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Vladimir S. Sheinkman

Ben-Gurion University of the Negev, Beer-Sheva, Israel
Earth Cryosphere Institute of Siberian Branch of the Russian Academy of Sciences, Tumen', Russia
Institute of Geography of Siberian Branch of the Russian Academy of Sciences, Irkutsk, Russia

SPECIFICITY IN DEVELOPMENT OF GLACIATION IN THE HIGH MOUNTAINS OF SIBERIA – AN ECOLOGICAL ASPECT

Glaciation in the High Mountains of Siberia has been notable for its specificity and characterized by the interaction of glaciers and permafrost. The combined activities of these agents determine development of such ecological phenomena as cryogenic-glacial systems (CGS). It requires an individual approach to each of the landforms and sediment bodies to determine if they can be interpreted as the relics of ancient glaciations. Most types of the CGS may be observed today along the mountainous belt surrounding Siberia from the south and east. They represent the key to estimate ecological situation and to reconstruct Quaternary environments because the range of climatic differences along this belt today is comparable to the range of climatic changes between Pleistocene glacial and interglacial conditions. All over the Pleistocene, the continental climate promoted spreading of permafrost under arid conditions in Siberia ('cryoaridization'). Under such conditions, glaciers developed only within the high mountains as valley forms. Consequently, glacial activity was inseparably linked with cryogenic ice bodies; icings were the most active agents among them. The latter occupied great areas and were comparable with the glaciers both in ice. Thus, ecological analysis on the base of study of CGS must take into account the specificity.

Key words: *permafrost; glaciation; ecological analysis; cryogenic-glacial systems.*

Introduction

Looking at the relief map (fig. 1), it is obvious that the high mountain belt surrounding Siberia from the south and east (here referred to as the 'Siberian Mountains') represents a wide range of environments. It was the region, where, at the end of the 19th century, Peter Kropotkin [26], a famous Russian researcher, first collected material for establishing his Glacial Theory. However, for a long time glaciological and palaeoglaciological phenomena from many mountain regions of Siberia were not studied in any detail. Reliable reconstructions of the Pleistocene glaciation were based on the only superficial geological survey, which had been completed in the 1960–1970s and eliminated the last blank areas from the geological maps. However, lack of knowledge did not allow the proper identification of the relics of former glaciations formed under continental climatic conditions dominated by low precipitation, which prevailed in the heart of the Eurasian continent.

Until today the discussion revolves around the longstanding debate between adherents and opponents of A.I. Voeikov [20]: this famous 19th century Russian climatologist claimed that it was impossible for great glaciers to form in the heart of Siberia because of its dry climate. From the very beginning of the debate many famous scientists took sides, with such celebrite as J.D. Cherski [30], supporting Voeikov's point of view, whereas V.A. Obruchev [27], a renowned researcher of Siberia, did not agree. The debate continues, and the discussion in respect to the ancient glaciation in the inland regions of Siberia is as topical now as ever; a large body of data shows this today, e.g. the recent sweeping generalizations [4, 5, 10–12, 14–16, 18].

The reason yielding the debate is considering the events in Siberia from the point of view of Alpine scientific school which did not give in detail development of glaciers under conditions of permafrost whereas at present the scientifically substantiated fact is that all glaciers in Siberia are very cold and situated in the area of cryolithozone. All-in-all, the first palaeoglaciological reconstructions were largely influenced by the classical European model and did not always take into account the specific environmental conditions of the Siberian Mountains. One reason for this is that the study of Quaternary phenomena largely focused on Northwestern Siberia, where the environment resembles that of northern Europe. In addition, glaciological investigation of modern glaciers in Siberia began in the Western Altai, i.e. in the most humid Siberian region, with its relatively mild climate and accessibility for people.

As a result, the Alpine palaeoglaciological concepts were widely transferred from Europe to the mountainous regions of Siberia, and for a long time, the similarity of the European and Siberian palaeoglaciological schemes was thought to form a firm basis for subsequent investigations. Because of their lesser accessibility the East and Northeast Siberian Mountains were studied much later and less intensively than those of the West. New information for the region only appeared in the 1970–80s with the next stage of scientific development and economic activity in Siberia.

Then, together with detailed evaluation of geological material, numerous data were collected during geocryological mapping and a general survey of glaciers, icings and ground ice at the area of all over Siberia. Eventually, towards the beginning of the 1990s this research included all the formerly neglected regions [15, 16, 22, 24, 25, 32, 34]. All these data have demonstrated that the old palaeoglaciological schemes have to be corrected, as the new data obtained at the present-day glacial and cryogenic objects should be taken into the consideration. Evidently, the Quaternary events in the Siberian Mountains did not coincide with their Alpine and other European equivalents, and some of the landforms and sediments previously considered to be of glacial origin were found to have been formed by non-glacial processes.

Overall, the development of glaciation in Western Eurasia (the Alpine scheme) was found to be differed fundamentally from that of the mountainous regions of Siberia [14, 32, 34, 35]. An important point is that the glaciological and geocryological investigations throughout Siberia [22, 24] have demonstrated that high moisture availability, and in turn, high snow accumulation volumes, which are usually associated with the development of glaciers, are not required for the formation of cryogenic ice. On the contrary, a continental climate promotes the freezing of rocks and prevents the development of glaciers. Both processes have occurred in the Siberian Mountains, against a background where the atmospheric circulation throughout the entire Quaternary acted according to the same principle [15–17]. Unfortunately, the original lack of exchange between glacier and permafrost research resulted in some major disagreement.

Some investigators, who promoted the view that cryogenic ice prevailed in Siberia during the Quaternary, underestimated the role of glaciers (e.g. [23, 29]). Whereas others (e.g. [4, 5]), did not considered thoroughly the permafrost and postulated giant ice sheets covering most of Siberia. After having studied both modern and ancient glaciation, as well as permafrost, along the entirely mountain belt surrounding Siberia for many years, the present author would not agree with such extreme points of view. Glaciation must be seen as a development of different glacial and cryogenic ice agents, which can shape the valley morphology either individually, in turn, or in combination [15–17, 32–33]. In order to reconstruct and assess the events across the region during the Quaternary, the study of former glaciation must include the interaction of both the geocryological and glacial processes through time. The present author wants to emphasize that in the case of ignoring such an approach, researchers loose much of important information, and it leads to distortion of the true picture of glaciation.

