



CRYOGENESIS AND GEODYNAMICS OF ICING VALLEYS

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Abstract: Due to local groundwater seeping and freezing in layers that accumulate over each other and create large ice clusters on the ground surface, specific conditions of energy and mass transfer are created in the atmosphere–soil–lithosphere system. In winter, the vertical temperature distribution curve is significantly deformed due to heat emission from the water layer above the ice cover during its freezing, and a thermocline is thus formed. Deformation of the temperature curve is gradually decreasing in size downward the profile and decays at the interface of frozen and thaw rocks. Values and numbers of temperature deviations from a 'normal' value depend on heat reserves of aufeis water and the number of water seeps/discharges at a given location. The production of the thermocline alters freezing conditions for underlying ground layers and changes the mechanism of ice saturation, thus leading to formation of two-layer ice-ground complexes (IGC). IGCs are drastically different from cryogenic formations in the neighbouring sections of the river valley. Based on genetic characteristics and the ratios of components in the surface and subsurface layers, seven types of aufeis IGCs are distinguished: massive-segregation, cement-basal, layered-segregation, basal-segregation, vacuum-filtration, pressure-injection, and fissure-vein. Annual processes of surface and subsurface icing and ice ablation are accompanied by highly hazardous geodynamic phenomena, such as winter flooding, layered water freezing, soil heaving/pingo, thermokarst and thermal erosion. Combined, these processes lead to rapid and often incidental reconfigurations of the surface and subsurface runoff channels, abrupt uplifting and subsiding of the ground surface, decompaction and 'shaking-up' of seasonally freezing/thawing rocks, thereby producing exceptionally unfavourable conditions for construction and operation of engineering structures.

Formation and development of river networks are heavily influenced by aufeis deposits and processes taking place at the aufeis surfaces, especially in areas of discontinuous and continuous permafrost where an average thickness of the ice cover on rivers ranges from 1.0 to 2.5 m, and the major part of the ice cover is accumulated layer by layer due to freezing of discharged groundwater. In the permafrost zone, the intensity of cryogenic channelling is clearly cyclical, and the cycles depend on accumulation of aufeis ice above the river level during the autumn low-water period. Five stages of cryogenic channelling are distinguished: I – pre-glacial development, II – transgression, III – stabilization, IV – regression, and V – post-glacial development. Each stage is characterised by a specific glaciological regime of runoff channels and their specific shapes, sizes and spatial patterns.

The channel network is subject to the maximum transformation in aufeis development stages III and IV, when the transit flow channel is split into several shallow-water branches, producing a complicated plan pattern of the terrain. In the mature aufeis glades, there are sites undergoing various development stages, which gives evidence that aufeis channelling is variable in a wide range in both space and time. With respect to sizes of aufeis glades, river flow capacities and geological, geomorphological, cryo-hydrogeological conditions, aufeis patterns of the channel network are classified into five types as follows: fan-shaped, cone-shaped, treelike, reticular, and longitudinal-insular types. The aufeis channel network is a reliable indicator of intensity of both recent and ancient geodynamic processes in the cryolithozone.

In Siberia and the Far East, the aufeis deposits are much larger, more numerous and more important in terms of morpholithology in comparison with the 'classical' (sedimentary metamorphic) icing structures. The more contrasting is the terrain, the more active are neotectonic movements, the lower is the mean annual air temperature, and the higher is the annual percentage of the territory covered by aufeis ice. The aufeis ratio of the permafrost zone is determined from parameters of over 10000 ice fields and amounts to 0.66 % (50000 km²). In mountains and tablelands, the total area of aufeis deposits amounts to 40000 km², and the number of ice clusters (0.77 km² in average) exceeds 60000. On the rivers up to 500 km long, the aufeis size depends on the stream rank. In all the natural zones, the majority of gigantic aufeis spots produced by groundwater are located in river valleys of ranks 3 and 4. The square area of aufeis deposits of mixed feed, i.e. produced by river water and groundwater, which occupy the entire river channel, yet do not go beyond the floodplain, amounts to 68000 km², i.e. by a factor of 1.7 larger than the area of all the aufeis deposits (taryns). The cumulative channel-forming effect of aufeis phenomena is expressed by an increment in the channel network relative to characteristics of the river segments located upstream and downstream of the aufeis

glade. This indicator is well correlated with the aufeis ratios of the river basins, morphostructural and cryo-hydro-meteorological conditions of the territory under study. The incremental length of the channel network, ρ_n per one groundwater aufeis deposit is increased, in average, from 3.5 km in mountains in the southern regions of East Siberia to 23 km in the Verkhoyansk-Kolyma mountain system and Chukotka. The value of ρ_n is decreased to 2.2 km in the plains and intermountain depressions of the Baikal rift system where the average dimensions of the ice fields are smaller. An average incremental length of the channel network per one large groundwater aufeis deposit amounts to 12.2 km, and the total incremental length in continuous and discontinuous permafrost areas ($F=7.6$ mln km²) is estimated at 690000 km.

Combined impacts of aufeis and icing processes on underlying rocks and the channel network is a specific (aufeis) form of cryogenic morpholithogenesis that is typical of regions with inclement climate and harsh environment. A more detailed research of these processes is required, including large-scale aerospace surveys, monitoring and observations on special aufeis polygons.

Key words: cryogenic phenomena, subsurface ice, aufeis, icing, naled, aufeis processes, aufeis channeling, channel networks, cryogenic movement of soil, ground heaving, pingo, mound, thermokarst.

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КРИОГЕНЕЗ И ГЕОДИНАМИКА НАЛЕДНЫХ УЧАСТКОВ РЕЧНЫХ ДОЛИН

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Аннотация: Локализованный выход подземных вод на поверхности земли, их намораживание в виде крупных ледяных массивов создают специфические условия энерго- и массообмена в системе атмосфера – почва – литосфера. Зимой кривая вертикального распределения температур существенно деформируется за счет выделения тепла наледным слоем воды при его промерзании, при этом образуется своеобразный термоклин. Деформация температурной кривой, постепенно уменьшаясь в размерах, смещается вниз по разрезу и затухает на границе мерзлых и талых горных пород. Величина и количество отклонений температуры от «нормального» положения зависят от теплозапаса наледобразующих вод и числа излияний в заданной точке пространства. Появление термоклина изменяет условия промерзания подстилающих грунтов и механизм их льдонасыщения, приводит к формированию двухъярусных ледогрунтовых комплексов (ЛГК), резко отличных от криогенных отложений смежных участков долины. По генетическим особенностям и соотношению составных частей наземного и подземного ярусов описано семь типов наледных ЛГК – массивно-сегрегационный, цементно-базальный, слоисто-сегрегационный, базально-сегрегационный, вакуум-фильтрационный, напорно-инъекционный и трещинно-жильный. Ежегодное формирование и разрушение наледей и подземных льдов сопровождается чередой особо опасных геодинамических явлений, среди которых ведущее место занимают зимнее затопление территории, намораживание воды, пучение грунтов, термокарст и термоэрозия. Совокупность этих процессов приводит к быстрому, часто неожиданному переформированию каналов поверхностного и подземного стока, резкому поднятию и опусканию земной поверхности, разуплотнению и «перетряхиванию» сезоннопротаивающих и сезоннопромерзающих горных пород, что создает крайне неблагоприятные условия для строительства и эксплуатации инженерных сооружений.

Наледеи и наледные процессы оказывают влияние на формирование и развитие речной сети. Наиболее широко оно проявляется в областях прерывистого и сплошного распространения вечной мерзлоты, где средняя толщина льда на реках колеблется в пределах 1.0–2.5 м, а основная часть ледяного покрова формируется за счет намораживания излившихся подземных вод. Интенсивность криогенного руслообразования в криолитозоне носит ярко выраженный циклический характер, зависящий от превышения наледного льда над урезом реки в осеннюю межень. Описаны пять стадий криогенного руслогенеза: 1) предгляциальная, 2) трансгрессивная, 3) стабилизационная, 4) регрессивная и 5) постгляциальная. Каждой стадии соответствует определенный гляциогидрологический режим каналов стока, их форма, размеры и пространственное распределение.

Максимальная трансформация русловой сети происходит в третью и четвертую стадию развития наледных долин, когда русло транзитного потока разбивается на ряд мелководных рукавов, создающих сложный плановый рисунок местности. На зрелых наледных полях выделяются участки, находящиеся на разных стадиях развития, что свидетельствует о широком диапазоне изменчивости наледного руслогенеза в про-

странстве и времени. В зависимости от размеров наледей, водности реки, геолого-геоморфологических и мерзлотно-гидрогеологических условий выделено пять видов наледной структуры русловой сети: веерообразная, конусовидная, древовидная, сетчатая и продольно-островная. Наледная русловая сеть может служить надежным показателем интенсивности геодинамических процессов в криолитозоне, как современных, так и древних.

По количеству, размерам и морфолитогенетическому значению наледи Сибири и Дальнего Востока многократно превышают «классическую» (осадочно-метаморфическую) форму оледенения. Чем контрастнее рельеф местности, активнее неотектонические движения и ниже среднегодовая температура воздуха, тем выше процент территории, ежегодно занимаемой наледным льдом. Относительная наледность криолитозоны, определенная с учетом параметров более 10000 ледяных полей составляет 0.66 % (50000 км²). В горах и на плоскогорьях суммарная площадь наледей равна 40000 км², а число ледяных массивов со средней площадью 0.770 км² превышает 60000. На реках длиной до 500 км размеры наледей зависят от порядка водоотков. Наибольшее количество гигантских наледей подземных вод во всех природных зонах располагается в долинах рек 3–4-го порядка. Площадь наледей смешанного питания (речных и подземных вод), занимающих все русло реки, но не выходящих за границу обычной поймы, составляет 68000 км² – в 1.7 раза больше, чем все наледи-тарыны. Кумулятивный руслообразующий эффект наледных явлений выражается величиной прироста русловой сети по отношению к участкам реки выше и ниже наледной поляны. Этот показатель находится в хорошей корреляционной связи с наледностью речных бассейнов, морфоструктурными и мерзлотно-гидрогеологическими условиями территории. Прирост русловой сети ρ_n , приходящийся на одну наледь подземных вод, в среднем увеличивается от 3.5 км в горах юга Восточной Сибири до 23 км в Верхояно-Колымской горной стране и на Чукотке. На равнинах и в пределах межгорных котловин Байкальской рифтовой системы величина ρ_n снижается до 2.2 км, что связано с уменьшением средних размеров ледяных полей. В среднем прирост русловой сети на одну крупную наледь подземных вод составляет 12.2 км, а общий прирост в области сплошной и прерывистой вечной мерзлоты ($F=7.6$ млн км²) оценивается в 690 тыс. км.

Совокупность воздействия наледей и наледных процессов на подстилающие горные породы и русловую сеть есть особая (наледная) форма криогенного морфолитогенеза, характерная для регионов с суровыми природно-климатическими условиями. Дальнейшее ее изучение требует крупномасштабных аэрокосмических съемок и режимных наблюдений на специальных наледных полигонах.

Ключевые слова: криогенные явления, подземные льды, наледи, наледные процессы, наледный руслогенез, русловая сеть, криогенное движение грунтов, бугры пучения, термокарст.

1. INTRODUCTION

Generally, a large aufeis deposit (taryn) is clearly visible in the terrain. In winter, even when frosts are severe, the taryn is typically marked by 'streaming' at groundwater seeping spots or evidenced by ice-covered surfaces extending for many kilometres. In summer, remarkable features are fresh green meadows located between sparkling white or emerald-green ice slabs. The 'exotic' shapes, puzzles and conundrums of aufeis deposits and ice-covered terrains have always been attractive for scientists, fishermen and hunters, as well as other nature enthusiasts. Only in the past 50–60 years, the secret of aufeis has been unveiled, and explanations were found for a number of once mysterious phenomena, such as explosive failure of heaving mounds, migration and decomposition of ice fields, feed and persistent variability of aufeis-generating sources etc.

Based on data collected in long-term studies, it is established that groundwater aufeis is a specific indicator of thermal conditions of the permafrost zone, as well as

a powerful factor controlling surface and underground runoff and causing changes in the microclimate, landscape, composition and structure of loose sediments and cryogenic terrains in general [Åkerman, 1982; Alekseyev, 1968, 1997, 2005, 2013; Baranowski, 1982; Carey, 1973; Sloan et al., 1976; Clark, Lauriol, 1997; Deikin, 1985; Fotiev, 1964; French, 1976; Froehlich, Slupik, 1982; Gorbunov, Ermolin, 1981; Harden et al., 1977; Heldmann et al., 2005; Hu, Pollard, 1997; Kolosov, 1938; Olszewski, 1982; Pollard, Franch, 1983; Priesnitz, Schunke, 2002; Romanovsky, 1972, 1973, 1974, 1993, 1997; Veillette, Thomas, 1979; Yoshikawa et al., 2007]. However, many aspects of aufeis and icing processes have still remained outside the scope of studies: heat interaction between ice clusters and underlying rock layers, specific features of underground icing, regularities of development of hazardous geodynamic phenomena, such as soil heaving, thermal erosion, thermokarst, suffusion etc. The information available from publications is mainly based on visual observations during short-term field studies; geocryological profiles, special maps and instrumental measurement data are quite rare.

2. REGIONS UNDER STUDY. INPUT DATA

This publication is based on data collected by the author in long-term field studies in Yakutia, Transbaikalia, Pribaikalia and East Sayan mountains and surface and aerial surveys of aufeis and icing processes on the Charskie Peski and Eden polygons, as well as on published data on other permafrost regions (Fig. 1), including remote sounding materials and satellite data available in Google.

The Charskie Peski polygon (15 km²) is located at the elevation of 710–750 m in the central part of the Upper Chara depression in the Stanovoe upland. Its major area is occupied by the right-side floodplain of the Middle Sakukan river, the wide boggy valley of the Bolotny brook, which is neighbouring the floodplain at the west, and valleys of the Kholodny and Alyonushka brooks, both going across the mass of drift sands. In this territory, the total thickness of the permafrost bed, including sand, sandy clay, boulder-pebble deposits, and peat, ranges from 300 to 350 m. It is cut by narrow thawing lenses of complicated shapes and ascending flows of artesian groundwater. In winter, the entire polygon is covered by the aufeis deposit which thickness ranges from 3.0 to 3.5 m. The soil under the ice cover is penetrated by the network of recurrent-vein ice, injected ice bands and lenses. Seasonal and perennial heaving mounds, thermokarst holes and small lakes are abundant. The snow cover is rarely thicker than 15–20 cm. In these regions, natural icing and vertical movement of the crust were studied from 1976 to 1980. The studies were combined with other geocryological, geographical and landscape surveys. For monitoring purposes, 330 reference points were established along 54 profiles [Alekseyev, 2005]. Simultaneously with research on the polygon, studies of aufeis and subsurface ice were conducted on routes in the Lower Ingamakit, Cheena, Apsat, Middle and Upper Sakukan river valleys and at the Chara river head.

The Eden polygon (1250 km²) is located at the border between Tofalaria and Tuva in the upper part of the Uda river basin at elevations from 1300 to 2000 m. It includes two basins of the Egegi and Eden rivers of ranks 3 and 4 and a part of the sublatitudinal segment of the Uda river valley of the glacial-tectonic origin. The territory is characterized by the strongly dissected relief, discontinuous and continuous permafrost (50 to 200 m thick), and irregular snow cover patterns (10 to 15 cm in the taiga belt; 50 to 80 cm in the sub-goltsy and taiga belts). From 1983 to 1992, the dynamics of cryogenic events was studied by methods of instrumental landscape profiling, field and remote mapping. Glaciation, hydrogeological and meteorological conditions were monitored at reference stations and points. The landscape profiles were constructed across the river/stream valleys at 0.1–0.5 km intervals. In total,

there were 142 landscape-glaciological profiles in the river valleys (Uda – 21, Bolshoy Eden – 51, Maly Eden – 30, and Egegi – 40). Five temporary meteorological stations operated in the region under study. Aerial photos and land survey data were consolidated in a database for mapping, and 13 large-scale landscape-glaciological maps covered sites located in the mountain-taiga belt (9 maps), sub-goltsy (2 maps) and goltsy belts (2 maps) [Alekseyev, 2005].

3. SPECIFIC FEATURES OF SUBSURFACE ICING IN AUFEIS SECTIONS OF RIVER VALLEYS

Aufeis and icing processes significantly affect the intensity of seasonal freezing and thawing of rocks, thermal modes and phase transitions of water in the soil layers. In some cases, subsurface icing may become more active and result in larger reserves of subsurface ice, or sometimes, the volume of subsurface ice may be reduced and its depths may be more shallow. On some sites, ice masses are buried and classified as aufeis deposits or snow patches in terms of their origin and viewed as subsurface ice with respect to their bedding and positions relative to the day surface.

During formation of aufeis deposits, specific conditions are created for subsurface icing, and such conditions differ from those in the neighbouring areas of the river valleys [Alekseyev, 1989, 2005; Boitsov, 1979; Klimovsky, 1978; Koloskov, Koreisha, 1975; Romanovsky et al., 1973, 1978; Shvetsov, Sedov, 1941]. In winter, the vertical temperature distribution curve is significantly disrupted due to heat emission from the water layer above the ice cover during its freezing, and a thermocline is thus formed (Fig. 2). Deformation of the temperature curve is gradually decreasing in size downward the profile and generally decays at the interface of frozen and thawed rocks. Values of temperature deviations from a 'normal' value depend on heat reserves of aufeis water. The number of cases when a thermocline is formed corresponds to the number of water seep cases, which is reflected in the total number of primary aufeis layers at the given point of the profile.

Sometime after the occurrence of water above ice, the frozen soil is partially thawing at the bottom due to 'sinking' of the heat wave. As a result of the phase transition of water, vacuum at the bottom of the frozen layer causes infiltration of ground water from the neighbouring horizons and sidewise inflow. After the water layer freezes above the ice, the temperature distribution curve straightens, and the thermocline disappears. At this time, a horizontal ice schlier is formed, and freezing of the underlying wet rock mass is ongoing. Such cycles of heterogeneous icing are repeated many times (Fig. 2). Therefore, on the one side, the ice thickness on the ground surface is increasing, and, on the other side,

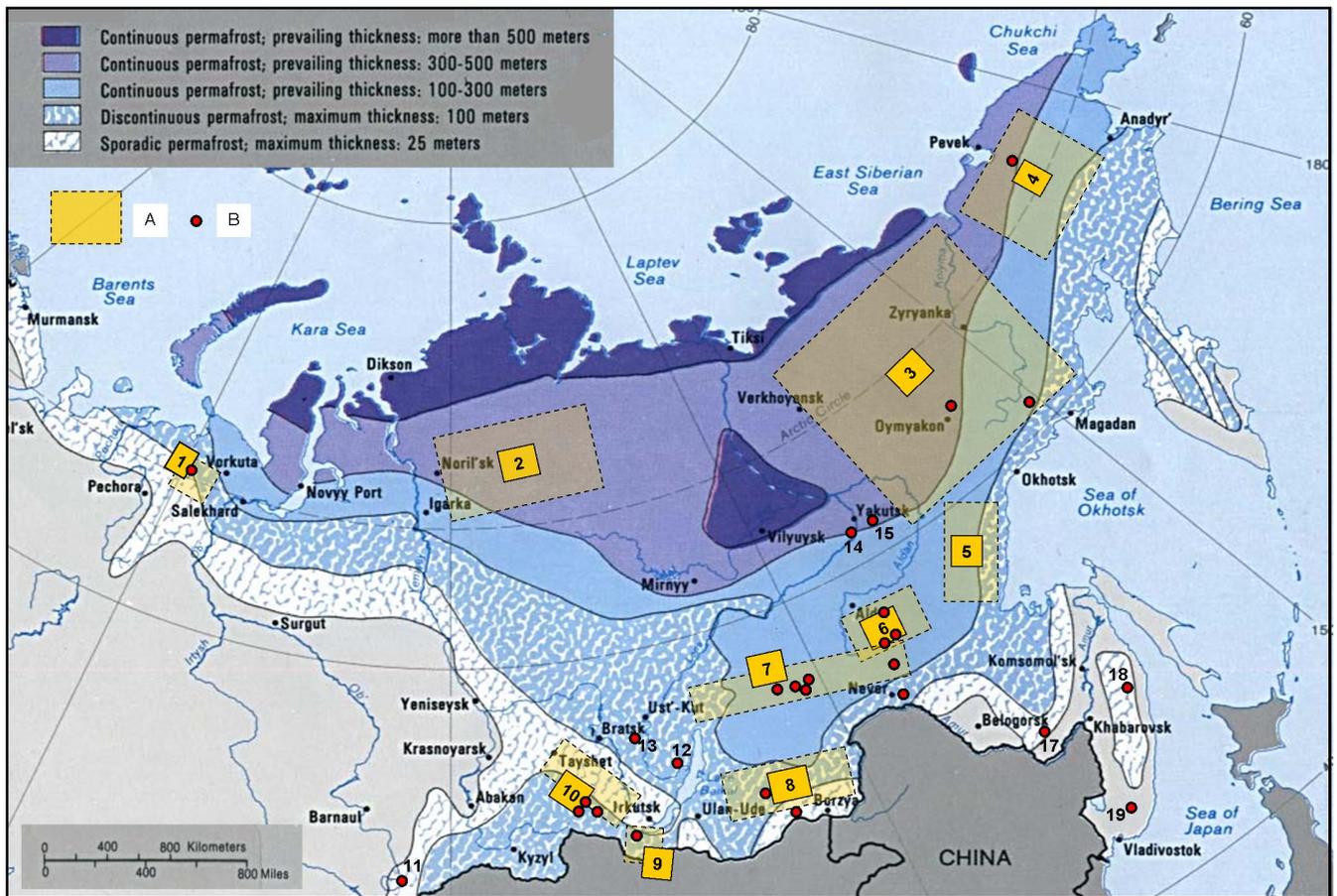


Fig. 1. The map showing surveyed locations and main observation points for studying aufeis phenomena in the territory of Russia.

Territories covered by remote ground-based and routine surveys with catalogued data on aufeis deposits (the routine survey sites are marked): 1 – Polar Ural [Oberman, 1985, 1989]; 2 – Putorana plateau [Aleksyeyev, Gienko, 2002]; 3 – Tikhon-Yuryakh and Anmangynda aufeis polygons in the north-eastern regions of Russia [Aleksyeyev et al., 2012; Lebedev, 1969; Simakov, 1959, 1961; Sokolov, 1975; Tolstikhin, 1974]; 4 – Kookvyn aufeis polygon in North Chukotka [Aleksyeyev et al., 2011]; 5 – Priokhotie [Shmatkov, Kozlov, 1994]; 6 – Samokit, Leglier, Chulman, Lokuchakit, and Iengra aufeis polygons on the Aldan upland [Aleksyeyev, 1973, 1975, 2005; Topchiev, 1979; Topchiev, Gavrilov, 1981; Sokolov, 1975; Boitsov, 1979]; 7 – Lower Ingamakit, Charskie Peski, Middle Sakukan, Mururin, Chutkanda, and Shakhtaum aufeis polygons in the Baikal-Amur Railroad zone [Aleksyeyev, 1975, 2005; Aleksyeyev, Kirichenko, 1997; Aleksyeyev, Furman, 1976; Deikin, Abakumenko, 1986; Deikin, Markov, 1983, 1985; Catalogue..., 1980, 1981, 1982; Prokacheva et al., 1982; Shesternev, Verkhoturov, 2006]; 8 – Ingoda aufeis polygon in Transbaikalie [Aleksyeyev, 1975; Shesternev, Verkhoturov, 2006; Chernyavskaya, 1973]; 9 – Tumusum, Khangarul, and Dabady aufeis polygons in the south-western Pribaikalie [Aleksyeyev, 1976]; 10 – Blue Rock, Shamanka, and Eden aufeis polygons in East Sayan [Aleksyeyev, 2005; Aleksyeyev, Kovalchuk, 2004; Kravchenko, 1985a]. Routine observations on polygons to study the dynamics of individual aufeis deposits: 11 – Aktru aufeis polygon in Altai [Revyakin, 1981]; 12 – Ilikta [Berkin, 1964]; 13 – Polovinka [Kazakov, 1976]; 14 and 15 – Ulakhan Taryn, Bulus [Piguzova, Shepelev, 1972, 1975; Tolstikhin, 1974]; 16 – Kerak [Rumyantsev, 1964, 1991]; 17 – Kuldur [Chekotillo et al., 1960]; 18 – Plastun [Tsvid, Khomichuk, 1981]; 19 – Southern mine [Tsvid, 1957].

Рис. 1. Карта расположения съемочных работ и основных пунктов режимных наблюдений за динамикой наледных явлений на территории России.

Территория, в пределах которой проведены наземные дистанционные и режимные съемочные работы, составлены каталоги наледей (места режимных наблюдений выделены пунсоном): 1 – Полярный Урал [Oberman, 1985, 1989]; 2 – плато Путорана [Aleksyeyev, Gienko, 2002]; 3 – Северо-Восток России; наледные полигоны Тихон-Юрях, Анмангында [Aleksyeyev et al., 2012; Lebedev, 1969; Simakov, 1959, 1961; Sokolov, 1975; Tolstikhin, 1974]; 4 – Северная Чукотка; наледный полигон Кооквын [Aleksyeyev et al., 2011]; 5 – Приохотье [Shmatkov, Kozlov, 1994]; 6 – Алданское нагорье; наледные полигоны Самокит, Леглиер, Чульман, Локучакит, Иенгра [Aleksyeyev, 1973, 1975, 2005; Topchiev, 1979; Topchiev, Gavrilov, 1981; Sokolov, 1975; Boitsov, 1979]; 7 – зона БАМ; наледные полигоны Нижний Ингамakit, Чарские Пески, Средний Сакукан, Мурурин, Читканда, Шахтаум [Aleksyeyev, 1975, 2005; Aleksyeyev, Kirichenko, 1997; Aleksyeyev, Furman, 1976; Deikin, Abakumenko, 1986; Deikin, Markov, 1983, 1985; Catalogue..., 1980, 1981, 1982; Prokacheva et al., 1982; Shesternev, Verkhoturov, 2006]; 8 – Забайкалье; наледный полигон Ингода [Aleksyeyev, 1975; Shesternev, Verkhoturov, 2006; Chernyavskaya, 1973]; 9 – Юго-Западное Прибайкалье; наледные полигоны Тумусун, Хангарул, Дабады [Aleksyeyev, 1976]; 10 – Восточные Саяны; наледные полигоны Синий Камень, Шаманка, Эден [Aleksyeyev, 2005; Aleksyeyev, Kovalchuk, 2004; Kravchenko, 1985a]. Режимные наблюдения на полигонах за динамикой отдельных наледей: 11 – Алтай; наледный полигон Актру [Revyakin, 1981]; 12 – Иликта [Berkin, 1964]; 13 – Половинка [Kazakov, 1976]; 14, 15 – Улахан-Тарын, Булус [Piguzova, Shepelev, 1972, 1975; Tolstikhin, 1974]; 16 – Керак [Rumyantsev, 1964, 1991]; 17 – Кульдур [Chekotillo et al., 1960]; 18 – Пластун [Tsvid, Khomichuk, 1981]; 19 – Южный рудник [Tsvid, 1957].

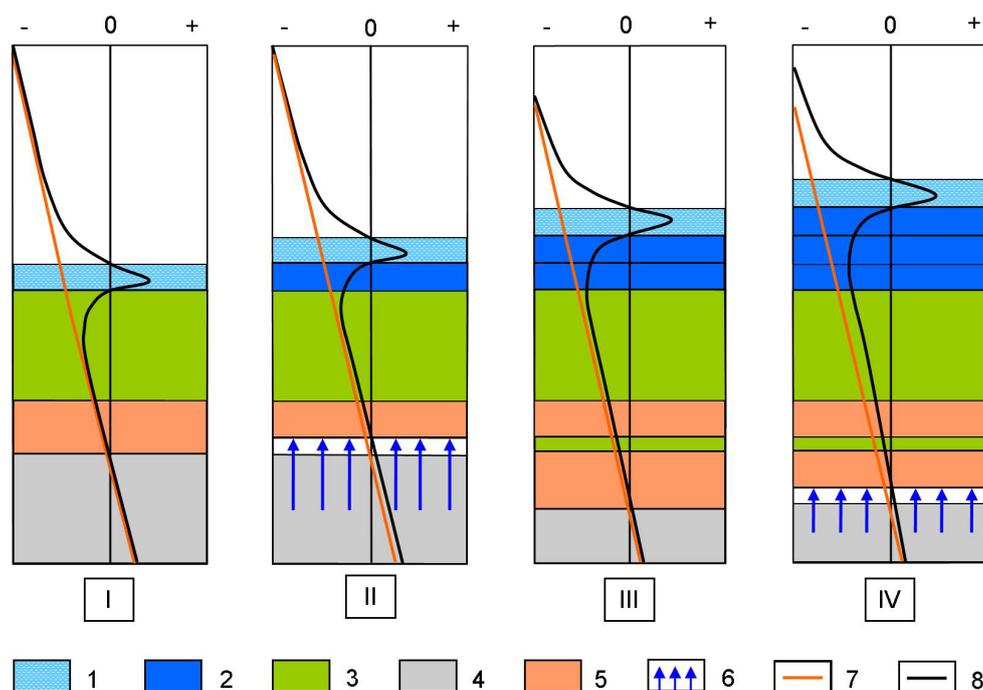


Fig. 2. Schemes of joint surface and subsurface icing.

