happened twice, in 1985 and 2003. Annual precipitation exceeded 800 mm in 2011, 2013 and 2014, while in previous years it was also observed twice, in 1949 and 1962.

Interestingly, in 2013, most precipitation, over 73%, was snow, while summer season was relatively dry and hot, with daily highest air temperature persisting above +30°C during ten days, 19 to 28 July, and hitting highest temperature on record, +34.0°C, on 22 July. This period was also dry, rainfall only totalled 6.8 mm between mid-July and mid-August. In 2016, the region experienced a rare drought event. No rainfall was recorded for 30 days, between 29 June and 28 July 2016, the longest dry period on record, and most minor creeks had completely dried out during this event.

CLIMATE CHANGE

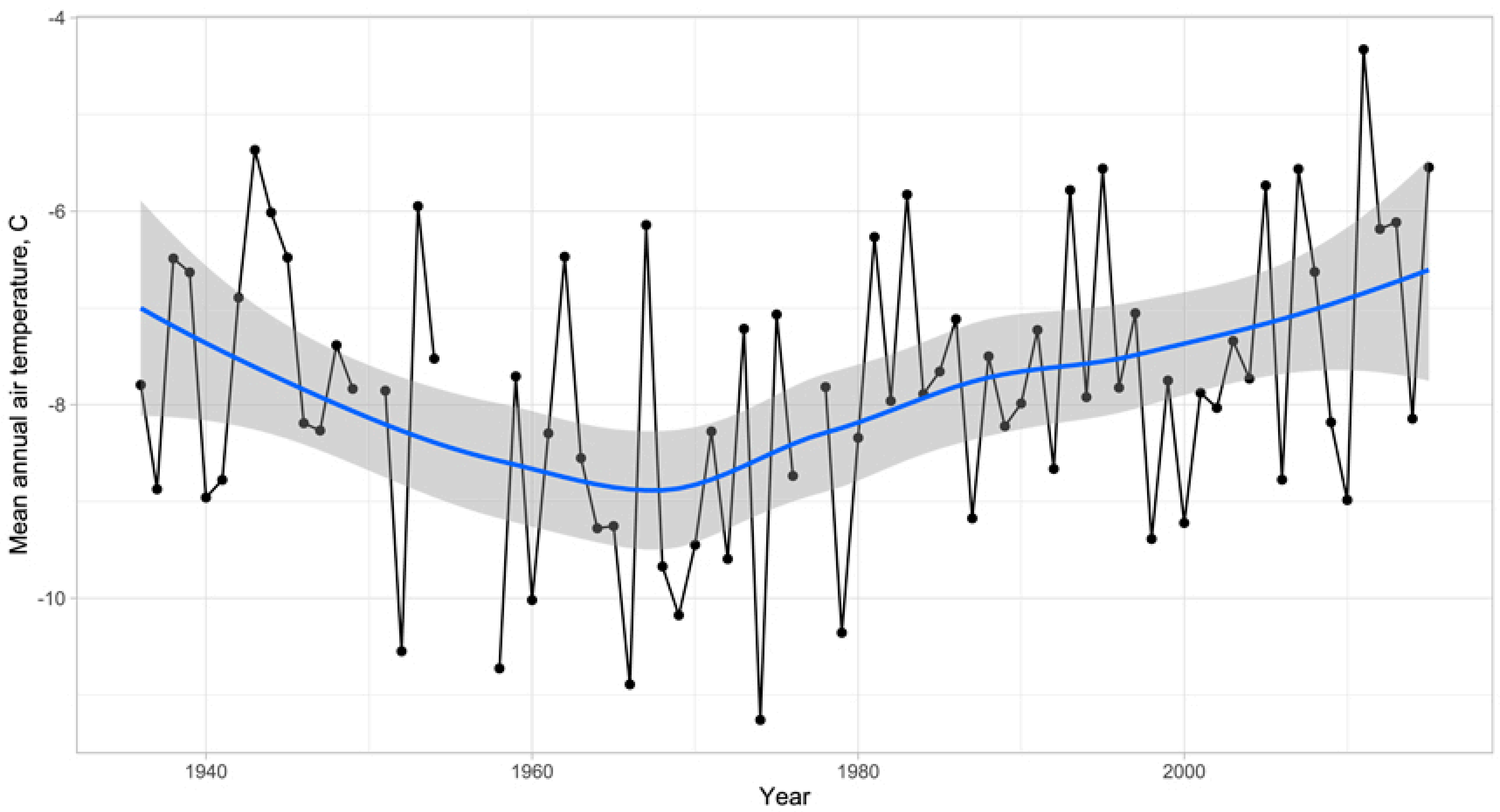
As the global warming advances in the Northern Hemisphere, its influence on the Northern Yenisey region also becomes apparent. A significant upward trend exists in MAAT, with $p < 0.05$ (1936-2018; see Figure A.1), while mean annual extreme temperatures and total annual precipitation show no significant trend. The two recent decades appear to be particularly warmer, with an average MAAT around -6.7 ± 1.3°C (2003-2018), compared to preceding periods: -8.7 ± 1.5°C (1949-1980) and -7.7 ± 1.1°C (1981-2002), resulting in a linear trend from 0.09 to 0.16°C/decade, calculated from Hodges-Lehmann means for homogenous periods and from Theil-Sen correlation.