Materials and methods of research

In respect to the Siberian mountain areas, standard methods of studying modern glaciers and reconstructing the extent of former glaciation from landforms and deposits are not always applicable. The reason is the interdependency of permafrost processes and formation of glaciers that intimately interacted in Siberia throughout the Pleistocene. To unravel the situation the present author has successfully applied a system approach by studying interaction of permafrost and glacial processes completely in the frames a cryogenic-glacial system (CGS). Glaciers in the Siberian Mountains are important, but they are not the only members of the CGS. The latter can include different forms of ice that may be regarded as 'glacial phenomena' in a broad sense [8, 46]. Some non-glacier agents of the permafrost genesis can become very active. Icings, for example (fig. 2), are not so infrequently comparable with glaciers both in volume of ice and in the volume of geological work they can achieve, although the processes involved are different. The original glacial landforms and deposits can be significantly modified by these processes. Thus the ice bodies consisting of the CGS should be considered as with respect to the water-equivalent mass, also with regard to the cold storage concentrated in those bodies [14–17, 32, 33]

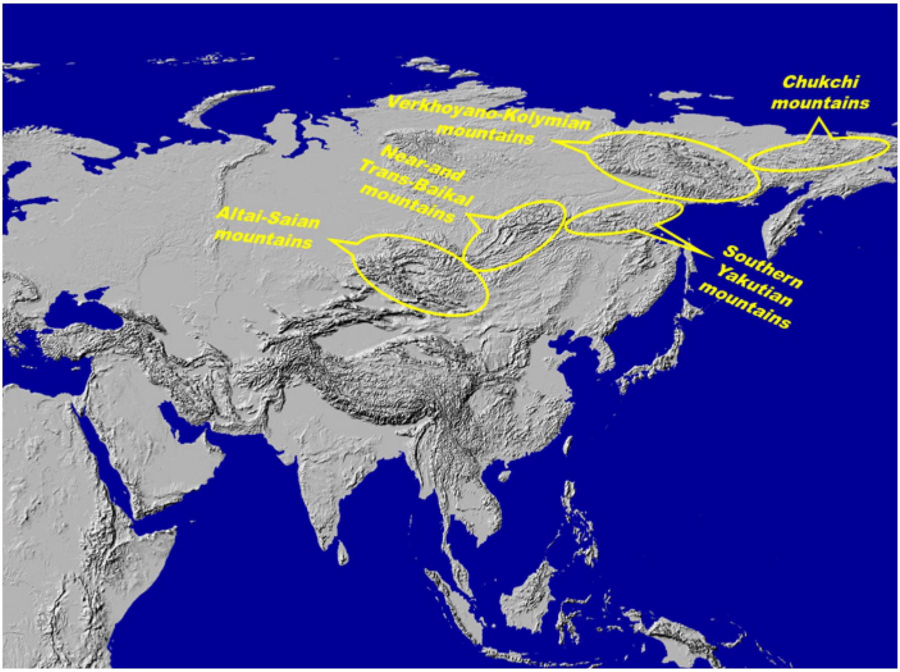

Fig. 1. Relief map of Asia and mountain formations spanning Siberia

Fig. 2. Icing reworking the Pleistocene trough in the valley of Adicha River, Eastern Yakutia

In order to use a system approach [1, 13], the main units of the CGS and their modes of geological work have to be first defined. Environmental diversity in the Siberian Mountains ranges from rather humid to extremely continental, and from relatively warm to extremely cold conditions (the coldest point in the Northern Hemisphere is situated in North-eastern Siberia). Most types of the CGS may thus theoretically occur in the Siberian Mountains. The principal characteristic of the CGS (see below) in this case becomes their cold storage capacity. Five main types of the CGS can be distinguished, based on differences in their temperature regime.

The main indicators of glacial environments used herein are as follows: (a) the temperature regime of glaciers and the surrounding rocks, and (b) the appearance or disappearance of icings and ground-ice phenomena in the non-glaciated areas. Glaciers, icings and ground ice control the geologi cal work of the CGS. These phenomena also clearly show, by their appearance or disappearance, the conditions of their development. Therefore each of them, and especially their peculiar combination, can serve as good indicators of glacial environments. It is very important to take in account such a situation because all glaciers in Siberia are in the permafrost area at present, and more so that they were under conditions of deep freezing during the Pleistocene cooling.

Background of permafrost development and glaciation in Siberia

If to look again at the relief map (fig. 1), the high mountainous belt surrounding Siberia in the south and east consists of numerous ranges characterized by many similar features. The ranges reach from the Altai through Trans-Baikal area to the Chukchi Peninsula. The highest mountains are found in the southwestern part of the belt, in the Altai, where many ranges exceed 3000 m above sea level, and a few peaks even above 4000 m (the highest point, Mount Belukha in the Katunskiy range, reaches 4506 m). In the Sayan Ranges many mountains reach 3000–3300 m, and the highest peaks of Transbaikalia are close to 3000 m. In Northeast Siberia the highest point (Mount Pobeda, Cherskiy Range) reaches a height of 3003 m. On the Chukchi Peninsula the mountains are lower; they are close to the 2000 m level (lower boundary of ‘high mountains’), though do not exceed it. All in all, the Siberian Mountains are characterized by a certain morphological uniformity.

Being situated in a relatively homogeneous climate and environment, most of them underwent a single complex of exogenous processes. At present, most of the mountain belt is under the influence of the Siberian Anticyclone, and the main feature of this area is a continental environment with low temperatures. Due to the westerly winds, precipitation can reach the inland regions of Siberia only from the Atlantic and West Arctic, warmed by the Gulf Stream. Monsoons from the Indian Ocean are blocked by the ranges of Hindu Hush and Himalayas, whereas moisture from the Pacific cannot penetrate deep into the inland regions; it meets Circumpolar Aerial Transfer’ resistance from the west and has been blocked up by the Gobi Desert as well. So, in Siberia the Pacific only affects the coastal zone of the Russian Far East and very narrow shore stripe along the Northeast Siberian terrain. As a result, trend of cryoaridization ('gradual increase in climatic continentality at a background of lowering air temperature') has been appeared along the described mountain belt (fig. 3).

