Quaternary glaciation in the High Mountains of Central and North-east Asia

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Abstract

Quaternary glaciation in the High Mountains of Central and North-east Asia is characterised by the interaction of glaciers and permafrost. The combined activities of these geological agents characterise the cryo-glacial systems (CGS) that shape the valleys of Central and North-east Asia. 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 the reconstruction of 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. During the Pleistocene cold stages, the continental climate promoted the spreading of permafrost under arid conditions ('cryo-aridisation'). Since the ridges in the belt are comparable in height and in their cold continental environments, the extent of Quaternary glaciation was controlled by temperature. Under cryo-arid conditions, glaciers did not coalesce to form ice sheets. They developed only within the high mountains as valley glaciers. Consequently, glacial activity was inseparably linked with cryogenic ice in the proglacial and periglacial zone where icings were the most active agents. The latter occupied great areas and were comparable with the glaciers both in ice volume and in volume of geological work.

Introduction

The high mountain belt surrounding Siberia on the south and east (here referred to as the 'Siberian Mountains') represents a wide range of environments. It was this region, where at the end of the 19th century, Peter Kropotkin, 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, towards the end of the 1960s, had been completed 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 long-standing debate between adherents and opponents of A. Voeikov, the famous 19th century Russian climatologist, who claimed that it was impossible for great glaciers to

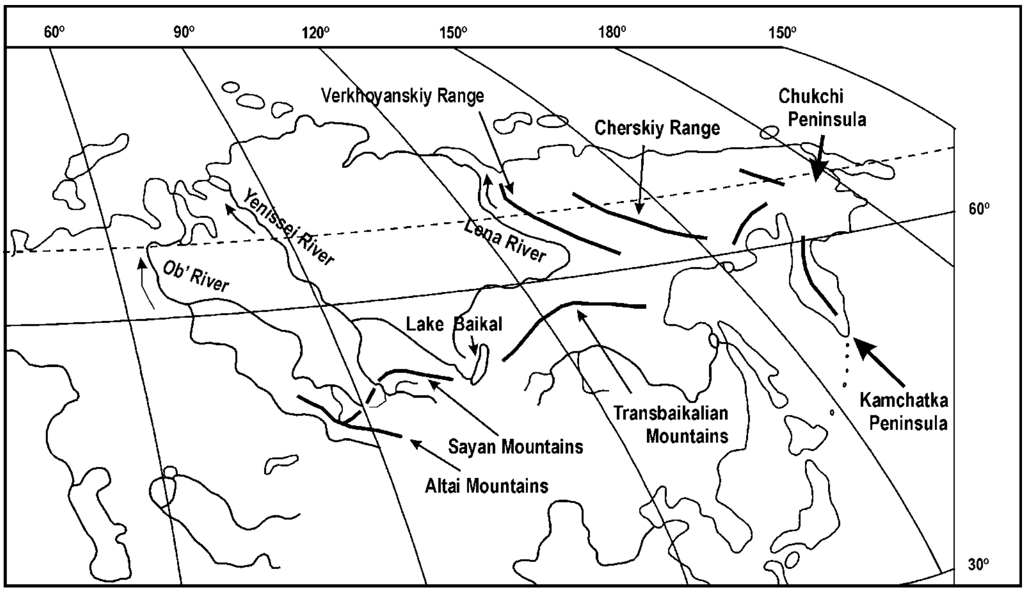

Fig. 1.
Location map.

Fig. 2. Near-glacier icing reworking the trough valley of the Obruchev Glacier (Cherskiy Range).

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 celebrities as J. Cherski and L. Berg supporting Voeikov's point of view, whereas V. Obruchev, a renowned researcher of Siberia, did not agree. The debate continues, and the discussion is as topical now as ever.

