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AUFEIS AREAS IN RIVER VALLEYS: ENGINEERING DEVELOPMENT PROBLEMS

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Groundwater-fed icing deposits (aufeis or *taryns*) in northern Eurasia, Canada and Alaska form giant fields covering tens of square kilometers. Every year Siberia develops about 60,000 large ice clusters with a total area of 45,000 km^2 (0.66 % of the permafrost zone), or 35 times as large as the area of all glaciers in the Asian part of Russia. Especially hazardous phenomena of winter flooding, formation of aufeis and ground ice, heaving, thermokarst, thermal erosion, etc. in river valleys pose engineering problems to development of the terrain. The aufeis hazard creates serious difficulties in construction, laying pipelines, production from placer mineral deposits, etc. Three basic principles of terrain development have been formulated proceeding from the conditions and patterns of aufeis formation, with reference to available experience in aufeis hazard mitigation. It is proposed to set up special test sites for further field and experimental studies of aufeis.

Aufeis, icing, aufeis mitigation, permafrost, ground ice, periglacial phenomena, permafrost zone

INTRODUCTION

Anybody who has ever traveled over the land of permafrost in Yakutia, Magadan, Chukchi Peninsula, or Transbaikalia wondered at ice masses persisting on valley bottoms in the warm season. Even local people used to surprises of northern nature are excited to see meters thick blocks of clear blue ice amidst the summer blooming taiga. Such a simple thing as aufeis (icing) keeps many secrets and enigmas. This name appeals and inspires, scares, and fascinates different people in different ways, depending on their age, job, and mode of life. Most often it means extremely dangerous water and ice hazard which is hard to predict and still harder to stop or get rid of. It is especially fearful for drivers, road workers, builders, fishers, and hunters. Woe to anyone who ever carelessly leaves a car on a smooth river ice or sends a convoy over a snow-covered river without reconnaissance: it is very easy to get trapped in slush, freeze into ice or, in the worst case, to fall under the ice and get drowned (Fig. 1). Pingoes and frost heaves may burst out and release violent torrents of water entraining tons-heavy blocks of ice and frozen ground that sweep trees and small bridges, rush on houses, pipelines, power pylons, etc. That is why aufeis parts of river valleys are places of extreme hazard in the permafrost zone.

Although aufeis is a well known phenomenon, its many aspects remain poorly investigated, for a simple reason: the very concept appeared not long ago. It is impossible to create a theory or solve practical problems without having a clear idea of the subject. According to the present views, icing (aufeis) is a sheet-like mass of layered ice or ice coats that form on the ground or other solid surfaces, as well as on river or lake ice, by freezing of successive flows of water that may seep from the ground or emerge from below river or lake ice [*Kotlakov, 1984; Alekseev, 2007*]. The greatest danger comes from large deposits of frozen groundwater discharge (spring aufeis).

UNKNOWN GLACIATION IN SIBERIA

Permafrost occupies $10.7 \cdot 10^6$ km^2 or 65 % of Russia's territory, including more than $5.2 \cdot 10^6$ km^2 (49 %) of continuous, $2.4 \cdot 10^6$ km^2 (22 %) of discontinuous, and $3.1 \cdot 10^6$ km^2 (29 %) of sporadic permafrost [*Koroleva, 2011*]. Large bodies of groundwater-fed aufeis locally called *taryns* in Yakutia are spread over $7.6 \cdot 10^6$ km^2 (71 % of the permafrost zone) and occupy about 56,000 km^2 or 0.66 % of this area. Taryns annually cover 45,000 km^2 in total (which is 3500 km^2 larger than the area of Switzerland), and the number of taryns with an average area of ~1 km^2 approaches 60,000 [*Alekseev, 2015*].

Is it much or not? For comparison, the surface area (F_i) and number (N_i) of glaciers in continental Russia are, respectively, F_i = 2551 km^2 and N_i = 1727 [*Dolgushin and Osipova, 1989*]. Thus, the total area of icing or congelation ice in this country is 18 times that of classical (sublimation) glaciation, and the large groundwater ice deposits are 35 times more numerous than valley glaciers in Asian Russia.

The existence of extensive aufeis fed from the subsurface long appeared puzzling: where may all this water come from? Being tight for water, permafrost

Fig. 1. Aufeis: one of most hazardous cryogenic effects in northern roadways.