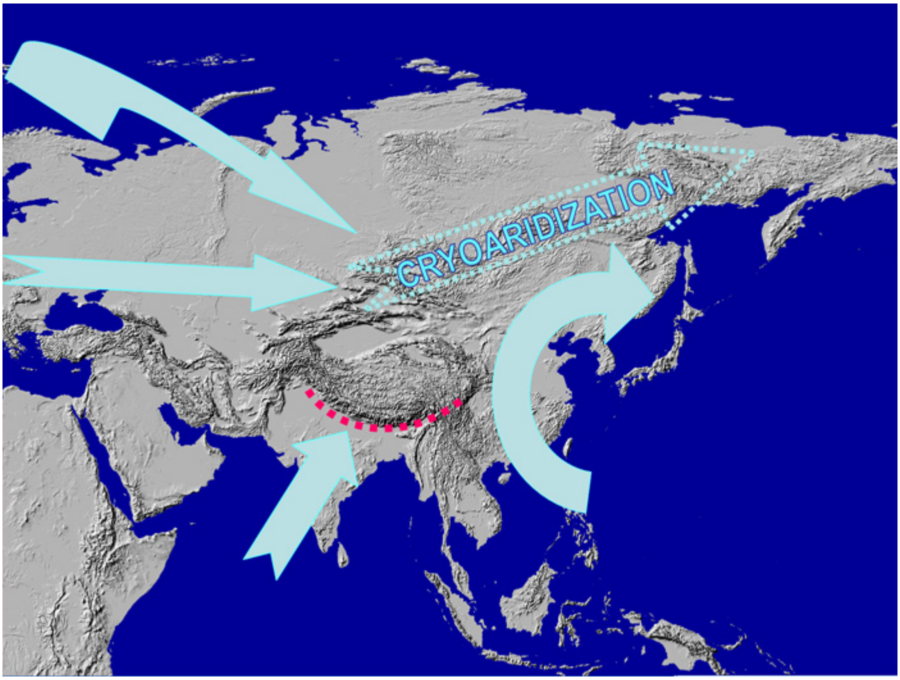

Fig. 3. Moisture-bearing air flows and cryoaridization trend along the Siberian Mountains

The evidences (fig. 4) showing distribution of polygonal ice wedges in Asia (their presence clearly demonstrates very cold continental climatic conditions) confirms this fact, because these wedges appear only under conditions when permafrost temperature has been lowered up to some –3°C [19]. Against this background, parts of the mountain belt are differentiated by a gradual change in temperatures and by differences in the distribution of precipitation. The southwestern part of the belt is still accessible for rather humid air masses and receives relatively abundant moisture. The reason is that under the present, interglacial conditions the warm Gulf Stream reaches the coast of Northwestern Siberia and influences the climate of the entire West Siberia. Cyclones formed under the influence of the Gulf Stream pass over the West Siberian Lowland and reach the western and northern slopes of the Altai-Sayan mountain system. As a result, the ranges of the West Altai receive about 2000 mm of annual precipitation; about 1000 mm/a are typical for the Northeast Altai and West Sayan ranges, and even the northwestern part of the East Sayan Ranges. Further to the east, and also to the inland part of the Altai-Sayan terrain, the humid air masses are exhausted, and precipitation decreases sharply, to only a few hundreds of mm/a. In those parts of the belt that cover thousands of square kilometers, the annual precipitation is in the order of 250–400 mm/a in the foothills, only increasing to some 500–700 mm/a in the high mountainous zone. In the intermountain depressions, precipitation can even decrease to 100–200 mm/a. The average annual air temperatures along the belt are everywhere below zero; they drop from –3 to –5°C (in the southwestern part of the belt) to –15 to –17°C (in the north-eastern part of the belt). As a consequence, permafrost phenomena occur everywhere and appear as permafrost with the temperature significantly higher than that of the ice wedge formation in the southwest of the belt, and, towards the northeast, the permafrost gets more severe, including very low temperature frozen rocks. Only a narrow zone in the relatively moist West Altai is characterized by sporadic permafrost, whereas most of the Altai mountain terrain is characterized by discontinuous permafrost that grades into continuous permafrost on the north coast of Lake Baikal.

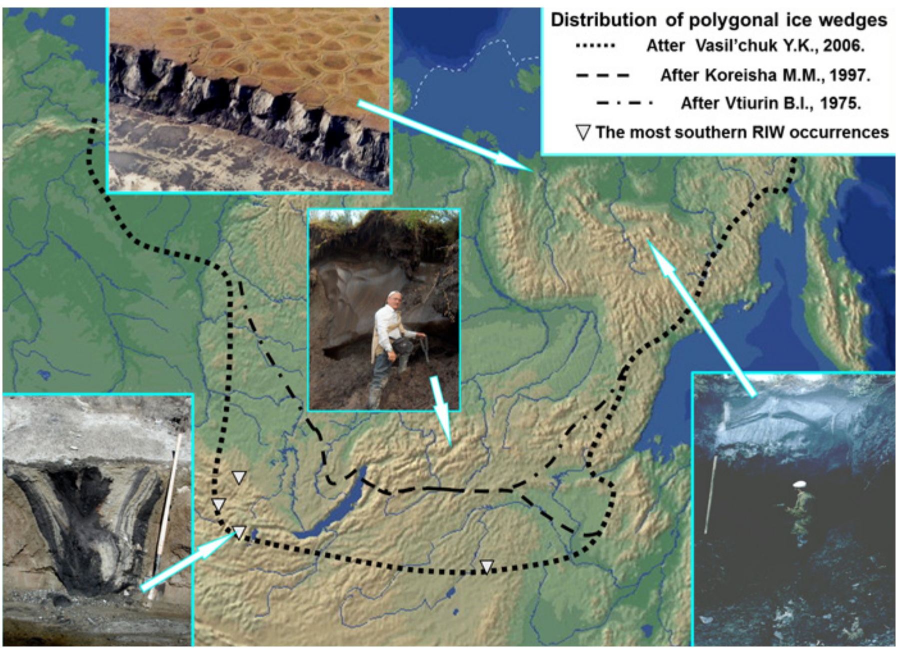

Fig. 4. Distribution of the polygonal ice wedges is shown as generalized after different authors with the added of the present author

Cryogenic ice along the belt ranges from small seasonal forms in the Altai to large, long-lived, perennial bodies within the mountainous terrain of Northeastern Siberia [3, 19, 21–33].

Investigators usually asses the annual temperature difference between the Pleistocene cold and warm stages as some 8–12°C [2, 7, 8]. Together with other climatic parameters this means that the magnitude of the present-day climatic differences found along the mountain belt surrounding Siberia in the east and south is similar to the variations that occurred during the Pleistocene as a result of the cold/warm periodicity.

