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The Pleistocene glaciation of Siberian mountains and atmospheric circulation

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ABSTRACT The paper presents a version of the impact of atmospheric circulation (circumpolar vortex, planetary high frontal zone, blocking anticyclones) on the development of glaciation in Siberia. On the basis of new data received by TL-dating and the nanocyclic method in the Chagan-Uzun Valley, a scheme of development of Pleistocene glaciations in the Altai is offered and its differences from processes in other regions of Siberia are discussed.

The phenomenon of Pleistocene glaciation has been examined by scientists from different points of view and caused continuous debates. In this article, the authors analyse the latest data on mountain glaciation in Siberia and compare paleoglaciological materials with the results of study of the atmospheric circulation mechanism. All this made possible to better understand ancient glaciation of the Siberian mountains and its nature.

The specificity of development of natural glaciers in Siberian mountains depends on the environment. During Pleistocene glaciation developed due to strong western winds and continentality of climate (Sinitsyn, 1980). As a result, in different regions glaciation differed by size, but on the whole its main features were similar within the whole territory up to Kamchatka, which was not isolated on the account of the draining of Okhotsk Shelf and freezing of the adjoining seas.

The size and character of ancient glaciation in Siberian mountains depend on the quantity of heat and moisture input and their redistribution within the region. Atmospheric precipitation had always been limited here and the further inland the less precipitation. Hence, atmospheric precipitation was the limiting factor for glaciation, while temperature was a controlling factor.

The study of Pleistocene events showed, that the fall of temperature that began at the end of Pliocene gradually progressed and every next cold wave was stronger than the previous one. The general climate changes went on simultaneously, although the response of nival-glacial systems to them was different (Velitchko, 1973; Svitoch, 1987; Sinitsyn, 1980).

In those cases, when mountains had similar heights, i.e. when the role of relief was not prominent, the largest glaciations developed in most humid places in the first half of Pleistocene and in most continental regions - in the second half of it. In the first case, the Pleistocene cold wave replaced the warm and humid conditions of Pliocene, and the combination of high humidity and big reserves of cold secured the development of large glaciers in any situation (it was characteristic of north-west of Siberia). In the second case, limited precipitation made possible a large-scale glaciation only in the coldest climate and in high mountains. This situation was typical of the south and east of Siberia. Consequently, in one situation climate cooling normally caused an increase of glaciation, in the other - its decrease. Atmospheric circulation played an extremely important role in the development of glaciation. Not touching upon the cause of Pleistocene climate cooling or its triggering mechanism (this question needs to be specially examined), we shall demonstrate a working hypothesis of a possible version of the circulation machine under the conditions of the starting cooling and will trace its impact on glaciation.

So, the air temperature trend in Pleistocene, if we analyse only the long-term fluctuations, has always been negative, since temperature constantly decreases from Early to Late Pleistocene. Every new impulse of cold was more intensive than the previous one, and relatively warm periods between the impulses on the whole did change the statistical characteristic of trend. The process of cooling was accompanied by expansion of circumpolar vortex and, accordingly, by the planetary high frontal zone's (PHFZ) movement to the south. Within PHFZ such weather conditions have been observed (primarily as concerns regime of precipitation) which are necessary for the development and stability of glaciers and ice sheets.

The movement of PHFZ from north to south and with it of the zone of the fronts' activities steady abundant precipitation, and deep penetration of Arctic air masses inland had occurred by impulses, similar to the expansion of circumpolar vortex, whose nature can probably be explained by the same reasons as the first Pleistocene cooling on the Earth and also by an internal fluctuational mechanism of the climatic system.

