PALEOGEOGRAPHY OF LATE PLEISTOCENE GLACIATION OF NORTH-EASTERN ASIA

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ABSTRACT

Two glacial complexes exhibiting erosional and depositional relief forms are found in the mountain regions of northeastern Asia and correlate with two horizons deposited during cold periods, separated by a horizon deposited during a warm one. The chronology of these horizons in various regions coincides with Zyryan and Sartan stades and Kargin interstades, which are recognized in Siberia. Paleogeographic reconstructions based on geomorphological analyses and stratigraphic and chronological data have shown that the Zyryan glaciation occupied about 40 percent of northeastern Russia and formed two glacial regions: Verkhoyan-Chukotsk and Koryak-Kamchatsk. The area of the Sartan glaciation was three times less than the extent of Zyryan ice. Glaciations had irregular, nodal distribution. Glaciers were concentrated in seven separate regions: Chersky, Anyui, Ekityki, Chukotsk, Okhotsk, Taigonoss, and Koryak. In environments of disjunct high to mid-elevation mountains, the Zyryan and Sartan glaciations developed similarly on a comparable scale. However, the scale and type of glaciation differed in the uplands. Regionally, and in separated glacial centers, there was a reduction in the distribution and scale of the Sartan glaciation from west to east in comparison with the Zyryan glaciation, which was due to the different reaction of mountain structures of different height and degree of disjunction to the rise of the regional snowline. Calculations show that the snowline during the Sartan epoch was 150-300 m higher than in the Zyryan. Late Pleistocene glaciations in this region were different from glaciations in Europe, where Late Valdai represented the maximum. In northern Asia, the Zyryan glacial maximum occurred in the first half of the Late Pleistocene.

INTRODUCTION

Currently, the most important problem in the study of Pleistocene glaciation concerns the paleogeographic reconstruction and correlation of glacial events. The origin and development of Quaternary glaciations are closely associated with large-scale climatic fluctuations. Establishing the association of regional features to Pleistocene paleoclimatic transformation, particularly, in its final stages, is very important in the prediction of future climatic scenarios.

Quaternary glaciations of northeastern Asia were first analyzed at the end of the last century in the works of P.A. Kropotkin, A.I. Voyeikov, and I.D. Chersky. Kropotkin proposed the existence of an ice-sheet type of glaciation that covered this entire area. On the contrary, Voyeikov (1881), who dealt with the problems of theoretical climatology, concluded that the beginnings of mountain glaciation possibly occurred in the eastern Siberia, but only in the limited areas. Chersky was the first to study the traces of mountain glaciations in the Kolyma and Indigirka river basins, where he found no evidence of past glaciation. Both Voyeikov and Chersky attributed poor glacial development to the occurrence of a continental type climate.

Many facts on the glaciation of this territory were collected during the first systematic study of regional geology and geomorphology in the 1920's and 1930's by S.V. Obruchev and Yu.A. Bilibin. The numbers of glacial epochs, their characteristics, and their dynamics have since been worked out, and the following glaciation types have been recognized: (1) passive ice-sheet, (2) embryonic, (3) broken, and (4) alpine and valley (Kolosov, 1945, 1947).

Numerous local and regional stratigraphic schemes have been constructed based upon the number and timing of glaciations documented by these early researchers. The working scheme of V.N. Saks, adopted at the International Stratigraphic Meeting in 1957, is currently used in stratigraphic and paleogeographic reconstructions. Names of glacial and interglacial horizons (Zyryan, Kargin, Sartan) have been adopted for a large part of the region.

Correlation analyses, which include geomorphic, paleoglacial, mineralogical, palynological, thermoluminiscence, radiocarbon, and stratigraphic data, have permitted the detailed distinction of glacial deposits of different ages and the refinement of the concepts of glacial and interglacial epochs. The prevailing idea in the 1940's through the 1960's of two to three regional glaciations (Kolosov, 1947; Shilo, 1961; Baranova and Biske, 1964) has been replaced by the belief that there have been five to six glaciations in most parts of mountain structures (Kartashov, 1966; Ananyev et al., 1979, 1984; Voskresensky et al., 1984; Chanysheva and Bredikhin, 1981). The majority of investigations have shown evidence of at least two independent glaciations during the Late Pleistocene.

Despite many years of examining the development of glaciations in northeastern Asia, the main questions are still not well understood. There is still no prevailing idea on the number of glacial epochs, character and scale of glaciation, glacial geography, and age boundaries. These unresolved questions also concern the Late Pleistocene.

GEOMORPHOLOGICAL ENVIRONMENT AND TIME OF LATE PLEISTOCENE GLACIAL COMPLEX FORMATION

Our paleogeographic reconstructions of Late Pleistocene glacial events are based upon the analysis of data from previous investigations and information obtained during field work in the upper reaches of the Kolyma and Indigirka river basins, Northern Priokhotye, Taigonoss Peninsula, and the Chukchi and Koryak Uplands (Glushkova, 1982, 1983, 1984, 1989; Glushkova and Sedov, 1984; Glushkova et al., 1987; Glushkova and Prokhorova, 1987; Glushkova and Smirnov, 1989).

Most of the study area, which lies to the east of the Yana and Indigirka rivers, contains mountain ranges with an average height of 500-700 m. Low-relief plains occupy comparatively small areas in the lower parts of the Indigirka, Kolyma, and Anadyr river valleys. Upstream, the basic topography consists of uplands exhibiting relief of 1,000-1,500 m and, farther on, the presence of relatively narrow ridges and isometric granitoid massifs reaching elevations of 2,000-2,600 m. Northeastern Russia forms the easternmost peninsular projection of the

Eurasian continent into the seas of two oceans. The main path of the Pacific-Arctic interfluve is located considerably south, along the Pacific shore.