In such a situation, significant modern glaciation exists in the opposite ends of the belt, supported either by low temperature (the northeast), or by abundant precipitation (the southwest). In the coldest regions of Northeastern Siberia, the longest glaciers, which flow down from the mountains from a height of about 3000 m a.s.l., reach 10 km in length whereas the total glaciation in this region occupies an area of about 380 km^2. Under similar climatic conditions on the Chukchi Peninsula, but with mountains of the lesser height, there are only a few small glaciers. In the middle of the belt, the adverse environment only allowed the development of very few small glaciers. They occupied an overall area of about 20 km^2 in Transbaikalia, although many ranges there include peaks of 2000 to 3000 m. An area of about 30 km^2 is covered by modern glaciers in the Sayan Ranges, although some of the mountains in these ranges reach beyond 3000 m. The most extensive modern glaciation is restricted to the highest and most humid Altai Ranges; where the glaciers reach more than10 km in length and altogether cover an area of more than 900 km^2. The ablation periods of the modern glaciers are very short; ranging from 75 to 120 days within the Altai mountain terrain, and decreasing to 50–60 days at the glaciers of Northeastern Siberia, and the long periods without any runoff are characteristic of the entire Siberian Mountains [24].

Glaciation as development of cryogenic-glacial systems and its specificity in Siberia

General positions

Combined development of glaciers and permafrost requires designing the special approaches to studying those phenomena. In order to understand both the underlying processes of the CGS and their difference in geological work in the Siberian Mountains, the principles of how a CGS functions must be considered. As any geological system, each CGS requires energy, initial material and information. They are used by the CGS to undertake geological work and heat-mass exchange with the environment. The results of activity of the CGS are seen as (a) landforms and deposits produced by the CGS, and (b) transformed material of the CGS with its remaining energy, and (c) new information. First of all input information for the CGS must be estimated. Like in any system [1, 13], it represents the totality of laws that control the development of the systems, whereas the information carriers (the material of the CGS, reworked rocks and landforms) eventually demonstrate characteristics which show the degree to which these laws have been applied.

The material of the CGS is its specific bedrock – ice, which composes its main elements, the ice agents, and can be transformed from the solid into the liquid state and back and also can absorb a certain quantity of other rocks. The geological effect of the CGS depends on the quantity and turnover of its material, which is controlled by its energy resources. If a CGS has been represents only a glacier, its energy is usually estimated through the kinetic component consisting of the potential energy of the ice mass. However, in the case of the Siberian environments, for the geological work the CGS can also use the transitions of the materials from solid bedrock (ice) into the melt (water) and back. In other words, in the case of the Siberian CGS not only the kinetic energy of the ice agents, but also their thermodynamic energy must be taken into account.

The latter is very important for understanding the specific glaciations in the Siberian Mountains. For example, if glaciers are morphologically similar, but energetically differ from one another, they will carry out different geological work. On the other hand, with icings, no motion of these ice agents can be observed, although they can achieve intensive geological work. Weathering is sharply increased within ‘icing glades’ (vegetation clearings formed along icings and covered by specific “icing alluvium”), and streams are deflected by icings. The result is a specific planation effect that causes widening the icing glades and filling of the valleys with particular deposits [25, 32, 33]. What is important, the trough after icing reworking looks much differently and it has to be taken in account in the case of carrying out palaeogeographical reconstructions (fig. 5).

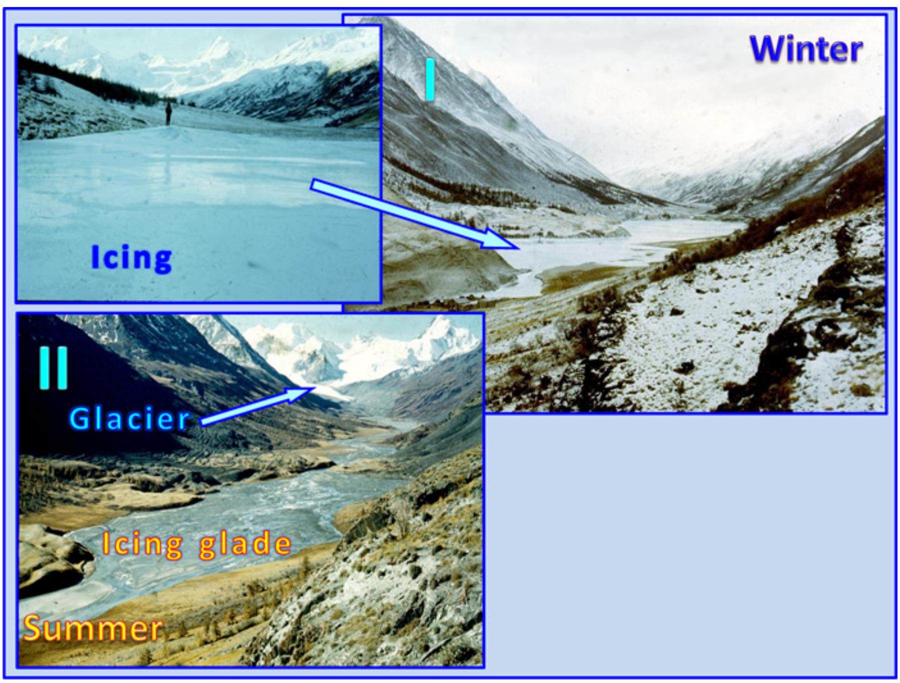

Fig. 5. A glade (II) left by a recent icing (I) in the Pleistocene trough in the valley of Taldura River, Central Altai

It should be noted that the development of any Siberian CGS follows certain common patterns. In order to form the CGS, its initial material (moisture) must first be evaporated from the ocean where the water vapour receives terrestrial and solar heat and, after that, is moved to the Siberian inland via atmospheric circulation. Due to the Circumpolar Aerial Transfer, moisture, in order to reach the Siberian interior, can be taken only either from the Atlantic, or from the Western Arctic, warmed by the Gulf Stream. Little moisture can ever reach most areas of the Siberian Mountains. Consequently, moisture supply must have sharply decreased during the Pleistocene cold stages, when the Gulf Stream did not operate, and, in addition, ice sheets in Northwestern Eurasia intercepted the remaining moisture. This mechanism caused a continental climatic environment to develop in the Siberian Mountains throughout the Quaternary. Therefore, the limited volume of moisture that reached the Siberian interior regions may be notwithstanding minor variations, conditionally considered as a constant; or, in other words, as insignificant. Another constant characterizing the CGS is the altitude of the Siberian Mountains, which has not changed principally during the Pleistocene. Thus, if the different Siberian CGS are considered as being equal in volume to their substance, the regime of the CGS, as well as their role in geological work, are mainly determined by their internal energy.

