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BASIC PROBLEMS OF GEOCRYOLOGY

GLACIERS IN SIBERIA AS COMPONENTS OF GLACIAL-PERMAFROST SYSTEMS

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The cold and dry continental climate of Siberia and a large extent of permafrost create specific conditions for the origin and dynamics of glaciers. The Siberian glaciers interact with permafrost and become a new component of cryodiversity (an assemblage of all effects produced by the cold). They develop upon frozen ground and have temperatures below freezing, thus acquiring properties more characteristic of permafrost than of the Alpine-type glaciers. It is reasonable to consider the Siberian glaciers, jointly with the related cryotic features, as components of glacial-permafrost systems.

Permafrost, glaciation, glacier-permafrost interaction, glacial-permafrost system

INTRODUCTION

The today's systematic knowledge of the cold world opens new avenues in cryological research, which requires synthesizing the available data into a framework of views covering all cold effects. All these effects can be considered as elements of cryodiversity [*Melnikov et al., 2013a*], within the single context of global geocryology.

Note that the terms *cold* and *warm* refer to human perception rather than to physical properties. The concepts of *cold* and *warm* characterize the thermal state of objects as people feel it, while physics deals with the parameter of *heat* and its amount corresponding to the energy transferred from one body to another during heating or cooling. At the same time, the concept of *cold* is a key one in permafrost science and refers to a medium at negative temperatures (below freezing), as well as other terms derived from the Greek word χρνοζ (*cryos*) meaning *cold*, *frost*, and also *ice* [*Dvoretsky, 1958*]. The Greek, which together with the Latin makes basis for the scientific terminology, is used broadly in the Mediterranean where the concepts related to cold and frost have been always associated with the ice, or the cold effect.

The terms derived from *cryos* are especially important elements of the basic permafrost terminology to name the effects of cold. The widespread term *cryogenesis* spanning various processes that develop below freezing and produce frozen bodies literally means *born by the cold*. The concept of *cold* referring to a medium at negative temperatures in permafrost sciences becomes ambiguous when applied to glaciers: it appears strange to attribute glaciers to cryogenesis, even if they belong to the permafrost zone. The reason is that historically the studies began before the permafrost science developed and concerned with glaciers lying outside the permafrost zone. However, being derived from snow, which is a result of atmospheric cryogenesis, glaciers may form either outside or within the permafrost. In the latter case, this is a product of cryogenesis in a complex and dynamic geological system consisting of snow and snow-derived ice upon frozen rocks.

Ground surface glaciation may also appear as icing caused by freezing of taliks and thus classified among permafrost phenomena. Unlike the glacier ice produced by deposition and compaction (metamorphism) of snow [*Shumsky, 1955*], icing forms by congelation, or rather re-congelation. The non-permafrost and permafrost glaciers, icing, and other related phenomena are different components of the global cryosphere, which can be systematized using a concise concept of *cryodiversity*.

In Siberia all glaciers occur within the permafrost and are related to cryogenic processes both in atmosphere and lithosphere [*Sheinkman, 2010, 2012*]. Thus glaciation becomes in focus of both glaciology and permafrost sciences, and has to be studied in terms of global cryology considering ice of all types as elements of cryodiversity and components of cryogenic geological systems [*Melnikov et al., 2010*], with due regard for the specificity of their constituents.

The cryogenic systems of Siberia include snow-derived ice which forms lithospheric geological bodies intimately related with other elements of the permafrost (cryolithozone) system. The snow-derived

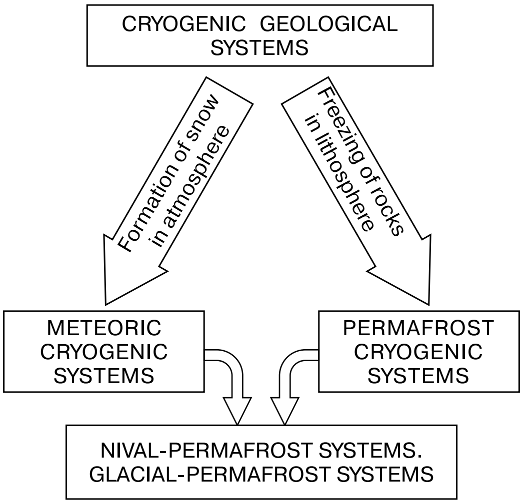


Fig. 1. Cryogenic systems.

ice is often treated conventionally as nival-glacial systems in terms of the genetic series "snow cover–snowpack–glacier". To describe these systems more precisely but with the common terms, we suggest to add the clarifying attributes *nival* or *glacial* to the name *permafrost* for the systems dominated by snow structures or ice flows, respectively (the glaciers being ice flows of meteoric origin according to *Shumsky* [*1964a*]). Thus, the cryogenic geological systems can be either nival-permafrost or glacial-permafrost ones (Fig. 1). The latter are the subject of this paper, which continues our earlier publications [*Melnikov, 2010; Melnikov et al., 2013b; Sheinkman, 2010, 2011, 2012; Sheinkman and Melnikov, 2011*].

TERMINOLOGY

It is pertinent to begin with a historic perspective of terms currently used to name the phenomena related to the cold as systematizing terminology in permafrost sciences is among the objectives of our study. The terms glacial (from the Latin *glacies* that means *ice*) and glaciation (*ice age*) were originally related to glaciers, though could, in principle, refer to any ice. These terms are most often associated with accumulation of ice in glaciers, and one has to take this usage into account to avoid confusions.

Furthermore, there is a German term *periglaziale* (*periglacial*) *Lozinski* [*1912*] suggested for the climate of areas around glaciers and related phenomena. Inasmuch as *glacial* (from the Latin *glacialis* meaning *related to ice*) was associated with glaciers and the prefix *peri-* (from the Greek περι meaning *near*) with something near them, the term was applied to phenomena caused by cryogenesis in glacier surroundings. Yet, in the terminology of the Alpine school it became used for all effects of cryogenesis, and the sense changed. The terms, however, remain etymologically and hence semantically the same, and the broad sense of *periglacial* synonymous to *cryogenic* inevitably restricts the processes to development of glaciers, but this is unacceptable for Siberia where there is a genetic difference between glacial and near-glacial zones.

Note that when using the terms *cryogenic*, *permafrost*, or *nival-glacial* in the common narrow sense, glaciologists and permafrost scientists mean any ice variety, but in fact try to avoid the cases of ice bodies produced jointly by glacial and permafrost processes. It is reasonable to employ the above terms to systematize the views of cryology. We suggest to estimate the permafrost evolution as part of complex cryogenic systems, with their mass and heat exchange, but to leave the same narrow meaning of commonly used terms.

A question may arise whether it would be simpler to treat glaciation in the conventional way as a nival-glacial system but to impart a new content to the old concept. However, a system with this name would refer to accumulation and transformation of snow in the genetic series "snow cover–snowpack–glacier". The term *cryogenic*, for which its literal translation of *born by the cold* is the best meaning, spans all groups of phenomena as far as they are produced by the cold, but the systems in which glaciation forms in the conditions of permafrost should be treated in a special way. In this respect, *glacial-permafrost* appears the right term as it refers to a complexly organized system consisting of the glacier and the permafrost components in its vicinity, related through heat and mass transfer and the effects (erosion and deposition) they jointly produce.

HISTORIC BACKGROUND

Approaches to glaciation: Alpine school

The knowledge of glaciers comes from the Alpine school existing for more than two hundred years. The fundamentals of the theory proceeding from studies in the Alps were first published by Horace-Bénédict de Saussure as his scientific observations gathered en route through the mountains under the general title *Voyages dans les Alpes* in 1779–1796. Those models explained formation of glaciers primarily by accumulation of snow far exceeding ablation and its subsequent compaction, fast recovery of lost ice by influx of its new batches, and ice resistance to melting due to a high melting point (334 kJ/kg). The resulting perennial snow and ice caps mostly lie upon unfrozen rocks.

The snow-rich settings subject to the warming effect of oceans (like those in the Alps) are obviously favorable for glaciers but unfavorable for ground freezing. On the other hand, the cold and dry climate of Siberia favors the development of permafrost but restrains (though does not prevent) the formation of snow-derived ice. For that reason the existence of glaciers in the cold and dry continental interior of Siberia was long thought to be impossible. This attitude was first expressed more than a hundred years ago, by *Voeikov* [*1881*], a famous Russian climatologist, and was supported later by S. Kalesnik, the founder of glaciology in Russia, in his book *General Geography* used by many generations of students [*Kalesnik, 1947*].