No driver would ever dare taking a winter road alone, only in a convoy (*a*), for the great risk of getting frozen into (*b*, *c*) or sinking under (*d*) the ice; it is problematic to get through an aufeis valley even in the warm season (*e*). Photographs borrowed from websites (Yandex.Photo, etc.).

would seem to seal underground reservoirs and prevent them from both recharge and discharge. The problem was resolved in the second half of the 20th century [*Sedov and Shvetsov, 1940; Shvetsov, 1951, 1981; Shepelev, 1987; Hu and Pollard, 1997*]: rather than being monolithic, the frozen part of the crust turned out to enclose a complex system of connected taliks making channels for water intake and output. Furthermore, there are widespread subpermafrost cryo-artesian basins of pressurized groundwater [*Tolstikhin, 1974*]. Aufeis, permafrost, and taliks, along with the active layer, form various types of cryo-hydrogeological structures which appear on the surface as ice-ground complexes (Fig. 2). The formation patterns and properties of these structures are poorly understood. It is because of this incertitude, that frozen ground seems so mysterious and worrying, which some prompt design makers prefer to ignore. It is urgent to discuss this issue now when large-scale development of mineral resources is on the plan and has

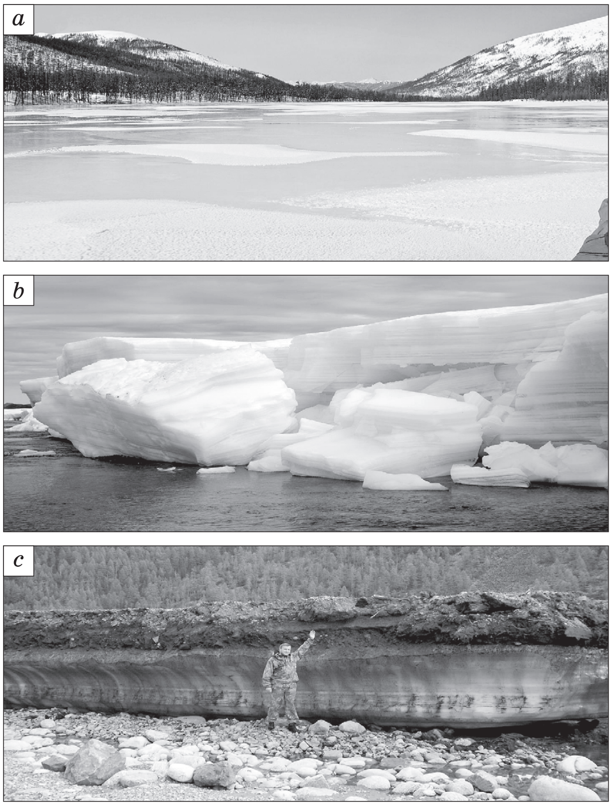

Fig. 2. Taryns in zones of continuous and discontinuous permafrost.

a: giant groundwater-fed aufeis in the Barguzin basin, Baikal region (photograph by the user *Polyach*, Yandex.Photo website 0_3f4c0_58bbdd94_orig); *b*: melting aufeis in a river valley in the Kolyma catchment (photograph by the user *Mochalova*, Yama River...45035806); *c*: intrusive ice in an aufeis field in the Algama River valley, Southern Yakutia (photograph by the user *irina-karman*, Yandex.Photo website ...00_437ed_13f9569b_orig. – https://img-fotki.yandex.ru/get/4201/irina-karman.4/0_437ed_13f9569b_S).

started already in the eastern part of the country, especially, in northern Siberia and Russian Far East.

MODERN MEASURES OF AUFEIS HAZARD MITIGATION

Engineering problems associated with aufeis in eastern Russia first arose during the construction of the Trans-Siberian railroad in the 1900s. Aufeis occurred almost in every river valley, along any stream in the Transbaikalian and Amur road segments. Relatively small (within 2–3 ha) ice sites posed much trouble to the engineering and operation of the railway. The melt water flooded bridges and embankments, rushed into houses and utility buildings, pulled out support structures, inundated road excavations and tunnels, destroyed drainage systems, etc. Almost three decades of trial and error were spent on working out protective measures, including those for automobile and horse traffic, which led to some solutions, though not final and restricted to few places. In those years mainly river and groundwater aufeis hazard could be somehow mitigated. The measures included putting up frozen belts, ground or wooden retaining walls, additional road excavations, heat insulation and straightening of river and creek channels, etc. Bulldozers, excavators, road scrapers, and cranes appeared in the post-war time to replace iron bars, shovels, and hand barrows used in the 1930s, but the approaches did not change much.