In conformity with the temperature trend, the trend of expansion of circumpolar vortex during Pleistocene was also of one direction. It is significant that in conformity with the movement of PHFZ, there were differences in the time of advance and quantity of peaks of the Pleistocene glaciations. In north latitudes an enormous glaciation began in Early Pleistocene, whilst further to the south it was postponed till Middle or Late Pleistocene. Maximum Pleistocene cooling in the Northern Hemisphere (or round the Globe) probably took place when the major changes of circulation reached the temperate and subtropical climatic zones, which, according to new data (Climate..., 1988), determined the temperature and baric background of hemisphere. Consequently, we propose that PHFZ reached the south of the temperature zone and the north of subtropics in Late Pleistocene, the time of the highest peak of Pleistocene cooling. Precisely at that time the mountain belt of Siberia and Central Asian mountains found themselves within PHFZ and because of this the largest Late Pleistocene glaciation occurred there, while in the earlier periods of Pleistocene this area could have been free of it. Moreover, heat and moisture characteristics of PHFZ in Late Pleistocene could secure glaciation only in high mountain regions. The further movement of PHFZ was detained by the South-Asian mountain chain. In addition, at that time circumpolar vortex reached its maximum possible expansion. Comparing the present and model baric fields received by Manabe & Hahn (1977), one may conclude that during Pleistocene PHFZ moved to the south approximately at 20° to 25° of longitude. After that the circumpolar vortex began to reduce and PHFZ went back to the north, again in a pulsating manner. In regions with stable PHFZ, conditions for glaciation were favourable but less so as during the first glaciation. As a result, two peaks of Late Pleistocene glaciation were observed in the high latitudes of the Northern Hemisphere. As to duration of Pleistocene, apart from certain bench marks, it may be dated from the beginning of circumpolar vortex expansion and up to the returning of the vortex to its starting point.

Latitudinal differences in the course of Pleistocene glaciations have been explained by an intensive development of block anticyclones. We can assume, that the intensity of block anticyclonal fluctuations could be the circulational reason for climatic fluctuations within Pleistocene. Moreover, if we proceed from the fact that atmospheric circulation of Pleistocene was characterized by centers of atmospheric action (Sinitsyn, 1980) similar to the present-day ones, then we can speak about an analogy of the block anticyclone processes as well: the main block zones were found in East Siberia from Taimyr to the east, up to the Lena River mouth and in the West Europe from the Scandinavian Peninsula westward. This assumption agrees with the results of Tronov (Noginsky & Tronov, 1949) on the North-European and East-Siberian anticyclones, as possible circulation factors of Quaternary glaciations in North Siberia. In the European sector, blocks were most common in spring and in East Siberia - at the end of spring and another maximum - at the beginning of winter.

In other words, today weather processes in spring are to a considerable extent similar to mean annual conditions in Pleistocene. This result contradicts the opinion of Sergin (1980) who believes that autumn is a Pleistocene analogy. On the whole, his reasoning is logical (a change from warm to cold, from Pliocene to Pleistocene), but it is not confirmed by the analysis of really possible atmospheric processes. The greatest development of block processes and meridional circulation (also monsoon on the coast) was observed during one of the peaks of Pleistocene glaciation in Northern Hemisphere, which is the maximum of Pleistocene glaciation in South Siberian mountains.

The differences in datings of Pleistocene glaciation in different parts of Northern Hemisphere may be explained by the asynchronism of blocks development in Asia and Europe. For instance, the Urals block-anticyclone is characteristic of the E-circulation form by the classification of Wangengeim-Gers, i.e. when large-scale atmospheric waves are forming over the continents and there is an intensive inter-latitude air exchange. All Pleistocene processes may be presented as a change of atmospheric circulation from W-form to E-form during the maximum Late Pleistocene glaciation, and to C-form in the stage of degradation. This corresponds to data of Krenke (Glaciers..., 1987) supported by recent materials, and implying that E-form is favourable for glaciation of Tien Shan (according to our data, Altai also) and for glaciers of the Canadian sector; C-form is good for glaciation processes in the North of the European USSR, and the Barents Sea.

The question about the peak of cooling and maximum of glaciation in the studied area is very important. In north latitudes the minimum of temperature (maximum of cooling) came later than the maximum of glaciation. This temperature minimum formed over well developed ice sheets and it was accompanied by a further spread of cold Arctic air masses from the north, by thermal radiation cooling, and other meteorological processes which were derivatives of the circulational situation, i.e. the presence of the cooling trend mentioned above. According to a number of researchers (Monin, 1982), the observed lag made about 20° by phase and embraced rather a long period of geological time, if we take the whole duration of Pleistocene. At the same time approaching the regions where PHFZ came closer to its limits (the mountains of South Asia), from which it began to go north, the maxima of cooling and glaciation should come together and finally become synchronous.