This means the state of the Siberian CGS is mainly determined by cold storage acquired firstly from the atmosphere and, secondly, by the additional quantity of cold storage resulting from freezing of the substrate (when the CGS are within the permafrost zone). It is generally considered in geographical-geological studies that the greater cold storage in any geosystem, the lesser is the energy and its effect of exogenous processes. Above all, this is because of a habitual approach to estimate activity of exogenous agents from the point of view of their kinetic energy, when there is very restricted surface drainage for most of the year. However, in the Siberian Mountains, under the limited precipitation over most of the area, annual runoff volume per unit area is small anyway. In contrast, significant cold storage, in spite of the overall low energy resources of the CGS, results in active erosion/accumulation processes yielded by the different ice agents. In fact, investigations by Serebryanny et al. [28] have demonstrated that greater geological work is carried out by frozen cold-base glaciers that are slowly moving, than by warm glaciers that move more rapidly. Anyway it concerns mountain-valley glaciers.

Principals of organization and types of the cryogenic-glacial systems

When observed as a whole, the Pleistocene environments in the Siberian Mountains have been distinguished in that the dominant members of the CGS during the cooling were the glaciers which increased then significantly. They were mainly valley glaciers, and became reticular forms during their maximal advance in the Late Pleistocene when they reached inter- and sub-mountain depressions and lowlands and formed large piedmont ice fields. Even then the glaciers were still connected with valleys and acted as members of the mountain valley CGS. At times, the glaciers dominated and filled all the valleys, with other elements of the CGS playing only a subordinate role.

At other times, the glaciers retreated and the non-glacial elements took over, actively reworking landforms and rocks left by the glaciers. In the latter case the glaciers are considered as the dominant in providing the environments in which the other elements of the CGS developed. Icings are the most active subdominants of the CGS in the Siberian Mountains. They took advantage of (a) the great cold storage accumulated by the CGS, and (b) climatic continentality, and (c) environments produced by the glaciers. Icings can be located directly on glaciers, abutted against glaciers or located at some distance from glaciers [31]. The glaciers and icings in such a situation are closely related via processes of their heat-mass exchange. Icings are not ice streams, but they act by growth and decay and through their melt water, and also through weathering. Firstly, intensive summer weathering occurs at the contact of icings and rocks. Secondly, there is a winter 'heat impact' of water forming the icings when it spreads through the frozen rocks of the icing glade – an effect comparable to boiling water being poured on bedrock in summer. Thirdly, the icing body acts as a dam forcing streams towards the banks, enhancing erosion. As a result, lateral erosion prevails. Fourthly, a talik (thawed rock) develops under the icing, which acts as a thermal insulator, and numerous small streams running under the icing will rework the valley specifically. Fifthly, due to the migration of streams forming under the icing, icings can move over the valley. As a result, wide, level icing glades are formed in the course of time, changing the former trough morphology (fig. 5).

It is along this pathway that in spite of low snow accumulation in most of the Siberian Mountains, redistribution of snow under the influence of wind sometimes causes formation of large snow-banks within the valleys. As members of the CGS, the snow-banks are of only local importance. Their erosion/accumulation activity is restricted to an increase of weathering along the snow-rock contact and washing-out of weathered debris from the snow-bank bed.

This process can yield pseudo-icing and pseudo-glacier landforms that must be taken into consideration, especially in regions that were not subjected to any Pleistocene glaciation. For example, at present, large wind-formed snow-banks often occur in the Chuckchi Peninsula at altitudes significantly lower than the climatic snow line and even the moraines of the maximal glacier advance, though annual precipitation in the region is only about 300 mm. This impresses at a background of low-temperature permafrost.

In respect to underground ice it should be noted that as an element of the CGS it has been also of subordinate significance. Its geological work is to turn unconsolidated rocks into a consolidated mass, to participate in cryogenic weathering, and to develop some forms of micro relief. The main significance of underground ice is redistribution of the material of the CGS and indicating the state of the CGS. According to Vtyurin [21], the total mass of underground ice in Siberia exceeds that of any other kinds of ice. Consequently, the presence or absence of certain types of underground ice is a clear indicator of the current state of the CGS.

On the whole, the revealed structure of CGS in the Siberian Mountains provides to distinguish a few types of such systems which characterize modern environments and equivalent environments in past. The different types of CGS are distinguished by their temperature regime. The same principles underlie many classifications of glaciers and permafrost. Although limited temperature data are available for the Siberian Mountains, they are able to provide well-distinguished features of the CGS. Besides, there is another way to establish the character of the CGS in such a situation: to use certain ice agents as indicators. These agents must be the most stable, and traces of their activity also have to be well expressed in landforms and sediments.

In the Siberian Mountains it is possible to follow the succession of the CGS, from one type to the other, by appearance (or disappearance) of different types of icings and ground ice (first of all – ice wedges) in front of the modern glaciers and along the Pleistocene troughs. Since all glaciers in Siberia are in the permafrost area and frozen rocks undelay them, we named all the systems as 'cold CGS'. However, taking in account that some of them are in the area of polygonal-ice wedges, whereas the others are outside of that (fig. 4), two subtypes – 'cold' and 'moderately cold' are also distinguished. As to the CGS which form under mild climatic conditions with abundant snow alimentation and not so low air temperature, they do not occur in Siberia; they appear in Caucasus and to the west of it – we name them as 'warm CGS'. In order to understand the difference, the first unit to be considered is the so-called 'warm CGS' which occur at the area with temperate climate characterized by some oceanic features. Glaciers included in this type of CGS are in an isometric temperature state close to 0°C when ice formation proceeds mainly in the warm firn zone; they dominate both in volumes of ice and in volume of geological work. As this CGS can accumulate little cold storage, the other elements are weakly expressed. The glaciers owe their existence to a high volume of snow precipitation. Snow accumulates cold storage in the free atmosphere and communicates it to the developed glaciers. Runoff from such glaciers occurs all the year round because they lie on an unfrozen base; the rocks in front of the glaciers freeze seasonally only. In Asia, at present this type of the CGS is well presented in Caucasus where periglacial zone has been characterized by luxuriant vegetation represented by wood of deciduous trees and lush grassland which can ascend almost to the glaciers (fig. 6-I). However the very elevated peaks are partly able to gain into the permafrost area [Мих] even in this case (fig. 6-II). The development of this type of CGS is impossible in the Siberian Mountains, because cryoarid environments prevailed there.

In the West Altai which is the most humid and warm part of the Siberian Mountains, all glaciers lay, nevertheless, on the frozen rock and temperature of their bodies is significantly below 0°C. It has been established [Aiz] by drilling the glaciers on the slopes of Mt. Belukha (4506 m).