The use of powerful machines created an illusion that coping with icing, as well as with any permafrost hazard, would be an easy thing. When doing geotechnical work for the Baikal-Amur railway and the East Siberia-Pacific pipeline, I heard many times people saying: “There is no problem with permafrost and icing now. If a roadbed caves in, we’ll fill it up, if a heave pops up, we’ll cut it off, if a bridge bends, we’ll fix it or build a new one”. They thought that the point was to lay a pipe or rails as fast as possible not caring about future problems: as good as done. However, the neglect of aufeis hazard savors of crime because it may lead to emergency, fatality, and environmental disasters. The experience of using roadways (Fig. 3) is a bright example of how urgent the icing protection is. The nature always revenges familiarity and punishes severely the lack of care and unwise strategy choices,

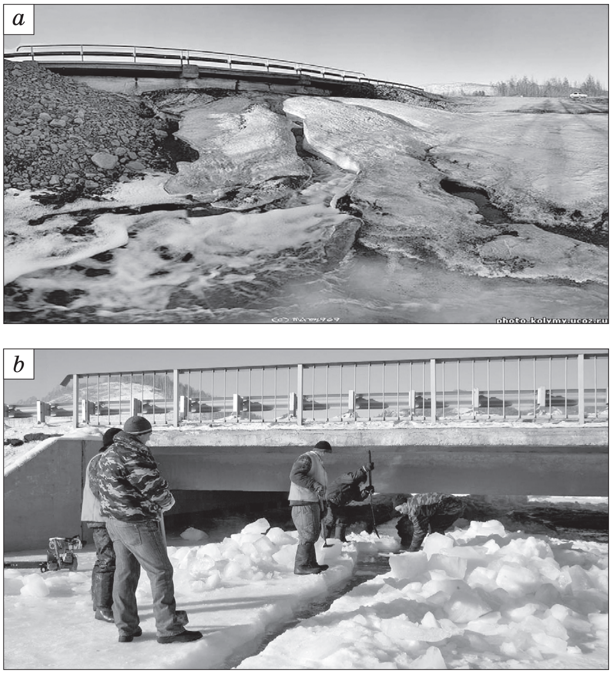

Fig. 3. Aufeis hazard on roadways widespread all over the permafrost zone.

a: aufeis under a bridge crossing on the Kolyma River (photograph by Vladimir Chekhovskikh); *b*: aufeis in the Shebala area, Altai (Yandex.Photo website...0_6e400_95c33476_orig).

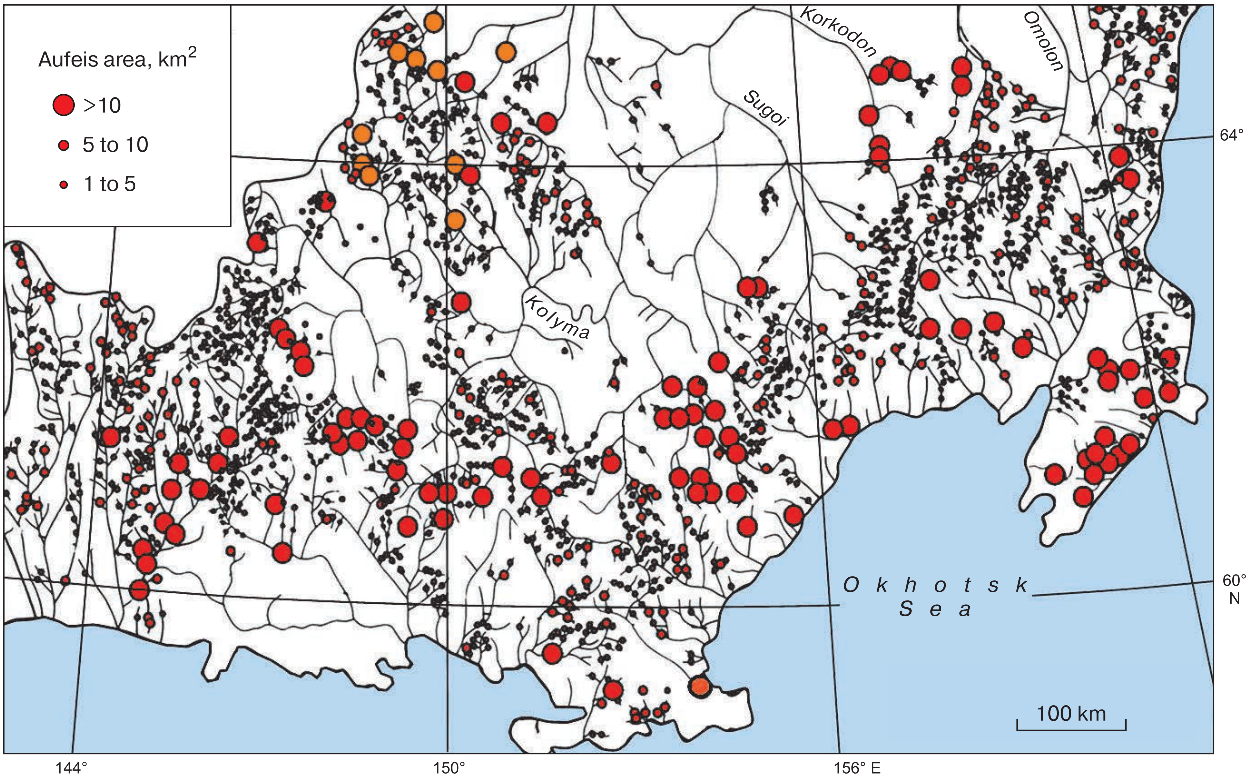

Fig. 4. Map of giant taryns in the Kolyma Plateau.