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 north-western Siberia, where the environment resembles that of northern Europe (Sax, 1953; Arkhipov, 1989; Zikin *et al*., 2000). In addition, glaciological investigation of modern glaciers in Siberia began in the most humid regions, in the western Altai with its relatively mild climate and accessibility. As a result, Alpine palaeoglaciological concepts from Europe were widely transferred 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 inaccessability the North-east Siberian Mountains were studied much later and less intensively than those of the West. New information only appeared in the 1970-80s with the next stage of development in Siberia. Then, together with detailed evaluation of geological material, numerous data were collected during geocryological mapping and a general survey of both glaciers and icings of the former USSR. Eventually, this research included all the formerly neglected regions (Nekrasov, 1976; Sheinkman, 1987; Koreisha, 1991). These data demonstrated that the old palaeoglaciological schemes had to be corrected. Evidently, the Quaternary events in the Siberian Mountains did not coincide with their 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 differ fundamentally from that of the mountainous regions of Central and North-eastern Siberia (Sheinkman, 1992, 1993, 1995; Sheinkman & Barashkova, 1991; Zamoruev, 1995).

An important point is that glaciological and geocryological investigations throughout Siberia (Vinogradov, 1966-1981; Yershov, 1988-1989) 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

Fig. 3. A valley snowbank in the Russian Mountains (Chukchi Peninsula).

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 (Sinitsin, 1980; Sheinkman & Barashkova, 1991).

Unfortunately, the original lack of exchange between glacier and permafrost research resulted in some major disagreement. Some investigators, who promoted the viewthat cryogenic ice prevailed in Siberia during the Quaternary, underestimated the role of glaciers (e.g. Danilov, 1978; Tomirdiaro, 1980). Whereas others (e.g. Grosswald, 1998), ignored 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, or in combination (Sheinkman, 1993). 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 cryological and glacial systems (CGS) through time.

Methods

Standard methods of reconstructing the extent of former glaciation from landforms and deposits are not always applicable in the Siberian mountain areas. The reason is the interdependency of glaciation and permafrost processes that intimately interacted in Siberia throughout the Quaternary. The present author has successfully applied a systematic approach by studying the complete 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 (Bates & Jackson, 1984; Kotlyakov, 1984). Some non-glacier agents of the permafrost regime can become very active. Icings, for example, are not 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 (Alekseev, 1987; Sheinkman, 1987, 1993; Romanovskiy, 1993). The original glacial landforms and deposits can be significantly modified by these processes.

In order to use a system approach, the main units of the CGS and their modes of geological work have to be first defined (Chrisopherson, 1998). Environmental diversity in the Siberian Mountains ranges from rather humid to

Fig. 4. Small icing near the Ak-Tru Glacier (North Chuiskiy Range, Altai).

extremely continental, and from relatively warm to extremely cold conditions (the coldest point in the Northern Hemisphere is situated in north-east Siberia). Most types of the CGS, may theoretically occur in the Siberian Mountains.

The principal characteristic of CGS (see below) is 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:

(i) the temperature regime of glaciers and the surrounding rocks, and

(ii) the appearance or disappearance of icings and ground-ice phenomena in the non-glaciated areas.

Glaciers, icings and ground ice control the geological work of the CGS.

Characteristics conditioning the development of glaciation

The high mountain belt surrounding Siberia in the south and east, consists of numerous ranges characterised by many similar features. The ranges reach from the Altai through Transbaikalia to the Chukchi Peninsula (Fig. 1). The highest mountains are found in the south-western part of the belt, in the Altai, where many ranges exceed 3000 m above sea level (a.s.l.), and a few peaks even above 4000 m a.s.l. (the highest point, Mount Belukha in the Katunskiy range, reaches 4506 m a.s.l.). In the Sayan Ranges many mountains reach 3000-3300 m a.s.l., and the highest peaks of Transbaikalia are close to 3000 m a.s.l. In North-east Siberia the highest point (Mount Pobeda, Cherskiy Range) reaches a height of 3147 m a.s.l. On the Chukchi Peninsula the mountains are lower; they are close to the 2000 m level (lower boundary of ‘high mountains’), but do not exceed it. All in all, the Siberian Mountains are characterised by a certain morphological uniformity, and, being situated in a relatively homogeneous climate and environment, most of them underwent a single complex of exogenous processes.