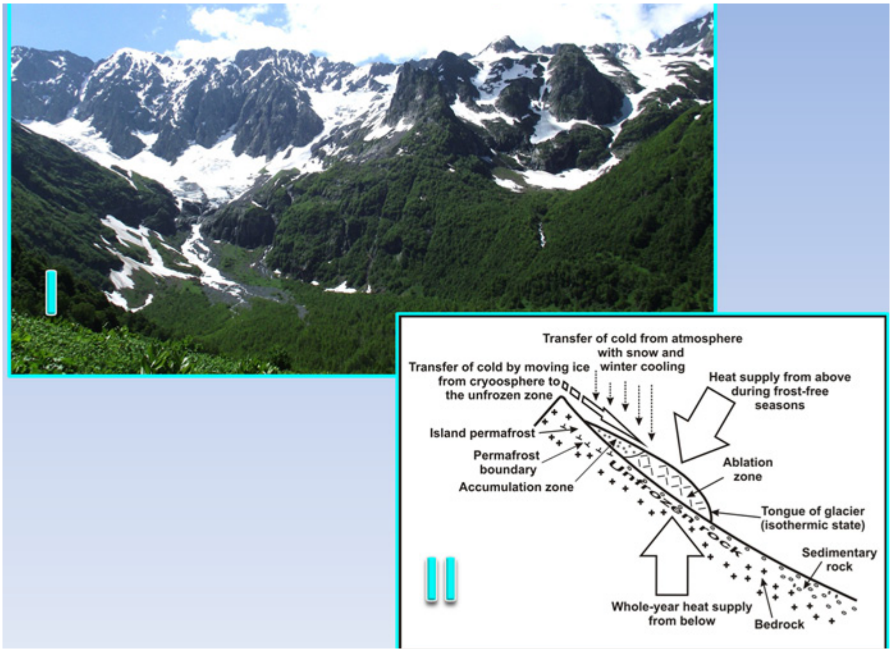

Fig. 6. The Kholodniy Glacier in the Western Caucasus (I)
and a scheme of the warm CGS development

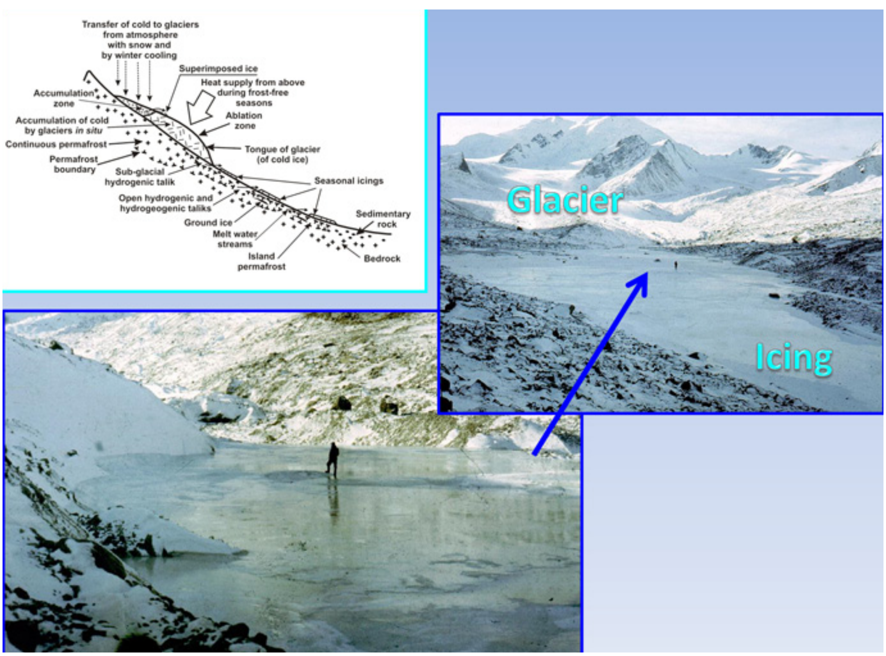

Fig. 7. A scheme of the moderately cold CGS development and its equivalent
in the area of Large Taldurinskiy Glacier, Central Altai

Taking in account that glaciers of Altai Mountains are outside of the area of polygonal ice wedge distribution (fig. 4), and in front of the glaciers continuous permafrost can be changed into island discontinuous permafrost, the sub-type of the CGS which occurs at that area has been named as the 'moderately cold CGS' (fig. 7). In this case the glaciers are significantly colder than those of the first unit, and their bodies represent a massif of cold ice (with temperature below 0°C).

Cold firn, and firn-ice, and ice zone characterizes ice formation at the glaciers in such a case by dint of development of super-imposed ice. Winter runoff is then absent, and part of the autumn runoff is intercepted by annually forming icings which can possess large-size bodies. The icings actively rework the primary glacial relief, but only in spring and summer because they are still seasonal phenomena; they are able to occupy areas up to 10 km^2 (and even more) where they cut forms of glacial micro relief, widen the valleys and change the composition of sediments [31, 33]. At present the CGS of this type are widespread in the Altai Mountains. When very cryoarid conditions prevailed during the Pleistocene cold stages, this type of CGS disappeared in Siberia and the merely 'cold CGS' take their place. Relict icing glades in front of the former glaciers confirm this fact.

So, the next unit is the 'cold CGS' which prevail at the area with continental severe climate. The glaciers in this case include masses of cold ice frozen significantly (sometimes more than ten degrees below 0°C), caused by downward freezing. Today this type of CGS is widespread from the right-bank upper reaches of the Yenissei River to the Chukchi Peninsula. They differ only in the degree of cold storage capacity; southern and northern parts of the area of the cold CGS distribution may be then distinguished. On the whole, in this type of CGS the glaciers and ground around are deeply frozen. In summer the surface of the glaciers is not infrequently without snow cover. Ice formation proceeds at the glaciers in such a situation due to the well-developed ice zone. As other main indicators of this type of the CGS, large perennial icings and repeatedly ice wedges have been appeared demonstrating freezing of rock at a temperature of as low as some –3°C (fig. 8).

A scheme of the cold CGS development, when glaciers and cryogenic ice agents found in front of the modern glaciers, as well as along the troughs of the Pleistocene glaciers, are caused by continuous low-temperature permafrost, has been presented on fig. 9-I. Runoff from the glaciers, which lie on the very frozen bed, is restricted to the warm season and a significant part of this water is intercepted by near-glacier icings (fig. 9-II), whereas different generations of polygonal ice wedges are revealed at the area around glaciers (fig. 9-III) . Reworking the sediments and landforms by icings in the Pleistocene troughs is very intensive in such a situation: major glacial and fluvio-glacial landforms (including lateral and terminal moraines, high terraces etc.) have been become very clearly expressed as most of the small-scale landforms have been removed by icing erosion. At present, the first perennial icings and repeatedly ice wedges appear in the Siberian Mountains within the right-hand upper reaches of the Yenissei River, in the East Sayan Ranges, Northern Mongolia included.