as it has been proven many times for the recent decades.

Siberia stores most of Russia's petroleum and mineral resources (oil, gas, metals, diamonds, coal, etc.), mainly within the permafrost zone, where the cryohydrogeological setting is of utmost complexity and giant icing deposits occur almost in each river valley (Fig. 4).

Spring taryns spread for tens of kilometers in many regions [*Shvetsov and Sedov, 1941; Tolstikhin, 1974; French, 1976; Shepelev, 1987*]. Ice masses beaded on the main stream periodically move along it forming large fields (glades) which straddle rivers and reach 1.5 to 3.5 m, or even 5–8 m thick or more. Aufeis in high-latitude and high-altitude permafrost areas can persist during warm seasons while the largest deposits are perennial. The relative amount of aufeis reaches 0.2–1.5 % of the surface area in mountains and 10–12 % in some small river catchemnts.

It would be naïve to fight this monster with the arms of the 1930s, but neither big excavators nor bulldozers will help anyway. Meanwhile, the challenge has to be met while developing permafrost areas. One might either detour a railway or a pipe line or traverse a 2 to 5 km wide ice glade ignoring the warning from scientists. However, is there any gain from such audacious breakthrough inherently doomed to enormous costs? Or, is there anybody to take on the responsibility for future troubles? The development strategies should take into account harsh climate and unusual water exchange in permafrost. To do this, the explorers, the designers, the engineers, and the future inhabitants should be aware of the facing hazard.

WHAT ARE THE PROBLEMS?

The available experience of engineering development in places of large taryns has been limited mainly to operation of winter roadways and the use of ice fields as landing and take off sites for helicopters and small aircrafts. Problems would seem not existing as there are no large structures at taryn sites: few people would let their pet project (a house, a pipe, a power pylon or a road) be flooded in bitter cold or stuck frozen into ice. Taryn hazard is mentioned in no handbook, manual, or technical standard document. However, this suppression only makes the development problems ever more topical, because there is no way round the future economic use of taryn fields.

The engineering development problems in terrains subject to periodic icing may be related to stability and durability of buildings and structures (i); appear in the course of production, construction, and other works as aufeis forms, breaks down, and melts out (ii); or result from violation of the norms and regulations of environmental and engineering safety