Icing stages: *I* – freezing-through of the aufeis bed, and formation of the first aufeis-forming layer of water; *II* – vacuum in the rock layer as a result of partial thawing of ground ice, infiltration of water from below, and formation of the second aufeis-forming layer of water; *III* – alignment of the temperature distribution curve, increment in the thickness of the ground-ice layer, and formation of the third aufeis-forming layer of water; *IV* – melting of the ground ice from below, vacuum at its lower surface, another infiltration of water, and formation of the next aufeis-forming layer. 1 – water; 2 – aufeis ice; 3 – frozen soil; 4 – thawed soil; 5 – ground ice; 6 – direction of cryogenic filtration of groundwater; 7 – temperature distribution curve between aufeis formation periods; 8 – temperature distribution curve at the period of formation and crystallization of the water layer on the ice.

Рис. 2. Схемы сопряженного формирования наледи и подземного льда.

Стадии льдобразования: *I* – промораживание наледного ложа и формирование первого наледнеобразующего слоя воды; *II* – образование вакуума в толще горных пород в результате частичного таяния подземного льда и подсос воды снизу; формирование второго наледнеобразующего слоя воды; *III* – выравнивание кривой распределения температуры, прирост толщины слоя подземного льда; формирование третьего наледнеобразующего слоя воды; *IV* – подтаивание подземного льда снизу, образование вакуума у его нижней поверхности, новый подсос воды, формирование очередного наледнеобразующего слоя. 1 – вода; 2 – наледный лед; 3 – мерзлый грунт; 4 – талый грунт; 5 – подземный лед; 6 – направление криогенной фильтрации подземных вод; 7 – кривая распределения температуры между периодами наледнеобразования; 8 – кривая распределения температуры в период образования и кристаллизации слоя воды на льду.

the thickness of frozen soil with the clearly layered cryogenic structure is also increasing.

Observations on the Charskie Peski polygon show that ice schlier stacks are most often oriented parallel to the icing surface and composed of pure transparent ice of prismatic or granular structures [Alekseyev, 2007; Sannikov, 1988]. In the layers composed of sand and sandy clay, the schlier thickness generally ranges from 2 to 50 mm; the layers maintain the strike and are limited by the plane surface of the host soil mass (Fig. 3, a). Distances between neighbouring ice inclusions can range from a few millimetres to 8–10 cm. The thickness of the soil layer between ice layers depends on the duration of the period of repeated icing: the longer is the time from water discharge to complete crystallization of the aufeis layer, the more lasting is freezing of the

underlying rocks and, correspondingly, the larger is the distance between the ice schlieren. The regular pattern is disturbed in soils of inhomogeneous composition, and frequent squeeze-out and wedging of ice inclusions result from irregular freezing of the soil layers as they differ in thermal characteristics and moisture contents. However, downward the profile, rhythmical icing patterns are sustained and generally correspond to the number of icing water outflow cycles. In analyses of cryogenic permafrost, this indicator may serve as a marker of potential development of aufeis.

Laminated cryogenic textures are lacking in clastic rocks and well-washed boulder-gravel beds. In rocks with a water-cut, which are not under pressure during freezing, a basic cryogenic texture is formed, and the 'free' space is completely occupied by ice. In such cases,

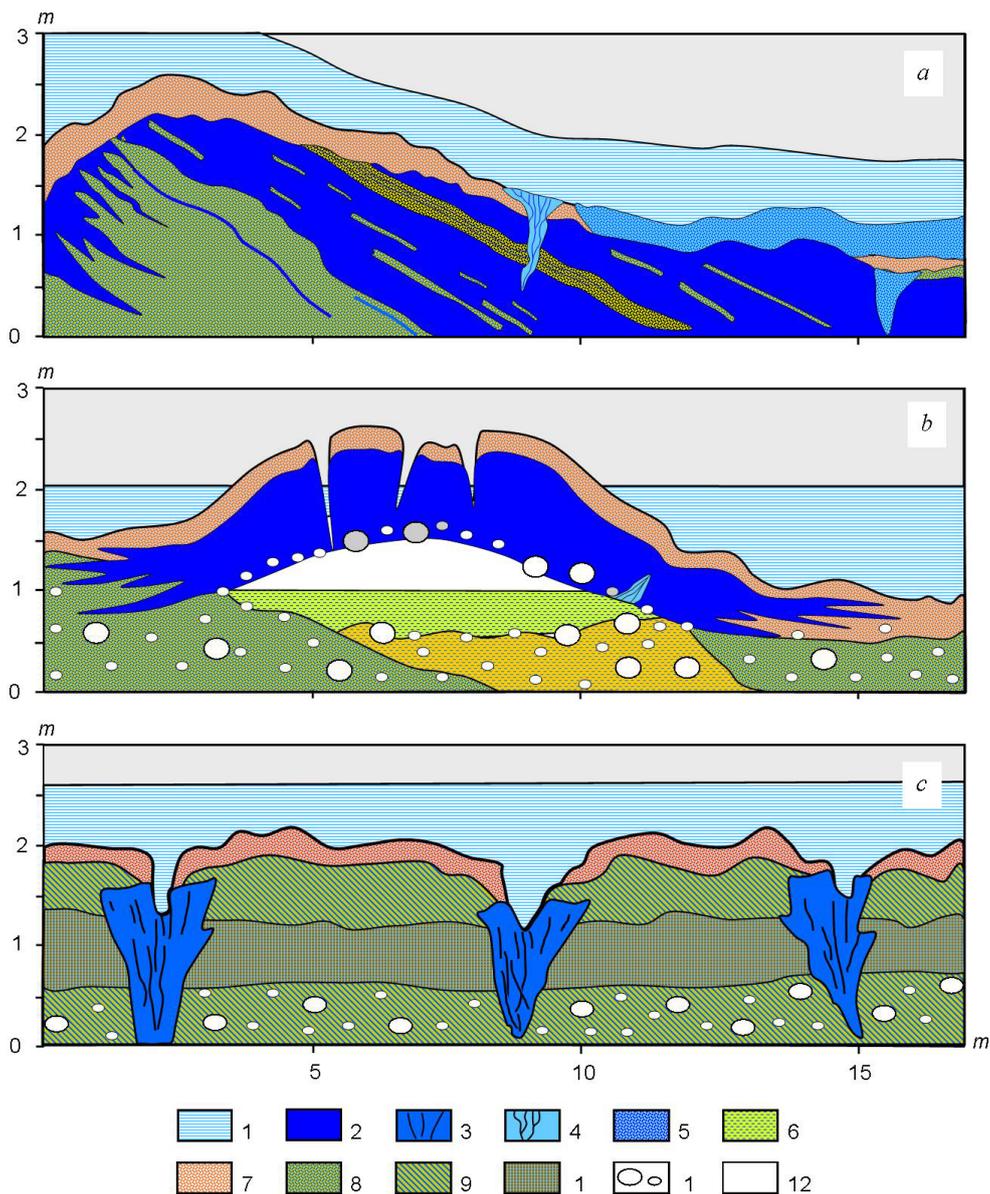


Fig. 3. Ice-ground complexes in the Charskie Peski aufeis polygon, the northern Transbaikalia.

a – Kholodny creek valley; *b* – Bolotny creek valley; *c* – right-side bank of the Middle Sakukan river. 1 – groundwater aufeis deposit. Ice types: 2 – injection ice, 3 – repeated-vein ice, 4 – fissure-vein ice, 5 – snow ice; 6 – water. Ground materials: 7 – seasonally thawing sand, 8 – perennially frozen sand, 9 – perennially frozen sandy loam, 10 – frozen peat, 11 – boulders and pebbles; 12 – air cavity in the ice mound.

Рис. 3. Ледогрунтовые комплексы на наледном полигоне Чарские Пески. Северное Забайкалье.

a – долина руч. Холодного; *b* – долина руч. Болотного; *c* – правый берег реки Средний Сакукан. 1 – наледь подземных вод. Лед: 2 – инъекционный, 3 – повторно-жильный, 4 – трещинно-жильный, 5 – снежный; 6 – вода. Грунты: 7 – песок сезоннопротаивающий, 8 – песок многолетнемерзлый, 9 – супесь многолетнемерзлая, 10 – торф мерзлый, 11 – валуны и галька; 12 – воздушная полость в теле бугра пучения.

particles are displaced in various directions, and cryogenic pressure forces the water flow into the neighbouring soil sections. Stresses associated with water crystallization are compensated by the pressure of aufeis ice and lateral water outflow and thus do not cause any significant deformation of the ground surface. The above-described mechanism of subsurface icing is typical of

open cryogenic systems. In our studies, we observed such profiles in river valleys which water levels are frost-dependent. It is revealed that the lower is the air temperature, the higher is the water level in the open part of the channel or in the ice hole, which gives evidence of water squeezing out during freezing of the host rocks.

It is often observed that closed water-bearing systems are formed in the aufeis sections of the river valleys, and their formation is accompanied by injection icing that leads to soil pulling apart and uplifting. The mechanism of water injection in contact areas between water-resistant beds is described in [Gasarov, 1966; Klimovsky, 1978, Sannikov, 1988] and other publications. It was discovered and proved by experiments in the Permafrost Institute SB RAS [Feldman, 1988; Feldman, Borozinets, 1983], as well as by results of theoretical studies by Ya.B. Gorelik and V.S. Kolumin in the Institute of the Earth's Cryosphere [Gorelik, Kolumin, 2002]. Results of out field studies show that the injection mechanism causing accumulation of huge mass of ground ice is most evident in conditions of aufeis formation, i.e. in a specific thermal regime with a high moisture content of the underlying rocks.

Injection ice layers start to form when the soil freezes to some depth in the neighbouring sections of the river valley. During this period, an over-permafrost talik (or unfrozen pocket) persists underneath the aufeis deposit due to high emission of latent heat. High pressures occur when its top gets frozen in periods between aufeis-formation cycles, and water is squeezed out laterally due to cryogenic impacts. The pressure drops down abruptly when the groundwater breaks out to the surface or gets injected as an independent lense between the thawing and frozen soil beds. In the latter case, the top of the talik is uplifted to a height that is sufficient to compensate the hydrostatic pressure. Further freezing of the injected water may be partial or complete. In case that the water lense is completely frozen, the pressure (which was increasing before) drops down abruptly after repeated water outflow in subvertical fractures and fault zones, which is accompanied by active bubbling and emission of dissolved air, followed by 'outburst' of actively growing ice crystals.

This process is accompanied by vertical deformations of the ground surface, which often remain unobservable under the aufeis. In case of complete crystallization of the injected water, the bottom of the frozen water body is covered by frozen-up fine soil (with a typical laminated cryogenic texture that has formed as described above), pebbles, boulders or coarse rocks (Fig. 3, b). By the next injections, this frozen soil is lifted up together with this ice cap and then jammed inside the ground ice bed.

In some cases, water is injected between the aufeis deposit and its bed, and plants frozen in ice are thus torn off. Generally, the injection ice volume increases after outflow cycles followed by crystallization of aufeis-generating water, as evidenced by numerous tongues at the periphery of ice domes (see Fig. 3, b). In parallel, healing of cracks and fractures with ice takes place as lode ice and repeated-ice wedges are formed.

Ice infill of such types is specific as it is supplied by either aufeis water (from above) or groundwater uplifted by cryogenic pressure (from below).

It may be noted in puzzlement at the first glance that rock layers, consistent in thickness and strike, and rock lenses are present in the injection-ice mass. Frozen rock xenolithes look like suspended in ice; they have clear contacts with the host ice mass and, in some cases, arranged in a kind of tiers and chains. Isolated clusters of pebbles and large boulders are often found inside the ice mass (Fig. 4). In records of such profiles, researchers usually state that foreign inclusions were formed by ingress of this material to the aufeis surface and its subsequent burial due to layer-by-layer water freezing. Such comments do not consider the absence of lamination in ice and a possible injection origin of the structure.

It is revealed that aufeis phenomena play a special role in frost shattering of soil and development of vein ice and recurrent-vein ice (see Fig. 3, c). Cryogenic fracturing of frozen rocks is known to occur at high temperature and humidity gradients – the lower is the temperature of the ground surface and the higher is its moisture/ice content, the smaller polygons are generated due to stresses. In the cryogenic fractures, ice is usually formed during the period of snow melting or spring flood. The development of fissure-vein ice is significantly impacted by aufeis processes. Firstly, in winter, due to discharge of aufeis-generating water, frost shattering of rocks in floodplains and terraces may not take place at all or may be substantially transformed. If aufeis processes start in autumn and continue without any interruption until spring, groundwater icing occurs in the vacuum-filtration mode, i.e. polygons are not formed. If icing takes place from the second half of winter, thermal stresses in soil lead to fracturing of the frozen ground, and polygons are weakly manifested.

Secondly, recurrent-vein ice is formed in the aufeis sections of the river valleys due to discharged groundwater, rather than melted snow. In such cases, formation of ice wedges is deferred by 2–3 months, i.e. to the middle of the cold season. Thirdly, as the aufeis mass covers the polygons, their development in the warm season is transformed; in particular, the depth of seasonal thawing is reduced, the intensity and composition of thermal erosion and thermokarst are altered, and rock heaving is obscured.

Aufeis phenomena play a special role in the head-on growth of recurrent-vein ice. There are two possible scenarios of icing. If aufeis water fills in a cavity above the ice vein in the incompletely frozen seasonally melting layer, crystallization of aufeis-generating water is accompanied by wedging of the host rock and formation of a series of conjugated ice schlieren that are thinning out with the increasing distance from the frost-shattered fracture. The ice mass is thus a natural

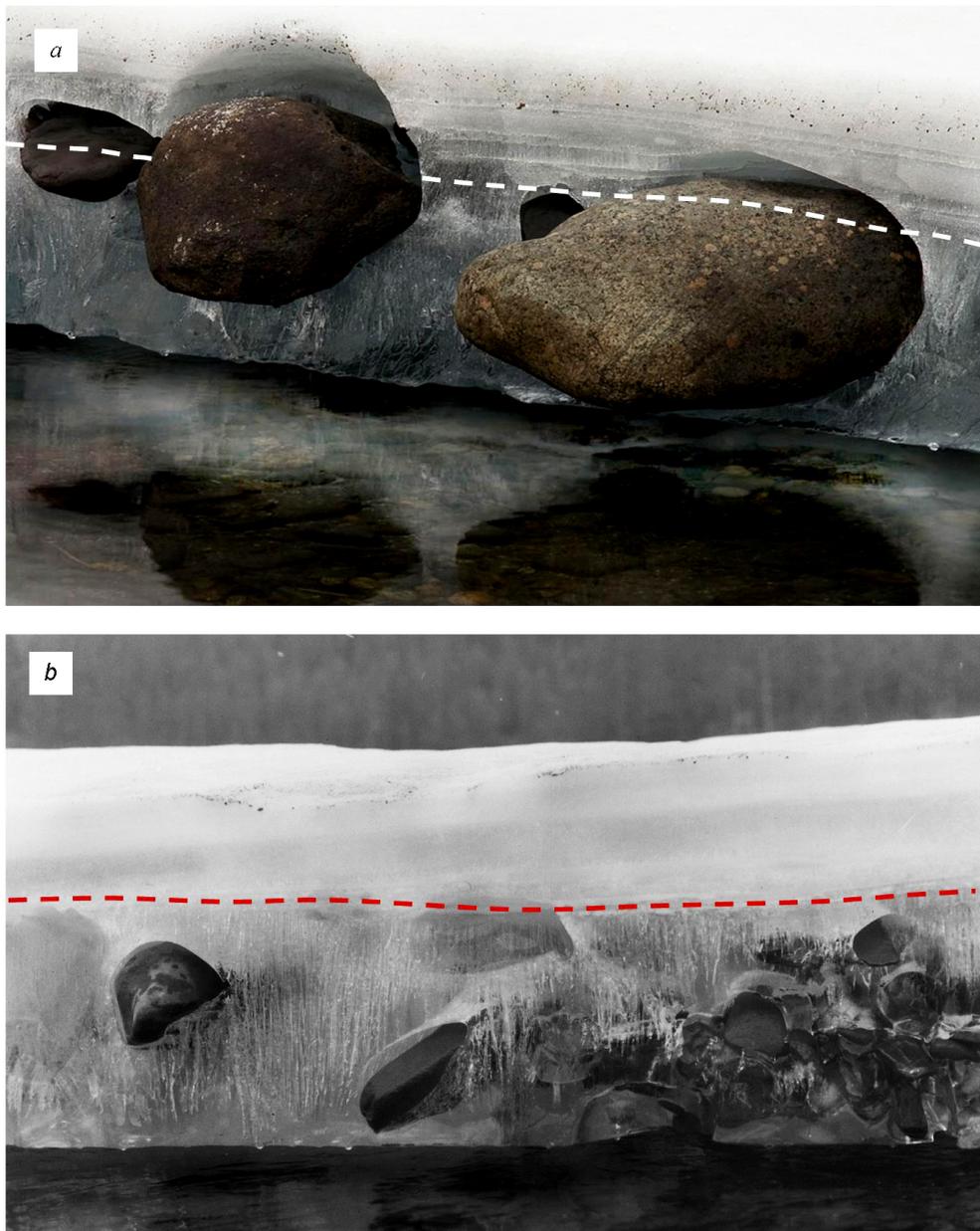


Fig. 4. Boulders and rock fragments in the vacuum-filtration ice layer.

a – on the aufeis glade in the Suntar river valley, Yakutia (photo by S. Karpukhin); *b* – on the aufeis glade in the Aunakit river valley, Patom plateau. The dashed line shows the lower boundary of the aufeis ice.

Рис. 4. Валуны и обломки горных пород в толще вакуум-фильтрационного льда.

a – на наледной поляне в долине реки Сунтар, Якутия (фото С. Карпухина); *b* – на наледной поляне в долине реки Аунакит, Патомское нагорье. Пунктиром показана нижняя граница наледного льда.

extension of the ice vein. It is typically characterized by a pronounced subhorizontal lamination that is complicated by subsequent frost shattering as ice occupies the cavity and gets fractured inside it.

If the cavity is located underneath the ice mass and filled in after the frozen seasonally thawing soil links with permafrost, water freezing takes place in a confined space. In this scenario, radially oriented crystals are formed, and gas bubbles are distributed concentri-

cally. In the central part of such ice mass, the mineral content is increased due to sequential freezing of dissolved salts.

In both scenarios, the build-up ice cap is often split by frost shattering and thus acquires a complicated texture. Under a corresponding regime of sedimentation, such processes seems to account for the major increase of the considered ice deposits. Sites with recurrent-vein ice of the similar origin are typically abundant at

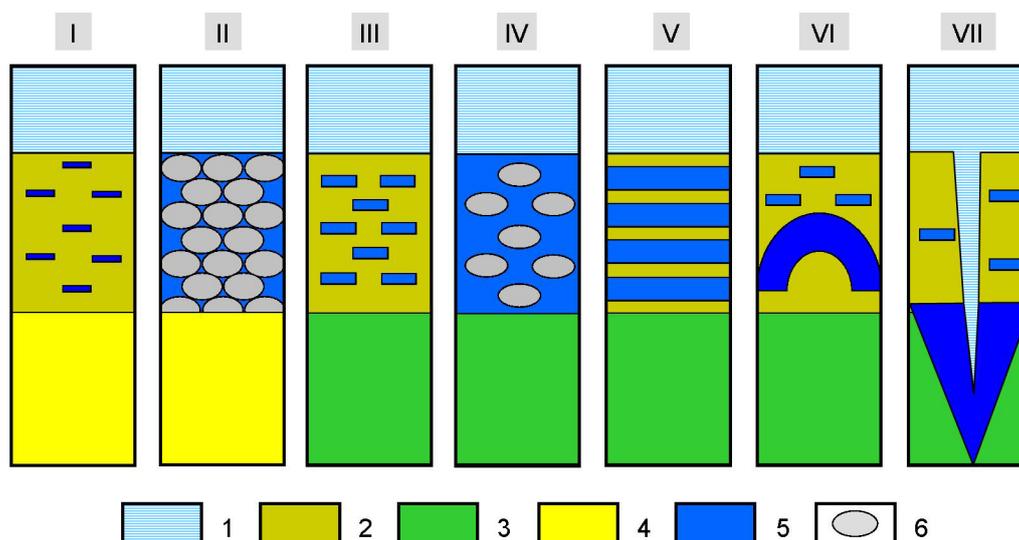


Fig. 5. Types of aufeis ice-ground complexes (IGC).

I – massive-segregation; *II* – cement-basal; *III* – layered-segregation; *IV* – basal-segregation; *V* – vacuum-filtration; *VI* – pressure-injection; *VII* – fissure-vein. 1 – aufeis deposit with intercalations of snow ice and snow; 2 – seasonally thawing layer of rocks; 3 – perennially frozen rocks; 4 – thawed and unfrozen ground materials; 5 – ground ice; 6 – boulders and pebbles.

Рис. 5. Типы наледных льдогрунтовых комплексов.

I – массивно-сегрегационный; *II* – цементно-базальный; *III* – слоисто-сегрегационный; *IV* – базально-сегрегационный; *V* – вакуум-фильтрационный; *VI* – напорно-инъекционный; *VII* – трещинно-жилный. 1 – наледь с прослоями снежного льда и снега; 2 – сезоннопротаивающий слой горных пород; 3 – многолетнемерзлые горные породы; 4 – талые и немерзлые грунты; 5 – подземный лед; 6 – валуны и галька.

the periphery of flat aufeis glades composed by fine sediments, as well as in river terraces formed below the floodplain regime level. The Middle Sakukan river valley in the Upper Chara basin can be viewed as an example of such environment. Its recurrent-vein ice mass (see Fig. 3, c) is classified as polygenetic. The bottom ice was formed epigenetically prior to aufeis depositing, while the top ice is of the syngenetic origin and accumulated during the long-term development of aufeis. It is most probable that 'purely' syngenetic ice veins may form in the lower parts of aufeis glades wherein accumulation of solid material usually prevails over its removal.

4. TYPES OF AUFEIS ICE-GROUND COMPLEXES

As described above, a complex two-tiered system containing paragenetically related frozen soil and surface ice is formed in aufeis areas of the permafrost zone. Its top is composed of aufeis ice, frozen sleet and snow, and its bottom contains ice-saturated rocks. The structure of the cryogenic system depends on two major processes, layer-by-layer water freezing on the ground surface and crystallization of groundwater in conditions of periodic variations of the heat flow density. By the ratio of components in the surface and sub-

surface tiers, we distinguish a series of genetically homogeneous structures termed 'aufeis ice-ground complexes' (IGC) that are significantly different from similar complexes located outside the aufeis glades. The IGC structure, joined development and locations determine geological engineering and landscape-geographical conditions that are of importance for development of such territories.

Since the upper tier does not show any diversity of its structure and consists of relatively homogeneous layers of aufeis (rarely, river ice and snow), it can be viewed as a single structural element of the system. Therefore, specific stratigraphic features of the profile are determined by the main types of subsurface icing (segregation, basal-cement, vacuum-filtration, pressure-injection, and fissure-vein). Together with surface ice accumulation, these processes generate patterns and cryogenic structures of the ice-ground complexes (Fig. 5). We distinguish seven major types of such complexes (see their descriptions below). IGC-I and IGC-II are typical of the open-system conditions when groundwater is crystallized without cryogenic head and without significant deformation of the host rocks. Other types result from freezing of closed water-bearing structures that are subject to high pressures during water transformation to ice. Under pressure, mineral soil particles are relocated, and the top layer of the ground sur-

face is uplifted and subject to considerable deformation. The IGC characteristics described below are based on the data collected during our field observations on the aufeis polygons.

IGC-I. Massive-segregation type. The top tier consists of two layers composed of aufeis ice and crystalline river ice mixed with frozen slush; its thickness ranges from 1.0 to 1.5 m. The bottom tier is formed in the middle or second half of winter and contains muddy, sand-and-gravel or pebble sediments with small, evenly spaced ice lenses or ice pockets; its thickness ranges from 0.2 to 0.8 m. The cryogenic texture of soil is mainly of massive lensoid type. The contact with the underlying non-frozen rocks is smooth. In spring, the water level is significantly below the bottom of the frozen layer. IGC-I is observed on floodplains and under the beds of freezing water flows in areas of over-permafrost and inter-permafrost taliks that get dry in winter. No visible movements of the ground or overlying ice layers are observed in such areas.

IGC-II. Cement-basal type. The upper tier consists of two or three layers composed of snow ice or crystalline river ice covered by river-water or groundwater aufeis; its thickness ranges from 1.0 to 2.0 m. The lower tier contains well-washed boulders and pebbles, and gaps between them are completely filled with ice; its thickness amounts to 1.0 m. The basal cryogenic texture forms in the second half of winter after freezing of the surface water flow in conditions of high water-cut of the channel alluvium. Such conditions are characteristic of river sections with 'diving' runoff (water appears and disappears through the channel length). In dry riverbed sediments, icing takes place in the middle or late winter due to ingress of aufeis water. In both cases, crystallization of water in cavities is accompanied by rock cementing/hardening with slight shifting of rock components relative to each another, but does not lead to uplifting of the top layer with frozen-up snow and ice.

IGC-III. Layered-segregation type. The upper tier (up to 2.5 m thick) consists of one or two layers composed of aufeis ice or aufeis plus snow ice. The lower tier is a seasonally thawing icy layer composed of fine rocks, such as sand, loamy soil, sandy clay or clay, underlain by permafrost. IGC-III is observed in peripheral areas of sodded aufeis glades in development stages I and IV. Three scenarios of freezing in the closed water-bearing system are revealed: (1) freezing of the layer starts before the beginning of aufeis formation, i.e. in November and December, and continues underneath the icing cover until its complete linkage with the permafrost base; (2) the soil freezes during layer-by-layer water freezing on the ground surface in between water discharge cycles; (3) the moist over-permafrost layer freezes after the decay of aufeis processes and stabilization of sub-zero temperatures throughout the profile. Layers of segregation ice (3 to 5 cm thick) are formed parallel to the

freezing front in the bottom part of the horizon in the first case, across the entire freezing bed in the second case, and under the aufeis in the contact layer in the third case. Cryogenic ground segregation is accompanied by uplifting of the ground surface together with the overlying aufeis ice by 10 to 30 cm, depending on the thickness of the seasonally thawing layer and its pre-winter moisture content.

IGC-IV. Basal-segregation type. The top single-layer tier (up to 3 m thick) consists of aufeis ice. In the bottom tier (0.5 to 1.0 m thick), boulders and large pebbles are suspended in transparent massive ice. Unfrozen water-bearing sediments are located below, overlaying the permafrost base or base rocks. When freezing, groundwater accumulates pressure and often gushes or penetrates into the contact zone between the ground surface and the aufeis deposit to form lenses and layers of clear blueish ice. Water transformation to ice is accompanied by ubiquitous relocation of boulders and pebbles relative to each other, and the frost-bound cap together with aufeis slabs is uplifted to a height of 0.5 to 1.2 m. In some locations, inside the sediment beds, there are horizontally consistent layers and lenses of injection ice (0.5 to 0.8 m thick) of the prismatic vertically oriented structure. IGC-IV formation lasts through the entire cold period of the year. It is abundant on beds of small rivers and streams that get dry by the beginning of winter. On mature aufeis glades, it can occupy dozens and hundreds of thousand square metres, while annual volumes of ground ice and magnitudes of ground movements due to hydrothermal factors may vary tremendously from year to year (Fig. 6). In summer, the lower tier of IGC-IV is often mistakenly viewed as an aufeis deposit that was 'dirtied' by the boulder-pebble material.