Fig. 8. Azarova's Glacier in the Kodar Range (II) and polygonal ice wedges around, Trans-Baikal region

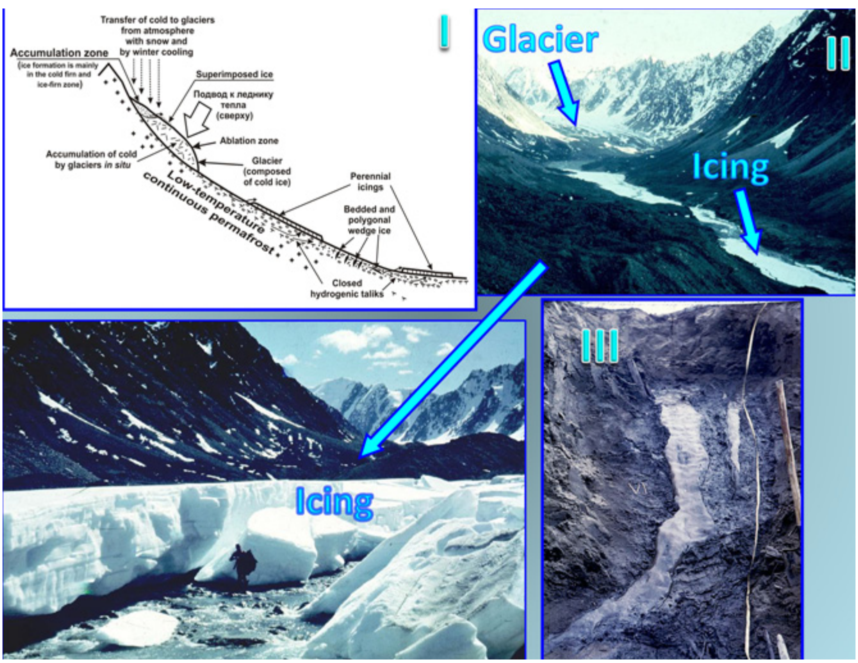

Fig. 9. A scheme of the cold CGS development (I) and its equivalent in the area of Obruchev's Glacier (II) and different generation of polygonal ice wedges (III) around, Eastern Yakutia

These ice phenomena trace from here along some 50°N to the Middle Amur River (North-east China) and further in northeastward direction. At the map of distribution of the polygonal ice wedges (fig. 4) a large southward projection has been formed then [6, 19], where these ice agents reflect low snow accumulation and deeply frozen bedrock [31,33].

Shallow segregation ice beds not infrequently characterize this area even in its southern part (fig. 10). In spite of that such environments belong to the enough southern area, in latitude about 50°N, the cold CGS characterize their features evidently. The modern glaciers occur at this area, but they are little in this part of Siberia, because the cold storage in their bodies is still not so great. The glaciers lie at the slopes of the mountains that can be enough high reaching a height of some 3000–3500 m; they are not covered, usually, by snow in summer and exist due to their alimentation by superimposed ice. Different icings occur around them in the valleys. It should be emphasized that at present the cold CGS appear already in so low latitudes and cover most of the Siberian Mountain terrain.

Fig. 10. Segregation ice formed in the bottom of the Darhad intermountain depression, Northen Mongolia

From the same CGS in the northern part of their area, the southern cold CGS differ only in the degree of cold storage capacity and by the lesser size of the ice bodies. What is interesting, the left-bank upper reaches of the Yenissei River are characterized today by the moderately cold CGS, whereas the relict Late Pleistocene landforms left by the CGS of the merely cold type (former icing glades, ice-wedge pseudo-morphs) occur in the periglacial zone of the former glaciers therein, in the inner parts of the West Sayan Ranges (fig. 11), and the analogous ice-wedge pseudo-morphs are revealed even in the Gobi Desert [9]. However they disappear in the Altai Mountains, i.e. this area was relatively less cold even during the Pleistocene cooling.

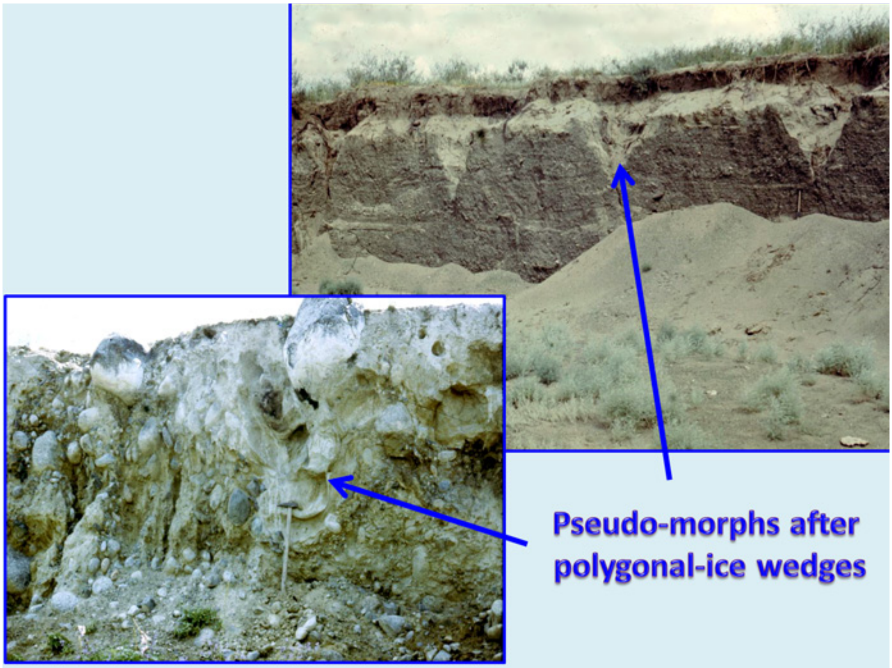

Fig. 11. Pseudo-morphs formed after polygonal ice wedges in the body of the Late Pleistocene basal moraine and fluvial-glacial alluvium in the left-bank upper reaches of Yenissei River

Since the difference between the southern and northern part of the area of the cold CGS distribution will be in the degree of thawing bedrock and in ice ablation, there are a few tens of small glaciers in Trans-Baikal region, restricted to mountains of about 3000 m a.s.l., whereas glaciers on the slopes of comparable mountains in Northeastern Siberia have developed dendritic forms and reach 10 km in length. Permafrost in Northeastern Siberia is frozen to – 10°C and below, and icings formed along the Late Pleistocene troughs therein Siberia may occupy many tens of km^2 (fig. 2).