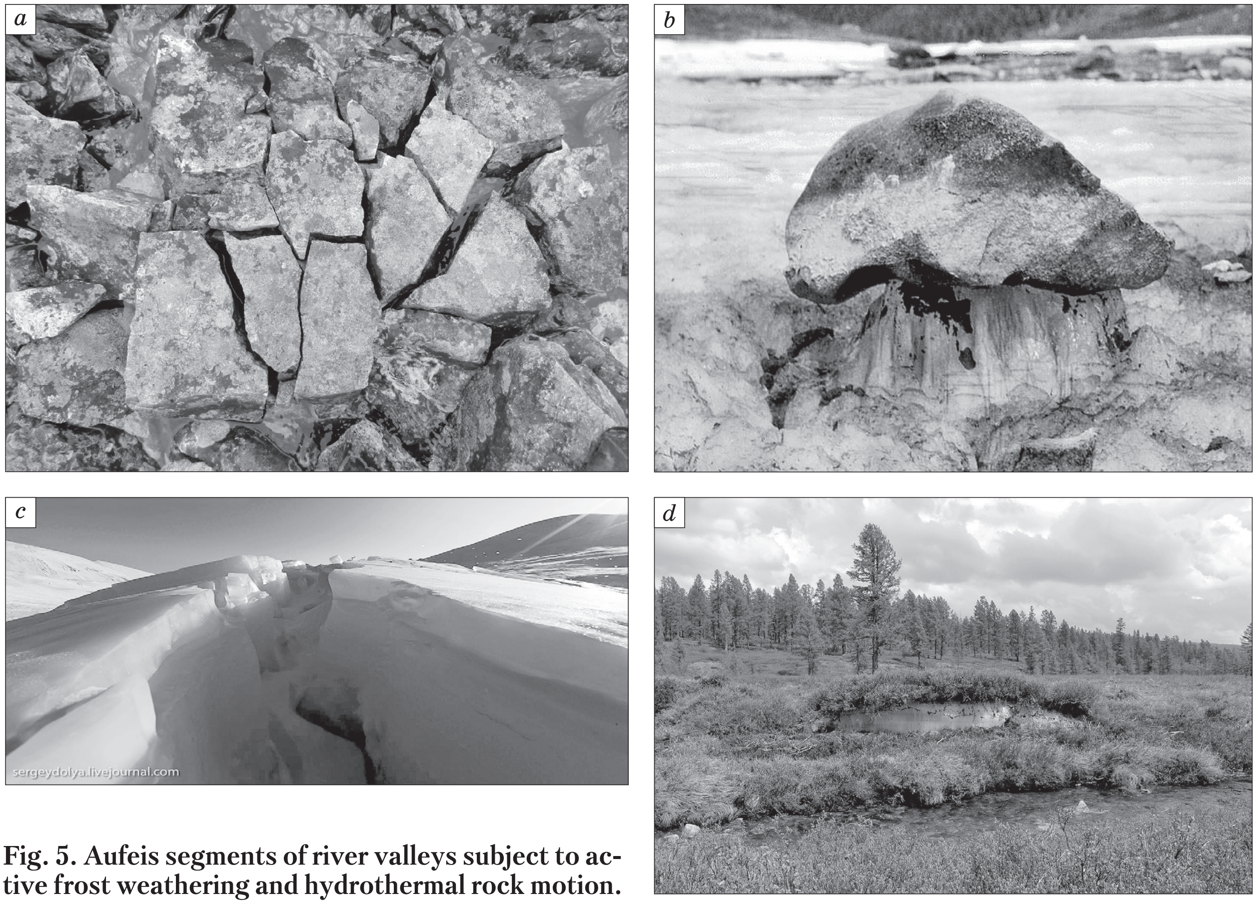

Fig. 5. Aufeis segments of river valleys subject to active frost weathering and hydrothermal rock motion.

a: mudstones in an aufeis field in the Yudoma River valley broken as a result of warming by aufeis water and ice wedging (photograph by the user *strannic1959*, Yandex.Photo website...0_8aa03_5ebecccc_orig. – https://fotki.yandex.ru/next/users/strannic1959/album/196489/view/567811?page=0); *b*: a granite boulder uplifted to a height of 0.5 m by growing intrusive ground ice in the Eden River valley, East Sayans (photograph by V. Alekseev); *c*: aufeis-induced heave in the Chukchi Peninsula produced by freezing of a suprapermafrost groundwater lens (photograph borrowed from the website chukotka_682); *d*: subsidence of ground enclosing a lens of intrusive ground ice in the Neryungra River valley, Southern Yakutia (photograph by the user *zhenyalevina*, Yandex.Photo website...0_70064_a2c01260_-1-orig. – https://fotki.yandex.ru/next/users/zhenyalevina/tag/%D0%BD%D0%B5%D1%80%D1%8E%D0%BD%D0%B3%D1%80%D0%B8/album/135046/view/458852?page=8&search-author=zhenyalevina).

(iii). The three groups of problems are associated with specific hydrothermal regime, structure, and properties of taryns that differ markedly from those in adjacent areas. Engineering problems are due to the following features of natural aufeis deposits.

1. Discharging groundwaters periodically flood many permafrost river valleys in winter. The emergent water freezes up producing layered ice over a large part of the developed area which coats objects on the ground surface. Groundwaters are often filtered through snow and propagate far beyond the limits of visible ice fields. The resulting slush poses great hazard to people, animals, and vehicles.

2. Freezing of successive flows of water and melting of ice are accompanied by changes of microclimate: aufeis floodplains are on average 1.5–2.0 °C warmer in winter and colder in summer than the surrounding areas. They also have higher backscattered solar radiation and air humidity; are prone to mists and cold snaps; have 30–45 days shorter vegetation of plants; show changes in flow hydrograph.

3. Spilling water produces a heat impact upon frozen surface; its freezing in cracks causes wedging, rapid frost weathering, and disintegration of rocks or construction materials (Fig. 5, *a*). Taryn sites are a sort of stone quarries where bedrock terraces become eroded and retreat five to ten times faster than in normal conditions while coarse-grained rocks, soils, and materials become fine-grained at rates ten to hundred times faster than outside such areas.