IGC-V. Vacuum-filtration type. The top single-layer tier (up to 2.5 m thick) consists of aufeis ice. The bottom tier (0.3 to 1.8 m thick) contains grass, sand and loamy soil mixed with small pebbles at some locations. Across the profile, there are layers of pure transparent ice (10 to 50 cm thick), going parallel to each other and separated by layers of jammed-in fine sediments with the lenticular cryogenic texture. At the periphery, ground ice layers are gradually tapering or split into branches looking like different-sized 'teeth' penetrating into the host rock. A gravity-feed water-bearing bed is located underneath the ground ice bed. No underlying permafrost has been revealed. In some outcrops, however, we observed fragments of ice-ground structures that are clearly of the vacuum-filtration genesis, yet might have been stored for more than one season. Transition of injection ice to permafrost might have resulted from re-deposition of sediments or storage of aufeis ice through the entire warm period of the year (during formation of the permanent snow patch). IGC-V is observed in outwash plain areas, that are devoid of vegetation, with dense networks of shallow multi-channel streams, as

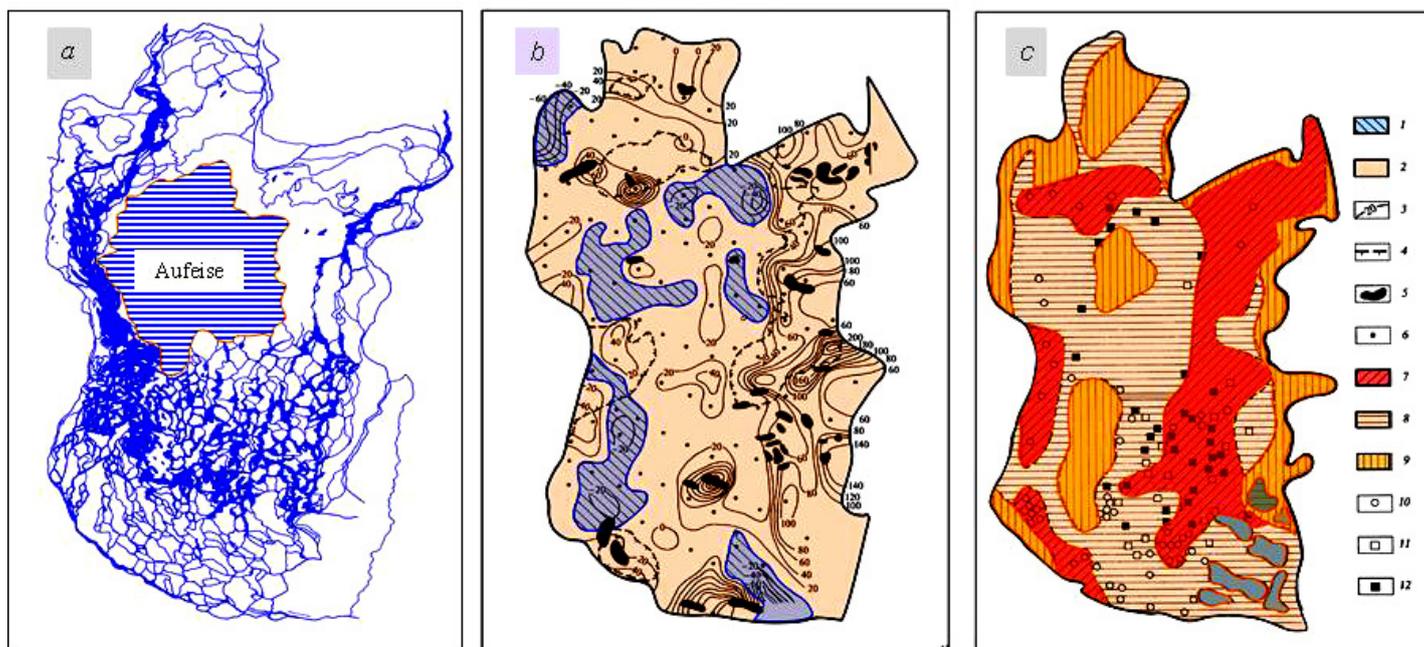


Fig. 6. The channel network on the aufeis glade and cryogenic movements of ground during formation of the gigantic Mururin aufeis deposit in the northern Transbaikalia.

a – channel network at the period of incomplete destruction of aufeis; *b* – situation according to observation data for the winter 1977–1978 [Kolotaev, 1980]; *c* – situation according to observation data for winter in 1978–1979 and summer 1980 [Deikin, 1985]. 1 – zone wherein the surface of the aufeis bed is subsided; 2 – zone wherein the rock surface is uplifted; 3 – isolines of higher elevation of the ground surface, m; 4 – zone of development of water-ice ridges; 5 – aufeis mound; 6 – measuring poles; 7 – zone of active water exchange and intensive uplifting of ground materials during formation of the injection-ice layer (0.73 m thick); 8 – zone of moderate water exchange and moderate uplifting of the ground surface during formation of the injection-ice layer (0.45 m thick in average); 9 – zone of weak injection icing or its absence; 10 and 11 – pits and profiles in areas of naturally outcropped injection-ice layers in 1979 (10) and in 1980 (11); 12 – pits and profiles in the ice-containing alluvium layer.

Рис. 6. Русловая сеть на наледной поляне и криогенное движение грунтов в процессе формирования гигантской Муруринской наледи на севере Забайкалья.

a – русловая сеть в период неполного разрушения наледи; *b* – ситуация по данным наблюдений [Kolotaev, 1980] в зиму 1977–1978 гг.; *c* – ситуация по данным наблюдений [Deikin, 1985] в зиму 1978–1979 гг. и летом 1980 г. 1 – зона понижения поверхности наледного ложа; 2 – зона повышения поверхности горных пород; 3 – изолинии повышения поверхности грунтов, м; 4 – зона развития водно-ледяных гряд; 5 – наледный бугор пучения; 6 – измерительные веши; 7 – зона активного водообмена и интенсивного поднятия грунтов при формировании инъекционных льдов средней мощностью 0.73 м; 8 – зона умеренного водообмена и умеренного поднятия поверхности земли при формировании и инъекционных льдов средней толщиной 0.45 м; 9 – зона слабого развития инъекционных льдов или их отсутствия; 10–12 – шурфы и разрезы, пройденные в 1979 г. (10), на участках естественного обнажения инъекционных льдов в 1980 г. (11) и в толще льдосодержащих аллювиальных отложений (12).

well as in some suffosion-erosional valleys near permanent groundwater sources (Fig. 6).

IGS-VI. Pressure-injection type. The top tier (0.5 to 1.5 m thick) consists of aufeis ice. The bottom tier (0.5–1.2 m thick) contains loamy soil, sandy loam, sand, grass, pebbles, large boulders or peat, i.e. rocks that differ in size of particles. In the profile, a plano-convex or biconvex lens of pure ice is always present; the lens contains torn-off trunks of shrubs, tree roots, grass, moss and pieces of rocks from the underlying layers. Ice domes as well as overlying ground are broken by gaping fractures; radially tilted trees are observed on slopes of heaving mounds, and there are air pockets and small lakes inside the mounds. No information is available on

configurations of the channels through which hydraulic-head groundwater is transported to the ground surface to form a ground ice lens and to cause uplifting of the ice-ground mass. Such channels may be represented by narrow talik fissures or oval 'tubes', judging by the fact that ISC-IV is observed in linear zones of tectonic faults, beds of small rivers and streams and local over-permafrost water discharge foci, all being clearly manifested in the terrain. In winter, the water discharge channels are blocked by ice and soil 'plugs'. Such plugs are periodically destroyed (sometimes with an outburst) under the pressure of ascending flows [Petrov, 1930; Podyakonov, 1903], and the ground surface bends down to acquire a parabolic profile. During freezing of closed

Table 1. Annual vertical ground movement amplitudes in aufeis sections of river valleys, according to observations on the Charskie Peski and Eden polygons (per 1 m profile), cm

Таблица 1. Амплитуда ежегодного вертикального движения грунтов на наледных участках речных долин по данным наблюдений на полигонах Чарские пески и Эден (в пересчете на 1 м разреза), см

| Development stages of aufeis sections of river valleys* | | Types of aufeis ice-ground complexes | | | | | | |
|---|-------------------------|--------------------------------------|--------|---------|--------|--------|---------|---------|
| | | IGC-I | IGC-II | IGC-III | IGC-IV | IGC-V | IGC-VI | IGC-VII |
| I | Periglacial development | 5–10 | 10–20 | 10–20 | | | | |
| II | Transgression | 10–20 | 20–30 | 20–30 | 40–50 | 50–100 | 100–500 | 20–40 |
| III | Stabilization | 10–20 | 20–30 | 30–40 | 30–40 | 40–70 | 50–300 | 10–30 |
| IV | Regression | 10–20 | 20–30 | 20–30 | 20–30 | 30–50 | 50–100 | 5–10 |
| V | Postglacial development | 5–10 | 10–20 | 10–20 | | | | |

Note. * – development stages are described below.

Примечание. * – описание стадий развития см. ниже.

cryogenic systems, pressures amount to dozens of thousand bar. In the Egegi river valley in East Sayan mountains, we recorded a case of a heaving mound located in front of a rocky bench composed of the flat-lying Proterozoic dolomite. In spring, the heaving mound was destroyed, and the rock slabs were literally broken out of the rock mass and set at an angle of about 40 degrees against their former position.

IGC-VII. Fissure-vein type. The upper tier (0.5–1.0 m thick) consisting of aufeis ice is underlain by fine icy sediments with the massive lenticular cryogenic texture and wedge-like inclusions of vein ice and/or recurrent-vein ice. In the period from mid-late December until the aufeis formation, the seasonally thawing layer of the bottom tier (0.5 to 0.8 m thick) is saturated with small lenses of randomly arranged segregated ice. In the same period, soil and permafrost are subject to frost shattering. In the second half of winter and in spring, snow melting provides for infill of fractures and fissures with ice. Depending on the composition and pre-winter soil moisture content, the ground surface can be uplifted to a height of 10 to 40 cm. IGC-VII is formed in conditions of low snow and low air temperatures at the periphery of the icing glades.

5. CRYOGENIC MOVEMENTS OF GROUND IN AUFEIS GLADES

Cryogenic movements of freezing rocks are well known [Rusanov, 1961] and described in many scientific and technical reports related mainly to issues of stability of buildings and facilities built on heaving soils. However, cryogenic movements of ground in aufeis glades have not been properly assessed yet. A few articles [Alekseyev, 1989; Kravchenko, 1983, 1985b] describe the dynamics of the ground surface under the influence of aufeis processes, as evidenced by instrumental monitoring data. In other publications [Gasa-

nov, 1966; Gorbunov, Ermolin, 1981; Klimovsky, 1978; Koreisha, 1969; Krendeleev, 1983; Petrov, 1930; Sannikov, 1988], the information is mainly descriptive. Nonetheless, the available data (Table 1) are sufficient to attempt at establishing regularities in annual morpho-structural transformations of aufeis sections of the river valleys.

The tabulated data suggest that mobility of the rocks underlying the aufeis deposit depends on types of the ice-ground complexes and development stages of the aufeis sections of the river valleys. The aufeis bed is uplifted due to formation of ground ice lenses and layers; it sinks down due to thawing of ice inclusions and thermal settlement of the mineral sediment mass. At the first and last stages of development of the aufeis sections, the ground surface deformation does not exceed values of the cryogenic movements recorded outside the zone wherein the aufeis deposit was formed. Moreover, deformation is reduced as the low floodplain and channel deposits are blocked from freezing by the aufeis-river ice cover. Neither soil heaving nor settlement can be visually detected in such areas, firstly, because the depth of seasonal freezing under freezing water streams seldom exceeds 0.2–0.5 m, and secondly, traces of winter movements of the subglacial alluvium are destroyed by spring-time ice drifting and erosion. At other stages of transformation of the aufeis valley, both positive and negative forms of the permafrost terrain are abundant, and the ground surface uplifting/sinking amplitude amounts to a maximum in the most active stage of transgression due to well-manifested processes of icing of the vacuum-filtration and pressure-injection types.

The scale and intensity of ground movements in mature aufeis glades are shown in Fig. 7. Our observations were conducted at the upper course of the Bolshoi Eden river at the boundary of the forest belt and the goltsy woodland (elevation 1800–1820 m). The aufeis

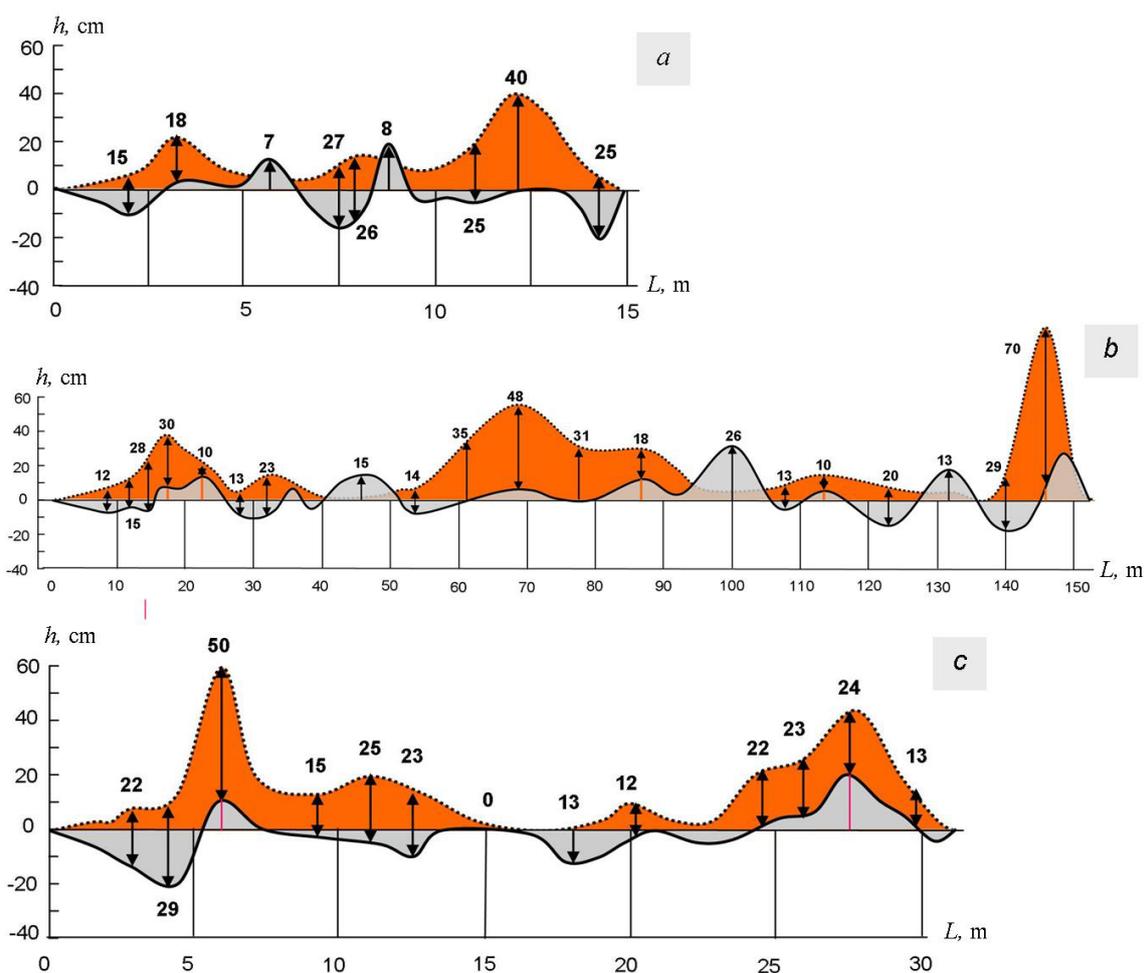


Fig. 7. Variations in the ground surface elevation of the aufeis glade in the Bolshoi Eden river valley in East Sayan, according to serial leveling data.

Heights above the reference points of observation (September 1986) with respect to the width of the aufeis section of the river valley, L : top curve – aufeis bed in May 1987, bottom curve – ground surface in September 1987 (after melting of the ice cluster). Arrows show directions of ground movements. Numbers correspond to absolute ground displacement values (cm) at the surface of the aufeis glade from May to September 1987. Colour codes: red – areas of ground heaving producing stratal ice and ice lenses of the vacuum-filtration and pressure types in winter in 1986–1987; grey – thermokarst and thermoerosion (below the zero line) and sediment redeposition and accumulation processes in conditions of injection-ice thawing in summer in 1987 (above the zero line). Positions of the profile: a – upper, b – middle, c – lower part of the aufeis glade.

Рис. 7. Изменение высоты земной поверхности наледной поляны в долине реки Большой Эден (Восточные Саяны) по данным серийных нивелировок.

Превышение h относительно базисных точек наблюдения (сентябрь 1986 г.) по ширине наледного участка долины L : верхняя кривая – ложе наледи в мае 1987 г., нижняя – поверхность земли в сентябре 1987 г. (после стаивания ледяного массива). Стрелками показано направление движения грунтов, цифрами абсолютное значение величины смещения (см) поверхности наледной поляны с мая по сентябрь 1987 г. Красный цвет идентифицирует процессы пучения грунтов с формированием пластовых и линзовидных льдов вакуум-фильтрационного и напорного происхождения в зиму 1986–1987 гг., серый цвет ниже нулевой линии – процессы термокарста и эрозии, выше нулевой линии – процессы переотложения и аккумуляции осадков в условиях вытаивания инъекционных льдов в летний период 1987 г. Положение профиля: a – верхняя, b – средняя, c – нижняя часть наледной поляны.

section (0.2 m² in total) is flat and gently sloping, composed of sand and gravel with inclusions of large (up to 2.5 m in diameter) boulders and rock fragments that had rolled down the steep slopes (almost 250 pieces). In winter, the aufeis glade is covered with ice (1.5 to 2.0 m thick) that melts completely only in mid-August.

Injection ice beds are located at depths from 0.3 to 0.5 m from the ground surface or directly underneath the aufeis deposit. The injection ice beds are consistent in strike, 0.5 to 1.2 m thick and occupy the area practically within the limits of the aufeis glades. In this area, the overlying soil is uplifted annually together with the

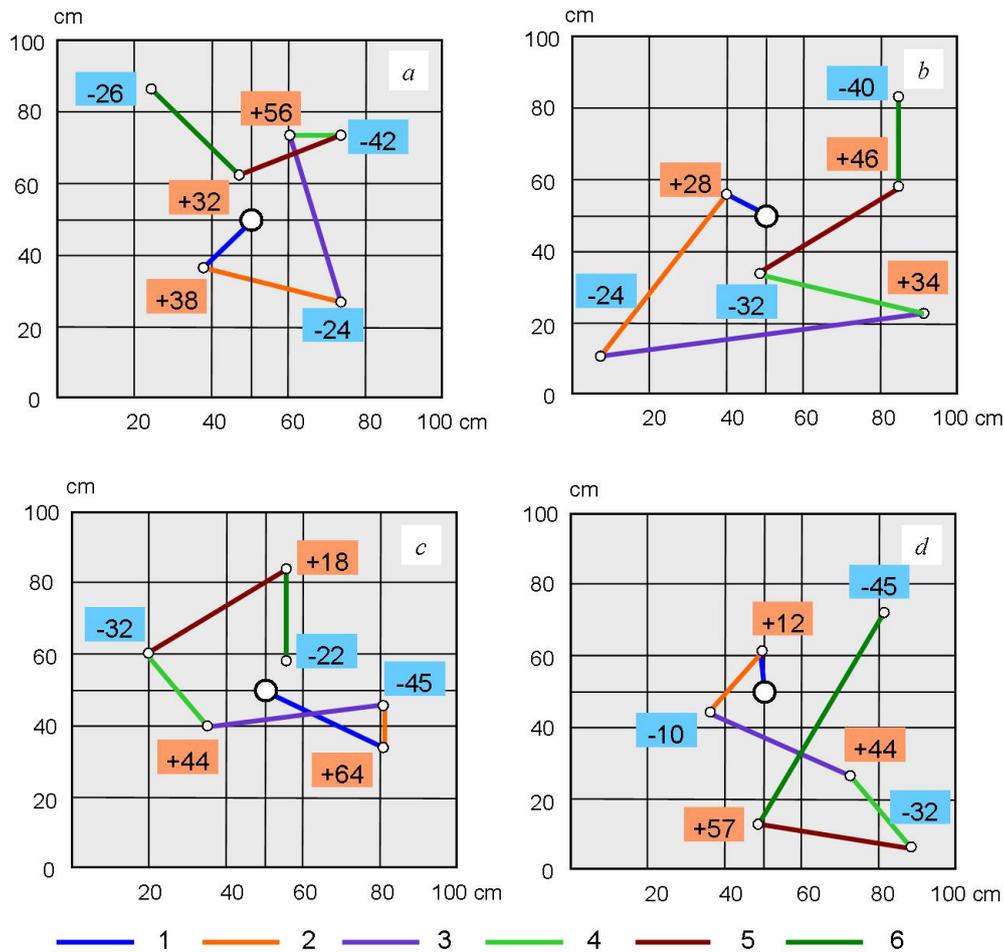


Fig. 8. Hydrothermal movements of large boulders in the aufeis glade in the upper reach of the Bolshoi Eden river in East Sayan according to serial leveling data for the period 1986–1989.

Horizontal (coloured lines) and vertical (numbers at reference points, cm) displacements of the reference marks: 1 – winter in 1986–1987; 2 – summer in 1987; 3 – winter in 1987–1988; 4 – summer in 1988; 5 – winter in 1988–1989; 6 – summer in 1989. Approximate weights of boulders: a – 0.5 t; b – 0.8 t; c – 1.2 t; d – 1.5 t.

Рис. 8. Гидротермическое движение крупных валунов на наледной поляне в верховьях реки Большой Эден в Восточных Саянах по данным серийных нивелировок 1986–1989 гг.

Смещение марки по горизонтали (цветные линии) и по вертикали (цифры у опорных точек, см): 1 – зима 1986–1987 гг.; 2 – лето 1987 г.; 3 – зима 1987–1988 гг.; 4 – лето 1988 г.; 5 – зима 1988–1989 гг.; 6 – лето 1989 г. Ориентировочный вес валунов: a – 0.5 т; b – 0.8 т; c – 1.2 т; d – 1.5 т.

aufeis deposit to a height of about 1.0 m. In spring, such locations are marked on the ground surface by fractured ice- or ice-ground mounds. It is noteworthy that some of the boulders (about 40 %), lying on the gravel base and scattered on the valley bottom, are frozen into the laminated aufeis mass, while the boulders located below the aufeis bed are enveloped by the near-contact or underground-water injection ice of the columnar structure. During the year, all the boulders, regardless of their positions in the profile and their weights, are displaced to distances of dozens centimetres in various directions both vertically and horizontally (Fig. 8). The movements are caused by cryogenic pressures of groundwater and solids during thermokarst and ther-

mal erosion processes. Any potential impact of the hydrodynamic pressure of surface water is excluded because the water flow is small and spread throughout the aufeis bed.

The dynamics of loose sediments in the aufeis valleys is specific – cryogenic movements take place in different directions in cold seasons, i.e. soil is uplifted together with ice in some locations, while in the other places it is subsided. This phenomenon was first discovered by hydrologists V.N. Kolotaev [Kolotaev, 1980] and V.N. Deikin [Deikin, 1985] at the Mururino aufeis deposit in the Upper Chara basin during the winter period of 1977–1978 (see Fig. 6). The mechanism of this process is not completely understood. It can be only

assumed that the ground surface subsides in the aufeis-formation zone in winter is due to redistribution of water reserves and groundwater head in the cryodynamic system as a result of its non-uniform freezing.

In the aufeis sections of the river valleys, local soil heaving deserves special attention. This process leads to formation of round-shaped or elongated mounds (hydrolaccoliths) which height ranges from 3 to 4 m (rarely 7 m), and the diameter is up to 150 m. In most cases, the mound height/width ratio is 1/10. The mounds can be annual or perennial, confined to areas of concentrated discharge of groundwater under pressure (around springs) or scattered at the periphery of mature aufeis glades in a random pattern (Fig. 9). Causes and mechanisms of their formation have not been properly studied yet. It is assumed that the mounds occur and grow due to cryogenic or hydraulic pressure of water-bearing systems during freezing; any details of this process are still unknown. As shown by profiles of the mounds, the top soil layer (0.5 to 0.8 m thick) is underlain by the ice dome (up to 1.5 m thick). Underneath the ice dome, there is a layer of water that is usually separated from the dome by an air bubble. A completely frozen water core of the mound is generally shaped as a plano-convex lens. Ground ice is transparent and latently laminated, with the hypidiomorphic-granular structure; it contains elongated cylindrical air bubbles that are oriented perpendicular to the freezing front.

While growing, the mounds periodically burst and let water and air gush out. The volume of water lenses may amount to dozens of cubic metres. An interesting case is a hydrolaccolith as big as a two-storey house (!) at the edge of the Charskie Peski mass. Geologists F.I. Anikeev and V.N. Samoylenko (Udokan Geological Expedition) drilled a small tunnel shaft at its base and let the water core discharge. Under the ice dome inside the hydrolaccolith, they found a large cavity, 7 m high and 28 m in diameter [Krendelev, 1983].

Generally, the ground-and-ice roof subsides after water discharges, and fractures are closed and sealed with frozen water. In winter, stress increasing/decreasing cycles repeat many times until the water-bearing system is completely frozen or until heat emission towards the day surface ceases. Formation of mounds starts in November and December and stops in spring during snow melt.

Destruction of mounds often leads to formation of roundish crater-like depressions framed by chaotically heaped ground banks with inclusions of fragments of ground, tree stems, shrubs and turf shred. The craters may transform to small lakes and thus become permanent ground water discharge sites. V.S. Preobrazhensky described an ice grotto located near the Charskie Peski mass, which replaced a partially destroyed hydrolaccolith, about 35 m in diameter and over 3.5 m high. At the

grotto bottom, there was a small lake (1.3+ m deep) and a streamlet flowing out of the lake along a fracture [Preobrazhensky, 1961].

Ablation of bedded ground ice may take place already during break-down of the aufeis deposit due to thermal erosion, and eventually thermokarst caverns (Fig. 10, *a*), furrows and ditches are formed in such locations. If the ground sinking areas are covered with vegetation, the vegetation is completely extinguished. In the postglacial development stage of the valley, it takes many years for the vegetation to restore. Uneven melt-out of ground ice often leads to formation of either single-level ice-ground terraces (0.5 to 0.8 m high) (Fig. 10, *b*) that are separated by shallow channels of migrating flows, or a series of flat-topped torso mountains underlain by injection-ice layers (Fig. 10, *c*). In summer, mushroom-shaped ice pillars may be found in the aufeis glades. A 'mushroom stalk' is made of melted-out ice, and a cap is either a piece of turfgrass with live plants or a large fragment of rock (Fig. 10, *d*). Besides, cones and chains can be formed, which interior is composed of aufeis- or underground injection ice.

While repeated-vein ice is melting out in the aufeis glades, deep ditches filled with water are first to form, surrounded by blocks of ground with the veins. In plan, such an area looks like a polygonal network with small lakes in nodes. Upon drainage of the ditches, permafrost soil rapidly degrades, and the aufeis bed is converted into a system of low butte mounds-silt pinacles that disappear soon due to thermal erosion activity of melt-aufeis-water flows.

Thermokarst processes are weakly manifested during melt-out of texture-forming ice. Thermokarst is mainly observed at the periphery of aufeis glades on sites where aufeis ice occurs only occasionally. Deformation of the surface of the aufeis bed are less significant on such sites. However, under certain conditions, there is potential for development of hazardous phenomena. In [Alekseyev, 1976], a case of the Tunka basin located in the south-western part of Pribaikalie is described. In May 1973, in the Tibelti river valley, aufeis melt water penetrated underneath seasonally frozen sand deposits. As a result, a large gully was formed in a few days. It was almost 250 m long, 10 to 15 m wide and 2 m deep (Fig. 10, *e*). The suffusion-erosion process was accompanied by typical subsidence fracturing and mass collapse of frozen blocks and overlaying aufeis-ice slabs.

6. AUFEIS IMPACT ON CHANNELLING

In the zone of continuous aufeis formation, pass-through water channels are influenced by specific glaciohydrological and cryo-geological phenomena, and seasonality of channelling is evident.

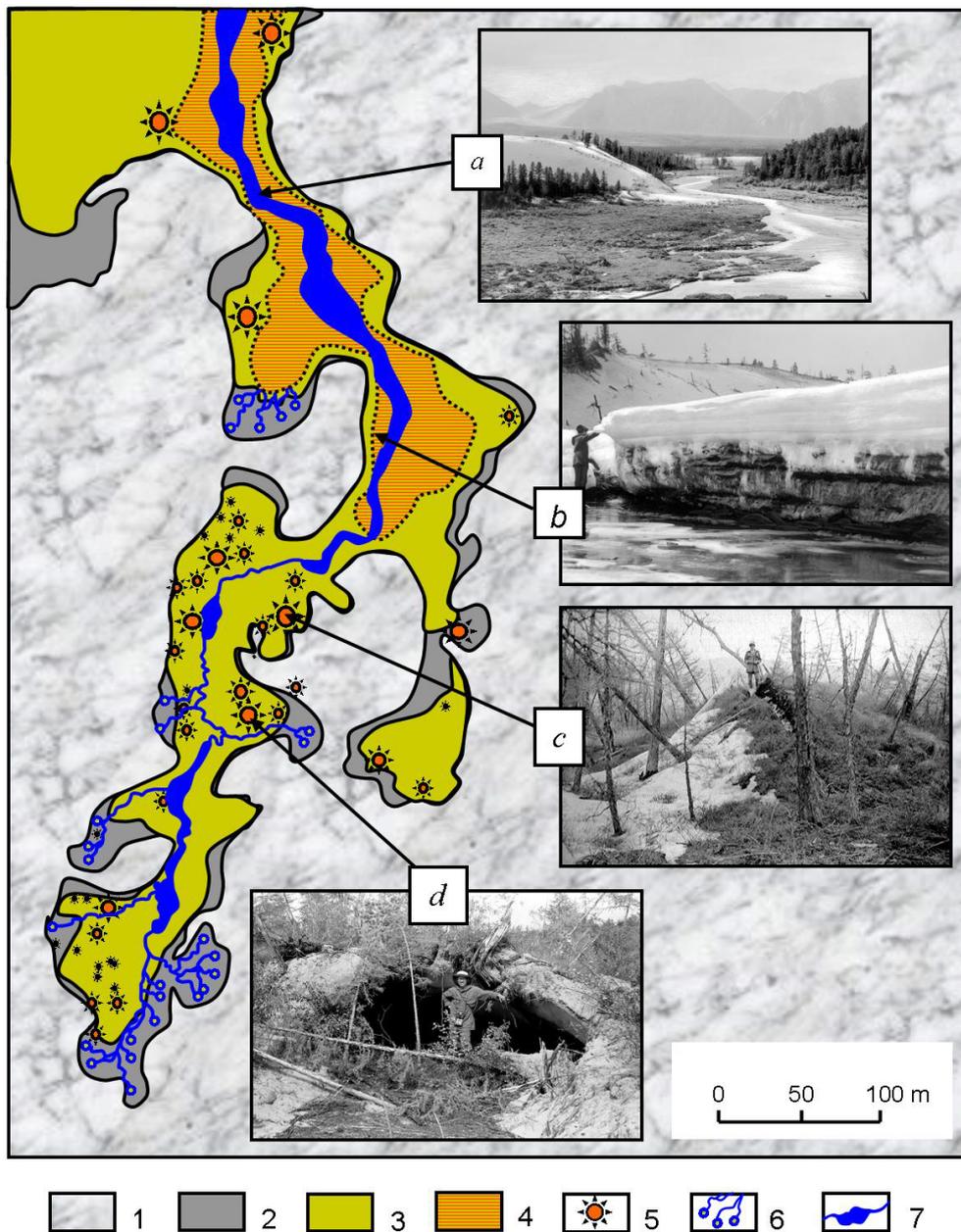


Fig. 9. Hydrothermal movements of ground materials in the aufeis valley of the Kholodny creek, Charskie Peski site in the northern Transbaikalia.