Consequently, in Pleistocene, the mountains of South and East Siberia were subjected to a stage of large and intensive glaciation only once, and it happened during Late Pleistocene. Although peaks of cooling and glaciation were being brought together, they were not yet simultaneous. The glaciation of North-West Siberia, like that of North Europe, could have been multiple with well expressed divided peaks.

Thus, on the other hand, the prevalence of west air streams now and in the past determined the role of Atlantic in providing Siberia with moisture, because the influence of Pacific Ocean was limited by a narrow coastal area in the east. If we take Eurasia, the similarity of paleoglaciological events is manifested for Europe and north of West Siberia (in both it has been intensified because ice moved from ancient not very high mountains to the plain). As for the movement deep onto the continents, the increasing continentality and the influence of the height of mountains enhance the differences there. On the other hand, these differences are conditioned by specific features of the circulational mechanism in Pleistocene.

For a long time Saks' conception (1953) about paleogeographical reconstructions prepared for north-west Siberia and in many respects similar to the European schemes served as a basis for Siberian reconstructions. Three glaciation ages were distinguished: Early, Middle, and Late Pleistocene with the maximum glaciation in the Middle Pleistocene. Subsequently, this scheme was more than once specified (Arkhipov, 1983; Kind, 1974), but the introduced terminology and principles are still used now. For North-West Siberia, where the Atlantic Ocean's influence was strong and secured repeated development of large glaciations, this scheme is justified from glaciological positions, the more so that it later on was supported by a great number of absolute datings (Afanasiev, 1987; Arkhipov, 1983; Isaeva & Kind, 1986; Kind, 1974). The tendency towards decrease of glaciation in Late Pleistocene was normally reflected by intensification of continentality and atmospheric circulational special features, the observed mid-Pleistocene maximum of glaciation in fact being explained by a poor preservation of large-scale glaciation traces in Early Pleistocene.

In the first place, the researchers tried to confirm the validity of Saks' scheme for South and East Siberian mountains. Some of them continue to do it today (Borisov & Minina, 1989; The Pleistocene..., 1984). Great amounts of new materials have been received in recent years (Endrikhinsky, 1985; Zamoruev, 1982; Kind, 1974; Kolpakov, 1979; Sheinkman, 1987 ; Sheinkman, 1990), and the adoption of absolute geochronological methods allowed to change the old ideas. As demonstrated above, progressing development in Pleistocene of cooling went on under continental conditions and specific features of atmospheric circulation, which led to the development of large glaciers only in Late Pleistocene when the mountains of the region reached the greatest heights. Paleoglaciological data confirm these results. For example, let us take Altai, which is interesting in this respect.

Altai is situated in the middle of the great Pamirs-Chukotka mountain arc, within which such continental conditions are found. In addition, it is quite well studied and is distinguished by its unique paleoglaciological formations, which reflect all movements of the Pleistocene glaciation. Taking into account high representativeness of most formations of Altai and similarity of its paleoglaciological situation to that of Pleistocene glacial troughs of South and East Siberia, we shall examine in more detail the valley of the Chagan-Uzun River which is most representative in its paleoglaciological aspects and this will show the difference of the events from those that have taken place in the north-west of Siberia in Pleistocene.

The Chagan-Uzun River begins at the largest modern glaciers - Taldurinsky and Sophiysky in the high altitudes of the South-Chuisky Range. It runs over areas with very continental climatic conditions and falls into the Chuya River, one of the tributaries of the Ob' River. The lower reaches of Chagan-Uzun within the first hundreds of meters are cut into a peneplain of an ancient planation surface and then open up to the Chuya intermontane depression. Here the river's channel is divided by a thick end-moraine complex. Depositions of a dammed lake are associated with this complex end-moraine cut down by a breach of valley and lying on the parent socle. Beyond, as a detailed investigation has shown, only the aura of the washout of this moraine is seen or the glacial-fluvial and glacial-lacustrine deposits are met with conditioned by the existence of a chocked basin already in Chagan-Uzun Valley. Ice streams have its limits from side tributaries situated down the valley, but on the whole it was not filled in by main glacier trunk. The fact that lake deposits reflect here existence of two reservoir systems - external situated beyond the limits of the end-moraine complex and the inner one whose deposits are mainly met with between the distal and proximate moraine banks. The deposits of the inner lake differ in age, in the section where they are divided by a layer of glacial-fluvial sediments and two rock masses, described earlier (Okishev, 1982), can be distinguished in the lake terrace scarps on the talweg.