4. Accumulated aufeis causes additional load on the ground (up to 10 t/m^2), which leads to its compaction or loosening and motion (landsliding or thrusting). Lateral variations in ice thickness pro-

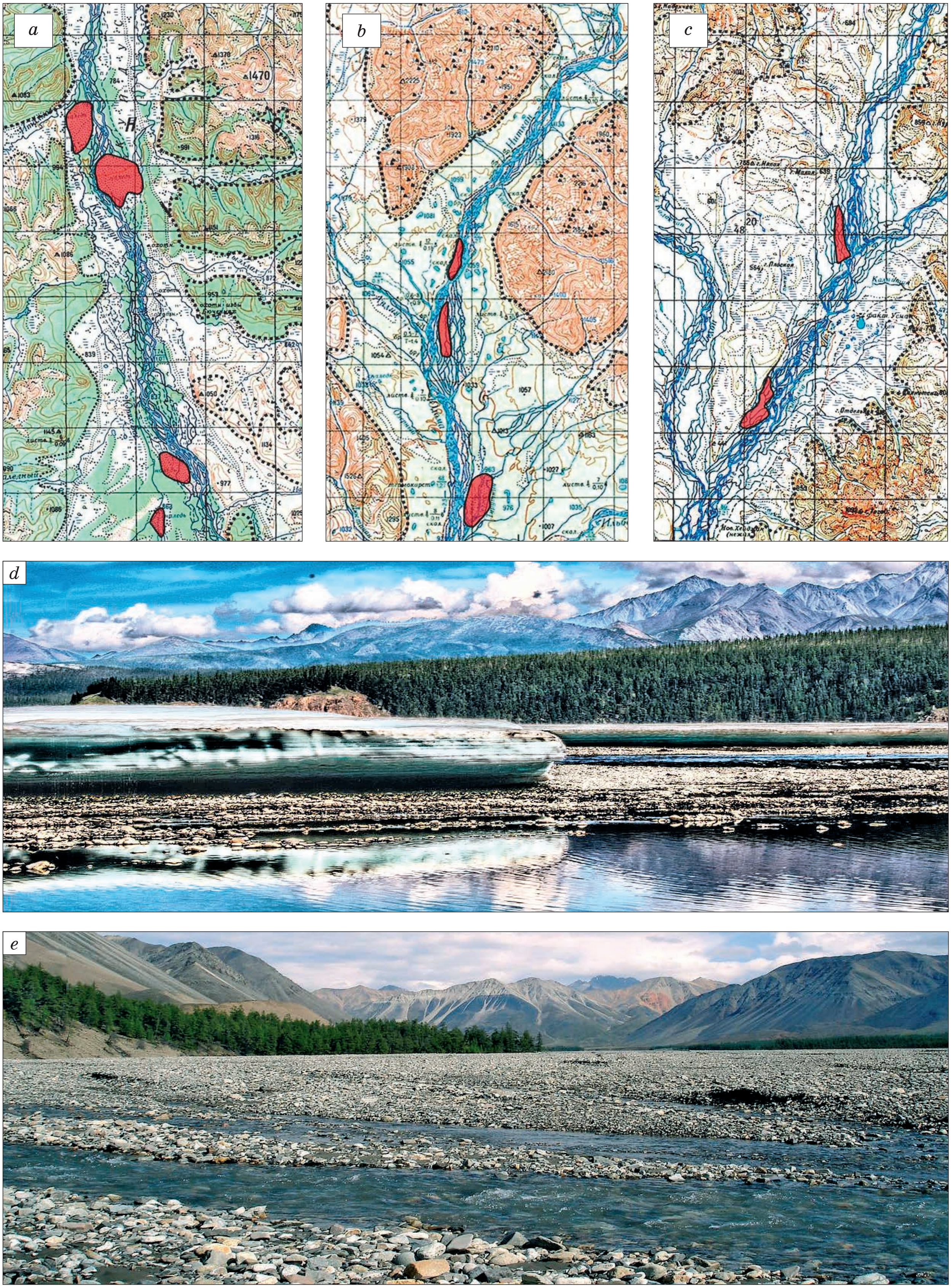

Fig. 6. Transformation of drainage network at taryn sites.

Fragments of topographic maps of the Verkhoyansk-Kolyma mountain province, with contours of paleo-aufeis fields (dothed line). Red color shows aufeis blocks on the day of shooting. 2 × 2 km grid. River valleys: Kuidusun (*a*), Yudoma (*b*), Inya (*c*). Aufeis river channels in the warm season: Bulkut River (*d*) (photograph by the user *Mekheda Alexander*, website Panoramio 81393575. http://www.panoramio.com/photo/134483594), *e* – Suntar River (photograph by the user *Yulya Ustinova*, Yandex.Photo website... 0_21bd1_54c451bc_orig).

duce a complex ground stress pattern. The subsidence and sliding of ice deform objects frozen into it (Fig. 5, *b*), as well as the underlying ground.