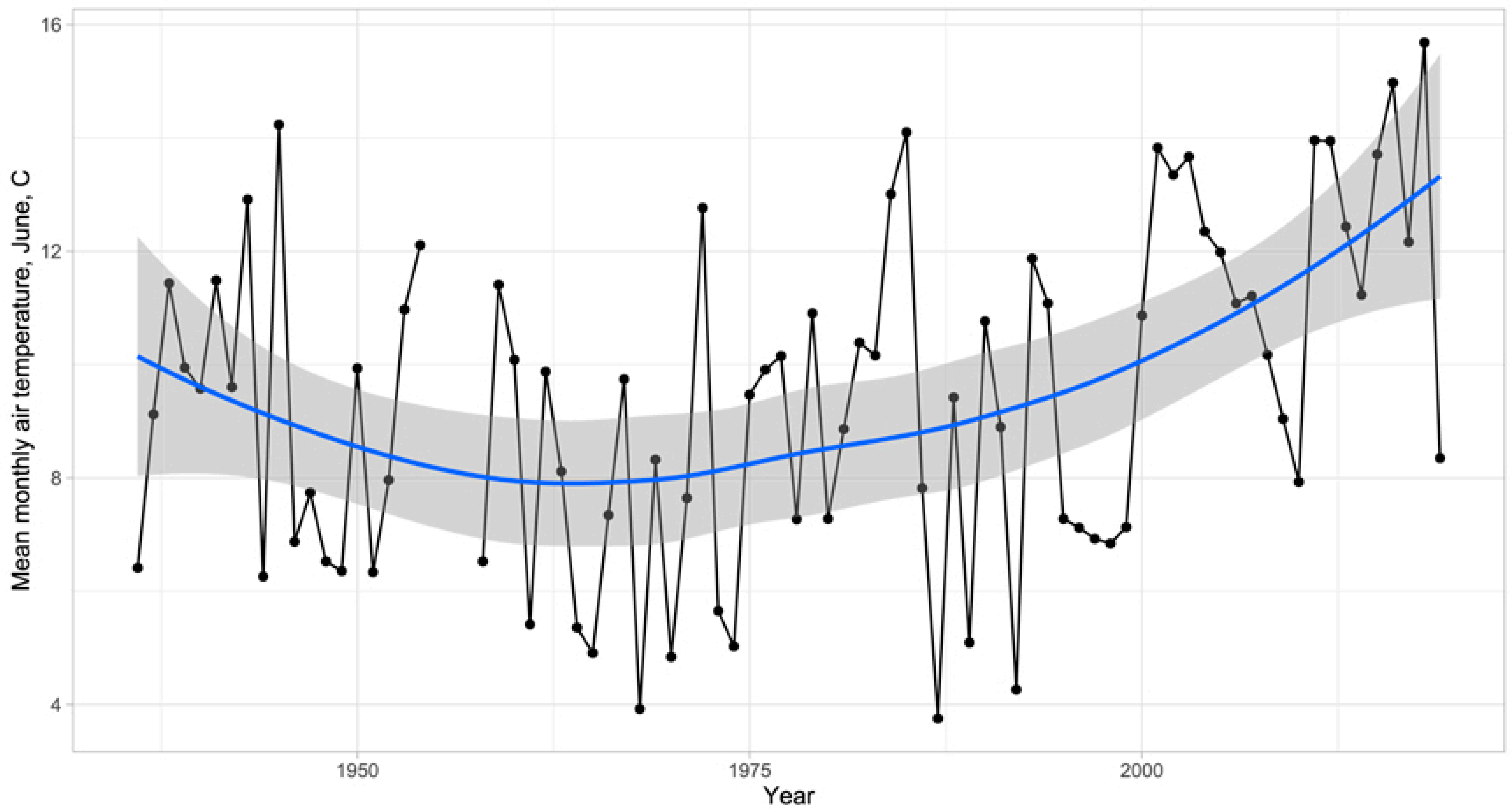
There appears to be a certain degree of visible coherence between MAAT and precipitation (P) time series. Moving mean time series comparison suggest several periods in temporal evolution: (1) *1930s to late 1950s*, with MAAT decreasing and P decreasing (counterphase); (2) *late 1950s to late 1970s*, cold and mostly humid; (3) *late 1970s to late 1990s*, moderate and dry; (4) *since late 1990s*, with MAAT and P increasing (synphase).

Observations suggest that Igarka climate is shifting gradually toward Köppen *Dfb*, or hot-summer humid continental climate. While during 1940s and 1950s on only falls average only two summer months, July and August, had mean air temperature above +10°C, and it was only July in certain years, in the 2010s all three summer months were consistently above +10°C, and September short by 1-2°C to join them. Higher June air temperature implies earlier snowmelt, longer snow-free conditions and, ultimately, deeper permafrost thaw in summer and autumn.

Mean June air temperature shows a significant upward trend (Figure A.2), $p < 0.005$, increasing from 8.5 ± 2.6°C (1936-1999) to 12.1 ± 2.1°C (2000-2019). Air temperatures are also getting warmer in March, $p = 0.01$, from -20.0 ± 3.9°C (1936-1987) to -16.7 ± 4.2°C (1988-2019). Shifts in monthly mean air temperature are most probably related to changes in regional weather patterns. Mean monthly extremes for both months also show an upward trend with $p < 0.01$.

Changes in mean monthly precipitation reflect the suggested alteration in dominant weather patterns toward milder winter and warmer autumn. An increase is observed in winter months, February and November, and a decrease - in September, all with $p < 0.05$, evidencing changes in cyclonic activity in the region.





HYDROLOGY

The hydrological landscape of the Igarka region is dominated by the Yenisey River, the largest in the Arctic, with mean annual daily flow ~ 18 600 m3 s^{-1} and annual runoff ~ 584 km^3 (1939-2016), and maximum daily flows exceeding 120000 m^3 s^{-1} in most years. The Yenisey R. water regime is affected by both climate change and human impact, the latter - through a number of hydropower construction projects on the main stem of the river and on its large tributary, the Angara R., operating since early 1970s. Hydropower operations have altered the natural water regime, mainly by reducing spring freshet peaks.