At present, most of the 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 North-west Arctic, warmed by the Gulf Stream. Monsoons from the Indian Ocean are blocked by the ranges of Hindu Kush and Himalaya, whereas moisture from the Pacific is blocked up by the Gobi Desert and only affects the coastal zone of the Russian Far East. Against this background, parts of the belt are differentiated by a gradual change in temperatures and by differences in the distribution of precipitation.

The south-western 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 North-western 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 North-east Altai and West Sayan ranges, and even the north-western part of the East Sayan Ranges (Revyakin, 1981). 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 kilometres, 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 intermontane 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 south-western 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 high-temperature permafrost in the south-west of the belt, and, towards the north-east, the permafrost gets more severe, including low-temperature frozen rocks. Only a narrow zone in the relatively moist West Altai is characterised by sporadic permafrost, whereas most of the Altai mountain terrain is characterised by discontinuous permafrost that grades into continuous permafrost on the north coast of Lake Baikal. Cryogenic ice along the belt ranges from small seasonal forms in the Altai to large, long-lived, perennial bodies within the mountainous terrain of north-eastern Siberia (Yershov, 1998).

Significant modern glaciation exists in the opposite ends of the belt, supported either by low temperature (the north-east), or by abundant precipitation (the south-west). In the coldest regions of north-eastern 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 (Sheinkman, 1987; Koreisha, 1991). Under similar climatic conditions on the Chukchi Peninsula, but with mountains of lesser height, there are only a few small glaciers. In the middle of their 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 include peaks of 2000 to 3000 m a.s.l. 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 a.s.l.. The most extensive modern glaciation is restricted to the highest and most humid Altai Ranges; where the glaciers reach 15-16 km in length and cover an area of more than 900 km^2 (Vinogradov, 1966-1981).

The long periods without any runoff are characteristic of the entire Siberian Mountains. The ablation periods of the modern glaciers are very short; ranging from 75 to 120 days in the Altai (Revyakin, 1981), and decreasing to 50-60 days at the glaciers of north-eastern Siberia (Sheinkman, 1987; Koreisha, 1991).

Functioning of the CGS

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 the 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 (i) landforms and deposits produced by the CGS, and (ii) transformed material of the CGS with its remaining energy, and (iii) new information.

Input information for the CGS, like in any system (Shannon & Weaver, 1999), 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 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 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 (Alekseev, 1987; Romanovskiy, 1993; Sheinkman, 1987, 1993).

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 north-western Arctic Ocean, 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 north-western Eurasia intercepted the remaining moisture. This mechanism caused a continental climatic environment to develop in the Siberian Mountains throughout the Quaternary (Sheinkman & Barashkova, 1991). Therefore, the limited volume of moisture that reached the Siberian interior regions may be, notwithstanding minor variations, conditionally considered

Fig. 5. Large icing in front of the Taldurinskiy Glacier (South Chuiskiy Range, Altai).

as a constant. Or, in other words, as very insignificant. Another constant characterising the CGS is the altitude of the Siberian Mountains, which has not changed 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 that 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 that the greater the cold storage in any geosystem, the lesser is the energy and its effect of exogenous processes. Above all, this is because of an 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, result in active erosion/accumulation processes yielded by the different ice agents. In fact, investigations by Serebryanny *et al*. (1989) 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.