Understanding the complexity of cold as a contribution to glaciation and the specificity of the latter in Siberia took quite a time. The earliest reports of perennial snow in the mountains, besides those of frozen ground, came from Siberian pioneers of the 17th century. However, the knowledge of frozen ground was vital for living while the studies of perennial snow in the remote and hardly accessible mountains waited till the late 19th century. The overviews of glaciation in the Altai mountains, the easiest to access in Siberia, appeared in the late 1940s [*Tronov, 1949*], about 150 years after the book by *Saussure* [*1779–1796*]. Such works concerning eastern and northeastern Siberia came out as late as after the IGY (International Geophysical Year) project of 1957–1960 [*Preobrazhensky, 1960; Koreisha, 1963, 1991; Grave, 1964; Vinogradov, 1966–1981; Sheinkman, 1987, 2011; Kotlyakov, 1997*].

The continental climate setting in Siberia was explained in the classical theory by *Voeikov* [*1881*], which however negated the existence of glaciers proceeding from the Alpine model. Voeikov had so much authority with scientists that some even did not dare to report the discovery of mountain glaciers in Transbaikalia [*Sheinkman et al., 2011*], or tried to find explanations somehow consistent with Voeikov's theory. Namely, the extant glaciers were recognized but interpreted as relict prehistoric ones formed in the past according to the Alpine model. For example, the glaciers discovered in Yakutia, with a strongly continental climate, were attributed to the past air circulation patterns when ten times more moisture than now would have reached the continental interior [*Vaskovsky, 1963; Grave, 1964*], but the causes of the situation were not explained.

Meanwhile ever more facts became brought to light. Low temperatures of glaciers, remaining negative all year round and playing an important role in their evolution, were discovered in the highest mountains in the Alps and the Caucasus, the southern regions subject to the warming effect of the Atlantic ocean [*Pogorelov, 2002; Mikhalenko, 2007*]. This required revision to the Alpine glaciation model, otherwise the scientists had to neglect data that were inconsistent with the classical theory.

For instance, the model of *Grosswald and Hughes* [*2002*] assumes moisture transport into interior Siberia and back to the ocean, in amounts orders of magnitude larger than at present and very rapid within the Pleistocene cold and warm rhythms. Otherwise, the model would fail to explain the existence of ice sheets in the center of Siberia. The model neglects that no signature indicates a direct effect of glaciers on permafrost, which means that there are no facts to support the reconstructions.

Another example is the model of *Balobaev* [*2005*] who suggested that the retreat of ice sheets could account for aggradation of permafrost observed locally in northern Siberia. However, glaciers in Siberia change the freezing conditions beneath them in a different way: by becoming higher or lower, their surface in fact changes the permafrost table. The thermal conductivity of ice is of the same order as in bedrock (2.2 and 2–4 W/(m·K), respectively), and Siberian glaciers, though being heterogeneous, are mostly void of snow cover [*Sheinkman, 2010, 2012*] and are actually conductors of cold rather than heat insulators. Snow-poor glacier tongues conduct cold and cool down the ambient rocks in winter, while in summer heat is spent on warming the upper ice layer to 0 °C and its subsequent melting. Then the meltwater, together with the heat it has received (including that spent on the ice-to-water phase change), flows away from the glacier.

During glacial events in Siberia, when the strongly continental climate limited the formation of glaciers, heat insulation was provided rather by snow fields [*Bolshiyanov, 2006; Sheinkman, 2008*], with their thermal conductivity ten times lower than in ice (it is about 0.7, 0.2, and 0.03 W/(m·K) in dense (highly compacted), medium-density, and fresh low-density snow, respectively). These must be the snow fields *Balobaev* [*2005*] meant when wrote about "fixed glaciers on the shelf and nearby plainland, which formed by long-term accumulation of snow surviving over the short warm season". More so that long-lasting (at least Late Pleistocene) multi-stage wedge ice occurs everywhere in Siberia, from the Yamal Peninsula as far as the Chukchi Peninsula [*Vasilchuk, 2006*]. It records a cold and dry climate, while its continuity prompts the absence of effects from ice sheets.

Approaches to glaciation: recent changes

Cryogenesis involves both the primary material of glaciers in the atmosphere and the glacier bodies on the ground, which imparts special features to them. However, it is not until recent decades that these features received due attention and glaciers took their appropriate place among different components of cryogenesis (an assemblage of all processes caused by the cold).

Nowadays it becomes clear that cryogenesis is a complicated cold-induced process, with all its constituents important for analysis of past and present glaciations. This is especially relevant to Siberia, where the interaction of heat and mass fluxes within glacial-permafrost systems maintains the coexistence and relationship of glaciers with other permafrost components as objects of cryodiversity.

In the glacial-permafrost systems consisting of cold ice flows and the related permafrost components in their vicinity, the elements of glaciation are organized in a different way than in the case of Alpine-type glaciers, and have to be analyzed according to the new content. The glaciers in the continental climate of Siberia experience strong cooling during long cold and dry winters and intense ablation in short but warm summer seasons. The summer is warm enough already at the Arctic Circle latitude, and most of the glaciers are located near or below it. Thus, in warm seasons, ice melts rapidly at these latitudes, and the accumulation line moves farther northward (e.g., at elevations about 2000 m asl, this line lies in the northern offshoots of the Verkhoyansk Range higher than the Arctic Circle latitude). The Siberian glaciers, unlike those in the Alpine model, are maintained by the stored cold in the form of superimposed ice. There are also a few small snowdrift glaciers that occur locally on windward slopes much below the climatic snow line, such as glaciers in the N–S Polar Ural or Kuznetsk Alatau ranges which bar the main air flows [*Sheinkman, 2010, 2012*]. Of course, they complicate the general setting but do not change it dramatically.

Note that the earliest data on Siberian mountain glaciers were first interpreted in terms of the Alpine model because they were collected in southwestern Siberia, somewhat similar climatically to the Alps. The focus was then on the morphology and traces of glaciers, which are similar irrespective of their physical state. The fact that the cold and dry continental climate is the basic feature of Siberia as a whole while the elements of Alpine climate restricted to a few areas are of local significance became properly understood only in the 1990s [*Sheinkman and Barashkova, 1991; Borzenkova, 1992; Gavrilova, 1998; Sheinkman, 2011*].

Ice sheets in the cold and dry western Arctic adjacent to Siberia are worth of special consideration. The Alpine model explains them by the accumulation line elevation as low as sealevel due to the high-latitude location, but it overlooks the features of glacier history. However, there is a complicated process of autochthonous evolution when both ice in the ice sheets and air above them cool strongly because of the large size and high-latitude position of the ice sheets. The glaciers in the Arctic islands make up a special system, which evolves in a different way than the past and present mountain glaciers of Siberia near and below the Arctic Circle [*Sheinkman, 2008, 2010, 2011; Sheinkman and Melnikov, 2011*], and will be the subject of a separate publication.

The specificity of glaciation in Siberia has remained neglected also in paleogeographic reconstructions, and even nowadays it is often interpreted in terms of Quaternary Alpine models, in spite of their conflict with field data [*Astakhov, 2006*]. *Galanin* [*2012*] suggested a reversal model for the interior of Siberia predicting ice waning during the Sartan glaciation, the coldest event (cryochron) of the Quaternary, but ice waxing during the previous Karga warm event (thermochron). We criticized this approach earlier [*Melnikov et al., 2013b*], and here we only note that the Siberian glaciers are controlled primarily by summer air temperatures being very sensitive to cooling increase and decrease [*Koreisha, 1991; Sheinkman, 1993, 2008*]. Therefore, ice can wane rapidly in response to even minor summer warming (which becomes considerable during warm climate events) and, correspondingly, wax during cold periods. The reversal model of *Galanin* [*2012*] can be disproved with glaciological postulates. Namely, the basic parameters of glaciation are often calculated via ablation, their principal control, which is estimated, in turn, using the method of Khodakov and Krenke [*Krenke and Khodakov, 1966; Khodakov, 1978; Krenke, 1982*]. Ablation correlates with accumulation of snow and ice at the accumulation line and, being a consequence of positive heat balance in the summer season, is found by means of an empirical relationship between the molten ice and average air temperatures for the warm season (June through August).