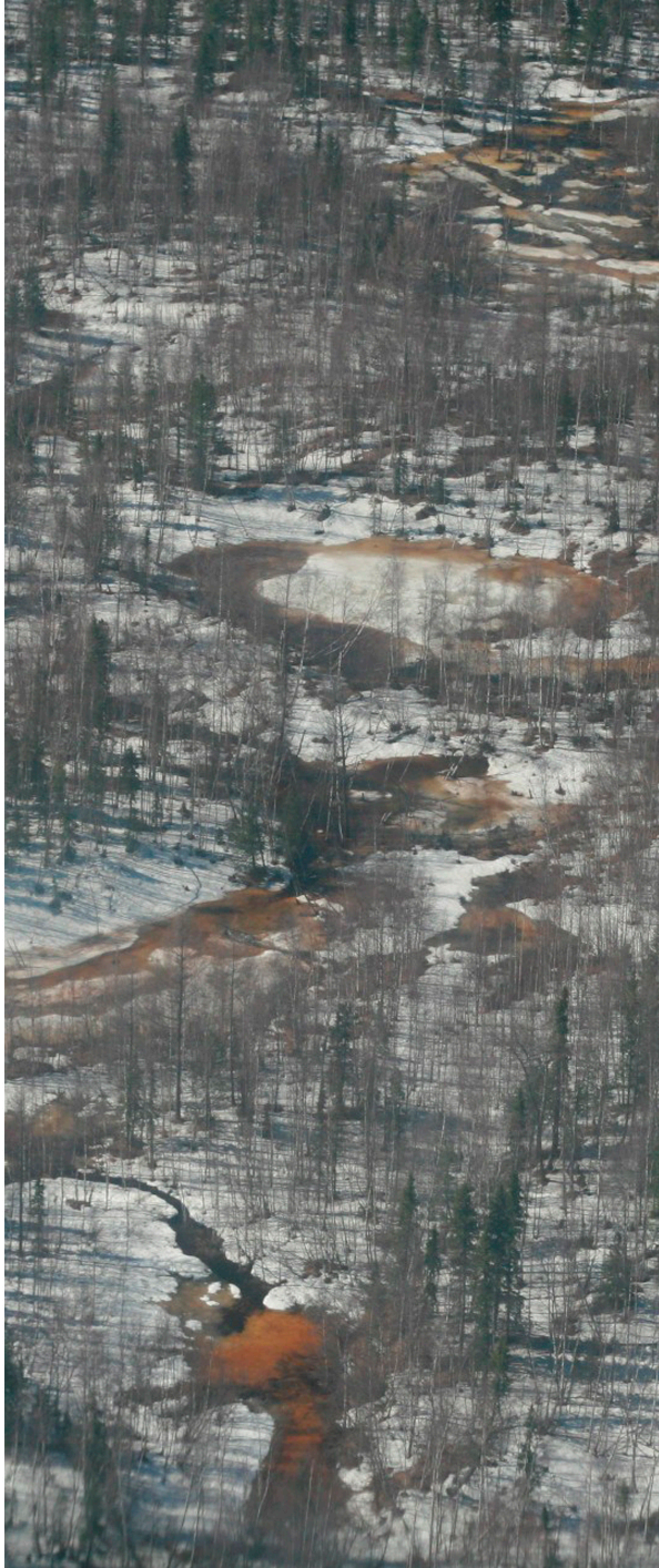
The medium Graviyka R. is the second important river in the region, providing water supply to Igarka from 1930s until late 2010s. A piled gauging station was maintained here from 1936 till 1993, and temporarily restored in 2014 by the Igarka Permafrost Research Station staff. Mean annual runoff is 0.160 ± 0.032 km^3 (1936-1992), that corresponds to mean annual daily flow of 5.08 ± 1.02 m^3 s^{-1}. Regardless of drought period, the annual runoff in 2016 was close to average, 0.169 km3, but the effect became apparent in 2017, when it fell below average, to 0.158 km^3, in a wet year with total precipitation exceeding 700 mm.

Regional hydrology is tightly related to geomorphology, *i.e.* stream position within a specific topographic. As described by N. Grigoriev, these levels differ in its paleogeographic context, prevailing sediments, and a set of dominant geomorphic processes. While contemporary floodplain is only present locally and is mainly occupied by lakes, higher terraces differ in their hydrologic performance. The largest streams of the region, *i.e.* the Graviyka and Chernaya (Black) R., originate in the plateau subzone and traverse the lower terraces before joining the Yenisey R. Smaller creeks, *i.e.* the Lisiy Log (Fox Creek) or Medvezhy Log (Bear Creek) are draining the second terrace, with discontinuous permafrost and loamy-clayey soils. Minor creeks originate from lakes and peatlands of the first terrace.

In tundra landscapes with mostly frozen organic soils (Graviyka R.) water chemistry suggests a decisive role of slow subsurface flow in mineral soils, most probably along the valley slopes, as major water pathway. In mixed forests on mineral soils (Fox Creek), streams are fed by fast subsurface runoff within the upper organic layer. Such runoff routing is supposedly related to permafrost conditions. In the Graviyka R. basin, a permafrost aquitard is active constantly in the landscape units underlain by mineral soils, which promotes the flow rerouting toward the hydrological network. In certain cases, two-layer, or non-merging permafrost can be observed. In the Fox Creek R. basin permafrost thaws rapidly during summertime, and water is either traveling fast toward the streams via organic layer or is lost to infiltration to the deeper aquifers. Therefore, permafrost performs hydrological functions by linking the sedimentary history of the region, its geomorphic features and contemporary hydrological processes.

The role of subsurface runoff is important for most catchments of the Igarka region. Subsurface non-frozen areas, or *taliks*, persist during winter, connecting lakes and peatlands to local streams. Besides, permafrost degradation in the recent decades have resulted in widespread occurrence of non-merging permafrost below seasonally frozen layer. As a result, rivers of the region appear to maintain connection to suprapermafrost groundwater throughout the year, potentially gaining significant hydraulic head by the end of winter.