Structure of the CGS

In the Pleistocene environments of the Siberian Mountains, the dominant members of the CGS were the glaciers. They were mainly valley glaciers, and only became reticular forms during their maximal advance in the Late Pleistocene when they reached inter- and submontane 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 (i) the

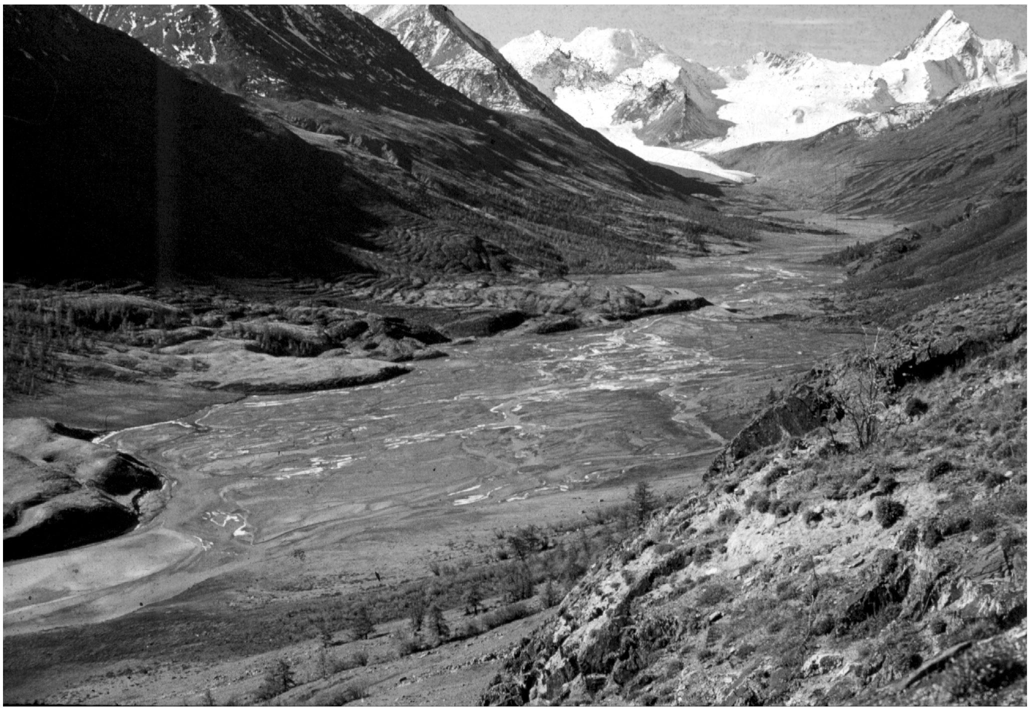

Fig. 6. Icing reworking the trough in front of the Taldurinskiy glacier (South Chuiskiy Range, Altai).

great cold storage accumulated by the CGS, and (ii) climatic continentality, and (iii) environments produced by the glaciers. Icings can be located directly on glaciers, abutted against glaciers or located at a some distance from glaciers. 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 meltwater, 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, that acts as a thermal insulator, and numerous small streams running under the icing will erode the valley. 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. 2).

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 snowbanks within the valleys. As members of the CGS, the snowbanks 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 snowbank 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 snowbanks often occur on the Chuckchi Peninsula at altitudes significantly lower than the moraines of the maximal glacier advance, though annual precipitation in the region is only about 300 mm (Fig. 3).

Underground ice as an element of the CGS is 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 (1975), 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.

Types and occurrence of the CGS

Five types of CGS are distinguished in the Siberian Mountains; four of them only occur under the modern environments and equivalent environments in past, and one type characterises the most cryoarid Pleistocene conditions. The different types of CGS are distinguished by their temperature regime. The same principles underlie many classifications of glaciers and permafrost (Kotlyakov, 1984; Yershov, 1998).

Only very limited temperature data are available for the Siberian Mountains. The only way to establish the character of the CGS in such a situation is to use certain ice agents as indicators. They must be the most stable; traces of their activity also need 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

Fig. 7. Reworking of the Late Pleistocene trough by a giant icing in the Adicha River valley (Cherskiy Range).

and ice wedges in front of the modern glaciers and along the Pleistocene trough valleys.

The first unit is the so-called 'warm CGS'. Glaciers included in this type of CGS are in an isometric temperature state close to 0ºC; 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. At present this type of the CGS occurs in the West Altai, the most humid and warm part of the Siberian Mountains. During the Pleistocene cold stages, the development of this type of CGS was impossible in the Siberian Mountains, where cryoarid environments prevailed.