1 – cluster of deflated sandy deposits; 2 – aufeis-free section of the valley wherein the annual ground surface uplifting amount to 10 cm; 3 – section of the valley that is annually covered by the aufeis ice layer (1.0–2.5 m thick) and subject to hydrothermal vertical movements ranging from 0.1 to 0.3 m; 4 – section of the valley with vacuum-infiltration ice layers, wherein the amplitude of cryogenic movements of ground materials range from 0.8 to 1.2 m; 5 – icing mounds (0.5–3.5 m high) with pressure-injection ice lenses; 6 – permanent sources of subpermafrost groundwater; 7 – channel of the creek with thawed ground ice in the expanding sections. Photos: *a* – general view of the estuarine part of the aufeis valley after aufeis ablation, September 1978; *b* – vacuum-infiltration ground complex in early July 1978; *c* – icing mound with the ice core – pressure-injection ice-ground complex, June 1977; *d* – air cavity in the decaying hydrolaccolith, July 1978.

Рис. 9. Гидротермическое движение грунтов в наледной долине ручья Холодного. Урочище Чарские Пески на севере Забайкалья.

1 – массив развеваемых песчаных отложений; 2 – безналедный участок долины с величиной ежегодного поднятия земной поверхности до 10 см; 3 – участок долины, ежегодно покрываемый наледным льдом толщиной 1.0–2.5 м, с амплитудой гидротермических движений 0.1–0.3 м; 4 – участок долины с пластами вакуум-инфильтрационного льда с амплитудой криогенного движения грунтов 0.8–1.2 м; 5 – бугры пучения высотой 0.5–3.5 м с линзами напорно-инъекционного льда; 6 – постоянно действующие источники подмерзлотных подземных вод; 7 – русло ручья с вытаявшим подземным льдом на участках расширения. Фотографии: *a* – общий вид устьевой части наледной долины после стаивания наледи, сентябрь 1978 г.; *b* – вакуум-инфильтрационный грунтовый комплекс в начале июля 1978 г.; *c* – бугор пучения с ледяным ядром – напорно-инъекционный ледогрунтовый комплекс, июнь 1977 г.; *d* – воздушная полость в разрушающемся гидролакколите, июль 1978 г.

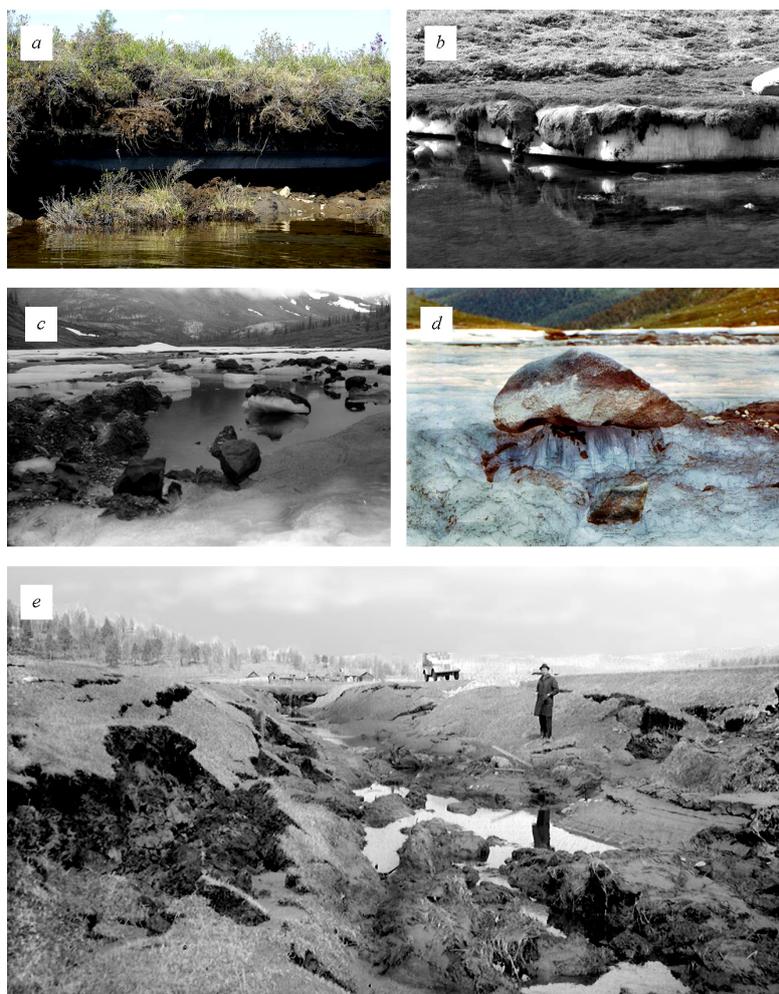


Fig. 10. Forms of cryogenic movements of ground materials in aufeis sections of river valleys.

a – thermokarst-induced subsidence of the roof of the injected ground-ice layer; *b* – thermoerosion terrace of the aufeis ice-ground complex; sod-cover pieces are squeezed in between the aufeis- and injection-ice layers; *c* – thermoerosion remnants in the place of the decaying vacuum-filtration ice mass; *d* – the boulder raised to a height of 1.2 m by injection icing; *e* – suffusion-erosion caving at the Irkutsk–Mondy motor road.

Рис. 10. Формы криогенного движения грунтов на наледных участках речных долин.

a – термокарстовая осадка кровли инъекционного подземного льда; *b* – термоэрозийная терраса наледного ледогрунтового комплекса; зимой куски дернины зажаты между слоями наледного и инъекционного льда; *c* – термоэрозийные останцы на месте разрушающегося массива вакуум-фильтрационного льда; *d* – валун, поднятый на высоту 1.2 м в результате инъекционно-го льдообразования; *e* – суффозионно-эрозийный провал у автомобильной дороги Иркутск–Монды.

In *winter*, water-carrying channels are influenced by three specific events: (1) obstruction of the water stream due to its freezing to complete cessation of the flow; (2) hydrodynamic impact of additional water inflow (subaqueous discharge of groundwater, water release from reservoirs etc.); and (3) static pressure of ice under external loads (snowfall, atmospheric pressure jump etc.). In the autumn-winter period (typically lasting for 2 or 3 months), nothing extraordinary happens – deformations develop under ice, and soils are redeposited according to schemes that are well-known and described in detail [Belokon', 1950]. In some sections of the river, as the runoff is depleting, river-water

ice is sagging or hanging over the water flow. In other sections, river-water ice is covered by a thin river-water aufeis deposit which boundaries are usually above the autumnal low water level by a few dozen centimetres.

In the winter-spring period (from December or January), channelling is completely finished, while a number of phenomena develop and later on play a dominant role throughout the course of transformation of the channel network. In this period, ice mounds are formed in the riverbeds between frozen river bars (Fig. 11), and stagnant water is periodically discharged at high pressure from the ice mounds. In small rivers

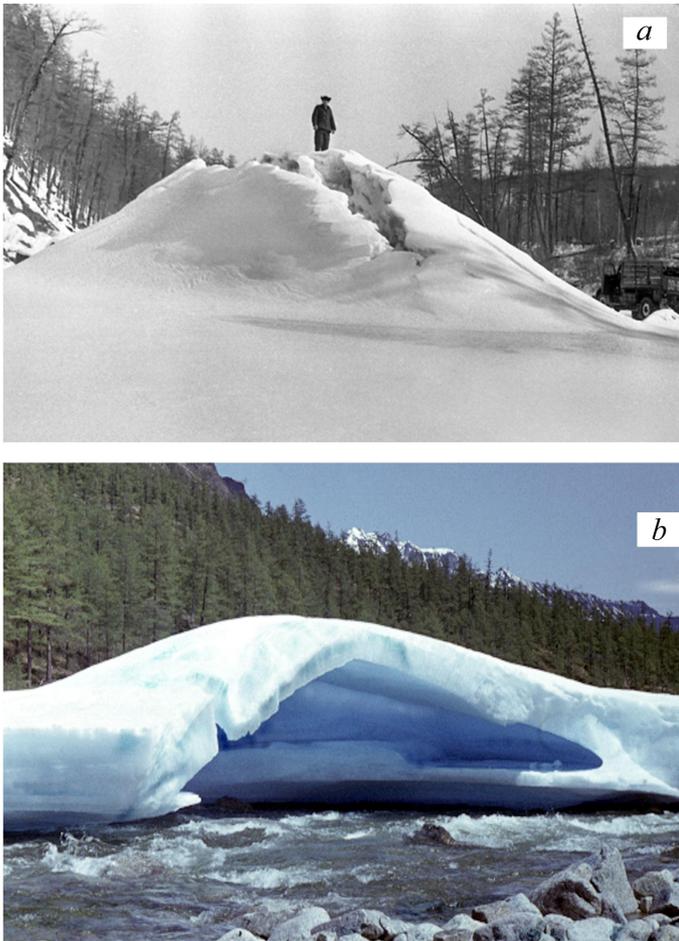


Fig. 11. Icing mounds in channels of icing rivers.

a – in winter (Oyumrak river in South Yakutia); *b* – in summer (Middle Sakukan river in the northern Transbaikalia) (photo by V.R. Alexeyev).

Рис. 11. Ледяные бугры пучения в руслах наледных рек.

a – зимой (река Оюмрак в Южной Якутии); *b* – летом (река Средний Сакукан в Северном Забайкалье) (фото В.Р. Алексеева).

beds, ice mounds are up to 3 m high, and radial fractures at their tops often follow each other for many kilometres. Once the water stream is completely frozen, the channel deposits are frozen up to the lower surface of the ice cover and uplifted together with ice during further freezing of the underflow, and a mound containing ground and ice is thus formed. Water, mud, large boulders and pebbles gush out of such a mound in case of its explosive failure. The Russian historical records describe a fatality case when a group of people and a caravan of horses were killed by explosive failure of the ice mound on the Zeya river in the Amur region. The only survivor was a little boy who had been knocked up by the air blast wave onto a nearby larch tree [Derpgolts, 1971]. Another example is explosive

failure of a ground-aufeis mound on the Onon river valley near the Amur-Yakutsk motor road in the spring of 1928. When the headwater cryogenic system exploded, large lumps of soil and ice were blasted out. Almost 19 m long, 5 m wide and 32 m thick lumps destroyed a motor-road bridge and, together with its debris, were carried away by gushing water streams to a distance of 120 meters down the river valley [Petrov, 1930].

In winter, the aufeis sections of the river valleys become an arena of intense ground movements through virtually their entire widths, not only within the limits of the freezing river beds. Under the aufeis deposits (including those located in forests), injection-ice layers and lenses (up to 1.0 m thick) are formed at depths from 0.3 to 0.8 m; they often include numerous boulders and pebbles. An area of their distribution can occupy from 10 to 80 % of mature aufeis glades. In the areas where stratal ice is formed, the overlying soil together with the aufeis ice can be uplifted to a height from 0.8 to 1.0 m, and, in case of a large local hydrodynamic pressure, by 4 to 5 m above its previous level. It is noteworthy that such vertical movements occur at some distance from the base of the mountain slopes and terraces, and by the spring time, the surface of the river valley's bottom acquires a pyramidal-convex shape complicated by hummocks and chains of hydrolocaliths. Thus, by the start of snow melting, an uplifted ice-ground plate (including icebound trees and shrubs) is formed in the zone of active aufeis formation in the river valley. Its thickness ranges from 1.5 to 3.5 m (up to 7–12 m in some locations). This ephemeral cryogenic structure extends across the entire width of the valley, blocks the way for flood waters (Fig. 12, *a*), and thus becomes an important factor predetermining further development of hydrological processes.

In *spring*, the river-water flow goes out of a narrow valley into a broad aufeis field, flattens and loses its speed, and its actual erosivity is vanishing. Gradually, however, water digs up several channels in ice, the channels quickly deepen, the flows cut through the ice mass and split it into several large ice slabs (Fig. 12, *b*) and begin to intensively erode the aufeis bed. The soil is actively redeposited in both the areas of open water flows and under the ice cover. At this time, subsurface erosion can significantly exceed soil drifting in the upstream sections of the river valley. Locations of ice channels tend to vary from year to year, and areas of erosion processes are thus shifted relative to each other. Therefore, the entire aufeis bed is subject to the mechanical impact of water flows. As a result, alluvial deposits are repeatedly mixed up, the soil-and-sod layer is destroyed, roots of trees and shrubs are washed out of the ground, the moss cover is torn off, the vegetation remain intact only in elevated parts of the terrain, i.e. on small islands and chains of hills with steeply-dipping, sloughing cliffs striking along the valley.

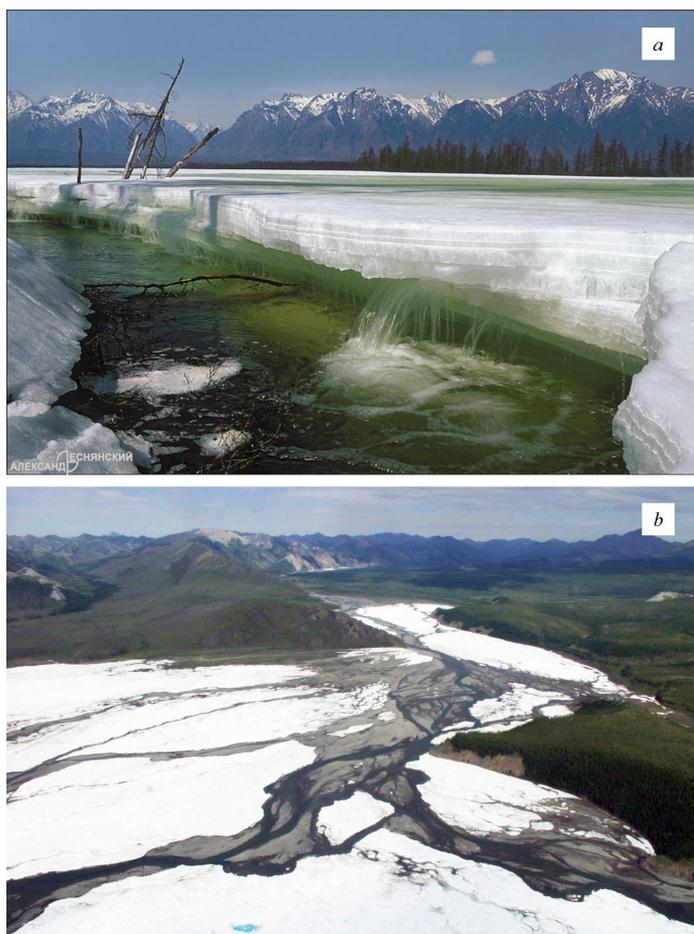


Fig. 12. Conditions of channeling in valleys of icing rivers.

a – during spring snow-melt period, a gigantic groundwater aufeis deposit in the Middle Sukakan river valley in the northern Transbaikalia (photo by A. Lesnyansky); *b* – in early summer, a gigantic aufeis deposit in the Bulkut river valley in the Verkhnekolymsky district of Yakutia (photo by A. Mekheda).

Рис. 12. Условия формирования русловой сети в долинах наледных рек.

a – в период весеннего снеготаяния; гигантская наледь подземных вод в долине реки Средний Сакукан на севере Забайкалья (фото А. Леснянского); *b* – в начале лета; гигантская наледь в долине реки Булкут в Верхнеколымском районе Якутии (фото А. Мехеды).

During the snow-melt period, the channels are often blocked by ice masses, and river-water flows have to go through V-shaped gaps along the contact of aufeis deposits and beach scarps. Such gaps, looking like fractures, occur between ice and ground due to solar radiation absorption and gradually develop into deep drainage channels. Generally, during torrential flood in spring, the major portion of water is transported by such channels. Water streams rapidly erode the river-bank sediments, and suspended drift and debris are delivered to the bottom of the aufeis glades, deposited

into the ice tunnels and/or thrown onto the ice surface. Drift and debris may concentrate in large amounts on the ice surface and bury the ice bed. Quite often, water penetrates very quickly underneath the seasonally frozen ground layer and begins to wash away the underlying melt deposits, which causes catastrophically rapid retrogress of the river banks as the frozen beds collapse and get destroyed by thermal erosion (see Fig. 10, *e*).

In *summer*, dissected ice slabs and large ice masses shield the area from solar radiation and precipitation, hamper thawing of alluvial deposits, and control the direction of water flows. The ice slabs are displaced during rain floods, and ice drift may occur. The top and side surfaces of the ice masses are subject to ablation; the bottoms are destructed by abundant under-ice flows of water. During the melt period, large portions of the ice fields hang over their beds or lie on the ground-ice pillars and ledges of frozen rocks, and the ice cover has to bend, crack and collapse. Massive ice collapse creates a sound like a gunshot heard at a distance of many kilometres. Falling roofs of the ice tunnels and subsiding and rolling ice slabs compact the soil, press down the stems of plants, break up and flattened tree stems and shrubs. During rain floods, aufeis-ice slabs attached to the slopes are washed away and collapse together with the living soil cover that was frozen up to the sides and bottom of the ice slabs.

After retrogress of the aufeis-ice edge, ground ice melting begins and initiates formation of thermokarst caverns, furrows, ditches and/or series of single-level thermal erosion terraces (0.5–0.8 m high) separated by channels of migrating water streams. Melting of injection ice can create mushroom-shaped ice pillars – a 'mushroom stalk' is made of melted-out ice, and its 'cap' is a piece of turfgrass with live plants. In other cases, broken rock heaps, esker-like cones, mounds and chains are formed with interiors composed of non-laminated transparent ice. Typically, they subside by autumn, and the surface of the aufeis bed is levelled. Destruction of the mounds result in creation of quite specific thermokarst landforms. Melting of the mound ice cores or roofs leads to formation of roundish crater-like hollows framed by chaotically heaped ground with inclusions of fragments of soil, turf shred, stems of trees and shrubs (Fig. 13, *a*). Such craters may transform to small lakes and thus become permanent groundwater discharge sites. Springs flowing out of the lakes create and shape longitudinal furrows/channels.

In mountain river valleys, dissected masses of buried aufeis deposits can be observed (Fig. 13, *b*). Aufeis ice is buried due to ample deposition of suspended drift during the spring floods, mudslides, landslides and collapse of rocks from the adjacent slopes. When the buried aufeis deposit is destructed, flat hills (up to 1.5 m high) are formed, which change the direction



Fig. 13. Ground-ice outcrops on aufeis glades.

a – injection ice of a decayed mound in the north-western Yakutia (photo by Yu.A. Murzin); *b* – buried aufeis deposit in the Algama river valley in the southern Yakutia (photo by I. Karman).

Рис. 13. Обнажения подземных льдов на наледных полях.

a – инъекционный лед разрушенного бугра пучения на северо-востоке Якутии (фото Ю.А. Мурзина); *b* – погребенная наледь в долине реки Алгама в Южной Якутии (фото И. Карман).

of water flows. Dry channels filled with loose ground can be observed around the hills in autumn.

While repeated-vein ice is melting out in the aufeis glades, deep ditches filled with water are first to form, surrounded by blocks of ground with the veins. In plan, such sites look like a polygonal network. Gradually, small lakes are formed at the nodes of the network. If the ditches are drained, low butte mounds-silt pinacles are formed, which are separated by streamlets and mud flows.

During aufeis melting, erosion within the aufeis glades has to cease because the energy of branched or sprawled water flows is now insufficient for mass transfer of ground. However, the carrying capacity of

the main river above the aufeis deposit is not only maintained at the same level, but critically increases during rainfall floods. As a result, the major part of trailed and suspended drift is deposited onto the smoothed part of the valley bottom (Fig. 14). Below the aufeis glade, the river flow energy increases again, firstly, due to the additional influx of melt water (resulting from melting of the aufeis deposit and ground ice), and secondly, due to recombination of all the small branches into a single channel.

In *autumn*, the aufeis deposits remain only in areas covered with thick ice beds (over 5 to 7 m thick), shaded sites and regions where summer is very short and cold, such as in the Arctic and in the mountains above the limit of forest. In this period, aufeis remnants do not affect the development of erosion processes as the surface runoff is either small in the already formed channels or completely absent. With the onset of winter, such aufeis remnants become a part of 'fresh' masses and perform regulatory functions in the new regime. In other parts of the aufeis glades, the setting is stabilized in accordance with regimes of no-ice sections of the valleys, i.e. thawing of frozen soil is ceasing, the water level in the channel network is lowered, the aufeis glade is drained and acquire typical features of post-cryogenic areas (Fig. 15). Before the onset of winter, the total discharge of water flows on the aufeis glade is much smaller than the volume of flow in the river at the inlet due to the fact that a part of water infiltrates into the interior of thawed soil beds while sprawling across the entire width of the valley. If cryo-hydrogeological conditions are favourable, groundwater is accumulated again in the main channel at the outlet of the aufeis glade. In the absence of barrage (frozen rocks or base rock ledges), filtering of groundwater through the thick loose alluvium is continued, and groundwater comes up to the ground surface on sites considerably distant from the feed centres, often in front of a new aufeis glade.

Characteristics of the channel network dynamics during the warm period of the year are shown in Fig. 16.

7. DEVELOPMENT STAGES OF AUFEIS SECTIONS OF RIVER VALLEYS

In active icing zones, significant changes take place in micro- and mesorelief, composition and properties of soil, vegetation, water streams and other elements of the natural complex. The changes may be related to global warming/cooling cycles, regional environment variations or transformations of the water-and-heat balance of the ground surface due to impacts of human activities. Besides, the cryogenic system may transform in the course of its self-development in relatively stable



Fig. 14. The Malaya Lagorta river bed in Polar Ural after aufeis ablation (photo by A. Titov).

Рис. 14. Русло реки Малая Лагорта на Полярном Урале после стаивания наледи (фото А. Титова).

hydro-climatic conditions. In any case, transformations of the valley take place under a specific scenario reflecting the impact of the major factor, namely, long-term and centennial variability of icing (aufeis) parameters. Under the aufeis influence, the valley bottom is gradually extended and graded, the vegetation is either extinct or transformed depending on the ice thickness and life cycle, and the channel network evolves into a complex system of shallow meandering channels which orientations, shapes and configurations are variable through the evolution of the aufeis terrain.

Our analyses of the available data give grounds to distinguish five typical stages of aufeis development in the river valleys.

Stage I. Pre-glacial development. This development stage is typical of the majority of non-freezing rivers with constant runoff and decreasing water levels through the entire cold season. The double-layer ice cover of their cryosystem comprises (Fig. 17) the bottom horizon (h_3) consisting of crystalline ice (80 to 85% of the total thickness) and the top horizon (h_4) containing aufeis ice (15 to 20 %). The aufeis ice results from obstruction of the flow cross-section (h_2) during partial freezing of the flow, and also forms due to an overload of the ice by the settled snow. The outer limits of the ice do not propagate to the floodplain and go somewhat higher than the autumn low-water level. In winter, with depletion of the flow, the ice cover either subsides or bends. Under the ice cover, redeposition of the bottom sediments is slowed down and does not result in any critical changes in the riverbed. The channel deposits are not frozen. The riverbank slopes and the floodplain freeze to a depth of 0.5 to 1.0 m. In spring, ice drift and floods take place

in the 'normal' mode, without affecting the high floodplain. Ice jams are rare. The ice plough ability is moderate and most often completely obscured by summer rainfall floods and land floods.

Stage II. Transgression. This stage is typical of through-freezing rivers. In spring, the ice cover has three-layers (h_2 - h_5). By mid winter, the river channel at river bars is completely filled with crystalline ice, and the thickness amounts to h_3+h_2 . The middle layer (h_4) consists of frozen river water. The upper layer (h_5) is formed due to freezing of underflow groundwater after its discharge to the ice surface due to partial freezing of alluvium (horizon h_1). The groundwater aufeis deposit occupies the entire floodplain. It may go beyond the limits of the floodplain, but does not reach the valley wall and the distant bench of the above-floodplain terrace. Typically, this part of the ice cover (0.3 to 0.8 m thick) is destroyed by the start of spring floods and thus does not impose any significant impact on channelling. When the ice thickness exceeds 0.8-1.0 m, vegetation is transformed and extinguished later on (Fig. 18, a). The river runoff is maintained almost until the mid winter. By spring, the soil is frozen to depths from 1.0 to 1.5 m, so that the ice bed is firmly joined with the underlying rocks. In the floodplain areas, the ice bed's bottom is 'armoured' with tree stems, shrubs and herbaceous plants.

The most important factor for channelling is ice-ground barrage under the riverbed. In its presence, water lenses located between the river bars freeze and swell, and fracturing and explosive failure of ice mounds take place. On the floodplain of small rivers,

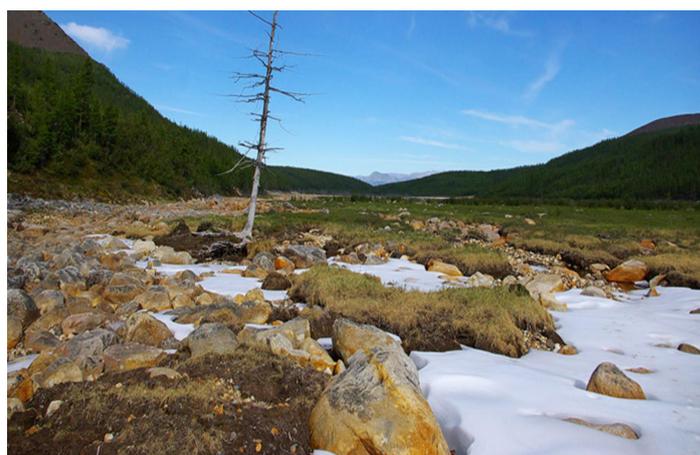


Fig. 15. The Aufeis glade in the Moma river valley in the north-eastern Yakutia in mid September (photo by Sandro).

Рис. 15. Наледная поляна в бассейне реки Мома на северо-востоке Якутии в середине сентября (фото Sandro).

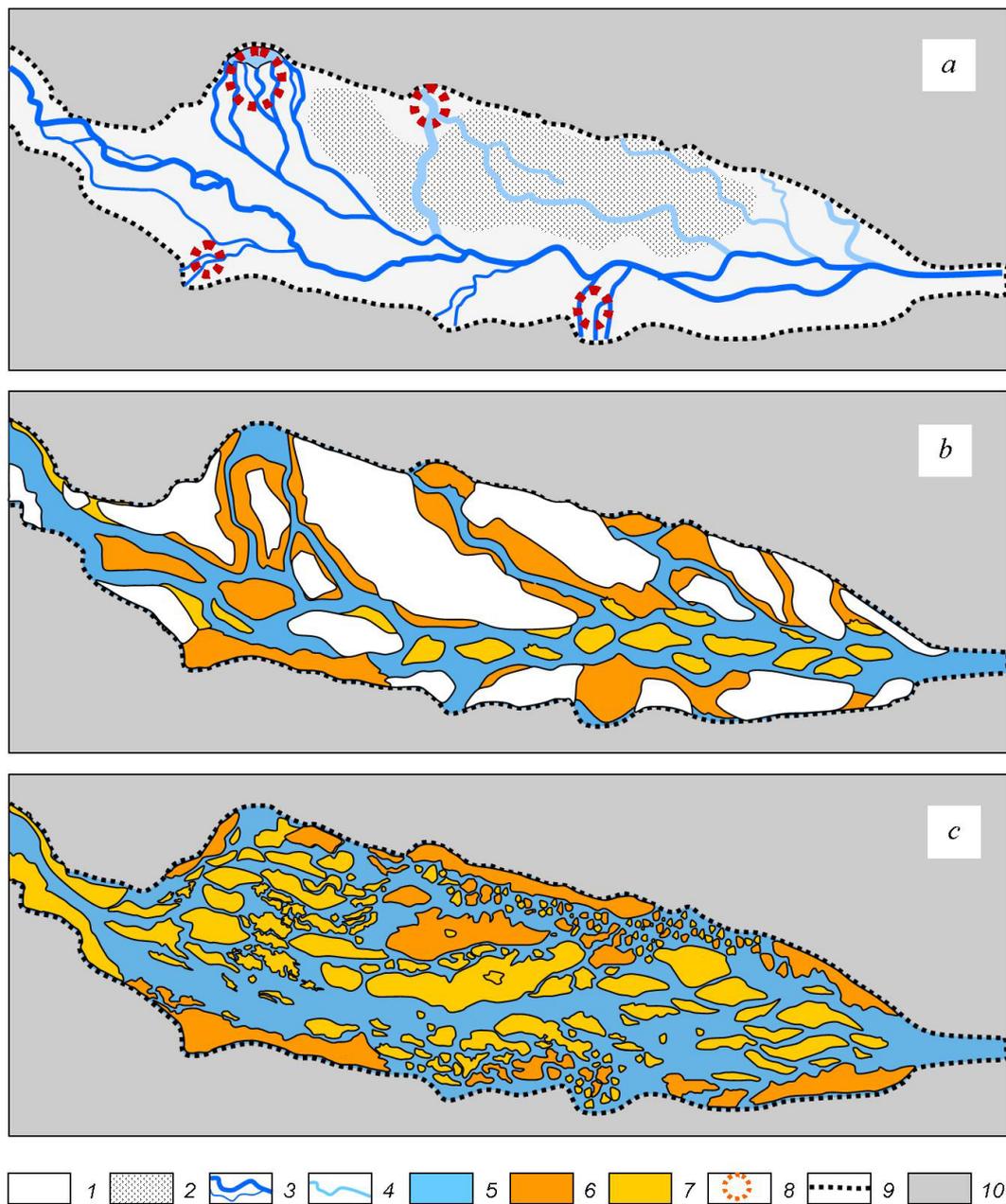


Fig. 16. Variations in the channel network configuration within the limits of the Bolshoi Eden aufeis deposit in East Sаяn according to ground-based survey data obtained in 1987. Absolute altitude 1800 m.