In the Graviyka R. waters several days ahead of the spring freshet peak, stable water isotope signature suggests massive input of heavily evaporated sources, the most evident being local lakes and peatlands. Lakes are soaking with coloured groundwaters late in the spring season and in the onset of summer, as is seen from the aerial view (Figure A.3 - refer to the image on the right). Brownish red waters drain to nearby creeks and rivers of the Yenisey R. terraces.



HYDROLOGY

Groundwater release to the river network can produce flash floods during spring season, as it was observed in mid-May 2014 (Figure A.4 refer to the images on the right), before the steady snowmelt had started, or even before the positive daily air temperatures had established. The reddish yellow water colour suggests its origin from local aquifers in talik zones.

Hydrological processes were studied by the Igarka Permafrost Research Station staff in 2014, and particular attention was paid to static snow sublimation. This process, long neglected, was recently shown to contribute to snow evaporation by multiple authors. Our results confirm the importance of this process for the regional water balance. During 10 days, from 15 to 25 April 2014, between 25 and 30% of the snow water equivalent, or around 19 mm, were lost to static snow sublimation on open terrain, in the minor river valleys.

15/05/2014

16/05/2014

17/05/2014

SUSPENDED SEDIMENTS & DISSOLVED SOLIDS

Igarka gauging station is a reference station as an outlet of the Yenisey R. Published data suggest that suspended sediment flux had declined remarkably as a result of hydropower construction. In 2014-2016, the Yenisey R. was sampled for suspended sediment measurements, including high-frequency observations during spring freshet. Contemporary annual suspended sediment flux, estimated using historical daily flows and a rating curve approach using LOADEST software, is 8.1 ± 0.5 Tg, which is twice higher than previously published estimates. Annual particulate organic matter (POM) flux, estimated from 2014-2016 survey data, is 1.6 ± 0.3 Tg, of which about 0.82 ± 0.04 Tg is particulate organic carbon (POC). Besides, annual bedload flux is estimated around 7.9 ± 0.1 Tg, based on approach proposed by N.I. Alekseevsky, raising total annual sediment flux of the Yenisey R. to 16.0 ± 0.6 Tg.

The Graviyka R. has annual suspended sediment flux of 1860 Mg, of which 406 Mg is POM and 183 Mg - POC flux. These estimates are based on the daily rating curve approach using data from the 2013-2014 sampling programme and historical discharge data. Suspended sediment fluxes in the adjacent catchments, though unquantified owing to lack of water discharge data, were found to be related to local geomorphology and permafrost. The Fox Creek consistently has higher suspended sediment concentration both during spring freshet and brief summer floods, exceeding 200 mg L^{-1}, while in other streams it rarely exceeds 25 to 30 mg L^{-1}. Bank erosion is considered as a major sediment source of the studied rivers. Suspended sediments have relatively high organic fraction, reaching 50 to 70%, except for the Fox Creek waters, rich in mineral fraction and only 20 to 30% particulate organic matter.

Mean annual dissolved organic carbon (DOC) flux was quantified for the Yenisey R. at Igarka using SWAT hydrological model, and equals 2.90 ± 0.56 Tg (2003-2013), or 1.14 ± 0.22 gC m^{-2} yr^{-1}. For the Graviyka R., mean annual DOC flux estimate is based on continuous fluorescent dissolved organic matter monitoring. Annual DOC fluxes were 1770 and 1690 Mg C in 2016 and 2017, corresponding to specific fluxes of 5.5 and 5.2 gC m^{-2} yr^{-1}, respectively. Most DOC export occurred during spring freshet. Autumn floods yield only 10% of the annual DOC export, but have the highest DOC loading, resulting in DOC concentration increase at peak flow, showing negligible dilution effect. Potential water and DOC contributors to autumn floods are large degraded permafrost peatland complexes, producing highly aromatic DOM.

LAKES & RESERVOIRS

The origin of most lakes in the Igarka region is supposedly glacial, with a minor fraction of thermokarst lakes, mostly overlaying vast peat plateaus eastward from Igarka. To date, lakes are the less studied ecosystem elements, though their influence on local hydrology and carbon cycling is expected to be extremely important.

The Khantayka Reservoir in its southern section is easily accessible from Igarka, either on snowmobiles during winter or by a helicopter. The reservoir is feared to merge with a group of lakes lying southward, which is drained toward the Yenisey R. via the Sukharikha R., flowing to the Yenisey R. some 70 km upstream from Igarka. Observations made in 2015 suggest a rather low bank abrasion rates, from 2.5 to 3.5 m yr^{-1}, though locally exceeding 8 to 9 m yr^{-1}.

SOCIAL HISTORY & PSYCHOLOGY

Social structure and dynamics of Igarka population, both residents and seasonal workers, was long neglected in Soviet times, so we are left with the only possibility to base our conclusions on oral narrative and rare publications. A young Arctic city had short historical past and in fact never needed one - its main scope and goal was to provide Soviet power with money, no strings attached. Only in the late 1980s, amidst perestroika and global 'oil glut', local governance, for the first time since 1930s, took a proactive social position, e.g. promoting seasonal workers to stay in Igarka as permanent employees. This was anyway too late, and besides, the collapse that followed was anything but unexpected.

In the mid-1930s, the Communist party leader of Igarka, Valentina Ostroumova, was received by Kalinin, one of the main figures in power, and the city was growing with its own newspaper and radio, libraries, cinema and classical theatre, a year-round collective farm and a weekly flight to Krasnoyarsk. The story of Igarka in the early 1930s was as brilliant, as painful was its gradual decline starting in 1937 and continuing up to now. Back then the Chief Directorate of the Northern Sea Route was subject to a violent purge caused in part by an uncommonly harsh winter in the region, ending the 'Warm Arctic' period, leading to numerous ships heading toward Norilsk being stuck in ice and further lost upon spring breakup.