The relationship applies at the regional scale and is an approximation of the form

$$A = k(T_s + c)^n,$$

where A is the ablation in mm/yr; T_s is the seasonal mean temperature (summer months June, July, August) over the glacier surface in °C, and k, c, n are regionally specific empirical coefficients.

In the Alpine conditions, ablation does correlate with melting of snow and firn formed at the accumulation line during the cold season. The warm season, and the heat input, in such regions lasts longer than three months. Ablation becomes compensated mainly by large amounts of frozen precipitation, and it is only dramatic rise of the temperature T_s that can cause notable change to the mass balance of glaciers.

However, the heat received by glaciers in Siberia is balanced with changes in their internal heat. First, the part of a glacier molten at the accumulation line represents accumulated snow, as well as frozen meltwater and the firn upon cold (much below 0 °C) ice it wets. The internal accumulation zone experiences regelation below the current accumulation layer, which can be calculated according to the old method of *Shumsky* [*1964b*]. Second, the summer heat is spent in Siberia on melting cold glaciers which first have to warm up to 0 °C, unlike the mainly warm glaciers in the Alps already existing at subzero temperatures. In this case, the main process consists in heat exchange in the glacier material, the turnover being very long. The extremely short warm season in the Siberian continental climate actually exposes the glaciers to a thermal shock. Therefore, the ice mass may change in response to even minor temperature fluctuations.

Warm glaciers likewise develop a layer of congelation ice at the base of the seasonal snow cover, but this is the only process responsible for re-congelation: it uptakes 10–20 % of meltwater, which is much less than in the cold glaciers (50 % or more [*Bazhev, 1973*]). Congelation proper likewise contributes to accumulation in the Siberian glaciers (see above), as meltwater freezes over the cold ice pad and produces a layer of re-congelation ice [*Sheinkman, 2011*]. That is why, the budget of incoming heat will comprise the heat used for melting snow as well as that for warming the upper glacier part till 0 °C, and that for melting the re-congelation ice. Otherwise, the glaciation parameters will bear large errors [*Koreisha, 1991; Sheinkman, 1993, 2008; Vilesov, 2013*].

Note that the snow-rich settings like that of the Alps were impossible in Siberia throughout the Quaternary. The moisture carried by the western air transport could not reach the continental interior while the monsoon effect was notable only outside Siberia. The monsoons from the Pacific mostly had to turn east because of western transport and those from the Indian ocean were blocked behind the Karakorum–Hindukush–Himalaya barrier (Fig. 2).

This setting has been shown clearly in different climate maps, including the basic ones by *Alisov* [*1964*], a reputed Russian climatologist. It is hard to divide Siberia, with its uniform smooth continental climate conditions, into distinct climatic provinces. In Alisov's map there are a Pacific province in the Anadyr catchment, a uniform Siberian province west of it as far as the Yenisei, and an Atlantic province west of Siberia. This division appears to be the most reasonable. The attempts of dividing it into two (Atlantic and Pacific) glacial provinces led to controversy as to their boundaries: either east of the Verkhoyansk-Kolyma mountain province [*Tushinsky and Malinovskaya, 1973*] or across it in the south [*Kotlyakov, 1997*]. The Pacific cyclones, even if reach the interior of Siberia, are turned by the western transport and actually become involved into the western air flow.

The climate in Siberia was extremely continental during the Quaternary glacial epochs (cryochrons), as the moisture moving inward the continent became captured by ice sheets in western Eurasia while the northern seas were frozen. Therefore, climate cooling and drying (cryo-aridization) changes in space, from west to east, at present (Fig. 2) but changed also in time in the past, on transition from warm to cold events (from thermochrons to cryochrons) [*Sheinkman, 2011; Sheinkman and Melnikov, 2011*].

The dry and cold climate has existed above ice sheets since the past times as a result of autochthonous glaciation in the western Arctic and was restricted to the peaks of glacial cycles in western Eurasia subject to the Atlantic influence [*Velichko, 1981*]. However, it has become predominant in the eastern Arctic and central Siberia, where the Quaternary warm and cold cycles differed only in terms of "more or less cold" and "more or less dry".

Currently, air circulation has been well studied. Air flows are much more intense during warm events than during cold periods: the ocean receives more heat and evaporates more moisture, and the circumpolar ice centers maintain active circulation, both in the ocean and in the atmosphere [*Sheinkman and Barashkova, 1991; Borzenkova,1992; Velichko et al.,1995; Sheinkman, 2008*]. At least, it was the case

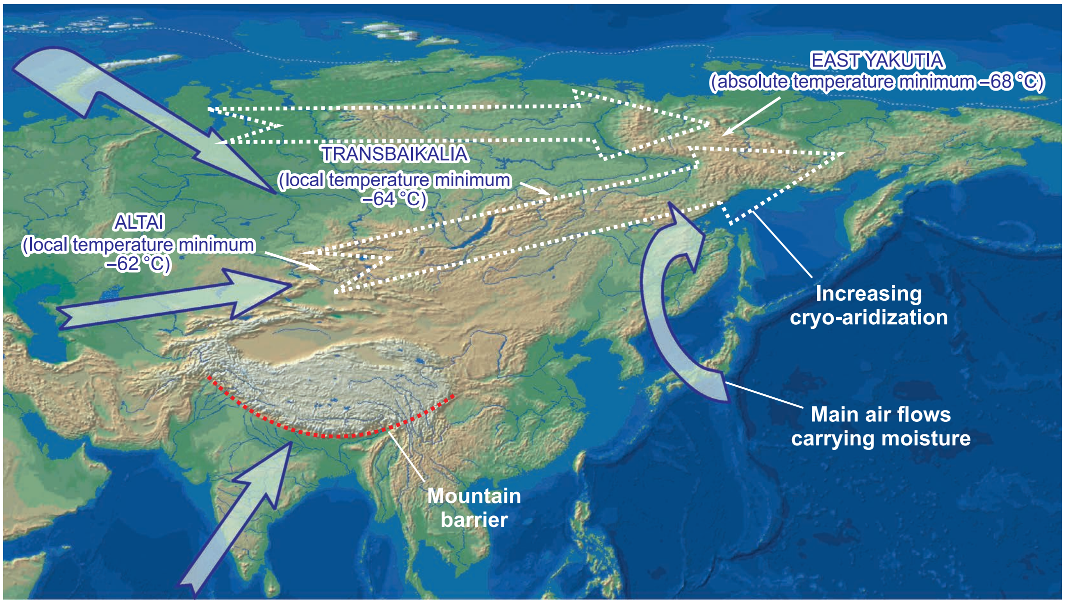


Fig. 2. Factors responsible for the specificity of Siberian glacial-permafrost systems.

when circum-polar ice caps persisted during the Quaternary, unlike the previous period of a warm iceless Earth [*Velichko et al., 1995*]. Summer seasons in warmer and wetter periods become longer and warmer, while they are the summer temperatures that control glaciation in Siberia. Therefore, the models with reverse heat dynamics [e.g., *Galanin, 2012*] are basically unrealistic.

Glaciation in the present Kamchatka peninsula is a classical example: moisture reaches 3000–4000 mm/yr, but the glaciers remain commensurate with those in Siberia, commonly within 10 km long, in spite of the 3–4 times greater accumulation source. Specifically, the ablation-accumulation budget at the accumulation line of the well documented Koryto glacier in the Kronotsky peninsula is as much as ~300 g/cm^2 but the glacier is within 8 km [*Vinogradov, 1966–1981; Kotlyakov, 1997*]. The reason is quite simple: the current warm climate (a Quaternary thermochron) prevents the growth of glaciers.

Thus, the approaches to glaciation have obviously changed lately, though glaciation in Siberia is still viewed sometimes in terms of the Alpine theory presuming that the cold and dry climate would be unfavorable for ice waxing [e.g., *Grosswald, 2009; Galanin, 2012*]. The respective models are inapplicable to Siberia and have been disproved by a wealth of local data collected after IGY.

Therefore, updating the approaches to glaciation in Siberia is quite logical and urgent. It is important to clear up the climate trends inferred from glaciation patterns because neglecting their features, associated with permafrost and cryogenic aridization throughout the Quaternary, may lead to wrong predictions. The specificity of Siberia consists in coexistence and interaction of glaciers with other permafrost components produced by the same heat and mass flows, which all are elements of cryodiversity and belong to cryogenic glacial-permafrost systems.