1 – subpermafrost groundwater aufeis; 2 – icing ‘bog’ on the surface of the ice cover; 3 – channel of the Bolshoi Eden river with ice banks in the snowmelt period; 4 – flows of melt water on the aufeis surface; 5 – river water flow in the period of intensive ablation of the aufeis and injected ground ice (20 June 1987) and after abundant summer snowfall (26 August 1987); 6 – gravel-sand deposits with inclusions of large boulders underlain by sheets of injected ground ice (flat outliers with scarp slopes, which heights range from 0.5 to 0.8 m); 7 – channel deposits without any visible signs of ground ice (ridges, beach plains, and mid-channel bars); 8 – icing mounds and fragments of ice domes; 9 – boundaries of the aufeis glade; 10 – slopes of the river valley which are composed of deluvial-colluvial sediments and covered with mountain-tundra vegetation.

Рис. 16. Изменение конфигурации русловой сети в границах Большой Эденской наледи в Восточных Саянах по данным наземных съемок 1987 г. Абсолютная высота 1800 м.

1 – наледь подмерзлотных подземных вод; 2 – наледное «болото» на поверхности ледяного покрова; 3 – русло реки Большой Эден в ледяных берегах в период снеготаяния; 4 – потоки талых вод на поверхности наледи; 5 – водный поток реки в период интенсивного разрушения наледи, инъекционных подземных льдов (20 июня 1987 г.) и после обильного летнего снегопада (26 августа 1987 г.); 6 – гравелисто-песчаные отложения с включениями крупных валунов, подстилаемые пластинами инъекционного подземного льда (плоские останцовые возвышенности с обрывистыми склонами высотой 0.5–0.8 м); 7 – русловые отложения без видимых признаков подземных льдов (гряды, косы, осередки); 8 – ледяные бугры пучения и фрагменты ледяных сводов; 9 – границы наледной поляны; 10 – склоны речной долины, сложенные делювиально-коллювиальными отложениями и покрытые горно-тундровой растительностью.

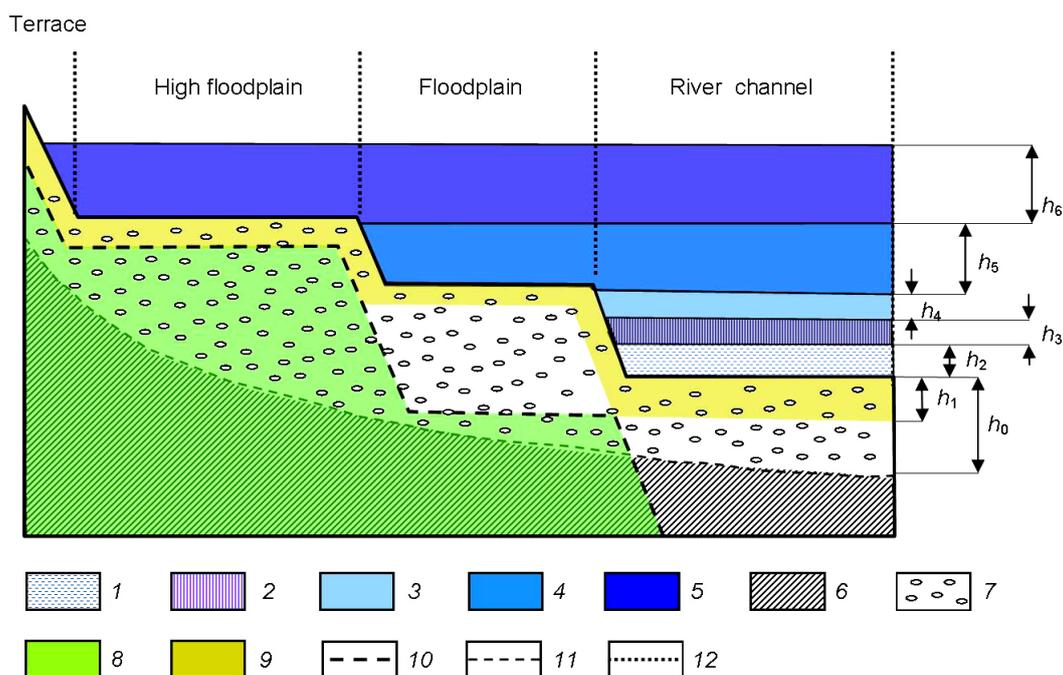


Fig. 17. Generalized scheme of cryogenic channeling conditions.

1 – water flow under the ice cover; 2 – crystalline river ice; 3 – river water aufeis and snow ice; 4 – aufeis deposits composed of suprapermafrost floodplain water and subchannel groundwater; 5 – aufeis deposits composed of intrapermafrost subchannel water and subpermafrost water; 6 – bedrocks; 7 – alluvium; 8 – perennially frozen rocks; 9 – layer of seasonal freezing and thawing ground materials. Boundaries: 10 – permafrost, 11 – rocks of different compositions, 12 – elements of the river valley with different ice-thermal regimes.

Рис. 17. Обобщенная схема условий криогенного преобразования русловой сети.

1 – подледный водный поток; 2 – кристаллический речной лед; 3 – наледь речных вод и снежный лед; 4 – наледь надмерзлотных пойменных и подрусловых подземных вод; 5 – наледь межмерзлотных подрусловых и подмерзлотных вод; 6 – коренные горные породы; 7 – аллювиальные отложения; 8 – многолетнемерзлые горные породы; 9 – слой сезонного промерзания и протаивания грунтов. Границы: 10 – вечной мерзлоты, 11 – горных пород различного состава, 12 – элементов речной долины с различным ледотермическим режимом.

icing is accompanied by formation of injection ice layers and ice-ground breccia. In spring, melted snow water have to pass the ice mounds and thus spread over the entire width of the valley's bottom. In valleys of small and medium-sized rivers, volumes of melted snow water are often insufficient to make the ice cover float up. Another hindering factor is the strong contact of the ice cover with the underlying frozen soil. As a result, ice drift does not take place on such rivers – ice is cut into fragments that gradually decay at their origin locations and protect the alluvium from erosion by the water flows. Flood waters are often concentrated at the contact of the ice bed with frozen riverbank sediments, penetrate beneath the sediments, easily wash out the thawing soil and cause fracturing and collapse of the frozen roof. Therefore, the riverbank slope is retrogressing, and a new channel is formed. A new channel can also be initiated along the ice channel-trenches following a system of random fractures and micro-depressions, including those across the valley. Thus, by the beginning of summer, the channel and

the floodplain are subject to annual changes that significantly affect further channelling.

Stage III. Stabilization. At this stage, the valley bottom is covered by aufeis ice from side to side. By spring, the aufeis thickness can reach 5 to 8 m. River crystalline ice is absent, i.e. in fact, a single-tier ice bed is formed (Fig. 18, b). Water freezing lasts through the whole cold period of the year. In the aufeis bed, layers and lenses are made of vacuum-filtration ground ice, which cause uplifting of the top rocks together with the aufeis deposit. Ice-ground chains and round-shaped mounds crack or explode, and water or mud flows gush out of the fractures. In 30 to 70 % of aufeis glades, underlying ground and ice are subject to heaving. The heaving zone's location shifts from year to year. In summer, ground layers are freed from ice and decomposed when ground ice is melting; small mineral fractions are transferred by numerous water flows to the bottom of the aufeis glade and further outside the aufeis zone. The rocks are thus not only annual 'shaken up', but also intensively washed. Finally, a specific 'aufeis' facies of alluvium is formed.

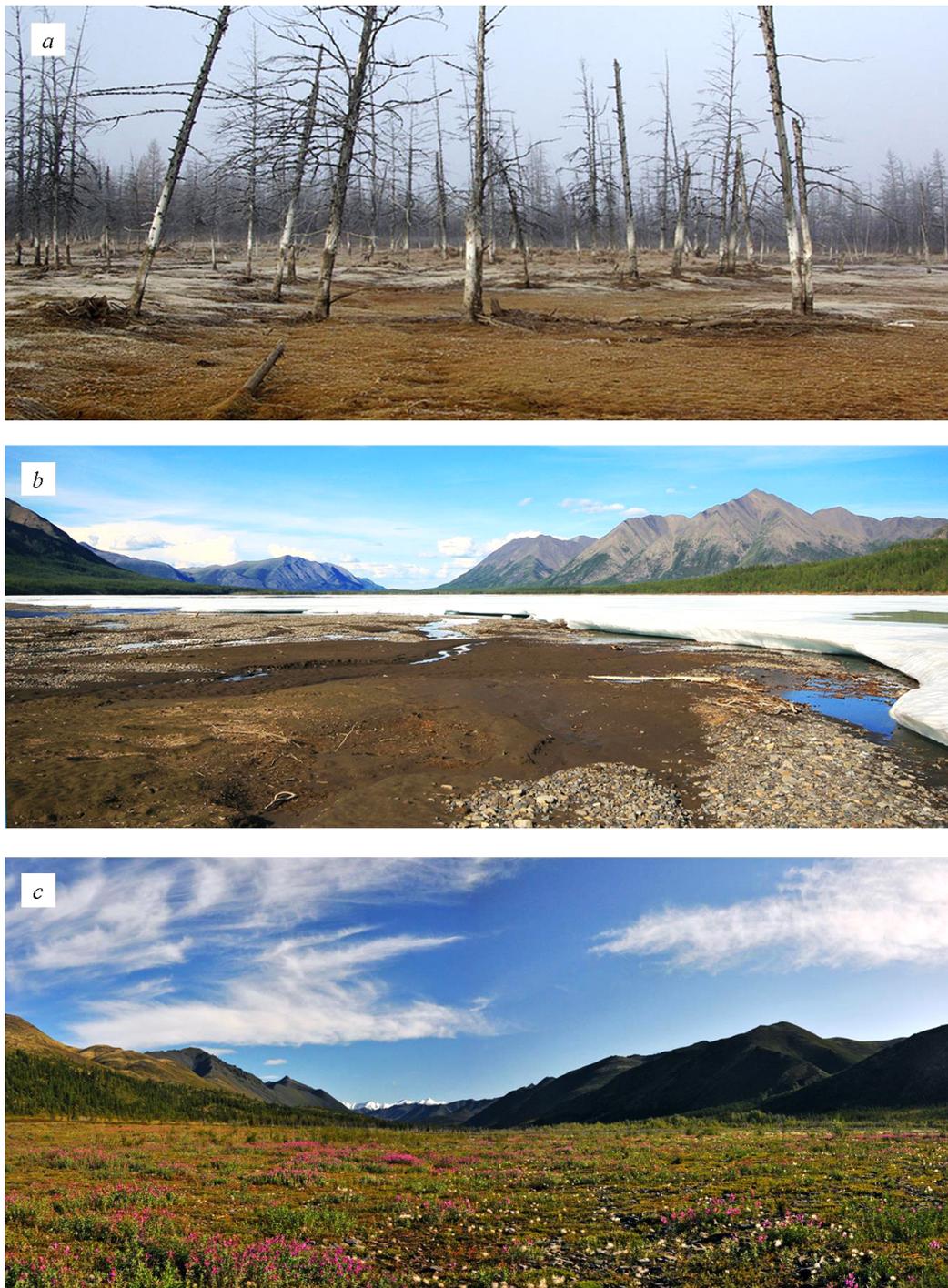


Fig. 18. Active development stages of aufeis sections of river valleys in Yakutia.

a – transgression: the soil-vegetation is destroyed, trees are extinguished, and the ice thickness can be determined from bleached stems of trees (the north-western Yakutia; photo by V. Solodukhin); *b* – stabilization: the vegetation cover is destroyed, and the underlying ground is redeposited and compacted (the Suntar-Khayata river channel divided into several broad shallow distributaries, and the Suntar-Khayata ridge in the north-eastern Yakutia; photo by M. Mestnikov); *c* – regression: the ice thickness is decreased, or the aufeis deposit has completely disappeared, the soil-vegetation cover is recovering (the Boryndzha river channel reassembled into one or several distributaries in the lower part of the valley, and the Mомsky ridge in the north-eastern Yakutia; photo by Sandro).

Рис. 18. Активные стадии развития наледных участков речных долин в Якутии.

a – трансгрессивная: гибнут деревья, уничтожается растительный и почвенный покров; мощность льда фиксируется по отбеленным стволам деревьев; Северо-Западная Якутия (фото В. Солодухина); *b* – стабилизационная: растительный покров уничтожен, подстилающий грунт переотложен и уплотнен; русло реки Сунтар разбито на ряд мелких широких протоков; хребет Сунтар-Хаята на северо-востоке Якутии (фото М. Местникова); *c* – регрессивная: мощность льда уменьшилась или наледь полностью исчезла; восстанавливается почвенно-растительный покров; русло реки Борынджа собирается в один или несколько протоков в пониженной части долины; Момский хребет, Северо-Восточная Якутия (фото Sandro).

Transformations of the aufeis bed continue until cessation of underground icing and completion of subsequent erosion-thermokarst redeposition of sediments. Afterwards, denudation processes gradually cease. The stabilization stage can last for a very long time, until the icing mode is significantly changed. As a result, the riverbed can spread through the entire width of the aufeis glade, loses its shape, and the aufeis bed often looks like a stone pavement with compactly and tightly placed boulders of flatiron-like forms (flat sides up).

Stage IV. Regression. The reduction of the aufeis volume or complete cessation of icing is accompanied by localization of the transit water channel. It gradually deepens and becomes the main drainage artery of the aufeis glade. Branches are drained or converted into small ditch-shaped lakes with stagnant water. Micro-depressions and gaps between stones are filled with fine-grained soil resulting from cryogenic weathering of rocks or brought by melt water from the slopes and the upper parts of the valley. The fine-grained soil is compacted and colonized by pioneer plant species. Soil-forming processes are activated; mosses, meadow and shrub vegetation come up; soils are secured by root system of plants and become more resistant to erosion caused by aufeis melt water and rainwater (Fig. 18, c). The above processes are accompanied by long-term freezing of aufeis alluvium. The ground-filtration talik persists only under the main river flow bed. Sodded areas initially appear at the periphery of the aufeis glades wherein snow and ice are the first to melt. Later on, sodded zones occupy the entire width of the valley as the seasonal icing area is steadily decreasing. In case of aufeis migration, some sections of the sodded area may be outcropped again, i.e. fall back to the previous regime. In the final phase of regression of the valley, the river comes into one channel and acquires characteristics of the adjacent (upper and lower) flow sections. Generally, aufeis degradation, i.e. reduction of the mean annual aufeis volume, lasts for many dozens and even hundreds of years. This process depends primarily on the intensity and duration of changes in climate characteristics and corresponding transformations of cryo-hydrogeological structures that are feeding the aufeis deposit.

Stage V. Postglacial development. This stage starts after the valley bottom is completely and permanently freed from ice, boulders are covered by soil and vegetation that is typical of no-aufeis sections of the valley. At this time, the ice-thermal regime of the river and the main channel configuration are almost identical to the flow regime and the runoff channel morphology in the periglacial stage. However, the former icing area can be clearly detected by a number of characteristic features, such as the lack of low terraces, flat terrain with typical chains and mounds, specific structure

of loose sediments, age, morphology and physical properties of soils, distribution and floristic composition of vegetation etc.

Generally, the development stages of the aufeis sections of the river valleys are well detectable from aerial and satellite images of medium and large scales (Fig. 19). However, determining their boundaries and assessment of duration of the development stages and phases is challenging as the relevant experience is lacking, and structural and dynamic features of the aufeis terrains have not been properly studied yet. Our observation data show that even one aufeis section may contain a wide variety of components of the aufeis bed (Fig. 20), and the wider is the range of annual and long-term variability of aufeis characteristics, the more difficult is establishment of trends in development of the aufeis segments, and more challenging is determination of the phase status of the entire cryogenic system. Moreover, aufeis terrains are variable depending on geographic latitudes and altitudes, underlying rock compositions, morphological parameters of the valleys, water-discharge talik configurations, thicknesses of permafrost and seasonal frost-bound layers etc. Therefore, studying aspects of channelling in the permafrost zone is a fairly complex problem of nature studies. This problem can be solved only by combined analyses of cryo-hydrogeological, hydroclimatic and landscape data. In this laborious research process, it is important to analyse the structure of the hydrographic network.

8. AUFEIS STRUCTURE OF THE CHANNEL NETWORK

Due to a combined effect of the above-described processes, the valley bottom is gradually extended and levelled in the aufeis sections. The vegetation cover is either extinct or transformed depending on the aufeis thickness. The channel network evolves into a complex system of shallow meandering channels which orientations, shapes and configurations are variable through the evolution of the aufeis terrain. Hydrographic networks in the active icing zones can be studied from large-scale aerial and satellite images and ground-based observation data. Besides, remote sensing techniques are particularly effective in obtaining parameters of the hydrographic networks and detecting the aufeis terrain boundaries within specified time limits. By comparing series of images taken in different years, it is possible to assess the channelling dynamics in annual and long-term cycles.

Based on our analyses of satellite images of the aufeis valleys located in East Siberia and the north-eastern regions of Russia, five types of channel network patterns can be distinguished: fan-shaped, cone-shaped, treelike, reticular, and longitudinal-insular types.

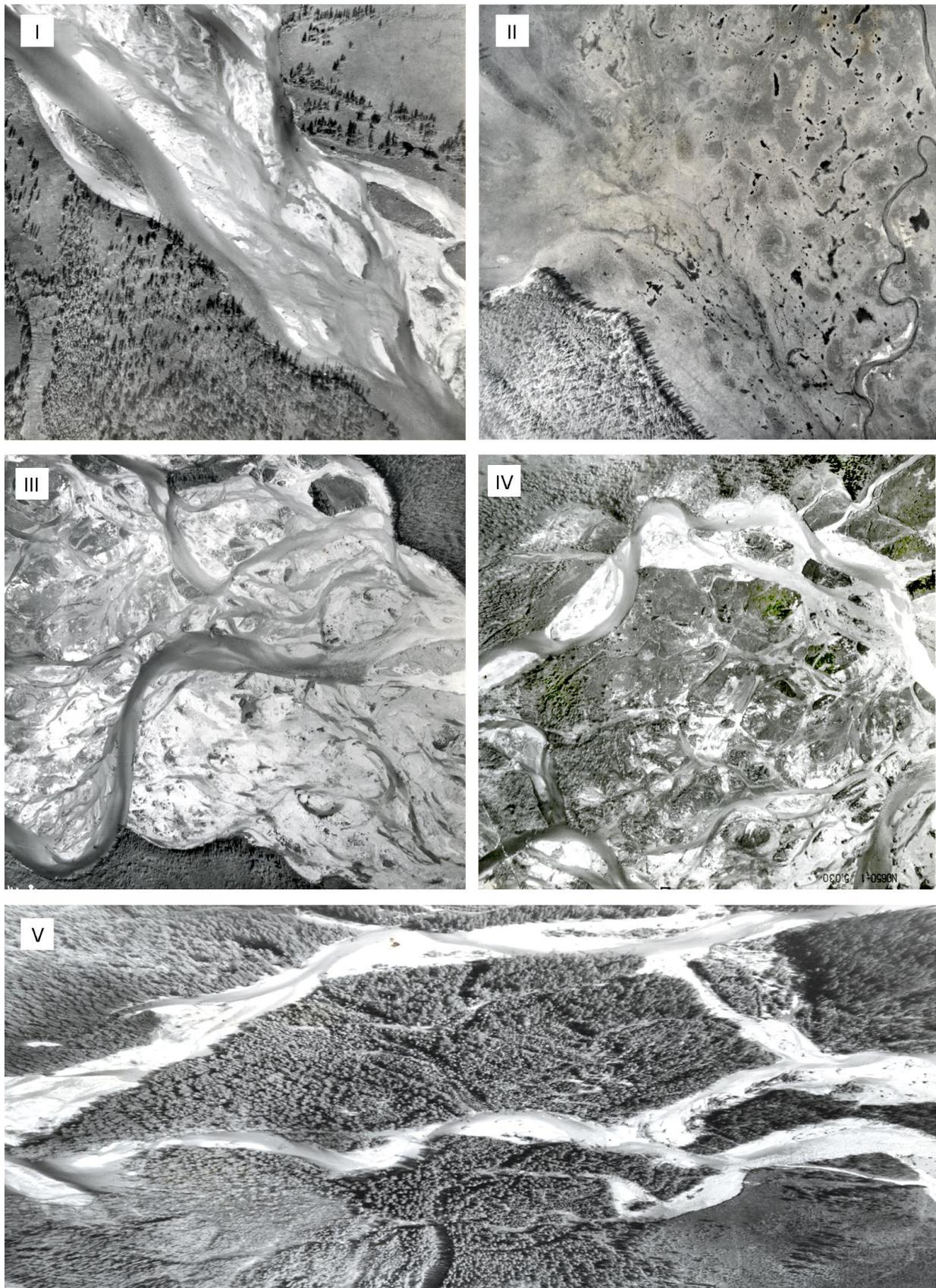


Fig. 19. Development stages of the aufeis section of the Middle Sakukan river valley. Chara basin. Stanovoe upland.

I – periglacial development, *II* – transgression, *III* – stabilization, *IV* – regression, *V* – postglacial development.

Рис. 19. Стадии развития наледного участка долины реки Средний Сакукан. Чарская котловина. Становое нагорье.

I – перигляциальная, *II* – трангрессивная, *III* – стабилизационная, *IV* – регрессионная, *V* – постгляциальная.

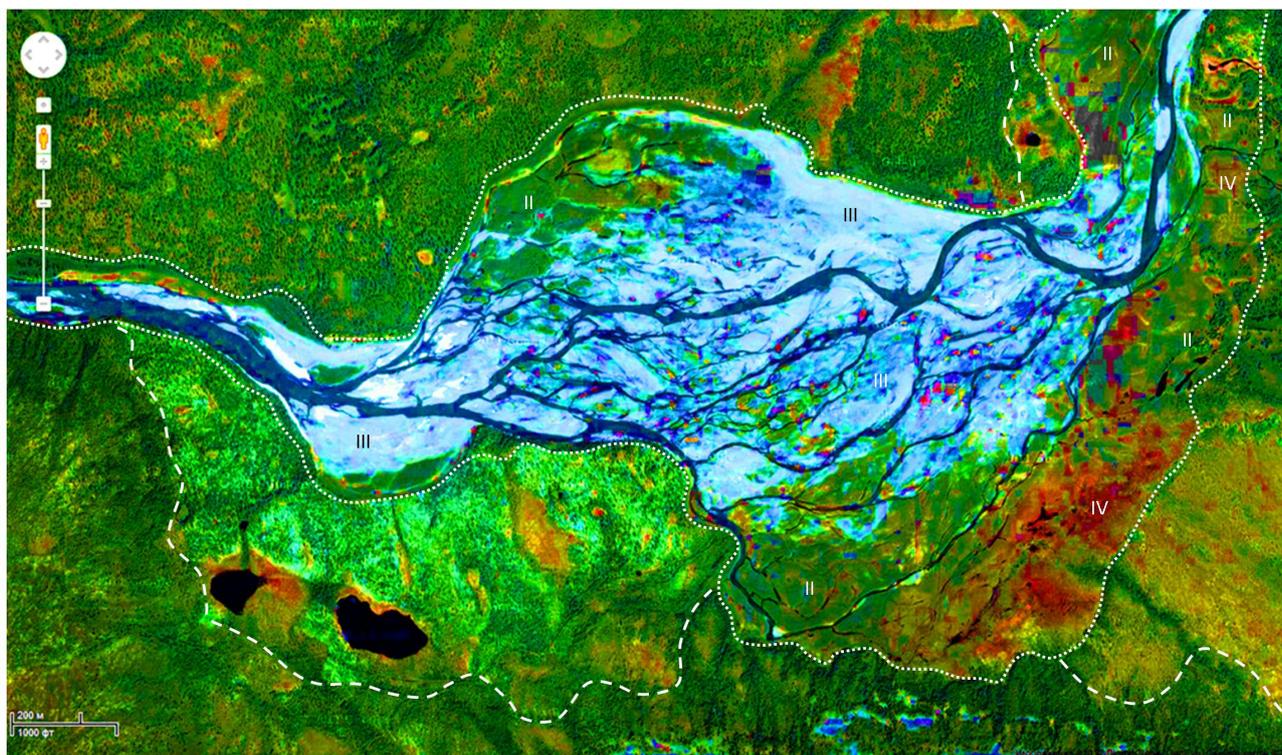


Fig. 20. A space image of the aufeis section of the Lower Ingamakit river valley (rank 3) in the northern Transbaikalia.

The dotted line contours the current aufeis glade with different stages of its development (Roman numerals). The dashed line outlines the relict icing zone.

Рис. 20. Космический снимок наледного участка долины реки Нижний Ингамакит третьего порядка. Северное Забайкалье.

Точечной линией показан контур современной наледной поляны с различными стадиями ее развития (римские цифры), пунктиром обозначена внешняя граница реликтовой зоны наледообразования.

The **fan-shaped pattern** is a system of disbanding and gradually disappearing channels, dry beds and ditches separated by outcropped primary surface zones with deformed or completely destroyed vegetation (Fig. 21, *a*). It forms in cases when aufeis-generating water can be discharged to the day surface as a concentrated flow, and it freely spreads over the slope to create a blade-shaped ice mass. This pattern can be observed (1) at outlets of side branches of small and medium-sized rivers, (2) at outlets of mountain streams going to flat terrain areas, (3) in front of frontal benches of retreating glaciers that are not wide (on outwash surfaces). The channel network is laid mainly in spring, during the passage of melt water flows that not only cut through the ice thickness in different directions, but also penetrate underneath the ice cover to intensely erode the bed. In most cases, the runoff channels are not connected with each other; they are straight and may be quite deep, with sloughing steep walls. Generally, the sediments are coarse.

The **cone-shaped pattern** of the channel network is typical of the lower parts of aufeis glades. This part of

the icing zone is the first to get free of ice. The runoff channels are formed in summer due to melt aufeis water, which spread in a wide front along the retreating ice mass (Fig. 21, *b*). With distance from the aufeis deposit, the water-intake ditches are split up. Downstream, they gradually gather into a single channel. The ditches are shallow, with low gently dipping slopes (0.2 to 0.3 m high) composed of fine material.

The **treelike pattern** of the channel network is typical of the upper parts of mature aufeis glades of any modification and location. Its shape resembles a branching tree trunk (Fig. 21, *c*). The runoff channels are formed in spring and early summer along fractures of tricky configurations in ice, which result from thermal erosion. The channels are rarely more than 0.5 m deep, with trapezoidal or roundish cross-sections. The channels are separated by outcropped or sodded elongated islands with flat surfaces. At the periphery of the aufeis glades, the water flow beds often join together for intake of the entire volume of river water and melted aufeis water. Loose sediments and the surface cover of the aufeis glade often contain wood scrap, dead grass,

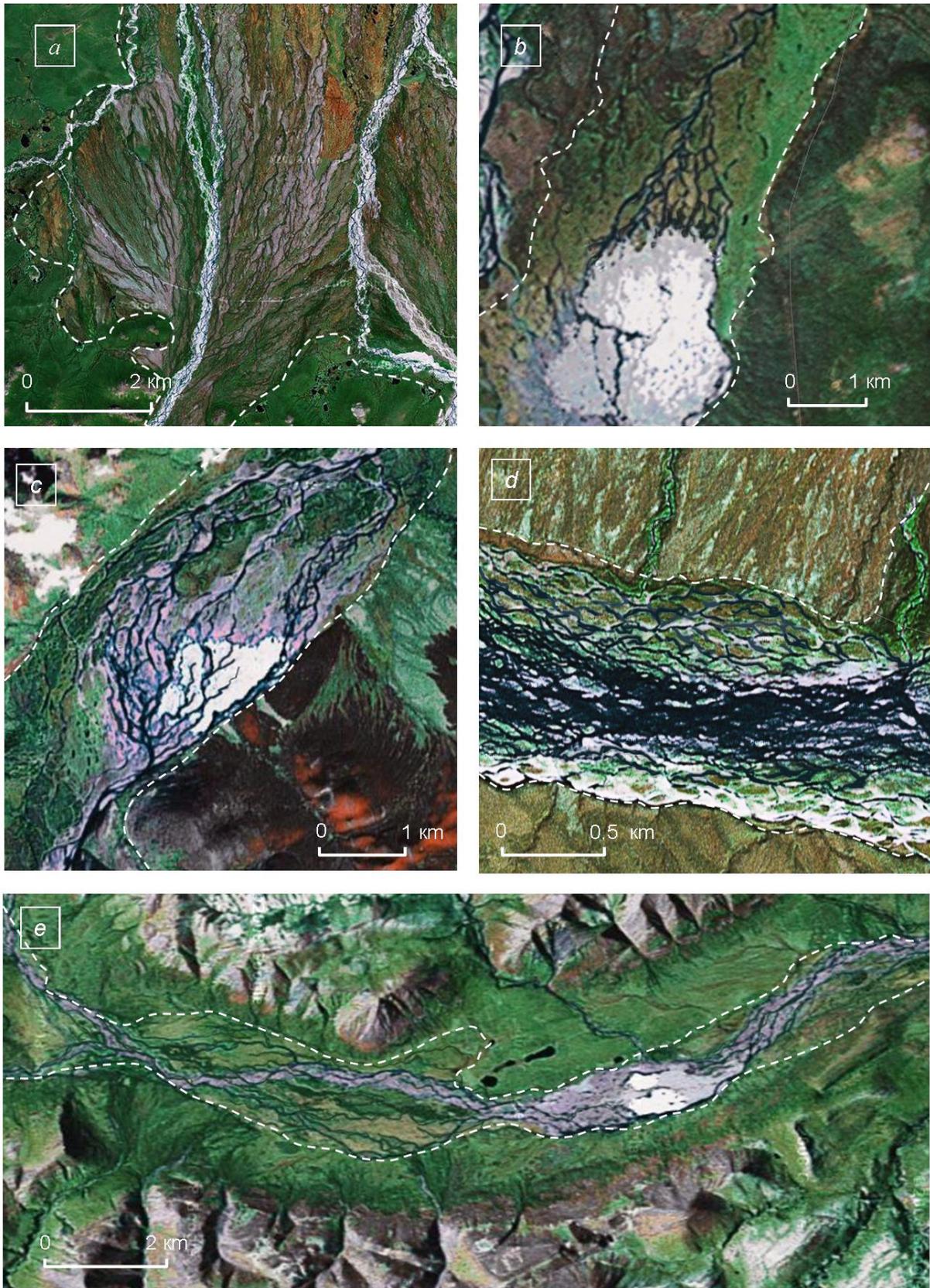


Fig. 21. Hydrographic network types in aufeis sections of river valleys in the north-eastern regions of Russia. *a* – fan-shaped, *b* – pyramidal, *c* – treelike, *d* – reticular, *e* – longitudinal-insular. The dashed line outlines the aufeis glades.