After 1938, when Ostroumova was incarcerated to be executed by a firing squad in 1940, Igarka was ravaged, almost literally, by the KGB squads, just as other Arctic cities, like Murmansk, Arkhangelsk, Naryan-Mar, Dudinka and Tiksi. And if Murmansk re-emerged later as a unique non-freezing Soviet Arctic harbor, Igarka, still an important lumber industry and marine port, remained balancing in mediocrity, which meant stagnation and decline. Renowned social geography expert, Nadezhda Zamyatina, having visited Igarka several times in the 2010s, explains this effect in terms of 'Jack London hypothesis' - as a story of a frontier city that had lost its development potential in the post-boom period because of its limited economic functions. In a post-Soviet reality, the city ended by failing to prove its importance and lacking creative potential, which was all lost since the 1930s.

Nonetheless, the citizens of Igarka appear to share, even in the most sombre time in 2010s, their proudness of being part of the Igarka community, - an unconditioned response, not even rooted in knowledge of its glorious history. 'Igarka is the city unlike the others, so are we', - such kind of reasoning is not uncommon even between those living elsewhere. Such attitude may well be innate, but can be acquired with time, as local narrative precises - in five to fifteen years, the time needed to be transformed into a genuine '*seldyuk*', an argotic name for Igarka people, subsisting on sardine cisco (*Coregonus sardinella merki*), locally known as '*turukhanskaya seledka*' and Arctic cisco (*C. autumnalis*), or omul'.

Notably, this transformation is long regarded as a highly selective process, and hence *Igarchane*, people of the Igarka community, is a closed society that one cannot simply decide to be a part of. Local narrative strictly differentiates between true Igarka locals who were somehow marked or accepted by Igarka, even if born outside the city, and other newcomers who will never have a chance to become locals simply because Igarka won't allow this. Beyond the general 'The Arctic will call you back someday' slogan, we believe Igarka to accommodate a particular genius loci that decides on its own whether one can be admitted to the club or not.

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Table 2

Ground temperature in Borehole No. 1159

(September 1949-May1950) at various depths, °C

Depth	IX.1949			X.1949			XI.1949		
	I	II	III	I	II	III	I	II	III
0.5	5.4	4.7	0.9	1.0	0.2	0.0	-0.3	-0.3	-2.6
1.0	1.5	1.5	0.5	0.4	-0.2	0.2	0.0	0.1	-0.1
1.5	0.1	0.1	0.0	0.0	-	-	0.0	0.0	0.0
2.0	-0.2	-0.2	-0.2	-0.2	-0.2	0.1	0.0	0.0	0.0
3.0	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2
4.0	0.0	-0.1	-0.2	-0.1	-0.2	-0.3	-0.3	-0.2	-0.2
5.0	-0.1	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2
6.0	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2
7.0	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2
8.0	0.2	-0.2	-0.2	-0.2	-0.2	-0.3	-0.3	-0.2	-0.2
9.0	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3
10.0	-0.2	-0.3	-0.3	-0.3	-0.3	-0.2	-0.3	-0.2	-0.2
11.0	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2
12.0	-0.3	-0.3	-0.3	-0.3	-0.3	-0.2	-0.2	-0.2	-0.2
13.0	-0.2	-0.3	-0.3	-0.2	-0.3	-0.2	-0.4	-0.4	-0.4
14.0	-0.3	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2
15.0	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2
16.0	-0.3	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1
17.0	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2

Depth	XII.1949			I.1950			II.1950		
	I	II	III	I	II	III	I	II	III
0.5	-2.8	-6.7	-10.0	-8.1	-9.9	-9.5	-12.1	-9.2	-8.7
1.0	-0.3	-0.2	-4.4	-4.0	-5.6	-5.6	-8.0	-7.0	-6.6
1.5	0.0	-0.1	-0.4	-0.9	-2.4	-3.0	-4.7	-4.5	-4.1
2.0	0.0	0.0	-0.1	-0.6	-1.3	-1.9	-2.8	-3.0	-2.8
3.0	-0.2	-0.3	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.3
4.0	-0.3	-0.3	-0.2	-0.2	-0.2	-0.2	-0.3	-0.2	-0.3
5.0	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2
6.0	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2
7.0	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2
8.0	-0.3	-0.3	0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2
9.0	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3
10.0	-0.3	-0.3	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2
11.0	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2
12.0	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2
13.0	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4
14.0	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2
15.0	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2
16.0	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1
17.0	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2

Table 2 (continued)

Depth	III.1950			IV.1950			V.1950
	I	II	III	I	II	III	I
0.5	-7.8	-7.2	-7.0	-5.9	-5.5	-3.8	-3.1
1.0	-5.2	-5.9	-6.0	-4.5	-4.2	-3.0	-2.7
1.5	-3.4	-4.5	-4.4	-3.4	-3.2	-2.5	-2.2
2.0	-3.2	-3.4	-3.3	-2.8	-2.7	-2.4	-2.2
3.0	-1.5	-1.6	-1.7	-1.7	-1.5	-1.7	-1.6
4.0	-0.4	-0.5	-0.5	-0.7	-0.7	-0.8	-0.6
5.0	-0.2	-0.2	-0.2	-0.2	-0.2	-0.4	-0.4
6.0	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2
7.0	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.1
8.0	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1
9.0	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.2
10.0	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2
11.0	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2
12.0	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.2
13.0	-0.4	-0.4	-0.4	-0.3	-0.3	-0.4	-0.3
14.0	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.3
15.0	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.3
16.0	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2
17.0	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2