The second unit is the 'moderately warm CGS'. In this case the glaciers are colder than those of the first unit, and near their surface a massif of cold ice appears; its temperature is well below 0ºC. Winter runoff from the glaciers is active as before, but part of the runoff is intercepted by annually forming small icings on the seasonally frozen ground, resulting from discontinuous permafrost in front of the glaciers. As a result, primary icings occur, reworking the near-glacier landforms and sediments in the periglacial zone (Fig. 4). At present the CGS of this type occurs along the north slope of the Altai-Sayan mountain systems. When cryoarid conditions prevailed during the Pleistocene cold stages, this type of CGS also disappeared.

The third unit is the 'moderately cold CGS'. The glaciers in this case lie on a mostly thawed base, but their bodies include masses of cold ice frozen significantly below zero, caused by downward freezing; the cold ice extends all over the glacier tongue surface. In front of the glaciers the permafrost is still discontinuous, although more frequent than in type 2. Large icings in the periglacial zone are clear indicators of this type of CGS (Fig. 5). The icings actively rework the primary glacial relief, but only in spring and summer because they are still seasonal features. The icings are already able to occupy areas up to 10 km^2 where they cut forms of glacial micro relief, widen the valleys and change the composition of sediments (Fig. 6). At present the CGS of this type are widespread in the inner regions of the Altai-Sayan mountains. During the Pleistocene cold stages they spread to the western end of the Siberian Mountains and replaced the warmer CGS types there. Relict icing glades in front of the former glaciers confirm this fact.

Fig. 8. Ice-wedge pseudomorphs at the margin of a Late Pleistocene trough valley in the Upper Yenissei reaches.

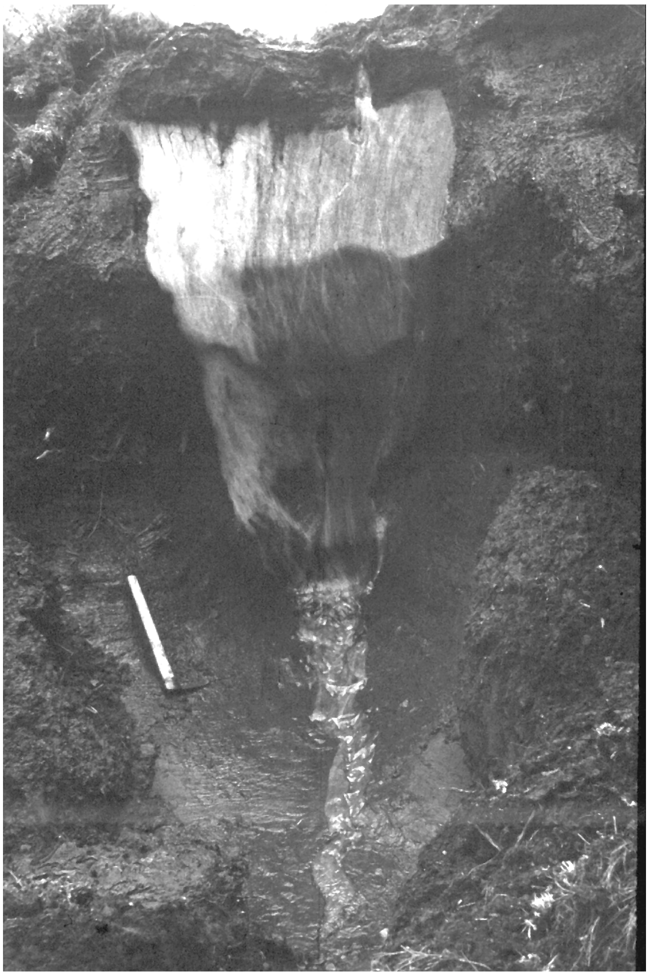

Fig. 9. A repeated ice wedge in the bottom of the Late Pleistocene trough in the Adicha River valley (Cherskiy Range).