Рис. 21. Типы гидрографической сети на наледных участках долин северо-востока России.

a – веерная, *b* – пирамидальная, *c* – древовидная, *d* – сетчатая, *e* – продольно-островная. Пунктиром показаны внешние границы наледных полей.

humus-like residue and other foreign materials that are brought from the upper parts of the valley during the spring flood.

The **reticular pattern** is mainly typical of central parts of large aufeis glades (2.5 to 3.0+ m thick). Usually, it frames a wide shallow channel of the main stream (Fig. 21, *d*). The aufeis bed is flat, almost horizontal; runoff channels are bordered by numerous turf-covered islands composed of boulder-pebble deposits with gravel-and-sand infill. The steeply dipping channel walls are 0.5 to 0.8 m high, and often contain layers of thawing ground ice. The channel network is formed in mid summer during ice mass breakdown due to thermal erosion, as well as after ice melting associated with thermokarst phenomena (sinkholes, landslides and ground settlement). The reticular pattern of the runoff channels can be quickly transformed to function as a water-transfer system of boulder-and-gravel beds when the water flow is spread over the entire width of the aufeis glade and quickly changes its configuration depending on the volume of aufeis ice, the location and the actual precipitation volume, i.e. according to the transit river flow volume.

The **longitudinal-island pattern** of the river network is typical of aufeis sections of large lengths with well-developed longitudinal profiles of the valleys. In such areas, the flat bed has been repeatedly subject to cryogenic and fluvial processes; the alluvium is relatively uniform; the main channel is quite well defined; flat outlier chains go along the main channel, and every year they are covered by a thin aufeis deposit. Under the main channel, there is a cut-through water-release talik. In spring, it provides for thawing of the ice mass at its bottom and facilitates under-ice channeling for a concentrated transit runoff and the lower thermal-erosion activity of the melt water in the adjacent areas of the bed. Elongated islands and chains varying in shapes and lengths are typically stretching along the valley's sides for many kilometres (Fig. 21, *e*).

The channel network patterns in the aufeis sections of the river valleys are variable in both space and time, depending on icing conditions, volumes of freezing groundwater and surface water, destruction of ice and frozen rocks, transit flow volumes and other factors. Generally, the patterns of different types are conjugated without any clear boundaries between them. At any large aufeis glade, elements of all types of the patterns may be present. It is a challenging task to decipher their complex combinations in order to reveal the dynamics of the cryogenic system and to determine its development stages and phases, and special studies and observations are thus required. There are good reasons to believe that morphological indicators and properties of the aufeis terrains can be reliably defined. Based on such knowledge, it will be possible to clarify the history and the dynamic state of the cryogenic sys-

tem and to forecast possible ways of its transformation in the near future.

9. AUFEIS RATIO OF THE PERMAFROST ZONE AND INCREMENT OF THE CHANNEL NETWORK

A relative aufeis ratio, c shows the aufeis development scale in the studied region. It is calculated as a percentage ratio of the total area of ice masses, ΣF_a in the period of their maximum development to the total square area of the studied region, F : $c=100 \Sigma F_a/F$. The aufeis ratio can be calculated for each type of aufeis deposits (river, groundwater, ice, melted snow water) or for all the types. A commonly applied factor related to groundwater freezing is c_{uw} . Another aufeis coefficient is k_a , showing a ratio between the river length, L_r and its part occupied by the river-water or groundwater aufeis deposit, L_a : $k_a=L_r/L_a$ [Alekseyev, 2005]. This article provides information regarding groundwater aufeis deposits.

The formation of groundwater aufeis deposits depends on a complex set of environmental factors pre-determining conditions of water- and energy exchange at a given geographical point. Aufeis depositing is most active in regions of continuous and discontinuous permafrost and can be observed on practically all the river valleys and basins. At some locations, aufeis deposits occur on mountain slopes and in watershed areas. The largest groundwater aufeis deposits are located in the Arctic regions and in mountains in the regions of contrasting neotectonic movements in Yakutia, Chukotka, Khabarovsk region, Transbaikalia and Pribakalie, the Altai [Alekseyev, 1975, 1976; Alekseyev et al., 2012; Alekseyev, Gienko, 2002; Alekseyev et al., 2011; Shesternev, Verkhoturov, 2006; Shmatkov, Kozlov, 1994; Tolstikhin, 1974], as well as in Spitzbergen, mountain regions in Alaska, Middle Asia, and Tibet [Åkerman, 1982; Carey, 1973; French, 1976; Gorbunov, Ermolin, 1981; Olszewski, 1982; Revyakin, 1981].

An aufeis deposit may occupy dozens of square kilometres, and a specific water reserve in aufeis ice is almost identical to the water reserve in the snowpack. In the southern regions characterized by discontinuous and sporadic permafrost, the number of aufeis deposits per unit area increases, while their average size decreases (Fig. 22). In mountain valleys, the groundwater aufeis thickness may reach 10 to 12 m. In average, the ice thickness ranges from 1.0 to 2.5 m. The aufeis deposits are fed by a complex system of water-absorbing and water-releasing taliks. In glacial areas, the feed depends on the number and altitudes of periglacial lakes that function as natural regulators of the surface and groundwater runoff.

The groundwater aufeis deposits are usually marked by *aufeis glades*. In [Alekseyev, 2005], a set of

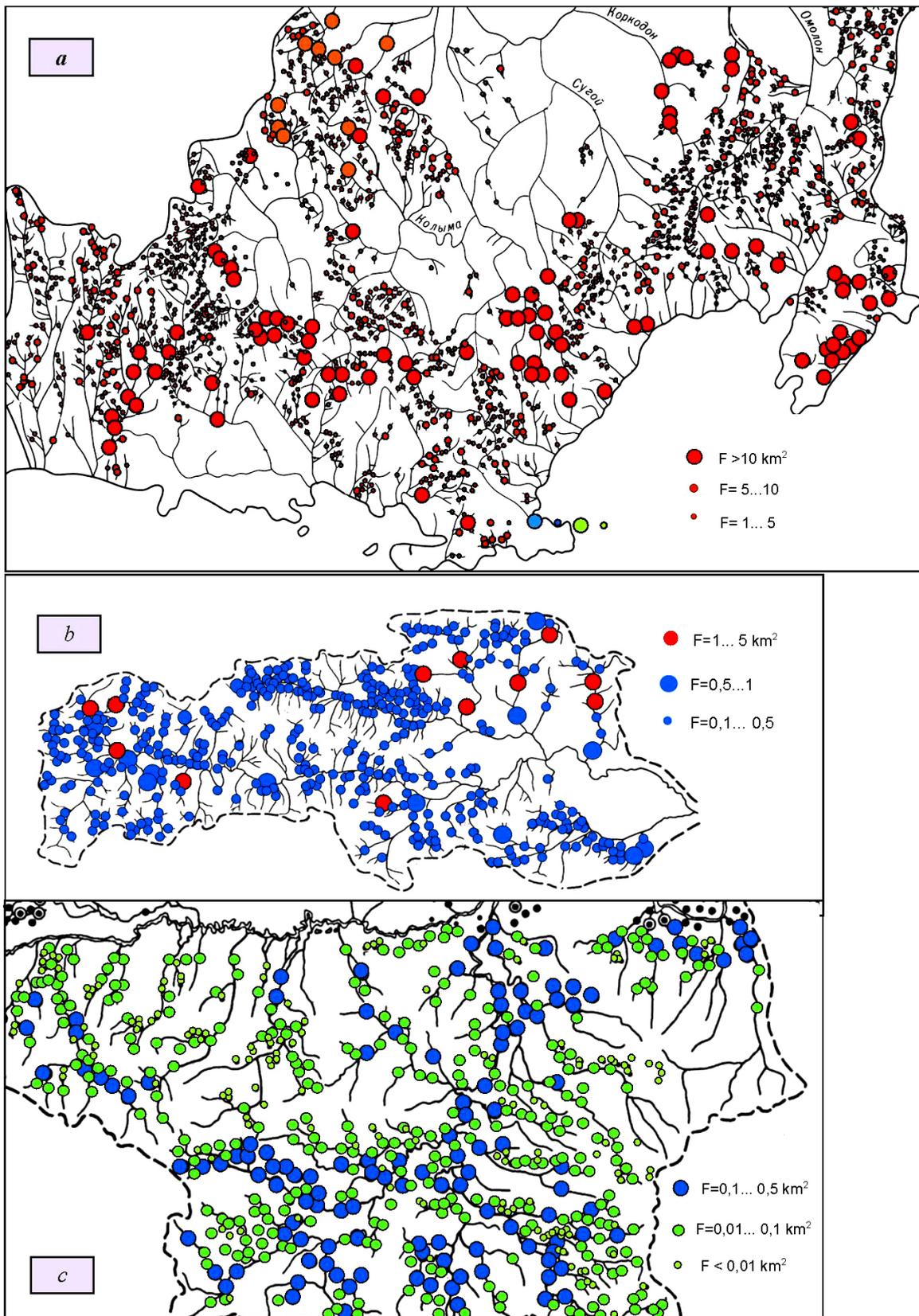


Fig. 22. Schematic maps showing distribution of groundwater augeis deposits in the territories of the Kolyma upland (a), the Muya river basin (Stanovoe upland, and Baikal-Amur Railroad zone) (b), and the southern part of the Irkut river basin (Khamar-Daban ridge, and Tunka valley) (c).

Рис. 22. Схемы распространения наледей подземных вод на территории Колымского нагорья (a), в бассейне реки Муя (Становое нагорье, зона БАМ) (b) и в южной части бассейна реки Иркут (хребет Хамар-Дабан и Тункинская долина) (c).

aufeis glade indicators is established, mean long-term characteristics of ice masses are estimated, and aufeis locations and dynamics are determined. The landscape-indication method was used to compile catalogues of the aufeis deposits observed in the Verkhoyansk-Kolyma mountain country, Chukotka, regions near the Okhotsk Sea, Putorana, South Yakutia, the Baikal-Amur Railroad zone, Transbaikalia and Pribaikalie, and the central part of East Sayan [Alekseyev, 1976; Alekseyev, Gienko, 2002; Alekseyev et al., 2011; Deikin, Abakumenko, 1986; Catalogue..., 1980, 1981, 1982; Shmatkov, Kozlov, 1994; Simakov, 1961; Tolstikhin, 1974; Topchiev, Gavrilov, 1981]. Based on the catalogued data, it became possible to determine quantitative indicators of aufeis of the permafrost zone and, based on the indicators, to assess the role of aufeis in development of the channel network.

The relative aufeis ratio in the permafrost zone varies widely. It is the lowest in flatlands and low-mountain regions ($c_{uw}=0.01...0.1$) and the highest ($c_{uw}=0.1...1.0$) in mountain-folded regions. The more contrasting is the terrain, the more active are neotectonic movements, the lower is the mean annual air temperature, and the higher is the annual percentage of the territory covered by aufeis ice. At the Putorana plateau, the region of the volcanic origin, the average relative aufeis ratio amounts to 0.37 % (maximum 0.87 %). At the Stanovoe upland with its sharply dissected terrain and thick discontinuous permafrost, the value of c_{uw} is increased to 0.69 %. In the north-eastern regions of Russia with the complex systems of frozen mountain ranges and plateaus, the value of c_{uw} amounts to 1.0 %. Thus, in the regions of more severe permafrost conditions, the aufeis deposits occupy larger areas and have larger lengths and widths, in average.

It is revealed that some characteristics of the aufeis deposits depend on ranks and lengths of water streams (Fig. 23). The ranks of water streams are roughly correspondent to the hydrologic classification of lengths of rivers. In average for the area, the higher is the rank of the river valley, and the larger are the average width and volume of groundwater aufeis deposits, while the aufeis-ice thickness is lower, and the aufeis ratio of the water streams is smaller. This trend is maintained as the river systems come to piedmont plains and lowlands. However, for rivers of ranks 5 and 6 and higher, the groundwater aufeis volume decreases sharply, and on the rivers longer than 500 km, no groundwater aufeis is formed, and it is replaced by river-water ice layers. In all natural zones, the majority of ice masses with maximum dimensions are located in the river valleys of ranks 3 and 4 (Fig. 23).

A similarity is established between the majority of cryo-geomorphological and hydrological processes on the aufeis sections of the river valleys located in different climatic zones and altitude belts [Alekseyev, 2005].

Practically at all stages of aufeis channeling, only relative sizes of the elements of the cryogenic system are changing, while their interface schemes remain the same. We rely on this important conclusion in estimations of the space-and-time regularities of aufeis control of erosion-accumulation processes taking pace in the permafrost zone. A channeling intensity indicator is given by the value of ρ calculated as a total incremental length of runoff channels, ΣL_a per unit length of an aufeis glade through its entire length, L_{ag} (km/km) or per unit square area of the aufeis section of the river valley, F_a (km/km²): $\rho_l = \Sigma L_a / L_{ag}$; $\rho_F = \Sigma L_a / F_a$. Parameter ρ characterises the channel network density within the limits of the aufeis glade without taking into account the length of the major water stream. Specific regional features of aufeis channeling can be also estimated with reference to the total incremental length of the river branches per one aufeis: $\rho_n = \Sigma L_t / n$, where ΣL_t is the total incremental length of the channel network in the given river basin, n is the total number of aufeis deposits of the similar size in the same territory.

In the study of the hydrographic structure of the aufeis sections of the river valleys, it is reasonable to consider the number of channels, m_a resulting from erosion and accumulation processes in the aufeis-formation zone (incremental values, σ_l and σ_F are determined as follows: $\sigma_l = \Sigma m_a / L_{ag}$; $\sigma_F = \Sigma m_a / F_a$), as well as the ratio of the total width of the water flows along the typical transverse profiles of the valley bottom, Σb_{ag} to the riverbed width above the aufeis, b_a and below the aufeis, b_b , to the width of the main water artery in the aufeis zone, b_r or to the width of the entire aufeis glade, L_{ag} . In a similar way, variations of depths of the erosion landforms can be estimated.

The scale of the channeling processes is estimated from $\rho_l = 2.5$ km/km. This value was obtained in the study of representative aufeis sections of the river valleys in the mountainous regions of the southern East Siberia (Table 2). It is an average value for the ice masses with the following parameters: $F_a=0.2...3.7$ km², $L_{ag}=1.4...4.7$ km, and $H_i=1.5... 2.9$ m, which provide for the bed expansion to $b_l=100...350$ m. These values correspond to the prevailing range of aufeis characteristics in the territory of continuous and discontinuous permafrost. Here H_i is an average thickness of ice at the end of the icing period. Average values ρ_F and ρ_n are also calculated for some basins and some regions as a whole.

The below data refer to the mature aufeis glades that are mainly in development stages III and IV and result from functioning of permanently active large-flow groundwater sources. The mature aufeis glades are well recordable by aerospace surveys. The available data are collected in published aufeis catalogues [Alekseyev, Gienko, 2002; Catalogue..., 1980, 1981, 1982; Deikin, Abakumenko, 1986; Deikin, Markov, 1983]. The

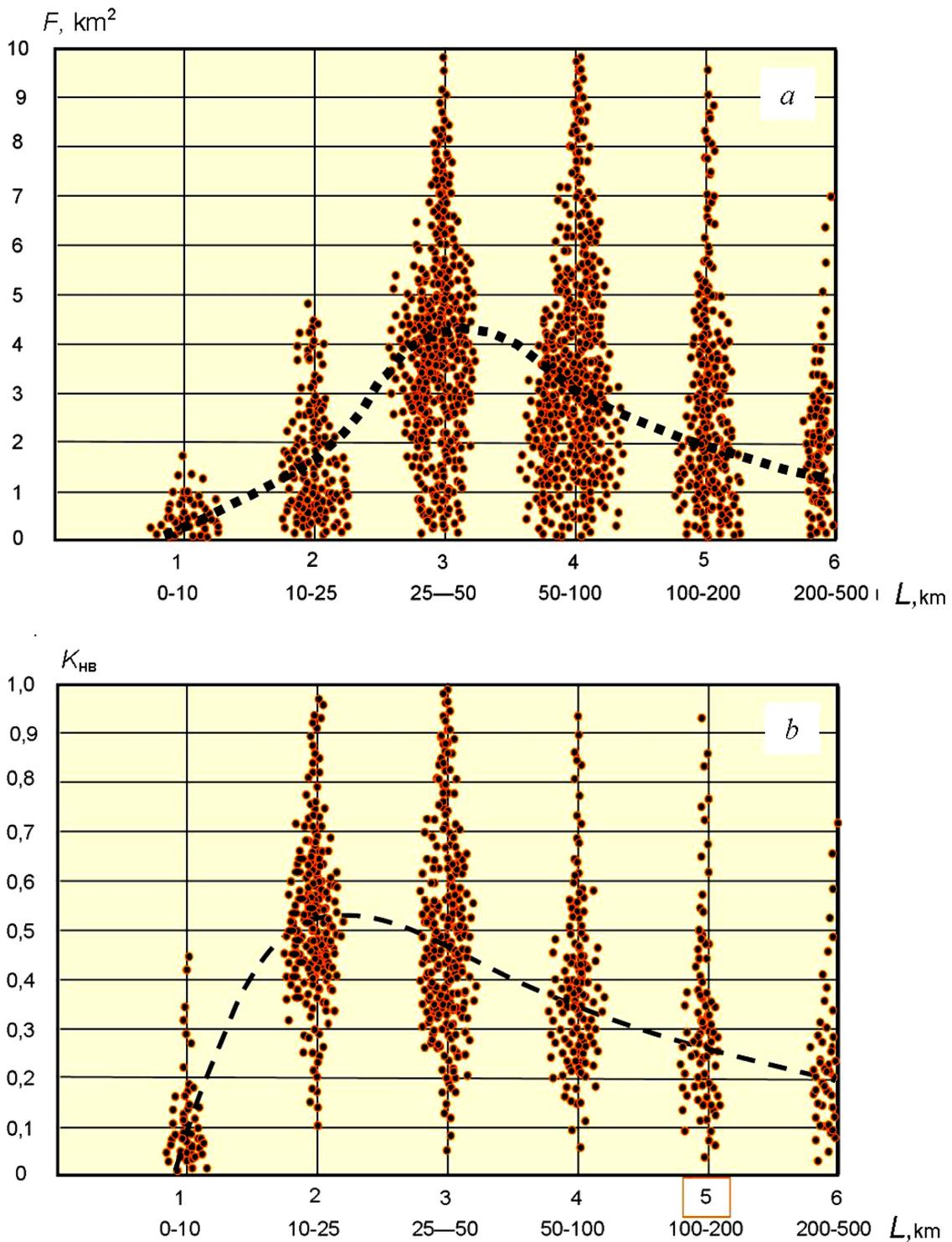


Fig. 23. Aufeis ratio variations depending on ranks and lengths of water streams.

a – variations in the square area of groundwater aufeis deposits with clearly defined aufeis glades (Putorana plateau); *b* – variations of the aufeis coefficient (%) of water streams fed by aufeis deposits composed by river water and groundwater in the river channels on the Stanovoe upland (Lower Ingamakit, Middle and Upper Sakukan, Apsat, and Chara rivers), Khamar-Daban (Khangarul, Tumusun, Zun-Murin, and Irkut rivers), and East Sayan (Bolshoi Eden, Ugega, and Uda rivers). Mean values are marked by dashed lines.

Рис. 23. Изменение некоторых характеристик наледности в зависимости от порядка и длины водотоков.

a – изменение площади наледей подземных вод с хорошо выраженными наледными полями (плато Путорана); *b* – изменение коэффициента наледности водотоков, обеспеченной наледями речных и подземных вод, сформировавшихся в руслах рек Станового нагорья (реки Нижний Ингамакит, Средний и Верхний Сакукан, Апсат, Чара), Хамар-Дабана (реки Хангарул, Тумусун, Зун-Мурин, Иркут) и Восточного Саяна (реки Большой Эден, Эгега, Уда). Пунктиром показаны средние значения характеристик.

Table 2. Comparison of channel networks in representative aufeis glades in East Siberia with regard to their square areas and development stages

Таблица 2. Сравнительная характеристика русловой сети репрезентативных наледных полей Восточной Сибири в зависимости от их площади и стадии развития

| Region | Aufeis glade and its development stage | F , km ² | H_i , m | L_{ag} , km | Channel parameters per 1 km river length | | | | | | Incremental length of channel network | | | |
|------------------|--|-----------------------|-----------|---------------|--|-------|----------|----------|-------|----------|---------------------------------------|------------------|-------------------------------|------|
| | | | | | width, m | | | depth, m | | | ΣL_a , km | ρ_l , km/km | ρ_F , km/km ² | |
| | | | | | b_a | b_b | b_{ag} | h_a | h_b | h_{ag} | | | | |
| Stanovoe upland | Lower Ingamakit | III | 3.7 | 2.0 | 4.7 | 25 | 50 | 300 | 1.3 | 1.0 | 0.7 | 11 | 2.3 | 3.0 |
| | Middle Sakukan | III | 2.5 | 1.8 | 3.6 | 45 | 65 | 250 | 1.2 | 0.9 | 0.5 | 8 | 2.2 | 3.2 |
| | Mururin | III | 2.2 | 2.0 | 2.4 | 40 | 55 | 350 | 1.2 | 1.0 | 0.3 | 7 | 2.9 | 3.2 |
| Aldanskoe upland | Leglier | II | 0.9 | 2.8 | 2.8 | 15 | 22 | 150 | 0.8 | 0.9 | 0.4 | 6 | 2.1 | 6.6 |
| | Samokit | III | 0.8 | 2.9 | 3.0 | 30 | 25 | 270 | 0.7 | 1.0 | 0.3 | 10 | 3.3 | 12.5 |
| East Sayan | Maly Eden | II | 0.3 | 1.5 | 1.5 | 8 | 15 | 120 | 0.8 | 0.5 | 0.3 | 3 | 2.0 | 10.0 |
| | Bolshoy Eden | II | 0.2 | 1.8 | 1.4 | 10 | 12 | 100 | 0.7 | 0.8 | 0.2 | 4 | 2.8 | 20.0 |
| Average | | | 1.5 | 2.1 | 2.8 | 25 | 35 | | 1.0 | 0.8 | 0.3 | 7.0 | 2.5 | 8.3 |

Note. Symbols: b_a , b_b , b_{ag} , h_a , h_b , h_{ag} – channel width (b) and water stream depth (h) above and below the aufeis and on the aufeis glade in autumn, average values. Other symbols are given in the text.

Примечание. Индексы: b_a , b_b , b_{ag} , h_a , h_b , h_{ag} – ширина русла b и глубина водного потока h выше, ниже наледи и на наледной поляне в осеннюю межень, средние. Остальные обозначения в тексте.

aufeis areas in development stage II usually do not have clear boundaries, do not form every year, and are not thick. Their role in channeling is insignificant, though numerous future runoff channels are often initiated within the icing zone.

The channeling effect of aufeis phenomena is well correlated with the main aufeis ratios in the river basins, morphostructural and cryo-hydrogeological conditions of the territory.

The incremental length of the channel network, ρ_n per one aufeis deposit is increased, in average, from 3.5 km in mountains in the southern regions of East Siberia (Table 3) to 11.4 km at the Putorana Plateau (Table 4) and 23 km in the Verkhoyansk-Kolyma mountain system and Chukotka (Table 5). The value of ρ_n is decreased to 2.2 km in the plains and intermountain depressions of the Baikal rift system where the average dimensions of the ice fields are smaller (Table 6).

In general, in the regions and the river basins, the total incremental length of the channel network, ΣL_t reaches gigantic values. For instance, in the section of the Baikal-Amur railroad zone from Ust Kut to Nyukzha (1256 km), 273 aufeis deposits occur near the railroad, and the total aufeis length is $\Sigma L_t=274$ km. The average square area of ice masses is $F_a=0.216$ km². The channel network length is increased by 685 km due to active icing processes. Therefore, the aufeis hazard is high in the territory along this railroad section (Table 6). In basins of the Chara (riverhead), Muya and Upper Angara rivers ($F=42000$ km²), the incremental length of the

runoff channels in the aufeis sections of the river valleys is $\Sigma L_t=3679$ km, i.e. about 80 metres per one square kilometre of this territory. In the river basins in the Putorana plateau ($F=433500$ km²), 2124 aufeis deposits are observed, the incremental length of the channel network exceeds 20.2 thousand km, i.e. in average, 11.4 km per one aufeis deposit or 40 m per square kilometre of this territory. In the north-eastern regions of Russia, the number of aufeis deposits is increased proportionally to the square area of the river basins, the average square area of the aufeis fields is dramatically increased, and the total length of watercourses in the aufeis glades is also increased correspondingly.