Depth	Mean tem perature	Highest te mperature	Highest temper ature observati on date	Lowest tem perature	Lowest temperatur e observation date
0.5	-4,3	5.4	10.VIII.1949	-12.1	10.II.1950
1.0	-2,9	1.5	10.VIII.1949	-8.0	10.II.1950
1.5	-1,7	0.1	10.VIII.1949	-4.7	10.II.1950
2.0	-1,3	0.0	20.XII.1949	-3.0	20.II.1950
3.0	-0,7	-0.2	-	-1.7	10.IV.1950
4.0	-0,3	0.0	10.VIII.1949	-0.8	30.IV.1950
5.0	-0,3	-0.1	10.VIII.1949	-0.4	30.IV.1950
6.0	-0,2	-0.2	-	-0.2	-
7.0	-0,2	-0.1	10.V.1950	-0.2	-
8.0	-0,2	-0.1	10.VIII.1949	-0.3	20.XII.1949
9.0	-0,3	-0.2	10.V.1950	-0.3	-
10.0	-0.2	-0.2	-	-0.3	-
11.0	-0.2	-0.2	-	-0.2	-
12.0	-0.2	-0.2	-	-0.3	-
13.0	-0,5	-0,2	-	-0,4	-
14.0	-0.2	-0.2	-	-0.3	-
15.0	-0,2	-0.2	-	-0.3	-
16.0	-0,1	-0,1	-	-0,2	-
17.0	-0.2	-0.2	-	-0.2	-

Table 3

Ground temperature at the Igarka Timber Factory industrial facility, °C, in 1973

Borehole No.	Observation date	Depth														
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
854	28-31.X	0.1	-0.2	-1.0	-1.1	-1.1	-0.8	-0.7	-0.5	-0.4	-0.2	-0.2	0.0	0.0	0.0	-
853	20-21.X	-	-0.4	-1,0	-1,4	-1,5	-1,0	-0,8	-0,6	-0,5	-0,3	-0,2	-0,2	-0,1	0,0	0,0
849	21-22.X	-	-	-1,4	-1,6	-1,3	-1,0	-1,0	-0,6	-0,5	-0,4	-0,3	-0,3	-0,2	0,1	0,0
848	25-26.X	-	-	-0,3	-0,4	-0,6	-0,5	-0,5	-0,4	-0,4	-0,2	-0,2	-0,1	-0,1	0,0	0,0
845	26-27.X	-	-0.6	-0,8	-1,1	-1,1	-1,1	-1,1	-1,0	-0,8	-0,7	-0,5	-0,3	-0,2	-0,1	-0,1
842	24-25.X	-	0.1	-0,8	-0,2	-0,2	-0,4	-0,3	-0,3	-0,2	-0,2	-0,1	-0,1	0,0	0,0	0,1
843	22-23.X	-	-	-0,8	-0,3	-0,1	-1,0	-1,1	-1,0	-1,0	-0,8	-0,7	-0,6	-0,5	-0,3	-0,2
847	1-2.XI	-0.3	-0.1	-0,2	-0,8	-0,5	-0,5	-0,6	-0,5	-0,5	-0,4	-0,3	-0,2	-0,2	-0,1	0,0
838	12-13.X	-	-	-0,8	-1,0	-1,3	-1,2	-1,2	-1,0	-0,9	-0,7	-0,6	-0,4	-0,4	-0,3	-0,2
836	5-6.XI	-	-0.3	-1,0	-1,4	-1,7	-1,9	-1,8	-1,7	-1,5	-1,2	-1,1	-0,8	-0,7	-0,5	-0,4
834	10-11.XI	0.0	-0.4	-0,7	-1,1	-1,4	-1,5	-1,4	-1,3	-1,0	-0,9	-0,7	-0,6	-0,5	-0,4	-
833	15-16.X	-	-	-0,8	-1,3	-1,6	-1,7	-1,6	-1,5	-1,3	-1,1	-0,9	-0,8	-0,6	-0,4	-0,3
831	13-14.X	-	-	-0,8	-1,0	-1,1	-1,2	-1,1	-1,1	-1,0	-0,9	-0,8	-0,8	-0,7	-0,6	-0,5
828	10-11.X	-	-	-0,8	-0,9	-1,0	-1,0	-0,9	-0,9	-0,8	-0,7	-0,5	-0,4	-0,2	-0,1	-0,1
827	9-10.X	-	-	-0,7	-0,9	-1,0	-1,1	-1,0	-0,9	-0,8	-0,6	-0,5	-0,5	-0,3	-0,2	-0,1
822	8-9.X	-	-	-0,6	-0,8	-1,0	-1,0	-0,9	-0,8	-0,6	-0,5	-0,4	-0,3	-0,2	-0,2	-0,1
860	27-28.XI	-	-	-0,5	-0,7	-0,8	-0,9	-0,8	-0,7	-0,5	-0,5	-0,3	-0,3	-0,2	-0,2	-
859	17.X	-	-0.2	-0,2	-0,3	-0,2	-0,2	-0,2	-0,2	-0,2	-0,1	-0,1	-	-	-	-
820	24-25.X	-	-0.2	0,0	-0,1	-0,2	-0,2	-0,2	-0,2	-0,2	-0,2	-0,2	-0,1	-	-	-
819	16-17.X	-	-	-0,3	-0,2	-0,3	-0,3	-0,2	-0,2	-0,2	-0,2	-0,2	-0,2	-0,1	-0,1	-
816	17-18.X	-	-	-0,8	-1,0	-1,1	-1,1	-0,2	-0,6	-0,5	-0,3	-0,2	-0,2	-0,1	-0,1	-0,1
810a	18-19.X	-	-	-0,2	-0,2	-0,2	-0,2	-0,3	-0,2	-0,2	-0,1	-0,1	0,0	0,1	0,2	-
867	14-16.XI	-	-0.1	-0,2	-0,2	-0,3	-0,2	-0,2	-0,2	-0,2	-0,1	-0,1	-	-	-	-
869a	23-24.XI	-	-0.2	-0,2	-0,2	-0,3	-0,2	-0,2	-0,2	-0,1	0,0	-	-	-	-	-
870a	21-22.XI	0.0	-0.2	-0,3	-0,4	-0,5	-0,3	-0,2	-0,2	-0,1	0,0	-	-	-	-	-
870	20-21.XI	-0.6	-0.2	-0,6	-0,7	-0,8	-0,9	-0,8	-0,7	-0,5	-0,4	-0,3	-0,2	-	-	-
813	19-20.XI	-	-0.3	-0,3	-0,6	-0,7	-0,8	-0,7	-0,6	-0,3	-0,1	0,0	0,0	0,0	0,1	-
863	25-26.XI	-1.0	-0.3	-0,3	-0,3	-0,3	-0,1	0,2	0,1	0,2	0,2	0,4	0,2	0,2	0,2	-