GLACIAL-PERMAFROST SYSTEMS: IDENTIFICATION AND STRUCTURE

Formation of any glacier requires an amount of frozen precipitation sufficient for snow accumulation and compaction and depends on how far the territory penetrates into the chionosphere. Irrespective of their physical properties, all glaciers live through the same morphological history from a nascent body to a large valley glacier, or even to an ice sheet at favorable conditions. Glaciers of the same morphological types look similar and produce similar geological effects (erosion and deposition). For example, the Sofiysky glacier (Fig. 3, *A*) in the ~4000 m high Central Altai mountains and the Djankaut glacier (Fig. 3, *B*) in the slightly higher Central Caucasus mountains look similar above the tree line (at locality-specific altitudes).

However, the apparently similar two glaciers differ in the use of basic resources and in the structure of ice complexes. The Siberian Sofiysky glacier occurs within permafrost and is involved in permanent interaction with its other elements. Note again that the Siberian glaciers have a dual nature: they result from the atmospheric cold transport by snow and, on the other hand, are a product of cryogenesis on the ground surface and an element of permafrost.

To put it different, glaciation in Siberia results in bodies of ice as a monomineral rock, which participate in cryogenesis *in situ* and become components of a glacial-permafrost system, with its particular structure and ways of using basic resources. Systematic views of the global cryology treating different aspects of glaciation as expression of cryodiversity (Fig. 4) can help understanding the problem.

Permafrost scientists almost never consider glaciers as objects of research while glaciologists almost never study the relationship of glaciers with permafrost components. However, in our case the subject is at the junction of both sciences, and we stress again the importance of cold which brings together all components and controls some other processes besides reducing ablation. The main thing is that glaciers become the major permafrost element and are exposed to cryogenesis. As a result, meltwater is partly captured, directly on glaciers, by cryogenic superimposed ice. On the other hand, glaciers in their surroundings become closely linked with other permafrost components: all kinds of ice exchange heat and mass, and produce geological effects, jointly or successively.

Thus, by distinguishing these systems we show the single mechanism that brings together all effects produced by the cold rather than mere formation of ice bodies. Thereby the *glaciation* concept preserves the common connotation but acquires a new broader meaning and becomes applied to a system of interacting ice varieties in the glacier and near-glacier zones. This highlights the contributions of other important permafrost components, including icing and ground ice. Ground ice in the glacier vicinity, together with icing, another form of perennial ice cover on the ground, may be about the size of the glacier itself and produce similar effects, jointly or alternately (though in different ways and with different resources [*Sheinkman, 2008, 2011*]).

The cryogenic geological systems can be grouped according to their characteristic features, with a hierarchy based on extent over certain areas and landforms. Their organization can reach elementary, local, regional, or global levels. The elementary level corresponds to a system with the simplest structure, which represents the glaciation phenomenon and exhibits the basic functions. In our case they are simple glaciers and related ice around them. When a system of ice bodies remaining genetically the same struc-

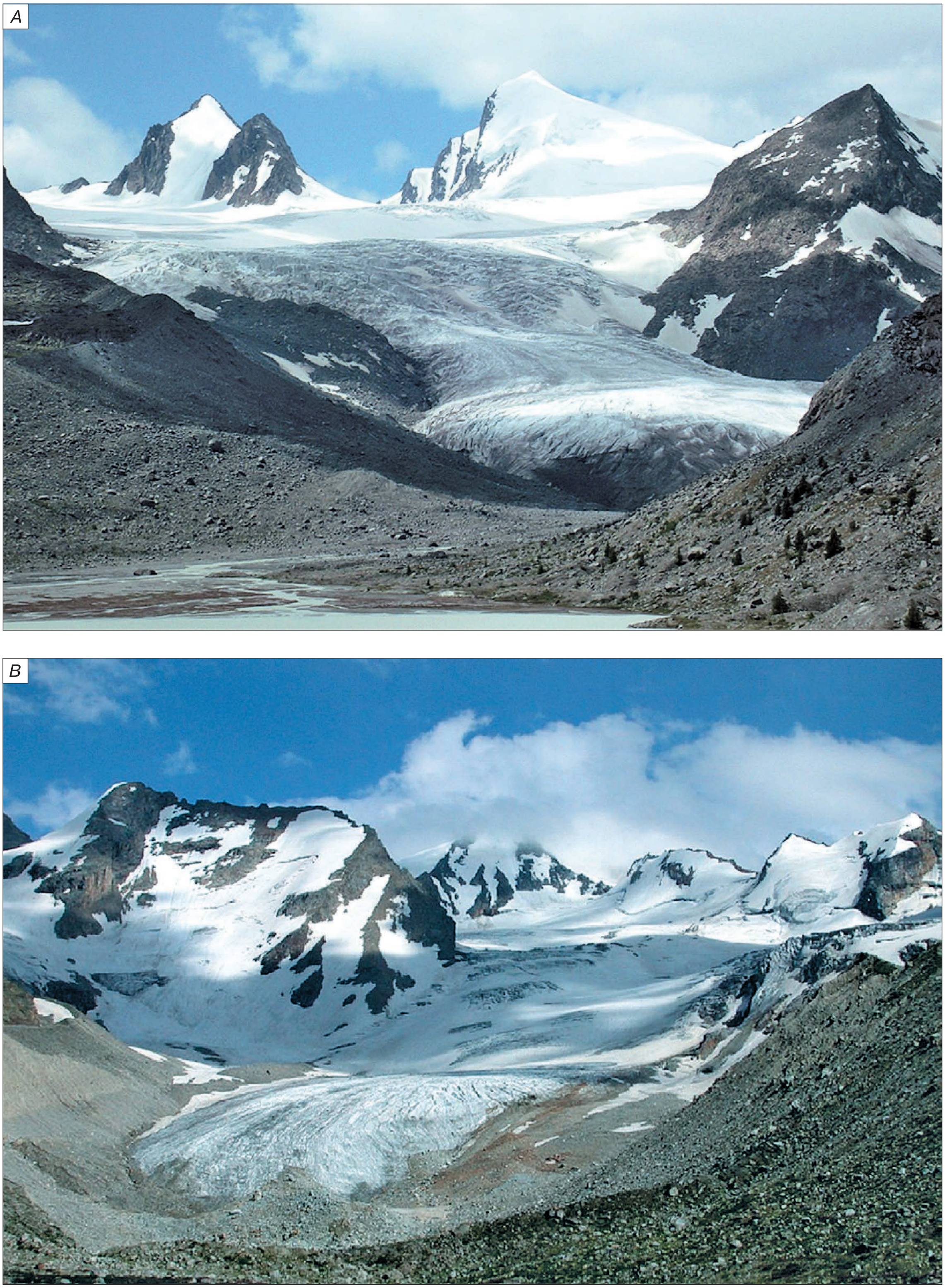


Fig. 3. Glaciers of Sofiysky in the Central Altai (*A*, photograph by V. Sheinkman) and Djankuat in the Central Caucasus (*B*, photograph borrowed from the archive of Cryolithology and Glaciology Department of Moscow University).