The fourth unit is the 'cold CGS'. 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. Southern and northern sub-types may be distinguished among these CGS. On the whole, in this type of CGS the ground is deeply frozen. As their main indicators, large perennial icings and frequent ice wedges occur. These ice agents are caused by continuous low-temperature permafrost. They are found in front of the modern glaciers, as well as along the troughs of the Pleistocene glaciers. Runoff from the glaciers is restricted to the warm season and a significant part of this water is intercepted by near-glacier icings (Fig. 2). Reworking by icings in the Pleistocene troughs is very intensive. Major glacial and fluvioglacial landforms (including lateral and terminal moraines, high terraces etc.) are still clearly expressed, whereas most of the small-scale landforms have been removed by icing erosion (Fig. 7).

At present, the first perennial icings and frequent ice wedges appear in the Siberian Mountains within the right-hand upper reaches of the Yenissei River, in the East Sayan Ranges. These ice agents reflect low snow accumulation and frozen bedrock at a temperature of as low as –3ºC. Relict Late Pleistocene landforms of the same type (former icing glades, ice-wedge pseudomorphs) occur in the periglacial zone of the former glaciers in the left-bank upper reaches of the Yenissei River, in the inner parts of the West Sayan Ranges (Fig. 8), but they disappear in the Altai (Sheinkman, 1993).

Permafrost in north-eastern Siberia is frozen to -10ºC and below. Thus the difference between the southern and northern sub-types of the cold CGS will be in the degree of thawing bedrock and in ice ablation. Consequently, there are only small cirque glaciers in Transbaikalia, restricted to

Fig. 10. Relict icing glade in front of Late Pleistocene terminal moraines in the Lunkide River valley (Cherskiy Range).

mountains of about 3000 m a.s.l., whereas glaciers on the slopes of comparable mountains in north-eastern Siberia have developed dendritic forms and reach 10 km in length. Icings formed along the Late Pleistocene troughs in north-eastern Siberia may occupy tens of km^2 (Fig. 7). Beyond the icings, large, frequent ice wedges can be developed (Fig. 9).

The fifth unit comprises the 'super-cold' CGS. They do not occur at present, but their relics (a very dense network of ice wedges, traces of very strong freezing etc.) are expressed in the valleys of north-eastern Siberia. Development of icings in the area of the super-cold CGS had been limited. The reason is that because of the great cold storage of the CGS, the underground water supply routes for the icings were largely frozen; thus large icings could form mainly in front of the glaciers, where water was supplied by the ice melting (Fig. 10).

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; during the Late Pleistocene these glaciers advanced and reached 70 km in length. In north-east Siberia, the present-day glaciers are less extensive than in the Altai, but they are surrounded by giant icings; the largest of which occupy areas up to 100 km^2. During the Late Pleistocene, the north-eastern 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.

Concerning the Kamchatka Peninsula, its highest point (Mount Klyuchevskaya) reaches an altitude of 4750 m a.s.l. At present the CGS there resembles the situation in the West Altai because the peninsula projects out into the sea and receives abundant precipitation, like most of the Russian Far East. During the Pleistocene cold stages, the shelf sea between the peninsula and the continent was frozen, and the peninsula became part of the giant frozen continent. As a result, Late Pleistocene glaciers on the peninsula reached only a few tens of kilometres in length, very similar again to the situation in the Altai Ranges.

Conclusions

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 cold stages (Frenzel *et al*., 1992; Kutzbach *et al*., 1998). 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 glaciation.

The glaciation 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 confined within their trough valleys, and only during the maximal advance did the glaciers reach the piedmont areas and form ice fields at the foot of the mountains. The largest glaciers developed in north-eastern Siberia, where some of them reached 150 km and more in length.

On the whole, most of the ice agents that can be observed in the Siberian Mountains today as specific cryo-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 European (Alpine) glaciations requires special adaptations for the Siberian Mountains, because of the very different environments.

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