Table 4

Ground temperature in the Borehole No. 295/417

Depth, m	Observation date			
	22-27.II.1938	11-13.VI.1940	23-24.I.1941	23.V.1941
1.0	-12.4	-7.0	-9.5	-4.4
2.0	-9.7	-5.2	-4.6	-6.5
3.0	-7.5	-4.3	-2.2	-6.4
4.0	-6.0	-2.6	-1.6	-5.4
5.0	-4.6	-2.2	-1.6	-4.4
6.0	-3.5	-1.8	-1.6	-3.4
7.0	-2.7	-1.7	-1.6	-2.6
8.0	-2.3	-1.6	-1.7	-2.0
9.0	-1.9	-1.6	-1.8	-2.0
10.0	-2.0	-1.7	-1.6	-1.7
11.0	-2.0	-1.7	-1.5	-1.6
12.0	-1.9	-1.8	-1.4	-1.6
13.0	-1.8	-1.7	-1.4	-1.5
14.0	-1.8	-1.7	-1.4	-1.5
15.0	-1.7	-1.7	-1.4	-1.4
16.0	-1.4	-1.4	-1.4	-1.4
17.0	-1.6	-1.5	-1.4	-1.4
18.0	-1.4	-1.4	-1.3	-1.3
19.0	-1.4	-1.4	-1.3	-1.2
20.0	-1.2	-1.3	-1.1	-1.0
21.0	-1.2	-1.1	-	-1.0
22.0	-1.1	-1.0	-	-1.0
23.0	-1.0	-1.0	-	-0.9
24.0	-0.8	-0.9	-	-0.9
25.0	-0.8	-0.8	-0.7	-0.8
26.0	-0.7	-0.7	-	-0.9
27.0	-0.6	-0.6	-	-
28.0	-0.4	-0.6	-	-
29.0	-0.3	-0.3	-	-
30.0	-0.2	-	-	-
31.0	0.0	-	-	-

Table 5

Borehole description from the IPRS drilling campaign in 1934

Water body location	Drilling season	Borehole location	Borehole depth, m	Borehole geology	Thermal state of su blacustrine ground
1	2	3	4	5	6
Lake 1, width 100m, length over 200 m, 3.5 to 4.0km from the Igarka Branch	September 1934	In the lake, 29m from the lake shore	16.7	Below the lake bottom: marsh vegetation (0.2 m), peat (3.1m), dark-grey silty clays, frozen from 16.1m, with ice crystals	Down to 16.1m non-frozen, then frozen
Lake 2, diameter 80 to 90 m, 2.5 km from the Igarka Branch	July 1935	In the lake center	26.7	Over-saturated peat (0.3m), grey silty clays, frozen from 26.1m with ice lenses	Down to 26.1m non-frozen, then frozen
Swamp, diameter 90 to 100m, right bank of the Igarka Branch, across the Wolf Creek	April 1935	In the swamp center	20.3	Snow (0.62m), ice (0.5 m), water (0.75m), peat (0.6m), dark-grey clay, frozen from 19.9m	Down to 19.9m non-frozen, then frozen

Table 6

Top of permafrost depth in the KladbishchenskyCreek area, IPRS data

Topography and vegetation	Top of permafrost depth, m	Maximum snow depth, m	Snow density, g/cm^3	Freezing depth, m
1946-1947				
Kladbishchensky Creek thalweg. Grassland	8.50	0.47	0.16–0.26	1.62
South-facing slope. Peat cover, shrubs	6.24	1.05	0.18–0.30	0.90
South-facing slope. Peat cover, sparse shrubs	5.87	0.80	0.19–0.33	1.43
Water divide, wind-blown surface. Peat cover	1.42	0.45	0.18–0.26	1.42
Water divide. Minor marsh y hollow with mosses	> 9.00	0.87	0.16–0.26	0.94
Water divide. Dry swamp	11.25	0.90	0.16–0.34	1.12
Water divide. Peat cover, sparse shrubs	5.04	0.68	0.19–0.33	1.30
Gentle north-facing slope. Peat cover, scarce shrubs	7.18	1.14	0.20–0.30	0.94
Gentle north-facing slope. Peat cover, sparse shrubs	7.20	0.90	0.18–0.26	0.98
1947-1948				
Kladbishchensky Creek thalweg. Grassland	–	0.38	0.15–0.25	1.94
South-facing slope. Peat cover, shrubs	–	1.02	0.13–0.27	1.33
South-facing slope. Peat cover, sparse shrubs	–	0.45	0.12–0.26	1.73
Water divide, wind-blown surface. Peat cover	1.35	0.48	0.14–0.25	1.35
Water divide. Minor marsh y hollow with mosses	–	1.10	0.14–0.30	1.14
Water divide. Dry swamp	6.00	0.88	0.13–0.29	1.44
Water divide. Peat cover, sparse shrubs	5.03	0.73	0.12–0.25	1.49
Gentle north-facing slope. Peat cover, scarce shrubs	–	1.10	0.14–0.30	1.27
Gentle north-facing slope. Peat cover, sparse shrubs	7.5	0.92	0.12–0.26	1.06
1948-1949				
Kladbishchensky Creek thalweg. Grassland	7.20	0.40	0.16–0.27	2.38
South-facing slope. Peat cover, shrubs	6.18	0.92	0.19–0.31	0.93
South-facing slope. Peat cover, sparse shrubs	5.87	0.39	0.17–0.32	2.14
Water divide, wind-blown surface. Peat cover	1.34	0.43	0.13–0.31	1.34
Water divide. Minor marsh y hollow with mosses	8.00	1.15	0.18–0.32	0.65
Water divide. Dry swamp	8.00	1.17	0.17–0.34	0.98
Water divide. Peat cover, sparse shrubs	5.03	0.70	0.19–0.30	1.53
Gentle north-facing slope. Peat cover, scarce shrubs	–	1.20	0.20–0.31	0.80
Gentle north-facing slope. Peat cover, sparse shrubs	7.50	1.05	0.19–0.33	0.57