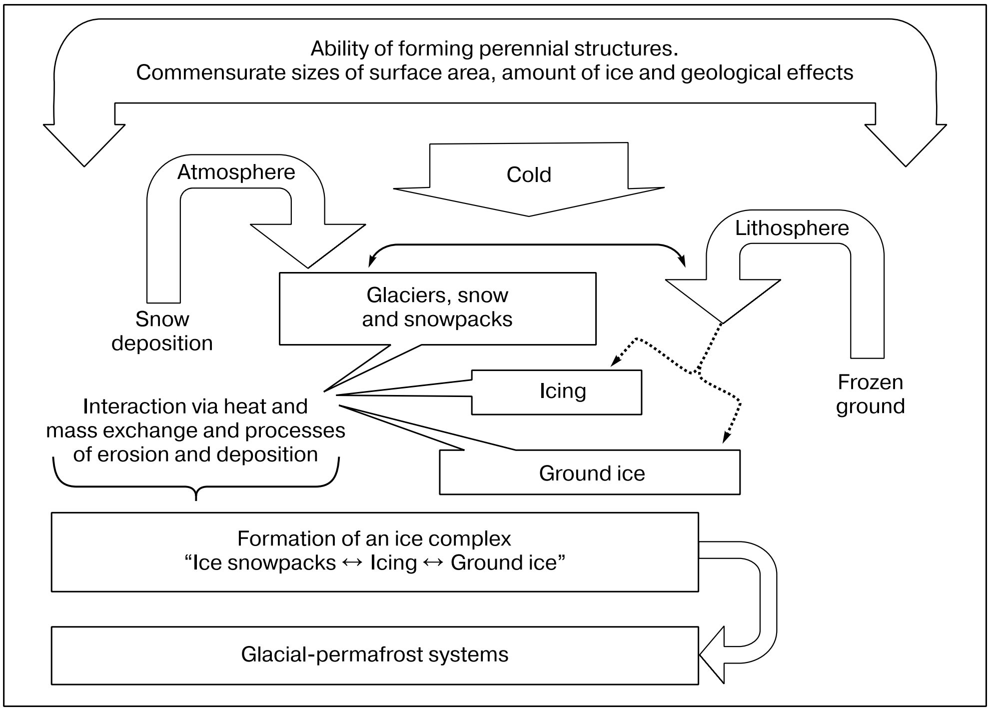


Fig. 4. Formation of glacial-permafrost systems.

tures grows to a more complex organization, it may include parts of complex glaciers with related icing and other ice varieties.

Most of glacial-permafrost systems in Siberia are of local level, but it is convenient to divide them into two sublevels depending on the relationship between topography and ice bodies: the mountain (valley) glaciers with related ice forms are controlled by topography while the ice sheets cover and control the topography themselves. All systems in Siberia have been of the former type since the past times [*Sheinkman, 2008, 2011; Sheinkman and Melnikov, 2011*] and never transcended valleys, even when near-glacier ice became commensurate with the glaciers and caused similar effects, and even during the Pleistocene glacials. The systems of ice sheets are currently restricted to a few islands in the western Arctic.

The glacial-permafrost systems can be classified according to their physics using the thermal properties. This classification has been successfully applied to both permafrost and glaciers separately, and has to be only slightly adapted to the case of glacial-permafrost systems.

Glaciers are often categorized by thermal characteristics and climate zones. In the widespread classification of *Ahlmann* [*1948*] they are: mid-latitude (temperate) glaciers lying on an unfrozen warm base and staying at the melting point (0 °C) throughout the year, from surface to base (i); subpolar glaciers, likewise lying on a warm base but rather cold on the surface (ii), and polar cold-based glaciers staying below freezing at the ice-ground interface, and thus frozen to the underlying substrate (iii); glaciers which are partly cold-based and partly warm-based are known as *polythermal*. Correspondingly, the glaciers are assigned to temperate, subpolar, and polar climate zones. More complex classifications include the influence of ocean, etc. It is reasonable to classify the glacial-permafrost systems primarily by the thermal state, as an integrate characteristic of all related ice forms [*Sheinkman, 2010, 2011, 2012; Sheinkman and Melnikov, 2011*]. The climate ties are less informative because mid-latitude glaciers in Siberia are below freezing from base to surface, while some glaciers in the western Arctic are polythermal. Therefore, we categorize the systems thermally, with the *warm-cold* dichotomy, proceeding from the degree of cooling of glaciers and indicators of frozen ground.

All cases of glacier-permafrost relationship cannot be discussed in terms of warm or cold systems within the scope of this paper. Below we formulate the principles for the endmembers, while the intermediate systems and transitional situations will be the subject of following publications.

WARM-BASED GLACIERS: AN ELEMENT OF THE ALPINE GLACIATION MODEL

In the relatively warm and humid conditions of Alpine Europe, where the science of glaciers has origi-

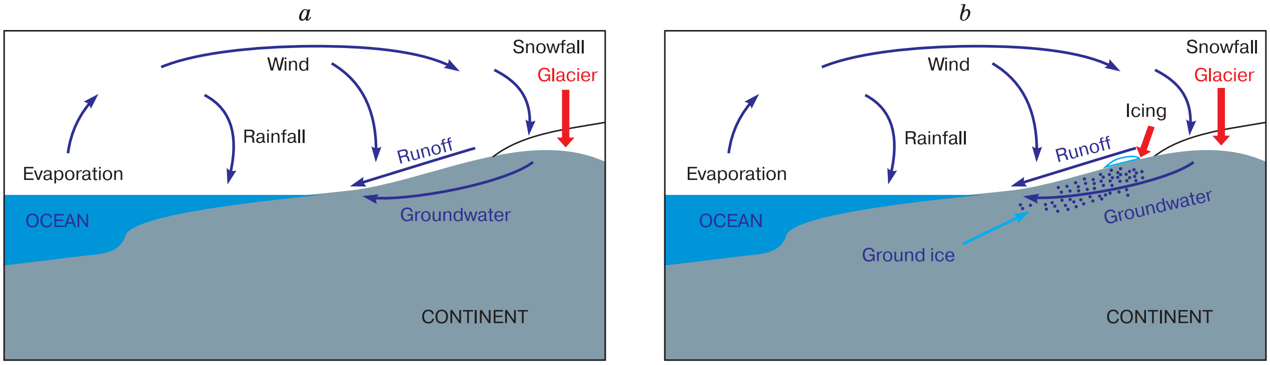


Fig. 5. Moisture turnover in the Alpine glaciation model (*a*) and in the Siberian glaciation model (*b*).

nated, glaciers survive for a geologically long time due to abundant supply and rapid turnover of moisture. Much moisture evaporates from the ocean, is transported to the land with air flows which travel rather short distances over the continent, and then becomes frozen to snow during further atmospheric transport; snow falls and accumulates on the ground, transforms into ice, and then melts. Thus, moisture is stored as snow and ice, commonly outside the permafrost zone (Fig. 5, *a*).

In such a system, moisture undergoes all conversions quite rapidly and soon returns to the ocean with unfrozen surface runoff and/or groundwater. Glaciation then represents only the moisture stored for a while in snowpacks and glaciers that form if the elevated land reaches the chionosphere. Note especially that the rapid precipitation and metamorphism of snow, mostly in the warm firn zone, is the key ice formation process.

One has to bear in mind that ice has a very high melting heat (334 kJ/kg), which is lower only in a few metals. Thus, melting the ice, even about 0 °C, which flows down from the cooler heights to the warmer elevations requires much heat; most of the heat the ice receives is spent to surpass the melting point corresponding to the high melting heat.

In this case, the incoming solar heat melts the ice from the surface in summer, while the heat coming from the ground below melts it from the base all year round. The glacier may hold for quite a long geological time, at a certain budget, as far as the input of new ice batches keeps up the ablation.

Glaciers in the Alpine model respond to climate cooling with abrupt decrease in ablation. First, the firn line descends due to abundant snow accumulation, thus inducing rapid growth of glaciers. This process continues as long as the cold and still wet phase of glaciation gives way to a cold and dry one [*Velichko, 1981*] when evaporation from the ocean reduces with the progress of cooling. The ice and snow mass preserves the underlying ground from freezing for a long time, and permafrost appears first in the coldest zones near glaciers and at the highest mountains. Only when the cold and dry phase culminates, cryogenesis can involve all glaciers, and permafrost can form underneath. Such glaciers reached large sizes during the Pleistocene cooling at the account of abundant precipitation during the initial wet phase of the glaciation. They could change from valley glaciers to ice sheets when ice expanded over vast territories, including mountains.