It should be borne in mind that the different types of the CGS during the Pleistocene changed the distribution of ice volume in different parts of the Siberian Mountains. Today the Altai Ranges support the largest glaciers, surrounded by not so large icings; however, during the Late Pleistocene these glaciers advanced and reached 70 km in length and surrounded by great icings. In Northeast Siberia, the present-day glaciers are less extensive than in the Altai, but they are surrounded today by giant icings; the largest of which occupy areas up to 100 km^2. During the Late Pleistocene, the Northeastern Siberian glaciers were twice as long as those in the Altai, although they were initiated from mountains about 1000 m lower than the Altai ranges. The greater cold storage of the CGS in the Siberian Mountains provided the maximum volume of glaciation then. The same features concern the Kamchatka Peninsula, which is a special region neighboring to Siberia. It has very peculiar environments due to surrounding by the seas of the Pacific. At present the CGS there resemble the situation in the better wormed and moistened part of the Siberian Mountains – West Altai because the peninsula projects out into the sea and receives abundant precipitation, like most of the Russian Far East. However during the Pleistocene cold stages, the shelf sea between the peninsula and the continent was frozen, and the peninsula became a part of the giant frozen continent. As a result, although the highest point of Kamchatka (Mt. Klyuchevskaya) reaches an altitude of 4750 m, Late Pleistocene glaciers on the peninsula reached only a few tens of kilometers in length, very similar again to the situation in the Altai Ranges.

Such features add details to the complete picture of glaciation. More so that this picture allow us to analyze productively the modern situation and obtain a reliable base for ecological prognostics (fig. 12).

Fig. 12. A way to fulfill the task of ecological prognostics on the base of studying the spatial changes on landscapes and CGS along the Siberian Mountains

Conclusions

The present-day climatic differences found along the mountain belt surrounding Siberia in the east and south is similar in magnitude to the variations that occurred during the Pleistocene cold stages. The reason is that the general circulation pattern of the atmosphere did not radically change during the Quaternary. It was the lowering of temperatures that mainly controlled the development of environment yielding glaciation. The latter represented the close interaction of glaciers, icings and underground ice, the totality of which clearly reflected the environmental changes. The relation of the different ice agents is a reliable indicator for the state of the glaciation. It demonstrates that the Quaternary glaciers in the Siberian Mountains did not reach the final form of their development, the ice sheet. Instead, they had been mainly confined within their troughs, and only during the maximal advance did the glaciers reach the piedmont areas and form ice fields at the foot of the mountains.

It should be emphasized that in the Siberian Mountains the CGS of the cold types prevail at present and certainly they dominated during the Pleistocene cold stages. Therefore most of the ice agents, which can be observed in the Siberian Mountains today in frames of specific cryogenic-glacial systems, were much more frozen during the Pleistocene cold stages. As a result, glacial sediments and landforms underwent significant reworking by other elements of the CGS, among which icings were the most active. Hence, comparison with Alpine types of glaciation requires special adaptations for the Siberian Mountains, because of they are yielding by very different environments. Anyway the researchers, who study the modern and ancient glaciation, as well as the landforms and sediments formed by ice agents, must take into account the specificity in the development of the CGS under continental climatic conditions of Siberia, where close interaction between glacial and cryogenic ice phenomena is not only an exotic peculiarity of this area. This is the characteristic feature in development of glaciation.

So, it should be ever considered that the glaciers and the other ice bodies around are not only a repository of water-equivalent mass but also a repository of cold storage that controls the behavior of the complete CGS. To make an objective evaluation of any glacial events is impossible if to ignore such a feature. This has an important bearing on the scenario which has been assumed as a basis for ecological prognostics.

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В.С. Шейнкман

Университет Бен-Гуриона в Негеве (г. Беэр-Шева, Израиль)
Институт криосферы Земли СО РАН (г. Тюмень, Россия)
Институт географии им. В.Б. Сочавы СО РАН (г. Иркутск, Россия)

СПЕЦИФИКА РАЗВИТИЯ ОЛЕДЕНЕНИЯ В ВЫСОКОГОРЬЕ СИБИРИ – ЭКОЛОГИЧЕСКИЙ АСПЕКТ

Принципиальным отличием оледенения высокогорных районов Сибири является то, что оно характеризуется тесным взаимодействием льдов ледникового и мерзлотного происхождения и контролируется не только балансом снежного питания. В значительной мере формирование ледовых образований здесь зависит от запаса холода, накапливаемого их телами. Все ледники в Сибири расположены в области криолитозоны. Уже поэтому их развитие имеет принципиальные отличия от тех ледников, которые формируются вне области многолетнемерзлых пород и рассматриваются с позиций традиционной Альпийской научной школы. Формируемые в результате взаимодействия льдов ледникового и мерзлотного происхождения криогенно-гляциальные системы (КГС) определяют в Сибири комбинированное геологическое воздействие этих льдов, совместно или поочередно обрабатывающих долины. Все это имеет большое значение в плане экологической оценки территории. В данном случае такая оценка требует проведения анализа экосистемы с позиций реализации холода как фонового ресурса, ибо он используется КГС для своего развития. В этой ситуации нужны подходы к изучению оледенения, принципиально отличные от тех, что привычно используются с позиций традиционной Альпийской научной школы.

Вопрос этот отнюдь не безобидный, поскольку имеет и научное, и практическое значение. Так как следы ледников хорошо поддаются расшифровке, они

нередко используются в прогностических сценариях изменений окружающей среды посредством экстраполяций в формате «от прошлого к настоящему и от настоящего к будущему». Это относится и к современным, и к четвертичным процессам и требует индивидуального подхода к изучению форм рельефа и отложений, интерпретируемых как реликты оледенения. Благодаря тому, что в горах Сибири современные обстановки очень разнообразны и представляют широкий спектр условий, большинство типов КГС здесь встречается и сегодня. Вдоль горного обрамления, окаймляющего Сибирь с юга и востока, четко прослеживаются их переходы из одного типа КГС в другой, отражая тем самым характер окружающей среды и соответствующих обстановок.

Изучение таких обстановок посредством анализа КГС служит ключом к проведению палеогеографических реконструкций, так как вдоль горного обрамления Сибири ясно прослеживается такое явление, как криоаридизация – постепенное охлаждение территории на фоне усиления континентальности климата. Во время плейстоценовых похолоданий это явление прослеживалось и во времени – по мере перехода от межледниковья к ледниковью. Все это создает надежную базу для оценки экологического анализа изучаемых территорий.

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