Table 7

Mean monthly snow cover temperature at (h) height from ground surface in the Igarka Region, ºC (Skryabin, Sergeev, 1989)

h, cm	Months							
	X	XI	XII	I	II	III	IV	V
1971-1972								
Air	–	-13.0	-22.1	-34.4	-26.3	-18.4	-9.7	-6.0
Snow surface	–	-13.6	-23.6	-36.8	-27.2	-20.3	-10.4	-5.8
0	–	-1.8	-1.4	-3.6	-5.5	-4.7	-2.8	-1.3
10	–	-3.9	-3.8	-9.0	-11.4	-8.0	-4.2	-1.5
20	–	-5.2	-6.6	-13.8	-16.0	-10.8	-5.2	–
30	–	–	-10.7	-20.0	-21.6	-14.3	-6.6	–
40	–	–	-16.7	-27.0	–	–	–	–
1972-1973								
Air	-14.8	-25.3	-29.9	-31.6	-19.8	-16.0	-9.7	–
Snow surface	-15.6	-27.0	-30.8	-32.0	-20.7	-16.8	-10.4	–
0	-3.2	-3.9	-3.6	-2.9	-3.6	-1.9	-1.4	–
10	-10.1	-13.7	-8.6	-7.2	-6.3	-3.7	-3.8	–
20	–	–	-13.9	-10.7	-8.4	-4.9	-5.0	–
30	–	–	-21.1	-14.9	-10.5	-6.2	-5.8	–
40	–	–	–	-19.0	-12.7	-7.6	-6.5	–
50	–	–	–	-22.1	-13.0	-9.4	-6.9	–
1973-1974								
Air	–	-16.1	-24.4	-39.6	-32.3	-21.3	-10.0	–
Snow surface	–	-16.7	-26.2	-43.2	-35.5	-23.5	-12.5	–
0	-1.4	-2.1	-4.3	-6.2	-4.3	-2.0	–	–
10	–							
20	–	-5.7	-6.8	-12.5	-13.5	-7.8	-3.7	–
30	–	-8.8	-10.0	-17.7	-17.5	-10.0	–	–
40	–	–	-14.1	-24.0	-22.9	-12.6	–	–
50	–	–	-20.0	–	-28.7	-17.3	–	–

Table 8

Ground temperature under natural forest-free plot in the vicinity of Igarka, °C, 1972

(Pavlov, Sergeev, Skryabin, 1976)

Depth, m	Months												Temperature range	MAGT
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII		
0.00	-3.6	-5.5	-4.7	-2.8	-0.2	12.3	12.4	10.6	2.9	-1.0	-3.9	-3.6	17.9	1.4
0.10	-2.3	-4.3	-3.5	-2.1	-0.5	6.9	10.0	9.7	4.9	0.1	-1.7	-2.2	14.3	1.6
0.20	-1.5	-3.2	-2.9	-1.8	-0.5	4.0	8.6	9.2	5.2	0.5	-0.9	-1.6	12.4	1.5
0.30	-0.8	-2.5	-2.4	-1.6	-0.5	2.8	7.2	8.7	5.4	0.8	-0.4	-1.1	11.2	1.6
0.50	-0.1	-1.3	-1.7	-1.3	-0.5	1.5	4.7	7.8	5.5	1.2	0.1	-0.5	9.5	1.5
0.75	0.3	-0.2	-0.7	-0.7	-0.4	0.3	2.8	6.3	5.3	1.6	0.5	0.1	7.0	1.4
1.00	0.6	0.3	0.0	-0.3	-0.2	-0.1	0.4	4.9	5.0	2.0	0.8	0.4	5.3	1.3
1.25	0.8	0.5	0.2	0.1	0.1	0.1	0.2	3.8	4.5	2.3	1.1	0.6	4.4	1.4
1.50	0.9	0.7	0.5	0.3	0.3	0.3	0.5	2.9	3.9	2.6	1.3	0.8	3.6	1.4
1.75	1.1	0.8	0.6	0.4	0.4	0.4	0.5	2.3	3.2	2.7	1.4	1.0	2.4	1.4
2.00	1.2	1.0	0.8	0.6	0.6	0.6	0.7	1.8	2.8	2.8	1.6	1.2	3.1	1.5
2.25	1.3	1.1	0.9	0.7	0.8	0.8	0.8	1.6	2.3	2.8	1.7	1.4	2.9	1.5
2.50	1.5	1.2	1.0	0.9	0.9	0.9	0.9	1.4	2.1	2.7	1.7	1.5	2.5	1.6
2.75	1.5	1.3	1.1	1.0	1.0	1.0	1.0	1.2	2.0	2.5	1.8	1.5	2.3	1.6
3.30	1.6	1.4	1.4	1.0	1.0	1.0	1.0	1.2	2.0	2.5	1.8	1.5	2.0	1.6