The only dating (^{14}C) from the upper lake stratum gave 25 000 ± 600 years and the TL-dating by old technology of the 1970s is nowadays being refuted by Shlyukov & Shakhovets (1987). The TL-dating carried out together with a new method (Shlyukov & Shakhovets, 1987) without earlier distortions, has given the following result: for lower lake stratum date is about 80 kyr, for the upper one - from 40 to 60 kyr (Sheinkman, 1990). Distal moraine samples have given thereabouts 90 kyr, the moraines of the next series - 70 kyr. In our joint investigations, for studying the lake sediments we used the nanocyclic method of Afanasiev (1987). For inner basin sediments, in the part of the valley untouched by river erosion, the date of 80±12 kyr was reached for the lower stratum. Moreover, a rhythm of deposits up to seasonal has been discovered. We also located an annual interruption of sedimentation along the whole thickness due to winter freezing for about four months, i.e. the lake existed under climatic conditions similar to the present-day ones, which confirms its interglacial or interstadial character and a moraine-damming genesis. A glacial dam, whose existence has been admitted by Okishev (1982), could not have developed in such situation. Thus, the formation of the complex under consideration may be referred to

Zyrianka Ice Age. Glaciation of that time began to form nearly 100 kyr ago and continued for about 50 kyr. Its last limit of end-moraines has not been defined so far, but it can be traced stratigrafically.

Thus the above date correlate quite well with materials of the study of the middle part of Chagan-Uzun Valley. There is a group of Chagan-Uzun sections, in which the events are reflected. The central scarp is most interesting. The local inhabitants named it Kuzul-Yar for the red-coloured Neogene stratum, on which grey Pleistocene sediments about 200 m thick have been deposited. In the lower part of the sediments, deposits of a local dammed lake are found bordered by a semiarid moraine 70 m thick. All above-lying strata are alterations of the main moraines, but on the whole they may be united in three climatic-stratigraphic "stadial-interstadial" complexes. Their TL-age turned out to be as follows. Samples of grey strata showed 125 and 135 kyr, and shingle stratum of multilayer moraine had the age of end-moraines. The interstadial deposits under the uppermost moraine are of about 60 kyr, fixing in this way the last boundary of Zyrianka Ice Age as being 50 kyr B.P. (Sheinkman, 1990).

The nanocyclic analysis of the lens of lacustrine deposits in the given section has shown, that its upper part formed 106±7 kyr ago, and the bottom one - 132±12 kyr, which coordinates well with earlier results. It shows that the lake associated with the lens reflects processes of preceding interglacial. Examination of red strata revealed a full saturation of TL-dosimeter, i.e. the age of 300 kyr B.P., beyond the TL-dating capacity.

Thus, in the first stage of Pleistocene glaciation of Zyrianka Age the Chagan-Uzun Glacier had not only filled in the whole valley, but also came out onto the middle and lower parts of planation surfaces, and further to the Chuisk intermontane depression, where the largest glacier formed. Such picture was quite common in the mountains of South and East Siberia. It characterizes the mountain-cover type of glaciation. When the centers of glaciation were not high enough, the glaciers were only of a mountain-valley type.

In respect to glaciations older than the Zyrianka one, we can say that they have been much smaller in size (later on their traces were buried or obliterated by younger glaciers) or have not evolved at all. In the second half of Late Pleistocene, a peculiar paradox appeared in this region. The progressive cooling with a peak in Sartan Age caused reduction of glaciers everywhere in Siberia due to peculiarities of atmospheric circulation. In continental areas cryoaridization of climate reached such scales that, in spite of mountains being at their highest, accumulation on glaciers began to decrease with the resulting decrease of the glaciers' size. The difference between Zyrianka and Sartan glaciers was quite significant. In the second stage of Late Pleistocene, in Sartan Age (in the mountains of South and East Siberia) glaciation became mainly of a mountain-valley type, although in the north-west glacial shields continued to form, but they were smaller than their forerunners.

The limits of this article do not make possible a detailed consideration of all problems of ancient glaciation in Siberian mountains and its connection with atmospheric circulation - this process is complex and versatile. Future investigations with new paleoglaciological information, including ample quantitative indices will allow us to come back to the above problems seeking solutions for them on a higher level of knowledge.

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