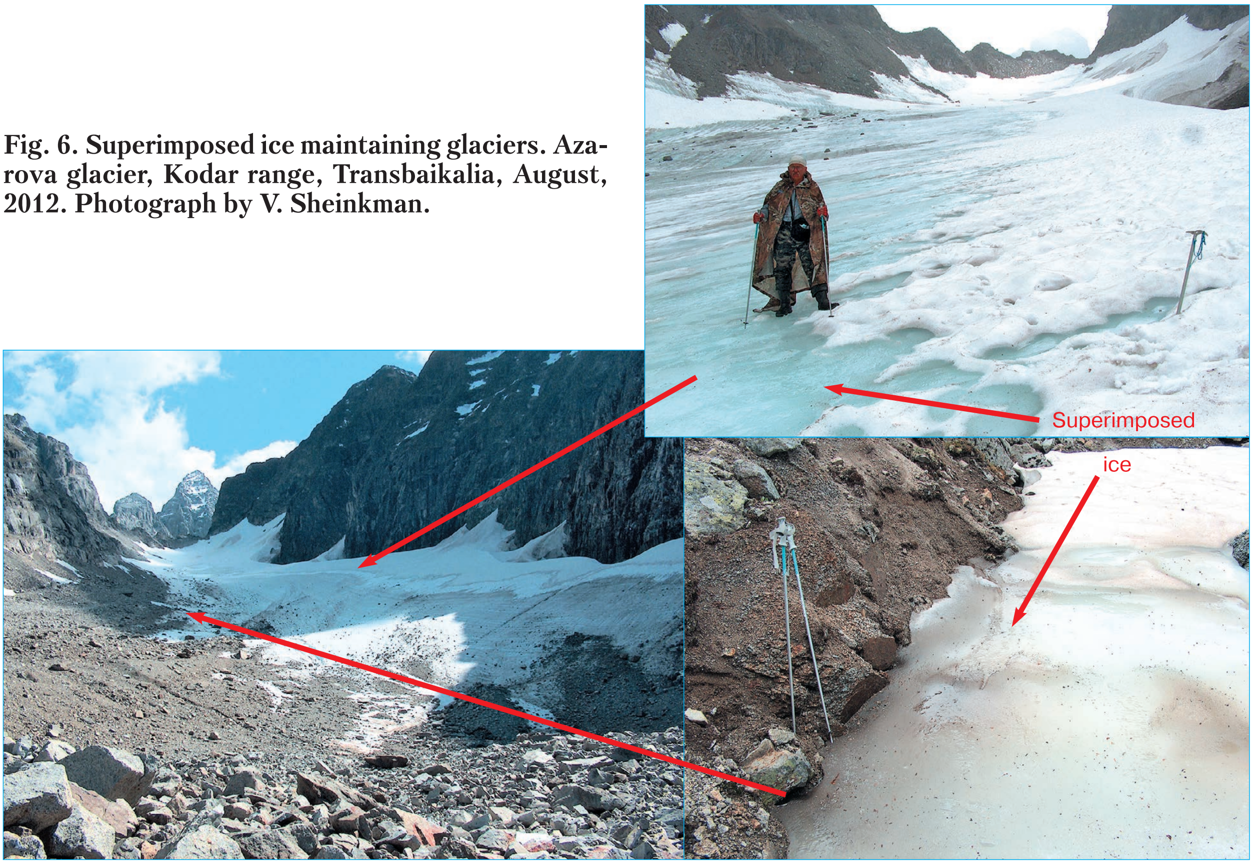
Note that glaciers in Kamchatka are an exception. Many mountains in the peninsula are exposed to prolific monsoon moisture, and the valley glaciers are often dominated by warm firn accumulation zones uncommon to Siberia. However, the seas around Kamchatka rapidly froze up during the Pleistocene cold events (especially, the closed and cold Sea of Okhotsk), the monsoon activity ceased, and the peninsula actually became part of a very cold territory in northern Eurasia. Therefore, during cryochrons, the glaciers of Kamchatka were similar to those of Siberia [*Braitseva, 1986; Sheinkman, 2008*].

COLD-BASED GLACIERS: AN ELEMENT OF THE SIBERIAN GLACIATION MODEL

The glacial-permafrost systems in Siberia use the fluxes of mass and heat in a more sophisticated way than the Alpine glaciers, because besides ice and snowpacks they include perennial ice of permafrost origin. As a result, the moisture turnover becomes different (Fig. 5, *b*).

Moisture is stored both inside and outside the glaciers, a large part being retained in permafrost ice. Moisture evaporated from the ocean travels long distances to reach the Siberian mountains and much of it is lost on the way. Nevertheless, the remaining amount (often small) may be sufficient to generate glaciers, though they form originally in a continental climate with active summer ablation in middle and subpolar latitudes. The reason is in the effect of cold that acts upon ice all year round in the area of perma-

Fig. 6. Superimposed ice maintaining glaciers. Azarova glacier, Kodar range, Transbaikalia, August, 2012. Photograph by V. Sheinkman.



frost-hosted glaciers, unlike the Alpine model in which ice receives cold originally in the atmosphere and then only during the winter season. When ice accumulation occurs in the cold firn, firn-ice, and ice zones [*Shumsky, 1955*], it is the cold rather than snow accumulation that maintains the existence of glaciers and keeps up the ablation at a limited amount of frozen precipitation which the glaciers use in the form of superimposed ice (Fig. 6).

Glaciers in Siberia formed on the background of permafrost, which appeared long before [*Gavrilova, 1978; Ershov, 1998*]. During global cooling events, first the ground became colder and then glaciers formed, provided that the elevation reached the chionosphere. Note that the climate became much drier during the Pleistocene ice ages because the ice sheets in northwestern Eurasia captured most of moisture transport inward the continent. Therefore, glaciers in Siberia have always formed upon the existing permafrost and then were involved in cryogenesis to become, first partially and then fully, a special component of the permafrost system.

We stress again that glaciation in Siberia transcends the limits of the chionosphere; unlike that in the classical Alpine model, the cold component defined by permafrost changes both the structure and genesis of glaciation. Namely, the structure includes the coexisting and interacting glacier and permafrost ice varieties while ice is of atmospheric and terrestrial genesis.

Another important feature is that ice flows in the Siberian glacial-permafrost systems grew slowly during the Pleistocene glacials, unlike the systems of warm-based glaciers. They originally stayed in the conditions of strong cryo-aridization which alternated between less and more dry and cold phases instead of changing from a wet to a dry cold phase [*Velichko, 1981*] in the Alpine conditions. The summer ablation remained high, and the accumulation line and the sizes of glaciers changed only when the warm seasons became shorter. The Pleistocene ice ages were geologically short, and the cold-based glaciers could reach only the stage of a large mountain glacier. Generally, large amounts of ice accumulated in Siberia during global cooling events, like in western Eurasia, but most of that ice was due to deep ground freezing and existed as permafrost ice more than in glaciers.

GLACIATION IN SIBERIA AS AN ELEMENT OF CRYODIVERSITY AND EVOLUTION OF GLACIAL-PERMAFROST SYSTEMS

In this section we analyze glaciation in Siberia as an element of cryodiversity and discuss some glacial-permafrost systems (though their classification will be a subject of a separate study). Glacial-permafrost systems with cold-based glaciers exist everywhere in the Siberian highlands, though have some local features. We illustrate the specificity of glaciation in Siberia on the regional and local scale with two cases, which clear up the consequences of neglecting the permafrost background in the area.

In one case, rocks near a glacier freeze in conditions of discontinuous permafrost with seasonal icing, below the wedge ice threshold. Glaciers in such glacial-permafrost systems look like their Alpine counterparts, which inspires the idea that warm glaciers would exist in Siberia as well. However, icing reliably indicates the presence of perennially frozen rocks around glaciers, though it may melt under intense insolation, in spite of quite a large amount of ice, and some particular skill is required to find its traces. One of us [*Sheinkman, 1986, 1991*] discovered permafrost-related icing in the course of special studies in a cold season and had to argue for its importance in hot discussions with colleagues who were not used to judge about glaciers proceeding from the state of the surrounding permafrost. Even if near-glacier icing experiences strong ablation in summer, it leaves imprint as topographically expressed fields indicating the formation of a talik recharged with meltwater from the glacier [*Sheinkman, 1993*]. The glacial-permafrost systems of this kind occur in the highlands of Altai and West Sayan, as well as in the Ural foothills, the Byrranga mountains, the Putorana plateau, and Kuznetsk Alatau, where accumulation is maintained by drift snow and glaciers lie within the permafrost zone but far below the climatic snow line. These glaciers have an unusual thermal field: they may be 0 °C in the firn zone and slightly warm up the underlying permafrost due to the warming effect of snow. However, the glacier body and the surrounding rocks are very cold in the tongue, with steady negative or variable ice temperatures [*Vinogradov, 1966–1981; Kotlyakov, 1997*].

In the other case, cold-based glaciers exist in continuous permafrost. These settings are identified according to the presence/absence of ice wedges, large fields of perennial icing and other indicators of strong freezing near the glaciers or at short distances. These glacial-permafrost systems currently cover the mountains of the Lake Baikal region: from the East Sayan where the first ice wedges appear as far as Transbaikalia and entire northeastern Siberia.