The average data for the studied regions (total area over 1.5 mln km²) are shown in Table 7. To the east of the Yenisei river, a clear trend is evident - the scale of aufeis control of channeling is increasing from the East Sayan ridges in the south-west to Chukotka, inclusively, in the north-east. It is known that in the same main direction, severity of climatic and permafrost conditions is increasing. In the southern regions of East Siberia and the Far East, wherein sporadic permafrost is dominant, the aufeis ratio is nearly twice lower than in the northern regions of the permafrost zone, although almost all the river beds are covered by heterogeneous formations through 60 to 70 % of their lengths – the bottom is composed of crystalline river ice, and the top is composed of aufeis ice. The ice cover of a similar vertical structure is observed on many mountain rivers of the North, mainly in the areas located between large

Table 3. Icing characteristics and incremental lengths of channel networks in aufeis sections of river basins in the Stanovoe upland
Таблица 3. Характеристика наледей и прирост русловой сети на наледных участках долин в бассейнах рек Станового нагорья

| River basin | Basin square area, thou km ² | | Aufeis ratio, % | | Icing characteristics | | | | Incremental length of channel network, km | | | | | | |
|----------------|---|-------------|-----------------|-----------|-----------------------|--------------------------|------------------------------|---------|---|---------|--------------|---------|-------------|----------------|-------------------------|
| | 9.6 | 10.6 | 21.8 | 42.0 | Quantity | | Square area, km ² | | Length, km | | Width, km | | total | per one aufeis | per one km ² |
| | | | | | total | per 1000 km ² | cumulative | average | cumulative | average | cumulative | average | | | |
| Chara | 9.6 | 10.6 | 21.8 | 42.0 | 220 | 23 | 100 | 1.040 | 425 | 1.93 | 47 | 0.215 | 1062 | 4.8 | 0.110 |
| Муца | 10.6 | 0.73 | 417 | 39 | 417 | 39 | 77 | 0.186 | 509 | 1.22 | 542 | 0.130 | 1272 | 3.1 | 0.120 |
| Upper Angara | 21.8 | 0.31 | 475 | 22 | 475 | 22 | 68 | 0.140 | 538 | 1.13 | 43 | 0.090 | 1345 | 2.8 | 0.042 |
| Total | 42.0 | | 1112 | | 1112 | | 245 | | 1472 | | 632 | | 3679 | | |
| Average | | 0.69 | | 28 | | 28 | 0.455 | | 1.43 | | 0.145 | | | 3.5 | 0.090 |

Table 4. Icing characteristics and incremental lengths of channel networks in river basins on the Putorana plateau

Таблица 4. Характеристика наледей и прирост русловой сети в бассейнах рек плато Путорана

| River basin, region | Basin square area, thou km ² | | Relative aufeis ratio, % | | Icing characteristics | | | | Incremental length of channel network, km | | | | | | |
|----------------------------|---|--------------|--------------------------|------|-----------------------|-------------------------|------------------------------|--------------|---|------------|------------|--------------|--------------|----------------|-------------------------|
| | 14.8 | 32.7 | 0.31 | 0.15 | Quantity | | Square area, km ² | | Length, km | | Width, km | | Total | per one aufeis | per one km ² |
| | | | | | total | per one km ² | cumulative | average | Total | Average | Total | Average | | | |
| North-western Kheta | 14.8 | 32.7 | 0.31 | 0.15 | 114 | 7.7 | 107.4 | 0.942 | 511 | 4.5 | 28 | 0.246 | 1277 | 11.2 | 0.086 |
| Maimecha | 31.0 | 24.1 | 0.15 | 0.04 | 49 | 1.6 | 45.6 | 0.931 | 132 | 2.7 | 15 | 0.306 | 330 | 6.7 | 0.010 |
| Kotui | 24.1 | 9.0 | 0.04 | 0.41 | 4 | 0.2 | 9.5 | 2.375 | 17 | 4.3 | 2 | 0.500 | 42 | 10.6 | 0.001 |
| Dudinka, Fokina | 9.0 | 20.9 | 0.41 | 0.85 | 37 | 4.1 | 36.9 | 0.997 | 109 | 3.0 | 10 | 0.270 | 272 | 7.4 | 0.030 |
| Norilskay | 20.9 | 28.8 | 0.85 | 0.40 | 160 | 7.7 | 178.0 | 1.113 | 543 | 3.4 | 43 | 0.269 | 1357 | 8.5 | 0.065 |
| Khangaikskoe water reserve | 28.8 | 41.5 | 0.40 | 0.31 | 123 | 4.3 | 115.2 | 0.937 | 358 | 2.9 | 35 | 0.285 | 895 | 7.3 | 0.031 |
| Kureika | 41.5 | 29.1 | 0.31 | 0.87 | 22 | 0.5 | 129.1 | 5.868 | 606 | 27.5 | 46 | 2.091 | 1515 | 68.9 | 0.036 |
| Kotui (upper stream) | 29.1 | 14.6 | 0.87 | 0.80 | 260 | 8.9 | 253.8 | 0.976 | 1027 | 4.0 | 60 | 0.231 | 2567 | 9.9 | 0.088 |
| Chirindakh | 14.6 | 15.2 | 0.80 | 0.01 | 58 | 4.0 | 117.0 | 2.017 | 248 | 4.3 | 21 | 0.362 | 620 | 10.7 | 0.042 |
| Prienseisky | 15.2 | 20.9 | 0.01 | 0.10 | 4 | 0.3 | 0.4 | 0.100 | 5 | 1.3 | 1 | 0.250 | 13 | 3.1 | 0.001 |
| Northern Erachimo | 20.9 | 11.7 | 0.10 | 0.10 | 48 | 2.3 | 24.0 | 0.500 | 103 | 2.1 | 11 | 0.229 | 257 | 5.4 | 0.012 |
| Nimde, Kochumdek | 11.7 | 13.8 | 0.10 | 0.05 | 27 | 2.3 | 12.1 | 0.448 | 56 | 2.1 | 5 | 0.185 | 140 | 5.2 | 0.012 |
| Tutonchana | 13.8 | 25.9 | 0.05 | 0.10 | 26 | 1.9 | 7.1 | 0.273 | 53 | 2.0 | 3 | 0.115 | 132 | 5.1 | 0.009 |
| Viv | 25.9 | 26.8 | 0.10 | 0.62 | 66 | 2.5 | 26.3 | 0.398 | 195 | 3.0 | 10 | 0.152 | 487 | 7.4 | 0.019 |
| Tembenchi, Yambukan | 26.8 | 33.4 | 0.62 | 0.48 | 215 | 8.0 | 166.4 | 0.774 | 889 | 4.1 | 39 | 0.181 | 2222 | 10.3 | 0.083 |
| Kochechum, Embenchme | 33.4 | 39.3 | 0.48 | 0.41 | 236 | 7.1 | 159.4 | 0.675 | 854 | 3.6 | 43 | 0.182 | 2135 | 9.0 | 0.064 |
| Total | 39.3 | 433.5 | 0.41 | | 265 | 6.7 | 160.4 | 0.605 | 1049 | 4.0 | 38 | 0.143 | 2622 | 9.9 | 0.067 |
| Average | | | 0.37 | | 2124 | 4.2 | 1741.5 | 0.820 | 7489 | 3.5 | 458 | 0.216 | 20220 | 11.4 | 0.040 |

Table 5. Icing characteristics and incremental lengths of channel networks in aufeis sections of river basins in the north-eastern regions of Russia
Таблица 5. Характеристика наледей и прирост русловой сети на наледных участках долин в бассейнах рек северо-востока России

| Icing areas according to [Tolstikhin, 1974] | Region square area, thou km ² | Relative aufeis ratio, % | Icing characteristics | | Square area, km ² | | Transiton coefficient* | Incremental length of channel network | | |
|---|--|--------------------------|-----------------------|-------------------------|------------------------------|---------|------------------------|---------------------------------------|--------------------|-------------------------|
| | | | Quantity | per one km ² | cumulative | average | | cumulative, thou km | per one aufeis, km | per one km ² |
| | | | | | | | | | | |
| Verkhoyano-Kolymskaya | 279.1 | 1.2 | 1026 | 3.7 | 2068 | 2.0 | 2.4 | 28.1 | 27.4 | 0.100 |
| Polousnensko-Verkhne-Kolymskaya | 135.2 | 1.3 | 534 | 3.9 | 1657 | 3.1 | 3.8 | 23.1 | 43.3 | 0.170 |
| Prilkolymskaya | 24.0 | 1.2 | 155 | 6.5 | 310 | 2.0 | 2.4 | 4.2 | 27.4 | 0.175 |
| Yano-Kolymskaya | 78.3 | 1.2 | 604 | 7.7 | 810 | 1.3 | 1.6 | 11.0 | 18.2 | 0.140 |
| Omolonskaya | 53.5 | 1.0 | 350 | 6.5 | 564 | 1.6 | 1.9 | 7.6 | 21.6 | 0.142 |
| Anyuisko-Chukotskaya | 21.2 | 0.4 | 65 | 3.1 | 84 | 1.3 | 1.6 | 1.2 | 18.2 | 0.057 |
| Okhotsko-Chukotskaya | 115.5 | 0.9 | 836 | 7.2 | 977 | 1.2 | 1.5 | 14.3 | 17.1 | 0.124 |
| Eastern Northern | 89.8 | 1.2 | 661 | 7.4 | 1130 | 1.7 | 2.1 | 15.8 | 23.9 | 0.176 |
| Kamchatsko-Koryakskaya | 140.0 | 0.6 | 415 | 3.0 | 771 | 1.9 | 2.3 | 10.8 | 26.2 | 0.077 |
| Pendzhinsko-Anadyrskaya | 61.3 | 0.8 | 342 | 5.6 | 244 | 0.7 | 0.8 | 3.1 | 9.1 | 0.050 |
| Total | 14.5 | 0.8 | 74 | 5.1 | 100 | 1.4 | 1.8 | 1.5 | 20.5 | 0.103 |
| Average | 1012.4 | 1.0 | 5062 | 5.4 | 8715 | 1.7 | 2.0 | 110.0 | 23.0 | 0.120 |

Note. * – transitional coefficient, k_t is a ratio between the average square area of icing in the north-eastern regions of Russia to the average square area of icing in the Putorana plateau. It is introduced due to the lack of data on the extension of icing in calculations of the total incremental length of the channel network: $\Sigma L_0 = k_t (n \rho_F)$, where $\rho_F = 11.4$.

Примечание. Переходный коэффициент k_t представляет собой отношение средней площади наледей на северо-востоке России к средней площади наледей на плато Путорана. Введен в связи с отсутствием данных о протяженности ледяных массивов для определения суммарной величины прироста русловой сети: $\Sigma L_0 = k_t (n \rho_F)$, где $\rho_F = 11.4$.

Table 6. Icing characteristics and incremental lengths of channel networks in aufeis sections of river basins located along the Baikal-Amur Railroad route in its section from Lake Baikal to Nyukzha (KR 622–1678)

Таблица 6. Характеристики наледей и прирост русловой сети на наледных полях, расположенных вдоль трассы Байкало-Амурской железной магистрали на участке от Байкала до Нюкжи (622–1678 км)

| River basin | Distance from Ust Kut, km | Icing characteristics | | | | | | Incremental length of channel network, km | | |
|----------------|---------------------------|-----------------------|------|------------------------------|---------|------------|---------|---|---------|-------|
| | | Quantity | | Square area, km ² | | Length, km | | Width, km | | |
| | | | | cumulative | average | cumulative | average | cumulative | average | total |
| Upper Angara | 422–633 | 26 | 1.9 | 0.075 | 14.0 | 0.539 | 3.0 | 0.117 | 35.0 | 1.3 |
| Muya | 650–770 | 50 | 5.8 | 0.116 | 48.6 | 0.971 | 6.3 | 0.126 | 121.5 | 2.4 |
| Vitim | 787–834 | 30 | 2.6 | 0.086 | 19.0 | 0.635 | 2.8 | 0.092 | 47.5 | 1.6 |
| Konda | 840–921 | 60 | 6.0 | 0.101 | 46.1 | 0.769 | 3.7 | 0.062 | 115.2 | 1.9 |
| Maloe Leprindo | 925–927 | 4 | 0.2 | 0.043 | 1.6 | 0.392 | 0.3 | 0.085 | 4.0 | 1.0 |
| Chara | 944–1203 | 60 | 26.3 | 0.438 | 97.0 | 1.616 | 14.0 | 0.233 | 242.5 | 4.0 |
| Khani | 1210–1300 | 17 | 9.4 | 0.550 | 32.0 | 1.886 | 8.4 | 0.496 | 80.0 | 4.7 |
| Olyokma | 1335–1395 | 11 | 4.8 | 0.432 | 11.0 | 1.570* | 0.7* | 0.098* | 27.5 | 2.5 |
| Nyukzha | 1405–1678 | 15 | 1.6 | 0.107 | 5.1 | 0.854* | 0.6* | 0.094* | 12.7 | 0.8 |
| Total | | 273 | 58.6 | | 274.4 | | 39.8 | | 685.9 | |
| Average | | | | 0.216 | | 1.026 | | 0.156 | | 2.2 |

Note. * – Olyokma: seven aufeis deposits; Nyukzha: six aufeis deposits.

Примечание. * – данные по Олекме – 7 наледей, по Нюкже – 6 наледей.

Table 7. General icing characteristics and incremental lengths of channel networks in aufeis glades in East Siberia and the north-eastern regions of Russia

Таблица 7. Общая характеристика наледности и прирост русловой сети на наледных полях Восточной Сибири и северо-востока России

| Icing area | Region square area, thou km ² | Relative aufeis ratio, % | Icing characteristics | | | | Incremental length of channel network | | |
|---------------------------------|--|--------------------------|-----------------------|-----------|------------------------------|--------------|---------------------------------------|--------------------|-------------------------|
| | | | Quantity | | Square area, km ² | | cumulative, thou km | per one aufeis, km | per one km ² |
| total | per one km ² | cumulative | average | | | | | | |
| North-eastern regions of Russia | 1012.4 | 1.00 | 5062 | 5 | 8715 | 1.700 | 110.0 | 23.0 | 0.120 |
| Putorana plateau | 433.5 | 0.37 | 2124 | 5 | 1741 | 0.820 | 20.2 | 11.4 | 0.040 |
| Priokhotsky | 117.1 | 0.84 | 1249 | 11 | 985 | 0.789 | 13.6 | 10.9 | 0.116 |
| Stanovoe upland | 42.0 | 0.69 | 1112 | 28 | 245 | 0.455 | 3.7 | 3.5 | 0.90 |
| South-western Pribaikalie | 14.8 | 0.39 | 1403 | 95 | 120 | 0.085 | - | - | - |
| T o t a l | 1619.8 | | 10950 | | 11806 | | 147.5 | | |
| A v e r a g e | | 0.66 | | 29 | | 0.770 | | 12.2 | 0.091 |

Note. Symbol “-” means “No data”.

Примечание. Прочерк в графе – нет данных.

ice masses (taryns). The major part of this channel system undergoes development stages I or V, i.e. the ice cover occupies the entire floodplain across the 'normal' flow cross-section, yet does not go beyond it. As a result, the cryogenic impact on channelling is mainly limited to destruction of the slopes during spring floods and expansion of the river channel due to thermal erosion. Thus, any 'additional' branching of the cryogenic origin does not take place, but shapes and dimensions of the runoff channels are significantly changed – they become wide and flat. A characteristic feature of such rivers is a smoothed longitudinal profile of the bed with long shallow natural bars or stretches.

10. LONG-TERM VARIABILITY OF THE AUFEIS CHANNEL NETWORK STRUCTURE

Even in the harshest climate conditions, the frozen zone of the lithosphere is penetrated by water-consuming and water-releasing taliks, which locations and configurations remain permanent for many years. Radical restructuring of the water-exchange system takes place only as a result of profound climate changes through many hundreds and thousands of years. Therefore, the aufeis deposits formed in the zone of permanently active groundwater sources are also quasi-constant in time, and their volumes range around some average values depending on local variations of the main characteristics of climate, particularly temperature and precipitation. However, substantial spatial changes occur depending on self-development of the cryogenic system with account of some random factors. Runoff channels maintain their relatively stable

positions only in aufeis development stages I and V when the ice-ground complex does not go beyond the level of high floodplain. In other cases, i.e. in stages of transgression, stabilization and regression, the channels are offset from year to year due to specific features of aufeis ablation and formation of cryogenic landforms. Another important factor is shifting of the geometric centres of ice masses from side to side of the valley and up or down the river.

During the snowmelt period, the runoff channels are cut at different places by melt water flows that spread over the vast ice field, so the configuration of the channel network varies from year to year. Such annual variations are accompanied by transformations of the aufeis glade, which mainly depend on the erosion-accumulation activity of branched water flows. A part of the aufeis glade may be temporarily out of the aufeis-formation regime and, later on, it is covered by new aufeis-ice layers. As a result, the valley bottom is flatten and expanded, and its longitudinal profile is stepped. It is noteworthy that in some years, many aufeis deposits demonstrate a sharp increase of their square areas (by 20 to 30 %), spread into the neighbouring forests (i.e. beyond the well-defined aufeis glade) and thus leave traces resembling passage of high floods. Inexperienced specialists are puzzled and led to false conclusions concerning the river regime in the warm season. In some cases, the aufeis deposits are steadily formed in the near-river forests and on islands and generate erosional landforms that are similar in shape to old channels but differ in genesis. The largest documented aufeis deposit located on the Moma river in Yakutia is such an example (Fig. 24). In other cases, the ice fields may decay or drastically reduce in size.



Fig. 24. The gigantic Moma aufeis deposit (Ulakhan Taryn) in the north-eastern Yakutia.

a – photo taken from an aircraft (photo by Sandro, Yandex: Fotki...0_6020d_1324d2b0_orig); *b* – hydrographic network after ice melt (satellite image, Google). According to different estimates, the area of the Moma aufeis deposit ranges from 76 to 112 km², its maximum thickness amounts to 6 m, and the average thickness ranges from 3 to 4 m. In spring, the width of the ice field exceeds 2 km, and large forested areas and numerous islands are ‘flooded’.

Рис. 24. Большая Момская наледь (Улахан Тарын) на северо-востоке Якутии.

a – снимок с самолета (фото Сандро, Яндекс. Фотки...0_6020d_1324d2b0_orig); *b* – структура гидрографической сети после таяния льда. Снимок из космоса, Google. Площадь Момской наледи по разным оценкам составляет 76–112 км², максимальная мощность достигает 6 м, средняя колеблется в пределах 3–4 м. Весной ширина ледяного поля превышает 2 км, при этом «заливаются» значительные участки леса и многочисленные острова.

Such a case is the Kyra-Nekharanskaya aufeis deposit (almost 100 km²) that has recently broken up into several separate ice masses.

In mature aufeis glades, annual transformations of the channel network are not always noticeable, as the runoff channels have low and flat banks, and inter-stream areas are devoid of vegetation. In some cases,

the aufeis bed can develop into a shallow pool that is periodically dried, and only special methods and observations can help detecting numerous traces of water flow movements taking place during ablation of ice masses (Fig. 25). Aerial surveys and satellite imagery are particularly effective in revealing the long-term changeability of the channel network. Valuable

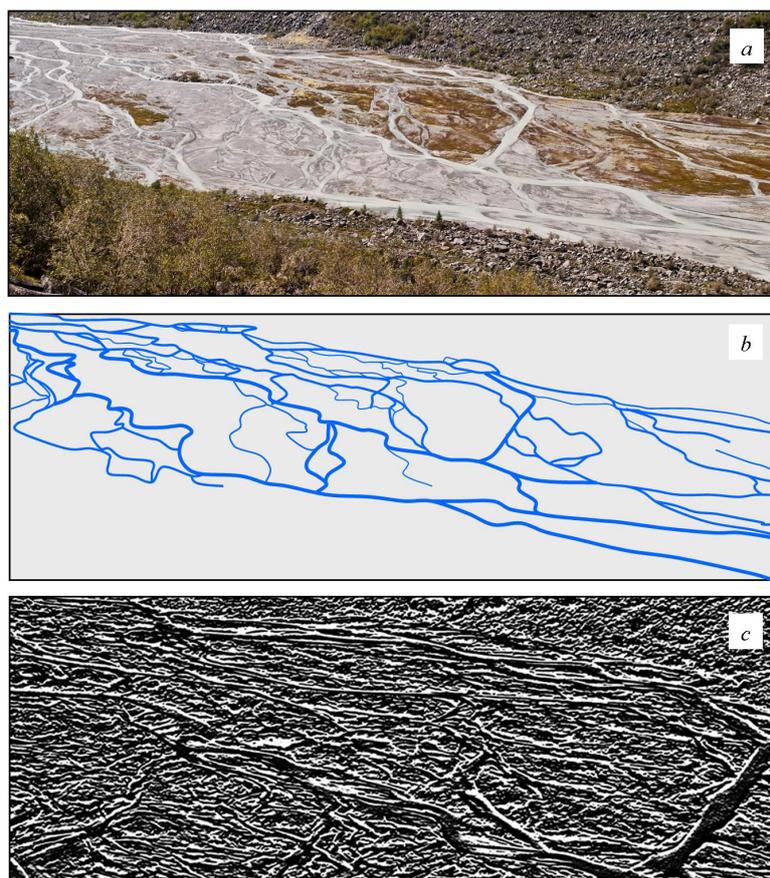


Fig. 25. The channel network on the aufeis glade in the Akkem river valley, Altai.

a – photo taken from a helicopter (NATA-SOLAR; Yandex: Fotki... 0_80592_66abc943_orig); *b* – configuration of the current river network as determined from the photo; *c* – surface of the aufeis glade with traces of erosion activity of water flows ('filtered-out' fragment of the photo of the middle part of the aufeis glade).

Рис. 25. Структура русловой сети на наледной поляне в долине реки Аккем, Алтай.

a – снимок с вертолета (NATA-SOLAR. Яндекс. Фотки... 0_80592_66abc943_orig); *b* – конфигурация современной речной сети, определенная по фотоснимку; *c* – поверхность наледной поляны со следами эрозионной деятельности водных потоков («отфильтрованный» фрагмент снимка центральной части наледной поляны).

information can also be obtained by comparing medium- and large-scale topographic maps constructed or updated in the past 60–70 years.

Our analysis of the available data shows that in the valleys of many rivers in the permafrost zone, aufeis multi-channeling does not occur locally and can be observed almost continuously for many dozens or even hundreds of kilometres (Fig. 26). This is caused by regional and local crustal faults, which zones are developed by river valleys of ranks 3 to 6. Tectonic faults of various generation ranks are associated with water-releasing taliks that feed large-flow groundwater sources and their corresponding giant aufeis deposits (taryns). Besides, it should be noted that square areas of the ancient aufeis glades are considerably larger than the areas of the current hydrographic network (Fig. 26, *a–f*). This fact gives an evidence of the activity and long-term variability of channeling in both the current

period and the distant past, including, probably, the Holocene (10–12 thousand years) and earlier periods. This aspect has not been studied at all, despite its high paleogeographical importance, in particular for exploration and evaluation of placer deposits of minerals.

11. ZONATION OF THE TERRITORY OF RUSSIA BY CRYOGENIC CHANNELING TYPES

Identification of large taxonomic categories from effects of ice and melt water to channeling should be based on the known axiomatic concepts that follow from the Grigoriev-Budyko periodic law of geographical zonality of natural processes [Grigoriev, 1966]. A channel is a linear type of landform which is formed by a water flow. Primarily, where there is no water, there is no channel (an example is the Moon surface). The

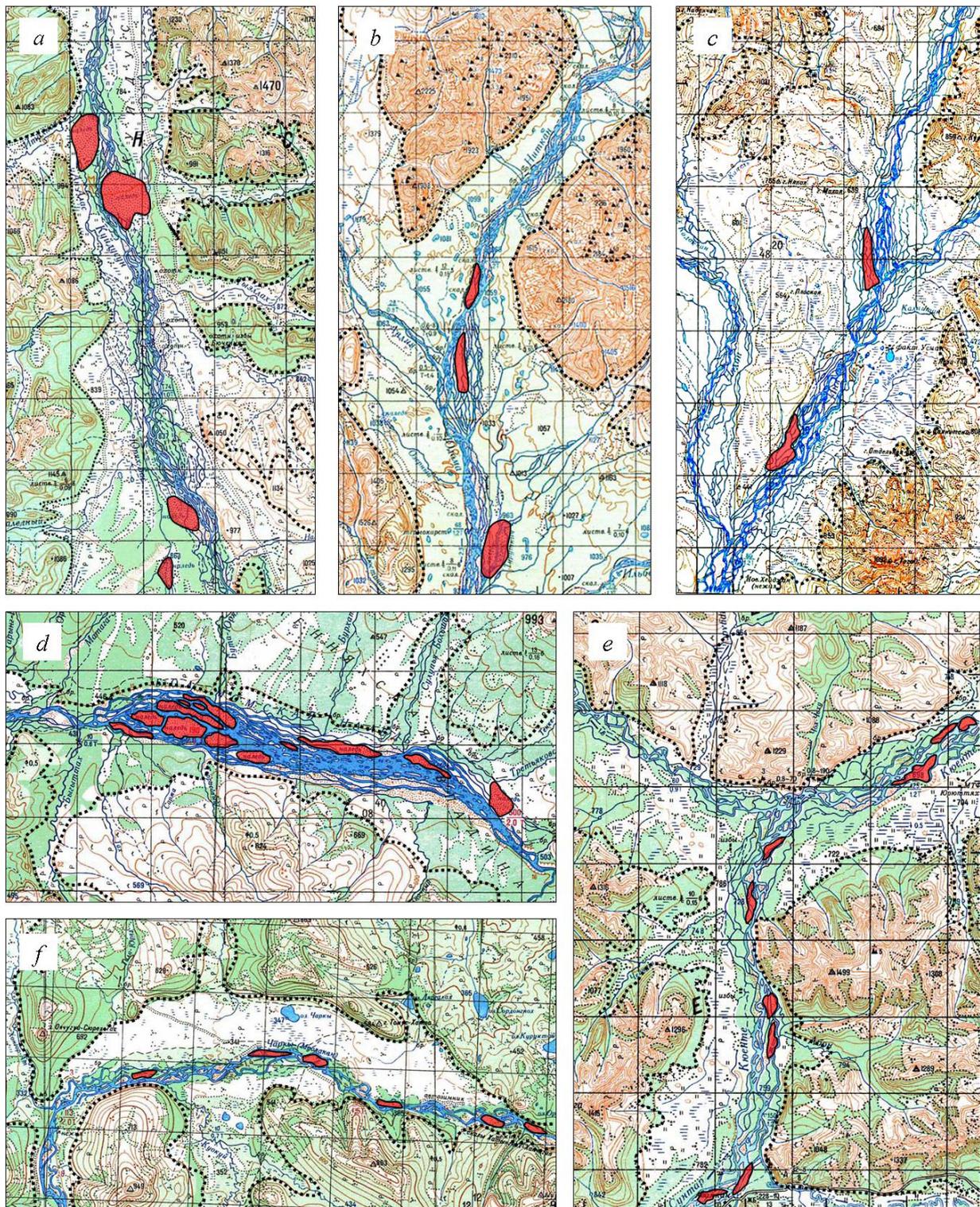


Fig. 26. Configurations of channel networks in areas of gigantic aufeis deposits (taryns) in the river valleys of the Verkhoyansk-Kolyma mountain system.

Fragments of topographic maps, scale 1:100000. Grid square 2×2 km. River valleys: *a* – Kuidusun, *b* – Yudoma, *c* – Inya, *d* – Moma, *e* – Suntar and Kyuente, *f* – Charky. The black dotted line outlines the ancient and contemporary aufeis glades. Remnants of the aufeis deposits as of the topographic survey data are shown in red.

Рис. 26. Конфигурация русловой сети на участках формирования гигантских наледей-тарынов в долинах рек Верхояно-Колымской горной страны.

Фрагменты топографических карт масштаба 1:100000. Квадрат сетки 2×2 км. Долины рек: *a* – Куйдусун, *b* – Юдома, *c* – Иня, *d* – Мома, *e* – Сунтар и Кюенте, *f* – Чаркы. Точечной линией черного цвета показаны внешние границы древних и современных наледных полей; красным цветом выделены остатки наледей на дату топографической съемки.

quantity of water involved in channeling is climate dependent. All climate zones of the Earth fall into one of three basic categories:

(1) zones with permanently positive temperatures of the near-ground air layer through the year; in such zones, channeling takes place under the laws of non-freezing rivers;

(2) zones with permanently negative temperatures at the boundary between the atmosphere and the lithosphere (permafrost conditions); in such zones, rivers are absent as all the water is accumulated as snow and ice (for example, in Antarctica and inner regions of Greenland);

(3) zones with alternating positive and negative temperatures at the ground surface; in such zones, rivers are covered by ice for many months, and the majority of the rivers freeze either partially or completely.

Zones in category 3 are parts of the transitional belt of the cryosphere, wherein the regime of water flows and corresponding erosional-accumulation events are dependent on the duration and severity of the cold period of the year, solid precipitation volumes, types of feed, presence of permafrost and seasonally frozen areas etc. Ratios of water, ice and frozen rocks, which determine specific features of channeling in the transitional belt of the cryosphere, are shown in Fig. 9. If the water layer in the runoff channel of thickness h_1 , does not get covered by ice through the year, channeling takes place under the laws of non-freezing rivers. In the permafrost zone, processes of this type take place rarely, mainly on sites of large permanent polynya formed by strong subaqueous groundwater sources, as well as at afterbays of river dams, and are always influenced by icing events that occur in the adjacent river sections. In all other cases, the presence of the ice cover and its temporal and spatial changeability provide for the stage-by-stage cryogenic development of the hydrographic network, which reflects principles of self-development of the geosystems within the limits of specific climate characteristics and uniform geological and geomorphological conditions. Obviously, seasonal, long-term and perennial changeability of the cryogenic systems of this types is manifested not only along the river of a certain rank, but also within natural and climatic zones and altitudinal belts, and this is reflected in characteristics of ice, the underlying bed and the hydrographic structure in general. These conclusions follow from an unsophisticated physical geographical analysis of the situation and are supported by the materials presented in the previous sections of this paper.

Based on the above, we propose a general classification of cryogenic channeling types. It refers to conditions of formation of the channel networks in practically all cold regions of the Earth (Table 8), primarily regions of the permafrost zone.

In our classification, the key indicator is represented by a ratio of thicknesses of genetically inhomogeneous glacial formations on rivers, specifically snow-ice thickness, h_{sn} , river- and groundwater aufeis thickness, h_a , and crystalline river ice thickness, h_{cr} . Five types of cryogenic channeling are distinguished according to the following conditions: (1) $h_{sn} > h_{cr} > h_a$; (2) $h_{snow} > h_{cr} < h_a$; (3) $h_{sn} < h_{cr} > h_a$; (4) $h_{sn} < h_{cr} < h_a$; and (5) $h_{sn} > 0 < h_a$.

Type 1. Snow ($h_{sn} > h_{cr} > h_a$). Snow-type channeling is typical of the regions characterised by short-term and seasonal freezing, short freeze-up periods (up to 4 months) and a relatively thin ice cover. Ice does not extend above the autumnal low-water level, sags while the subsurface feed is depleting, decays without ice drift, and does not put any significant impact on channeling. The floodplain sections of the valley are deformed and the sediments are redeposited during the spring-flood period due impacts of melted-snow water.

Type 2. Snow-ice ($h_{snow} > h_{cr} < h_a$). Snow-ice channeling is typical of the regions characterized by deep seasonal freezing of soils and rocks, sporadic and massive sporadic permafrost (up to 50 % of the area) on mountain slopes and in boggy river terraces (rarely on high floodplains). By spring, due to river-water aufeis depositing, the ice cover extends beyond the autumnal low-water level and reaches the inner boundary of the floodplain. During the snow-melt period, the ice slabs floats with melted snow water and contributes to redeposition of riverbed material and floodplain alluvium, but does not cause any significant changes in the structure of the river banks and the river bed.

Type 3. Ice-aufeis ($h_{sn} < h_{cr} > h_a$). Ice-aufeis channeling is typical of the regions with discontinuous permafrost (50 to 95 % of the area) and freezing river systems. In the first half of winter, the crystalline-ice cover is overlaid by river-water aufeis deposits and, in the second half of winter, by groundwater aufeis deposits. In the aufeis-formation period, the snow cover gets included in the ice bed and creates cloudy bubble-rich ice sublayers. The glacial complex, extending to the level of high floodplain, is complicated by aufeis- and ground-aufeis mounds. In spring, the river bed is significantly transformed during the ice-drift period – the bank slopes are deformed; alluvial deposits, that are frozen in and frozen up to the ice slabs' bottoms, are transferred; bars, chains and scattered structures containing sand, gravel boulders and pebbles are constructed on the beaches; subaqueous furrows and runoff channels are formed. During the ice-drift period, ice may be deposited outside the floodplain. It melts in place and thus does not put any impact on channeling.