5. Short-period variations of air temperature, with an amplitude exceeding 10–15 °C, induces cyclic thermal expansion and contraction of ice: it decreases in linear size and in volume upon cooling and increases upon warming. The coefficient of volumetric thermal expansion (contraction) of homogeneous ice β_t is presumably constant ($\beta_t = 0.158 \cdot 10^{-3}\,°\mathrm{C}^{-1}$); that of linear expansion is $\alpha_t = \beta_t/3 = 0.053 \cdot 10^{-3}\,°\mathrm{C}^{-1}$. Thermodynamic stress leads to cracking, heaving, and thrusting of ice masses onto bridge supports and power pylons. Deformation is the strongest in spring, at temperatures from 0 to –20 °C.

6. Freezing of water lenses and layers inside the ice creates extremely high pressure on the ground underneath which can contort and flatten casing strings, pull out and displace piles, and destroy protective boxes and containers. Freezing of confined water lenses deforms the host rocks and produces pingos and frost heaves (Fig. 5, *c*) which can burst out and lift in air tons-heavy blocks of ice and frozen ground. The formation of water lenses is hard to predict as their location changes randomly from year to year.

7. Particular ice-ground complexes form at taryn sites and pose great hazard all year round. Such complexes consist of cover ice on the top, seasonally frozen ground with intrusive ice in the middle (Figs. 2, *c* and 5, *d*), and permafrost or unfrozen wet rocks at the base. The ground and ice experience 0.5–1.0 m (on average) of uplift in winter and subsidence in summer. These annual vertical movements induce softening and mixing of the ground and reduce strongly its bearing capacity.

8. Spring aufeis transforms the structure of the drainage network: river channels become split into several small meandering arms which annually move relative to one another and produce a reticulate pattern of ice fields (Fig. 6, *a–c*). The average river network increase per one taryn varies from 3.5 km in the mountains of East Siberia to 11.4 km in the Putorana Plateau, and to 23 km in the Verkhoyansk-Kolyma mountain province and in the Chukchi Peninsula. The total drainage network increase in areas of continuous and discontinuous permafrost ($F = 7.6 \cdot 10^6$ km^2) reaches 690,000 km. In summer, ephemeral ice-ground islands (Fig. 6, *d*) or drained surfaces of aufeis fields or irregularly shaped shallow lakes (Fig. 6, *e*) often form in the place of taryns. The complex structure and prominent dynamics of the drainage network control the temperature, configuration, and variations of frozen and unfrozen (talik) zones and pose problems to construction and operation of engineering structures.

9. Aufeis fields change in size from year to year and can either break up and disappear or expand far over their surroundings, the variability being independent of their size. The volume of spring aufeis shows short-period cyclicity, with 3–5 to 10–11 year cycles which differ in time, even in genetically uniform taryns, irrespective of air temperature and moisture. This variability impedes prediction of icing processes and increases the hazard.

10. The cryological and hydrogeological features of aufeis floodplains remain insufficiently studied. It is still unknown where permafrost and talik zones are exactly located under ice masses. Hypothetical dependence of temperature and water content of rocks on ice thickness and area has been poorly supported by field data, which impedes estimating the state of permafrost-groundwater systems at different evolution stages and solving specific problems of their interaction with subsurface and surface geotechnical structures.

Therefore, development of river valleys with taryns occurs in extremely complex natural conditions. It may be said without exaggeration that this issue encompasses all main engineering problems topical for high latitudes, southern Siberian mountains, as well as for the whole permafrost zone.

ENGINEERING DEVELOPMENT PRINCIPLES IN AUFEIS TERRAINS

There is nothing impossible for the man: moving mountains, creating seas, and wandering the Universe. Perhaps, it is even possible to win over the great 100 km^2 Moma aufeis field in the Indigirka basin. But at what costs? Is it really necessary to appease the powers of nature instead of dodging an hazardous place? However, the tens of thousand taryn sites in northeastern Asia are too many to skip them all around. The areas of huge taryns will come into development sooner or later, and the troubles will not be too long to wait. In this case, special achievements of scientists and engineers will be in demand. Some engineering development principles and ways of aufeis hazard mitigation for future construction in the most dangerous places of the permafrost zone can be suggested proceeding from available knowledge of spring aufeis fields and their evolution patterns.

Principle I. Avoiding hazard by elimination of icing sources:

a) displacement of groundwater discharge by underground capture culverts, dewatering holes, wells, manmade taliks that take up or let out water, etc.;

b) freezing aquifers and underground discharge channels by natural or manmade cold.