Generally, most of present glaciation centers in Siberia are located within the wedge ice zone, except the Altai and Polar Ural areas (Fig. 7) where glaciers exist among both continuous and sporadic permafrost.

Of course, glaciers existed also during the Pleistocene cold events when permafrost was much thicker and colder. Its traces are evident in paleo-cryostructures found already in pre-Quaternary deposits even in southern Siberian mountains while traces of glaciers appear mostly in the second half of the Pleistocene [*Ershov, 1998; Sheinkman, 2002, 2011; Alekseeva, 2005; Sheinkman and Melnikov, 2011*]. To put it different, the Quaternary glaciers inevitably formed upon permafrost. This inference is illustrated below with several examples of cold glaciers and permafrost around them (to argue against the Alpine type of glaciation in Siberia).

Middle altitudes in the Altai correspond to the zone of sporadic permafrost, but earlier it was hard to judge how high into the mountain this permafrost may spread, for the lack of data. Furthermore, the reported temperature measurements of Altai glaciers turned out to be wrong: *Mikhalenko* [*2007*] wrote about accumulation within the warm firn zone and *Nikitin et al.* [*1986*] claimed that some glaciers would be cold only from above, which appears unrealistic given the wide spread of permafrost and low mean annual air temperatures (–3 to –6 °C even at middle altitudes). The reason is that the reported measurements were taken in summer while the logged boreholes were filled with meltwater [*Sheinkman, 2008, 2010*].

At present the continuous-discontinuous permafrost boundary has been estimated to lie slightly below 2000 m in the central and eastern Altai and slightly above this height in the western Altai, and the glaciers are located obviously higher. The permafrost thickness in the area reaches 300–400 m while the glaciers are no thicker than 200 m [*Vinogradov, 1966–1981; Shats, 1978; Sheinkman, 1986, 1991, 2010, 2011; Ershov, 1989; Kotlyakov, 1997; Mikhailov et al., 2006; Gorbunov and Seversky, 2007*], i.e., permafrost is much thicker than glaciers even during the current warm period.

Ice in the accumulation zone and near the bed of the western Altai glaciers is as cold as –16 °C and –14 °C, respectively (hereafter, the temperatures are quoted for the base of the seasonally active permafrost) [*Aizen et al., 2006*]. There is no data on the glacier tongues but they must be entirely cold, given their temperatures, thicknesses about 200 m, and descent to elevations of 2000 m, which is supported by cryogenic indicators in the surroundings. Flow from beneath these glaciers stops in November and becomes partly preserved in nearby icing [*Sheinkman, 1986, 1991, 2011*]. This is possible only when a glacier lies upon a frozen bed, with a small talik under its end produced by meltwater percolating into the glacier bed through ice cracks and caves.

The temperatures of ice in the central Altai logged in 15 m deep boreholes at the outlet of the accumulation cirque and in the lower part of the ~100 m thick Maly Aktru glacier descending to 2200 m are, respectively, –9 and –4 °C. The tongue of the neigh-

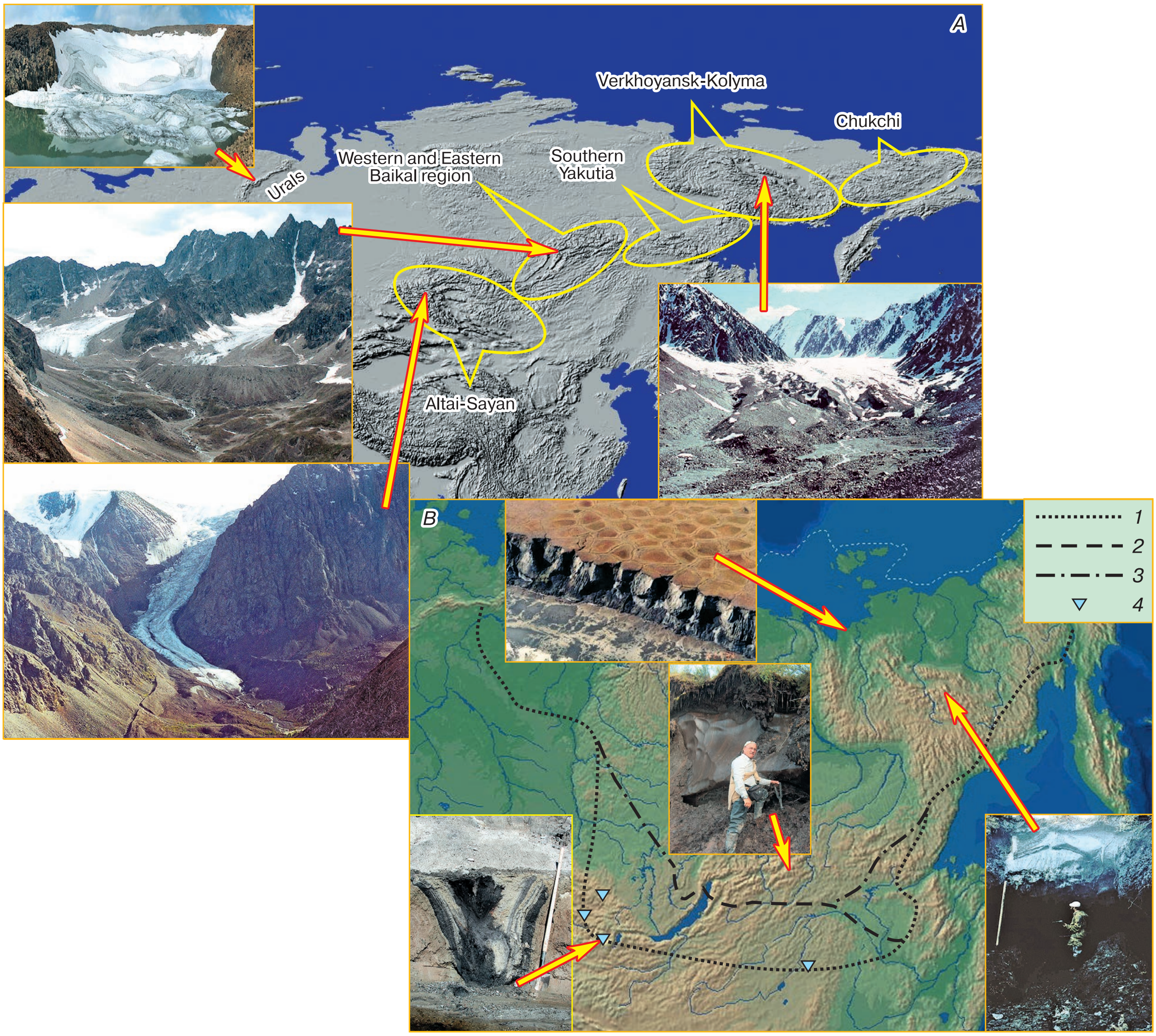


Fig. 7. Present glaciation centers (*A*) and the extent of wedge ice in Siberian mountains (*B*), compared.

B: southern boundary of wedge ice: after *Vasilchuk* [*2006*] (*1*); after *Koreisha* [*Kotlyakov, 1997, Map 220*] (*2*); after *Vtyurin* [*1975*] (*3*), and southernmost finds of ice wedges (*4*). Photograph of ice wedges in the Primorsky Plain (Inset *B*) is borrowed from the archive of Cryolithology and Glaciology Department of Moscow University; other photographs are by V. Sheinkman.

bor Vodopadny glacier, poorer in snow, ~60 m thick, and going down to 3000, is as cold as –15 °C. The beds of the two glaciers likewise must be very cold, judging by temperature curves [*Nikitin et al., 1986; Narozhny, 1993*]. They have small terminal taliks, which stop releasing water in November but hold it in the form of icing [*Sheinkman, 1986, 1991, 2011*]. Note that the curve for hillslopes below the Sofiysky glacier [*Mikhailov et al., 2006*] shows rock temperatures –3 to –4 °C. *Fukui et al.* [*2007*] wrote about ice wedge polygons but did not mention any find of ice veins proper. The ground in the area has temperatures above the wedge-ice limit (they must be much colder in coarse sediments for ice wedges to form) [*Romanovsky, 1977*]), but is quite strongly frozen anyway.