Type 4. Aufeis ($h_{sn} < h_{cr} < h_a$). Aufeis channeling is typical of regions with continuous permafrost (more than 95 % of the area) and ubiquitous freezing of water flows. The thick aufeis deposit (composed mainly of

Table 8. Characteristics of cryogenic channeling types (for rivers of ranks 1 to 6)

Таблица 8. Типологическая характеристика условий криогенного руслообразования (для рек 1–6-го порядка)

| Characteristics | Types of cryogenic channeling | | | | | |
|--|-------------------------------|-------------------------|-------------------------|-----------------------------------|-----------------------------------|-----------------------------|
| | 1. Snow (S) | 2. Snow-ice (SI) | 3. Ice-aufeis (IA) | 4. Aufeis (A) | 5. Glacier (G) | |
| Map symbol | 1 | 2 | 3 | 4 | 5 | |
| Intensity of cryogenic channeling | Very low | Low | Medium | High | Very high | |
| Period of maximum manifestation, month | III | IV | V–VI | V–VII | VI–VIII | |
| River runoff under ice, month | Continuous XI–III | Continuous X–IV | Intermittent X–I | Intermittent X–XI | None | |
| Duration of freeze-up period, number of month | 1–4 | 4–6 | 6–7 | 7–8 | 8–10 | |
| Average ice thickness, m | snow, h_{sn} | 0.3 | 0.3 | 0.2 | 0.5 | |
| | crystalline, h_{cr} | 0.2 | 0.5 | 0.7 | 0.3 | |
| | aufeis, h_a | 0.1 | 0.2 | 0.5 | 1.5 | |
| | total | 0.6 | 1.0 | 1.5 | 2.0 | |
| | ratio | $h_{sn} > h_{cr} > h_a$ | $h_{sn} > h_{cr} < h_a$ | $h_{sn} < h_{cr} > h_a$ | $h_{sn} < h_{cr} < h_a$ | $h_{sn} > 0 < h_a$ |
| Presence of permafrost | seasonal ($h > 1$ m) | None | In floodplain | In floodplain and under river bed | Under river bed | None |
| | perennial | None | Sporadic | Discontinuous | Continuous | Continuous |
| Taliks | over-permafrost | None | None | In floodplain | Under river bed | Under river bed |
| | inter-permafrost | None | None | Under river bed | In floodplain and under river bed | Under river bed and glacier |
| Snow cover thickness, m | 0.5–0.8 | 0.3–1.0 | 0.2–0.8 | 0.5–1.0 | 1.0–1.5 | |
| River feed in the critical period of the year (zero precipitation) | Subsurface | Subsurface | Subsurface | Aufeis | Glacier | |

groundwater) occupies the channel, floodplain and low terraces and often spreads through the entire width of the river valley. Lenses and layers of injection ice form under the aufeis deposit, and the soil layers have to bulge and thus obstruct the way for melt and rain water. As a result, the water flows are forced to change their directions. The underlying bed and the beach scarps are intensely eroded. Due to melting of aufeis ice and injection ice, an additional network of streamlets is created, and thermokarst collapse is accompanied by the formation of small lakes or lengthy trenches that accumulate the melt water runoff. In the icing zone, the sediments are redeposited, and large fragments of rocks are displaced every year. As a result, the river bed is expanded and flattened, and the water flow is spread and divided into a series of shallow-water branches and loses its velocity and carrying capacity.

Type 5. Glacier ($h_{sn} > 0 < h_a$). Glacier-type channeling develops below tongues of mountain-valley glaciers and at the walls of ice caps in conditions of continuous recent or relict permafrost. In case of complete freezing of the icing bed, the channel network is formed only due to erosion-accumulation activity of thawing snow and glacial water. The runoff regime is characterised by evident daily water level variations due to atmospheric air temperature changes. The flow rates may reach catastrophic values; in such cases, glacial materials are

considerably redeposited and reworked, and river channels shaped in the previous year are significantly transformed. Generally, the bottoms of glacial valleys are flat and cut by numerous channel branches that are filled during daily increase of the water level and in case of rains. The impact of glacier floods can be traced for dozens and hundreds of kilometres down the valley; it is reflected in the morphological structure of near-glacier outwash plains.

At the edge of the warm glaciers containing the reserve of intra- and subglacial water that is discharged in winter, the snow-aufeis complex is formed. It modifies the activity of melt water, and in some cases leads to formation of typical aufeis glades with mounds and intra-soil injection-ice layers that are sometimes viewed as remnants of a degraded glacier.

Zonation by the cryogenic channelling types is shown in Fig. 27. Almost 2/3 of the territory of Siberia and the Far East, the northern part of the Ural and Priuralie and the Arctic islands are strongly influenced by cryogenic processes, which is evidenced by the structure and functioning of the hydrographic network, in particular its upper part (water streams of ranks 1 to 5). The aufeis deposits play a significant role in this large-scale natural phenomenon, which should be taken into account in infrastructure engineering projects aimed at development of the permafrost zone.

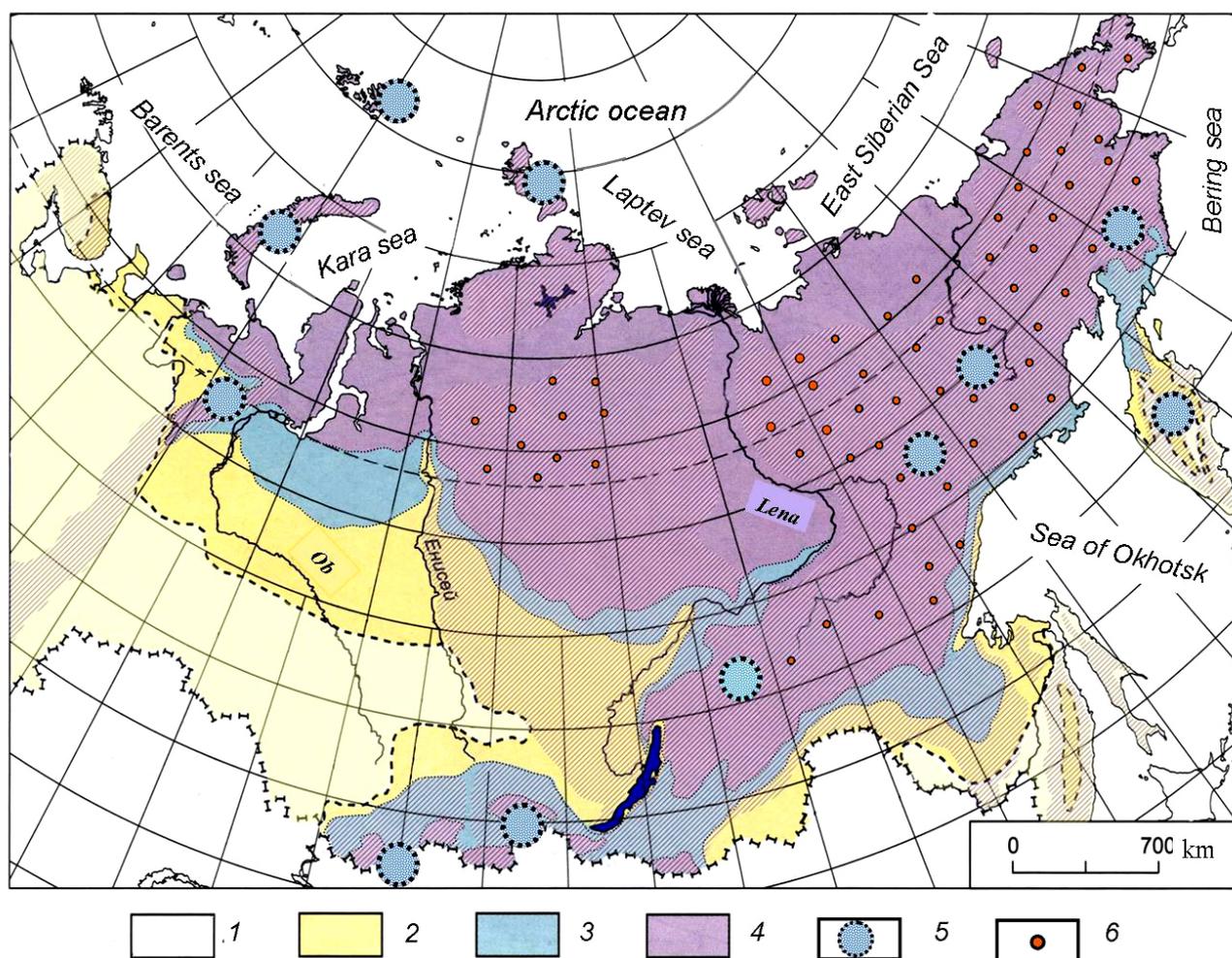


Fig. 27. Zonation of the territory of Russia by cryogenic channeling types.

Cryogenic channeling types: 1 – snow, 2 – snow-ice, 3 – aufeis-ice, 4 – aufeis, 5 – glacier (channeling conditions are described in table 8); 6 – areas of gigantic aufeis deposits (taryns). Mountains and plateaus are shaded.

Рис. 27. Районирование территории России по типам криогенных руслообразующих процессов.

Типы криогенных руслообразующих процессов: 1 – снежный, 2 – снежно-ледовый, 3 – наледно-ледовый, 4 – наледный, 5 – ледниковый (характеристика условий руслогенеза см. в таблице 8); 6 – районы распространения гигантских наледей-тарынов. Штриховкой показаны горы и плоскогорья.

12. DISCUSSION

According to the recent studies [Koroleva, 2011], the permafrost zone of Russia amounts to 10.7 mln km² (65 % of the territory), including 5.2 mln km² (49 %) of continuous permafrost, 2.4 mln km² (22 %) of discontinuous perennial permafrost, and 3.1 mln km² (29 %) of mass-sporadic and sporadic permafrost. Groundwater aufeis zones are large and well manifested by aufeis glades in the territory of 7.6+ mln km² (71 % of the permafrost zone). The relative aufeis ratio determined from parameters of 10000 ice fields amounts to 0.66 % in average (see Table 7), i.e. almost 56000 km². If an error of 20 %, that occurs because the aufeis fields are less numerous in the lowland plains, the total annual

square area of the groundwater aufeis deposits amounts to almost 45000 km². The number of ice masses, each occupying an area of 0.770 km² in average, may be significantly larger than 60000. Many or few? For comparison, we can refer to the square area (F_g) and the number (N_g) of glaciers in the continental Russia: $F_g=2551$ km², and $N_g=1727$ [Dolgushin, Osipova, 1989]. Thus, the total aufeis (congelation-ice) square area in the permafrost zone is higher by a factor of 18 than the 'classical' (sublimation, sedimentation-metamorphic) icing area. The number of large groundwater aufeis deposits, which square area is equivalent to the mountain-valley glaciers in the Asian regions of Russia, is significantly more than 60000, i.e. by a factor of 35 exceeds the number of glaciers. Estimations

based on the above-mentioned data show that the total increment of the hydrographic network amounts to 690000 km in the territories of continuous and discontinuous permafrost ($F=7.6$ mln km²).

The above values do not take into account aufeis deposits of the heterogeneous origin (fed by river water and groundwater) which, as a minimum, occupy 60 % lengths of the rivers of ranks 1 to 5 in the remaining regions wherein permafrost is developed. In Siberia and the Far East, the total length of rivers of ranks 1 to 5 (up to 500 km long) amounts to 6.641 mln km. Almost half of such rivers run in the territories of continuous and discontinuous permafrost. Rough estimates for Siberia and the Far East show that the total square area of the aufeis deposits occupying the entire river channels, but not exceeding the limits of the 'standard' floodplain, amounts to 68000 km², i.e. twice as large as all the groundwater aufeis deposits with 'fixed' beds (taryns).

The above-mentioned values are just the first approximation. Anyway, such data give evidence of the significant role of aufeis phenomena in channeling, as well as in the evolution of the structure and dynamics of the geosystems in the northern territories. Considering hydrological, geological and landscape development aspects, there are grounds to conclude that the role of aufeis deposits is many times more important in this respect than the role of glaciers. This conclusion is based not only on the above-mentioned information, but also on the comparison of the aufeis and glacier runoff volumes. The thaw-aufeis water volumes are just incomparable to the glacier water runoff. Most of the aufeis deposits are subject to complete ablation during the warm season each year, and their annual 'active layer' equals the aufeis-ice thickness. All the thaw-aufeis water goes into the river network and actively participates in channelling. As for the glaciers, only the top thin parts are 'in operation' and only in the ablation zone, which square area is generally significantly smaller than that of the accumulation zone.

Anyway, glaciers have always been given special attention in all the regions in the USSR and Russia. There is still a trend to report a 'geographical discovery' even when presenting a description of a small-sized glacier located somewhere in Pribaikalie or on the Koryak tableland. Aufeis deposits were less 'lucky' and became the subject of active studies only about 50–60 years ago; however, in the past two decades, the aufeis studies ceased. Why the current situation is inadequate? There is no need here to mention factors of 'perestroika' and the social and economic crisis; the negative consequences are evident. There is, however, a number of subjective factors – an adequate understanding of glacial phenomena and especially aufeis is lacking among many researchers, engineers and science managers, and the importance of such phenomena for de-

velopment of regions with cold climate is underestimated. The aufeis sections of the river valleys, being the 'hottest' spots of the permafrost zones, are unavoidable and cannot be eliminated. The only way is planning human activities with account of the aufeis phenomena, which requires the knowledge of laws and regularities of development, structure and properties of the cryogenic systems. Long-term monitoring, testing and experiments are needed to obtain such knowledge. Besides, a wide-scale inventory of relevant research subjects needs to be conducted. Neither Skolkovo nor Olympic Games projects can be sufficient for solving the scientific and applied problems of nature resources development in our country of abundant snow, ice and permafrost. It is critical to plan and implement independent nature research programmes targeted at problem solving in the specified fields of science and practice.

In late 1980, large-scale research data were consolidated in the USSR Glaciers Catalogues. The World Atlas of Snow and Ice Resources, presenting a unique summary of the current knowledge on snow and ice on the Earth, was published in 1997. Less ambitious, yet no less successful initiatives and publications by individual scientists and research teams should be also mentioned as valuable contributions to the knowledge on aufeis phenomena [Alekseyev, 2007; *Catalogue...*, 1980, 1981, 1982; Shesternev, Verkhoturov, 2006; Sokolov, 1975; Tolstikhin, 1974]. Unfortunately, the techniques and methods applied in these studies were imperfect, and the input information was motley. Now it is challenging to analyse and compare such data. Many aspects were skipped as the input data was lacking. Today, when data obtained by highly efficient GIS technologies and nearly simultaneous serial space imagery can be available, the pressing demand to revise and update the databases can be met. It becomes feasible to stock-take the icing and glaciation objects of the entire Earth or the territory of Russia, as a minimum, by establishment of monitoring sites for ground-truth observations to confirm satellite data. Studies of ice-ground complexes as a unique phenomena of icing on the Earth should be also included in a comprehensive research programme. With this approach, many issues of cryogenic morpholithogenesis, including those mentioned in this article, can be clarified.

The materials reviewed herein and data on other regions published in [Petrov, 1930; Podyakonov, 1903; Romanovsky, 1983, 1993; Sannikov, 1988; Strugov, 1955; Tsvid, Khomichuk, 1981] show that annual formation and ablation of aufeis and subsurface ice are accompanied by soil heaving, thermokarst and thermal erosion. Combined, these processes lead to a rapid (often unexpected) reconfiguration of the surface and subsurface runoff channels, abrupt uplifting and subsiding of the ground surface, decompaction and 'shaking-up' of sea-

sonally thawing and seasonally freezing rocks, thereby producing exceptionally unfavourable conditions for construction and operation of engineering structures. All the above-described phenomena need to be taken into account in applied research and engineering for development of natural resources in the northern regions.

It should be noted that aufeis hazard has not been duly considered yet in applied aspects, despite the availability of scientific and engineering publications on glaciology, hydrogeology and geocryology of the northern and north-eastern regions of Russia [Alekseev, 2005]. Researchers are mainly focused on studies of ice and water above ice. Processes under the ice caps and aufeis deposits remain unknown, and the lack of such knowledge hampers the search for solutions of applied problems. An indicative case is the Kerak aufeis deposit at the Transbaikalian (Far East) Railroad (KP 7352). For over 50 years, the railroad bed and icing on site were monitored [Rumyantsev, 1964, 1991]. Nearly every year, management decisions concerning assurance of safe railroad operations were taken on the basis of theoretical considerations, without any research of 'inherent' factors leading to hazardous engineering geological processes, and such decisions were actually useless. Only after core-drilling studies initiated by hydrogeologist P.N. Lugovoy and detailed observations on this site, a correct and reliable method was selected for protection of the railroad bed, and the aufeis hazard was thus eliminated.

Obviously, aufeis problems are well known to scientists and engineers, especially those involved in road construction projects [Chekotillo et al., 1960; Kazakov, 1976], yet aufeis studies are generally limited to road sides. Typically, front-end engineering surveys do not include long-term field observations that would facilitate clarification of the origin and dynamics of aufeis and cryogenic-geological phenomena – it is conventionally believed that aufeis hazard can be eliminated by standard protection actions. It is, however, evident that regularities of formation of ice-ground complexes and their development depend on a complex combination of many natural factors, including the topography and geological setting of the territory, permafrost and hydrogeological conditions, geographic latitudes and elevations of areas subject to icing etc. In order to solve applied problems, it is required to employ specialized approaches on a case-by-case basis as specific indicators of the above-mentioned relationships have not been established yet. Besides, total and unit sizes of aufeis deposits should be taken into account. Based on results of his studies of the northern Amur region, B.N. Deykin made the following conclusion: within the limits of the well-defined aufeis glades, the square area and the volume of stratal ice amount to 41.5 % and 15 % of the unit dimensions of an average aufeis de-

posit, respectively [Deikin, 1985]. In our preliminary calculations based on the established indicators, similar values (55 % and 20 %) are obtained. What is the extent of distribution of injection ice and mounds in the areas wherein giant aufeis deposits (taryns) occupy dozens of square kilometres? Does formation of the ice-ground complexes differ in the northern and southern areas of the permafrost zone? These questions remain unanswered. The studies that started 30–35 years ago at the Baikal-Amur Railroad, in Yakutia and the north-eastern regions of Russia were suspended and have not been resumed yet. The information collected for road construction projects in the southern regions of the permafrost zone is evidently insufficient for assessment of the extent and specific development features of hazardous aufeis phenomena in areas of harsh climate conditions. That is why the express methods applied for engineering design of industrial linear facilities, such as the East Siberia - Pacific Ocean pipeline (ESPO), fail to fully provide for reliable assurance of stability and environmental safety of the industrial systems.

The problem will be surely aggravated in construction of linear facilities of large lengths, such as a transcontinental railroad to Alaska – by-passing or crossing the 'hot spots' without any environmental risk will be the major challenge. In view of the above, special studies are required to catalogue the data on aufeis glades and to study the aufeis dynamics, conditions and development with account of interactions of the ice masses with the underlying rocks and the environment. Upgrading the methods for identification and assessment of aufeis hazards is of high practical importance, and new techniques should be developed with application of remote sensing and ground-truth observations to confirm satellite data.

In order to solve engineering problems related to aufeis sections of the river valleys, it is proposed to establish sites for pilot testing and monitoring. Studies on such sites can facilitate the identification of specific features in the behaviour of natural and man-made systems, such as pipelines, embankments, bridges, underground and surface utilities and other facilities operating in complicated conditions, as well as contribute to establishing principles and methods of design, construction and operation of engineering structures in territories subject to aufeis hazards. It will be possible to test theoretical models and technological schemes aimed at development of the territories wherein hundreds of thousand square kilometres are ice-covered each year.

In our opinion, it is also important to study the aufeis alluvium, specifically its structure, locations and development. This well-washed and sorted material is affordable and can be widely used in construction of various facilities. The aufeis glades can be considered

as a kind of traps for placer gold due to the annual 'shake-up' of loose sediments, decay of the energy of water flows and morphological characteristics of the channel network in the aufeis glades. The aufeis glades are abundant in the 'golden belt' stretching from the Sayan mountains to the Kolyma upland in the north-eastern regions in Asia, as well as in Alaska. It stands for reason that Yu.A. Bilibin, the pioneer and expert in geology of gold placers, gave much attention to studies of aufeis phenomena when prospecting for 'gold-bearing sands' [Bilibin, 1963]. Specialized mining and tunnelling works are needed to study this aspect. Hopefully, this problem will attract the attention of specialists who can conduct proper scientific and applied studies.

Based on our analyses of the current state of knowledge on the aufeis sections of the river valleys, some topical problems can be stated for the future studies. In our opinion, objectives for the near future shall be as follows:

(1) Conduct detailed studies of cause-and-effect relationships and regularities in seasonal and long-term development of geodynamic and glaciohydrological phenomena in the zone of active icing; such studies shall be based on long-term observations on special aufeis polygons;

(2) Develop a technique for field surveys and mapping of aufeis hazard sites in the regions wherein giant aufeis deposits (taryns) are abundant; reveal and evaluate indicative properties of the aufeis deposits and aufeis glades;

(3) Study how industrial facilities, such as pipelines, utilities, roads, railroads, bridges, dams, towers of overhead power and communication lines etc., interact with aufeis deposits and aufeis ice-ground complexes of the main types;

(4) Determine principles of engineering development of the aufeis sections of the river valleys in zones differing in climate and geocryological conditions; propose and develop standard technological schemes for design, construction and operation of engineering structures on sites of active icing;

(5) Study deposits on the aufeis glades as sources of building materials and accumulators of some useful minerals.

The above-mentioned problems can be solved only by joint efforts of specialists from interested institutes and authorities, who can establish a multi-discipline team for implementation of a comprehensive project titled "*Development of concepts and methods for assessment, mitigation and elimination of aufeis hazard in the permafrost zone of Russia*". It is reasonable to conduct activities aimed at preparation and implementation of the project with resources of the Siberian Branch of RAS, particularly with involvement of specialists from Melnikov Permafrost Institute (Yakutsk),

Institute of the Earth's Crust (Irkutsk), Earth Cryosphere Institute (Tyumen), and Sochava Institute of Geography (Irkutsk).

13. CONCLUSION

1. The groundwater aufeis deposits, which are abundant in the territory of Siberia and the Far East, are many times more substantial than the 'classical' (sedimentary-metamorphic) form of icing, considering their number, dimensions and the current morholithogenetical importance. The more contrasting is the terrain, the more active are neotectonic movements, the lower is the mean annual air temperature, and the higher is the annual percentage of the territory covered by aufeis ice. The aufeis ratio of the permafrost zone, which is determined from parameters of over 10000 ice fields, amounts to 0.66 % (50000 km²). In mountains and tablelands, the total area of aufeis deposits amounts to 40000 km², and the number of ice clusters (0.77 km² in average) exceeds 60000. On the rivers as long as 500 km, the size of aufeis depends on ranks of the streams. In all the natural zones, the majority of gigantic aufeis spots produced by groundwater are located in river valleys of ranks 3 or 4. The area of aufeis deposits of mixed feed, i.e. produced by river water and groundwater, which occupy the entire river channel, yet do not go beyond an ordinary floodplain, amounts to 68000 km², i.e. by a factor of 1.7 larger than the area of all the aufeis deposits (taryns).

2. Due to local groundwater seeping and freezing in layers that accumulate over each other and create large ice clusters on the ground surface, specific conditions of energy- and mass transfer are created in the atmosphere – soil – lithosphere system. In winter, the vertical temperature distribution curve is significantly disrupted due to heat emission from the aufeis layer of water during its freezing, and a thermocline is thus formed. Deformation of the temperature curve is gradually decreasing in size downward the profile and decays at the interface of frozen and thawed rocks. Values and numbers of temperature deviations from a 'normal' value depend on heat reserves of aufeis water and the number of water seeps/discharges at a given location. Upon occurrence of a thermocline, the mode of water freezing and the mechanism of ice saturation of the underlying layers is changed, and double-layered ice-ground complexes (IGC) are formed. IGCs are drastically different from cryogenic deposits in the adjacent segments of the river valley. By specific genetic characteristics and ratios of components in the surface and underground layers, seven types of aufeis IGCs are distinguished as follows: massive-segregation, cement-basal, layered-segregation, basalt-segregation, vacuum-filtration, pressure-injection, and fissure-vein. IGC struc-

tures and properties are variable depending on icing conditions and processes.

3. Annual processes of surface and subsurface icing and ice ablation are accompanied by highly hazardous geodynamic phenomena, such as winter flooding, water freezing, soil heaving, thermokarst and thermal erosion. Combined, these processes lead to a rapid (often unexpected) reconfiguration of the surface and subsurface runoff channels, abrupt uplifting and subsiding of the ground surface, decompaction and 'shaking-up' of seasonally thawing and seasonally freezing rocks, thereby producing exceptionally unfavourable conditions for construction and operation of engineering structures.

Impacts of aufeis deposits and genetically associated cryogenic-geological processes are most actively manifested in the formation and development of the channel network. Five types of cryogenic channelling are distinguished with regard to ratios of thicknesses of crystalline (h_{cr}), aufeis (h_a) and snow (h_{sn}) ice layers, conditions and specific impacts of icing: (1) snow ($h_{sn} > h_{cr} > h_a$), (2) snow-ice ($h_{sn} > h_{cr} < h_a$), (3) aufeis-ice ($h_{sn} < h_{cr} > h_a$), (4) aufeis ($h_{sn} < h_{cr} < h_a$), and (5) glacier ($h_{sn} > 0 < h_a$). The cause-and-consequence relationships concerning the above-mentioned types of channelling are controlled by infill of the runoff channels with ice and the ice thickness, as well as by the degree of discontinuity of permafrost and depths of seasonal freezing and thawing of soil.

4. The impact of aufeis ice on channeling and the underlying rocks is most vivid in the regions with discontinuous and continuous permafrost. The average thickness of the ice cover on rivers ranges from 1.0 to 2.5 m, and its major part (90–95 %) is formed due to discharge and subsequent freezing of river- and groundwater. It is revealed that the intensity of cryogenic channeling depends on aufeis deposits above the autumnal low-water level. If the runoff channel is filled with ice up to the level of high floodplain, channeling of the *ice-aufeis type* takes place, and the river bed is deformed mainly due to thermal erosion and exaration during the spring ice-drift period. The beach scarps, river bars, islands and midstream sandbanks are cut off; chains, bars and scattered structures containing sand, gravel boulders and pebbles are constructed at the river sides; subaqueous furrows and other cryogenic terrain structures are formed; the riverbed is expanded and box-shaped. If ice extends above the level of high floodplain, all the indicators of channeling of the *aufeis type* are observed. This type of channeling is manifested by aufeis glades, i.e. expanded and flattened sections of the river valley, devoid of wood vegetation, with flat terrain and the network of shallow-water branches. The aufeis glades are arranged as a 'string', one after another, on the main water-artery bed and indicate locations of permanent groundwater

sources with large flow rates.

5. It is revealed that the aufeis sections of the river valleys develop by a typical sequence of events due to self-development of the geosystems and transformations under the influence of climate changes and cryo-hydrogeological conditions. In the regions with continuous and discontinuous permafrost, five stages of cryogenic channelling are distinguished: I – pre-glacial development, II – transgression, III – stabilization, IV – regression, and V – post-glacial development. Each stage is characterised by a specific glaciohydrological regime of runoff channels and their specific shapes, sizes and spatial patterns. In the mature aufeis glades, there are sites undergoing various development stages, which gives evidence that aufeis channelling is variable in a wide range in both space and time. The channel network is subject to the maximum transformation in aufeis development stages III and IV, when the transit flow channel is split into several shallow-water branches, producing a complicated plan pattern of the terrain.

With respect to sizes of aufeis glades, river flow capacities and geological, geomorphological, cryo-hydrogeological conditions, the aufeis patterns of the channel network are classified into five types as follows: fan-shaped, cone-shaped, treelike, reticular, and longitudinal-insular. Trends in further development of the river valleys with aufeis deposits can be determined from the structure and the status of their channel networks, and such knowledge is valuable for industrial and economic development of the regions.

6. The cumulative morpholithogenetical effect of aufeis phenomena is expressed by an increment in the channel network as compared to parameters of the river segments located upstream and downstream of the aufeis glade. This indicator is quite well correlated with the main characteristics of the aufeis deposits in the river basins, morphostructural and cryo-hydro-meteorological conditions of the territory under study. In the mountain regions, multiple branches of small and medium-sized rivers, which are formed due to aufeis processes, can be traced for dozens and hundreds of kilometres almost without any gaps; such branches are highly variable in both time and space. The increment in the channel network, ρ_n per one groundwater aufeis deposit is increased, in average, from 3.5 km in mountains in the southern regions of East Siberia to 23 km in the Verkhoyansk-Kolyma mountain system and Chukotka. The value of ρ_n is decreased to 2.2 km in the plains and intermountain depressions of the Baikal rift system where the ice fields are smaller in size. The average increment in the channel network per one groundwater aufeis deposit amounts to 12.2 km, and the total increment in continuous and discontinuous permafrost areas ($F=7.6$ mln km²) is estimated at 690000 km.

7. A combination of impacts of aufeis and icing processes on underlying rocks and the channel network is a specific form of cryogenic morpholithogenesis that is typical of regions with inclement climate and harsh environment. Annual formation and ablation of aufeis deposits provide for development of specific geodynamic processes and phenomena, such as destruction and transformation of vegetation, formation of laminated and lenticular ground ice layers, activation of cryogenic weathering of rocks, soil heaving, formation of ice- and ice-ground barriers, mechanical compaction and cryogenic relocation of alluvial deposits, thermokarst subsidence and caving, thermal erosion and exaration, redistribution of water resources, and melted aufeis runoff. The above-mentioned processes create specific

conditions, in which the riverbeds and river valley bottoms are subject to major changes, leading to variations in their status in the seasonal, perennial and secular cycles of development. The aufeis morpholithogenesis predetermines not only the geometric structure and dynamics of the system of rivers of ranks 1 to 5, but also the composition, structure and properties of alluvial deposits in the vast regions of the permafrost zone. In order to reveal regularities in the formation and development of the aufeis sections of the river valleys, it is required to conduct long-term studies with application of simultaneous aerospace imagery and ground-truth observations to confirm satellite data on the polygons for monitoring and observation of the aufeis phenomena.

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