Principle II. Reducing hazard by changing conditions for aufeis formation (management of water flow and freeze up):

a) providing transit of water by controlled surface and/or subsurface run-off (making cold proof channels, culverts, or drains; deepening or straightening river channels, etc.);

b) confinement of aufeis by retaining walls, fences, additional excavations.

Principle III. Conservation of natural icing regime:

a) freezing and thawing of underlying ground locally without changing the conditions for groundwater discharge;

b) leaving everything as is.

Principles I and II can be applied in the case of using the standard engineering constructions without adapting them to changing conditions, while principle III implies modification of existing structures and technologies or creation of new ones adapted to the complex development conditions. The choice and use of different principles will require detailed investigation into formation and long-term variations in aufeis and its sources, as well as prediction of possible changes in aufeis formation and general permafrost and groundwater settings under effects of climate change and human activity. Obviously, the choice of the nature management principles depends on development objectives (Table 1). Anyway, efficient use of aufeis terrains is impossible without gaining more theoretical, practical, and methodological knowledge.

There are reasons to expect that future construction within the present aufeis terrains will bring about new engineering solutions for all development stages.

Table 1. **Recommended engineering principles for different ways of aufeis terrain development**

Objects	Engineering principles					
	I		II		III	
	a	b	a	b	a	b
Civil buildings and structures (urban and industrial objects)	+	+	+	+		
Pipelines			+	+	+	+
Cables and other underground communication lines			+	+	+	
Roadbeds and construction sites			+		+	+
Bridges and viaducts			+	+	+	
Winter roads, ice crossings, landing places and air strips on ice						+
Landing places and air strips on ground	+	+				
Power and transmission lines					+	+
Water intakes and aqueducts			+			+
Dams and artificial lakes (water reservoirs)					+	+
Winter storages			+	+	+	+
Development of placer mineral deposits	+	+	+	+	+	+
Dredging			+			+
Stocking			+	+		
Tailings and impoundments	+	+		+		+
Navigation of small vessels and boats			+			

STATE OF THE ART AND FUTURE RESEARCH OBJECTIVES

Predicting future events is one of main tasks of the science. Foreseeing the future is important, but it is more so important to anticipate the recklessness of decisions, i.e., to provide preparedness to and mitigation of possible disasters. Icing hazard is insidious and dreadful. Knowing the essence of all intricacies of natural powers is indispensable for winning them over. Therefore, special research, observations, and experiments are required. Many scientists and engineers were trying to look into the icing effects and fathom their secrets, but many failed. Aufeis monitoring for three to thirty years was set up at about thirty test sites in Transbaikalia, central and southern Yakutia, northern Urals, Cukchi Peninsula, Altai, and Far East, almost all over the Russian permafrost zone. However, many aspects of origin and dynamics of spring aufeis remain poorly understood. The permafrost and groundwater settings and their relation to dynamics of its sources and freezing patters have been investigated at few places only [*Sedov and Shvetsov, 1940; Tolstikhin, 1974; Shepelev, 1979, 1987; Yoshikawa et al., 2007*]. The reason is that the research lacked coordination and a single program, used different methods and did not include studies of the hidden subsurface part of aufeis systems: no integrated drilling, geophysical, climatic, glaciological and other necessary works have been undertaken. The monitoring at test sites was limited to measuring ice thickness and contouring ice masses; sometimes water flow observations were performed as well. However, the collected data were obviously insufficient for conceiving and modeling the whole cycle of effects that control the morphology and changes of surface aufeis.

Taryns represent the thermodynamic state of the uppermost crust. They are only a link in a complex system of water exchange between large and small permafrost-groundwater structures and their environment. The structure and properties of soft sediments within aufeis fields change annually as a result of groundwater migration, freezing and thawing of water paths, formation of lenses and layers of intrusive ice, frost heaving, static and dynamic loading from ice masses, etc. [*Alekseev, 2015*]. Discovering the driving mechanisms of these complex processes requires integrated research at special test sites. The program of such studies has been elaborated and was published many years ago [*Alekseev and Sokolov, 1980; Alekseev, 1989*] but its implementation stopped in the early 1990s because of political and social cataclysms. The interest to the program has rekindled recently as extensive development of Arctic and Eastern territories of Russia is coming to play. Furthermore, comprehensive investigation of taryns is of strategic significance: creating coordinated outrunning field observations and experiments will ensure the environment safety, stability, and cost efficiency of future natural-engineering systems used in the high latitudes (roadways, pipelines, buildings, utilities, etc.). Working out a new long-term program for investigation of groundwater-fed aufeis is an urgent task for permafrost scientists and engineers.

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