There are no temperature logs available for the eastern Altai, but the flow ceasing early in the cold season, well pronounced icing, and other cryogenic effects around the glaciers indicate colder ground than in the central Altai [*Sheinkman, 1991, 1993*]. The ground becomes ever colder further eastward and northeastward, and continuous permafrost surrounds glaciers and predominates in high, middle, and low highlands already in the Baikal region. Ice wedges, which appear first in the East Sayan (Fig. 7), are common to this area, though there is a ~500 m vertical zone of warmer rocks on the Baikal shore due to heat emission from the lake [*Sheinkman et al., 2011*]. Glaciers in Transbaikalia and Yakutia are not extremely cold: –7 °C and –8 to –10 °C, respectively [*Koreisha, 1963; Vinogradov, 1966–1981; Nekrasov, 1976; Sheinkman, 1987, 2008; Kotlyakov, 1997*], but the temperatures of the glaciers as a function of ice thickness are cold till the bed, the curves being steep, with small gradients.

Note that Gorny Altai is the largest, highest, and wettest present glacial center of Siberia, where mountains reach 4506 m and moisture is from 2000 mm/yr in the western Altai to 1000 mm/yr in the central Altai. The mountains in Yakutia occupy a similar surface area but are much lower (within 3003 m) and receive only 500–600 mm of precipitation annually. However, the Yakutian glaciers existing in the very dry and cold climate are only twice less in number than in the Altai and have a much larger extent of icing, while the surrounding rocks are richer in ice. As a result, the two glacial-permafrost systems are commensurate in the volume of ice.

CONCLUSIONS

The fascinating phenomenon of glaciers, with their versatile resources and attractive aspect, have been a subject of theoretical research and discussions for more than two hundred years. The research has been mostly based on ideas of the Alpine school, which reduced the range of approaches to the features of glaciers and their relationship with the underlying rocks. As more thorough studies began in Siberia, it became clear that glaciers developing upon frozen and unfrozen rocks are basically different and the older glaciation models need revision.

Glaciation in permafrost areas, such as Siberia, obviously evolves in a particular way but, paradoxically, the permafrost scientists rarely treat glaciers among objects of their studies while the glaciologists most often neglect the effects of permafrost. Thus important features of permafrost-related glaciation become overlooked, which leads to controversy of research results. These results focus commonly on the evolution of homogeneous snow, glacier, icing, or other systems but take no account of their relationship and interactions. Meanwhile, interaction among different ice varieties is an established fact impossible to neglect in the case of Siberia.

The paradox is due to direct extrapolation on Siberia of stereotypes common to the Alpine setting because all glaciers of same morphological types, whether being located within or outside the permafrost zone, look similar and produce similar geological effects (erosion and deposition). However, although being apparently similar, the Alpine- and Siberian-type glaciers differ basically in the use of resources and in the structure of their ice complexes. Thus, it is reasonable to consider different ice varieties in the context of cryodiversity, as interacting components of glacial-permafrost systems and the carriers of comprehensive interrelated information.

For instance, the glacial-permafrost systems that include wedge ice and large icing fields around glaciers develop in a strongly continental climate, while the glaciers are cold-based, mostly mountain ones (in the conditions of Siberia) and highly sensitive to minor changes in summer air temperatures. The systematic approach is especially important for paleogeographic reconstructions, in which the glaciation rhythms have practical implications rather than being a subject of theoretical debates.

The predictive strength of paleogeographic models "from past to present" and "from present to future" depends on the ideas lying at their base. Assuming continental glaciation in Siberia during the Pleistocene requires assuming also rapid (within the geologically brief cold and warm events) transport of large amounts of moisture and heat to the continental interior and back to the ocean. This means dramatic changes in air circulation, i.e., a catastrophic rather than evolutional scenario of the Pleistocene history in the area. However, analysis in terms of glacier-permafrost systems shows that such dramatic changes are unrealistic, and permafrost was the key background factor of evolution in Siberia throughout the Pleistocene.

Generally, it is urgent to develop new approaches as a basis for the theory of geological systems with an ice component. This is currently a front line of research, where we belong.

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REVIEW

To the paper by *V.S. Sheinkman* and *V.P. Melnikov* ***Glaciers in Siberia as Components of Glacial-Permafrost Systems***, with comments and suggestions

The reviewed paper is a conceptual study with a focus on two basic postulates: (i) Glaciers in a strongly continental climate of Siberia have their origin, occurrence, and evolution basically different from the classical Alpine glaciers; (ii) Glaciers and ground ice are coupled and interacting components of glacial-permafrost systems.

The former postulate is explicitly and convincingly treated, but hardly it is pioneering (we admit though that the authors do not claim to be the first to put forward this idea and refer to their forerunners). The theoretical background for the specificity of Siberian glaciers appeared already in the 1930s, in the classification by H. Ahlmann, as well as in a more thorough treatise by P. Shumsky (1955). The features of cold-based glaciers were reported long ago from field observations by M. Koreisha and by one of the authors (V. Sheinkman), while the misfit of these glaciers to the Alpine model was a well known saying by G. Tushinsky. However, the particularity of Siberian glaciers is highlighted in such a concise way, and their origin and effects are exposed so exhaustively, that the paper by V. Sheinkman and V. Melnikov can be rated among most brilliant and fundamental works undermining the conventional approaches of alpine glaciology. The readers will certainly appreciate their ideas, while the existence of firn-free glaciers may become an unexpected but valuable discovery for the glaciological community outside Russia.

The other postulate is born uniquely by creative thinking of the authors. It amalgamates the two concepts of permafrost-glacial systems V. Sheinkman suggested in 2008 at the Glaciological symposium in Irkutsk and an idea of cryodiversity based on the cryosophy paradigm by V. Melnikov. The two authors demonstrate, clearly and with full reasoning, that the interplay of permafrost and glacial processes is especially obvious in continental Siberia, where the glaciers partly or fully consist of permafrost-induced superimposed ice, with icing systems as an intermediate link in periglacial zones. The authors rightfully oppose superimposed ice to the other ice types associated with re-crystallization and infiltration. Thus, in terms of the permafrost science, superimposed ice is a syngenetic object of the cryosphere unlike other types of ice which are rather epigenetic: syngenetic ice forms together with the primary snow deposition during the same season, whereas epigenetic ice can grow for years going through stages of snow diagenesis and firnization of its unmelted residue.

This critical contribution to the theory of natural geological systems is worth being published by all means. At the same time, we suggest some comments* that may help the authors to improve the manuscript, unless they find some counter-arguments.

1. It is unclear why the authors fail to mention the classification of ice types by P. Shumsky, which is relevant to their key postulate of specific ice formation ways in Siberian glaciers. Reasonably characterizing this specificity and including the local glaciers into the domain of permafrost via the formation mechanism of hydrogenic superimposed ice seems strange without ever using Shumsky's term *infiltration-congelation ice*.

2. The Alpine-type glaciers are interpreted throughout the paper as structures outside the permafrost. Meanwhile, the concept of permafrost comprises also discontinuous (insular) permafrost widespread in the periglacial zones of the Alps, Caucasus, Andes, and many other mountain systems with temperate glaciers. Furthermore, even warm-based glaciers with firn-type ice formation (e.g., in Scandinavia or in the Atlantic part of the Subarctic regions) preserve the cold regime in their tongues, and often prevent any talik formation beneath them. Therefore, the thesis that *being derived from snow ... glaciers may form either outside or within the permafrost* (p. 1) appears not quite correct. For snow to begin accumulating and to survive the summer season (at the onset of cryochrons), the ground it lies upon has to be initially frozen. As for taliks, they can form underneath ice only later when the glacier becomes thick enough to insulate the ground from the winter cold, provided that the glacier evolution follows the "warm" scenario.

3. Note that the warm-based glaciers, like the cold-based ones, also develop a layer of infiltration-congelation ice at the base of the seasonal snowpack throughout the ablation zone in the beginning of the warm season.

* The original Russian version of the review included ten comments out of which only those of general interest have been translated, while a few particular points concerning references, writing, and style were omitted.

In the end of the warm season, this layer is traceable between the lines of glacier growth and firn (though being much narrower than in the Siberian glaciers). Therefore, the difference in this respect is purely quantitative rather than qualitative.

4. Speaking about the *dual nature of Siberian glaciers*, it appears doubtful that the glaciers themselves were a product of cryogenesis. Cryogenesis rather produces superimposed ice as their main feature.

This work belongs to conceptual studies which are advantageous because, being actually subjective, they become open to further discussions.

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