Much of the region is influenced by a wide Siberian anticyclonic weather pattern that provides the lowest winter temperatures in the northern hemisphere. The influence of moderate Pacific marine air masses from lower latitudes is smaller. Permafrost is essentially continuous in the region. Modern glaciers, in the Chersky Range system and Koryak Upland, develop considerably lower than the climatic snowline. The effects of a continental climate were even more pronounced during the Pleistocene cold epochs because of changes in ocean circulation patterns, lowered worldwide sea level, and subareal exposure of vast areas of the continental shelf. These factors and the relatively low relief of the mountains did not promote the development of ice-sheet type of glaciations but predetermined their mountain-valley character.

Modern landforms are often the result of relict glacial morphosculpture. Late Pleistocene and Holocene deposits that overlie these glacial features have been sampled and analyzed at some locations. Analyses of the geomorphology, stratigraphy, and chronology of glacial complexes and correlative sediments were used to reconstruct the paleogeography of the Late Pleistocene.

Our investigations indicate that sculptural and accumulative glacial landforms belong to two independent glacial complexes. These complexes differ in geomorphological position, degree of transformation by denudational processes, areal extent, and time of formation. In the sections of unconsolidated deposits there are two moraine and intermoraine layers; in correlative deposits there are two horizons that were deposited in cold periods, divided by a horizon deposited in a warm period (Gol'dfarb, 1972; Giterman, 1985; Ivanov et al., 1986). They are Late Pleistocene in age and correspond to the established Siberian glaciations, Zyryan (Early Würm, Early Wisconsin), Sartan (Late Würm, Late Wisconsin). They are also analogues of Itkillik and Walker Lake glaciations in the Brooks Range of northern Alaska (Porter et al., 1986). The two glacial epochs are divided by the 25,000-year Kargin period, during which glaciers retreated to the high-mountain regions, where they are also found today.

Problems concerning the climatic condition of the Kargin epoch in northeastern Asia are not resolved. However, radiocarbon-dated paleobotanic samples (Lozhkin, 1976, 1984; Lozhkin, et al., 1982; Giterman, 1985) show that the climatic conditions for the majority of the region during most of the Kargin time interval were similar to modern conditions with some periods closer to the conditions of the Holocene optimum.

Geomorphological classification of glacial structures based upon analyses of aerial photographs and spectrographic satellite images were confirmed by field investigations. This analysis shows that deposits and structures of the first (Zyryan) glacial complex are well-developed in many valleys, intermontane hollows, and on the submontane plains. The mounded-ridge relief of the main moraine, arcuate end moraines, and other accumulative glacial forms are strongly modified by erosional, cryogenic, and slope processes.

Deposits and structures of the second glacial complex (Sartan) are less extensive in distribution and are essentially confined to the higher elevations of mountain structures. Erosional and accumulative forms that comprise this complex are very well preserved, with little or no alteration by weathering processes. The large differences in the regional distribution, geomorphologic position, degree of preservation, and relative positions of terminal moraines, are the primary characteristics used in mapping the areas of glaciations of different ages.

The existence of two distinct glaciations is supported by the correlation between glacial complexes and river terraces. Sartan and Zyryan glacial complexes are clearly represented in river valleys. In the upper river valleys, only one flood plain terrace is cut into the inner (Sartan) glacial complex. This terrace has been dated at Late Pleistocene-Holocene (Kolpakov and Belova, 1979; Glushkova and Lozhkin, 1990) based upon palynological analyses and radiocarbon data. Two to three river terraces are cut into deposits of the second (Zyryan) complex. The ages of the second and the third terraces are equivalent to the Kargin-Sartan and Late Zyryan-Kargin intervals, respectively, but vary somewhat in different valleys.

ZYRYAN GLACIATION

Mapping of the Zyryan glacial complex shows that glaciers and ice occupied about 40 percent of the region (Fig.1.1) and mainly developed in the mountains along the Pacific-Arctic divide and in the Chersky Range and Koryak Upland. Ridges and massifs of the inner-continental regions higher than 1,000 m were glaciated. In the coastal regions, glaciers were generally formed at similar heights to modern sea level. Reticulated glaciers were widespread at the maximum stage of glacial development. Thick ice fields formed on plains and plateaus. Many valleys were completely filled with ice and glaciers and often spilled from one basin to another across low saddles in the ridgeline. On the flanks of high mountain ridges and in the uplands, a complex system of valley glaciers extended 80-100 km downslope. These glaciers flowed through large and small valleys to intermontane depressions and submontane and coastal plains, where they coalesced into vast piedmont glaciers. Perimeters of the largest arcuate end moraine in the Moma, Malyk-Siyen, Amguema, Busk, and other depressions exceed 15-25 km. End moraines form bars across the mouth of fjords (Avenarius, 1982). These features were also seen on seafloor profiles in shallow waters of the Krest and Mechigmen Gulfs (Ivanov, 1986).

In the Tanyurer River Basin, along the northern flank of the Nizhne-Anadyr lowland, the Zyryan glacial complex is particularly extensive (Fig.2). Depositional glacial features, exhibiting positive-relief morphology, are numerous and various in the Tanyurer River valley, the submontane plain near Pekul'ney Ridge, and the low montane massifs of the southern flank of the Chukchi Upland. These features include a main moraine with mounded-ridge relief, eskers, kames, oriented lakes, arcuate end moraines, and amphitheaters. Based on their configuration, areal distribution, interrelations, and size, a reconstruction of one of the largest submontane glaciers in northeastern Russia can be made by retracing the main stages of its retreat. The maximum advance of Tanyurer glacier is fixed by a series of undulating ridges that extend for 90 km to the banks of the Anadyr River.

The ridge configuration and the orientation of associ-

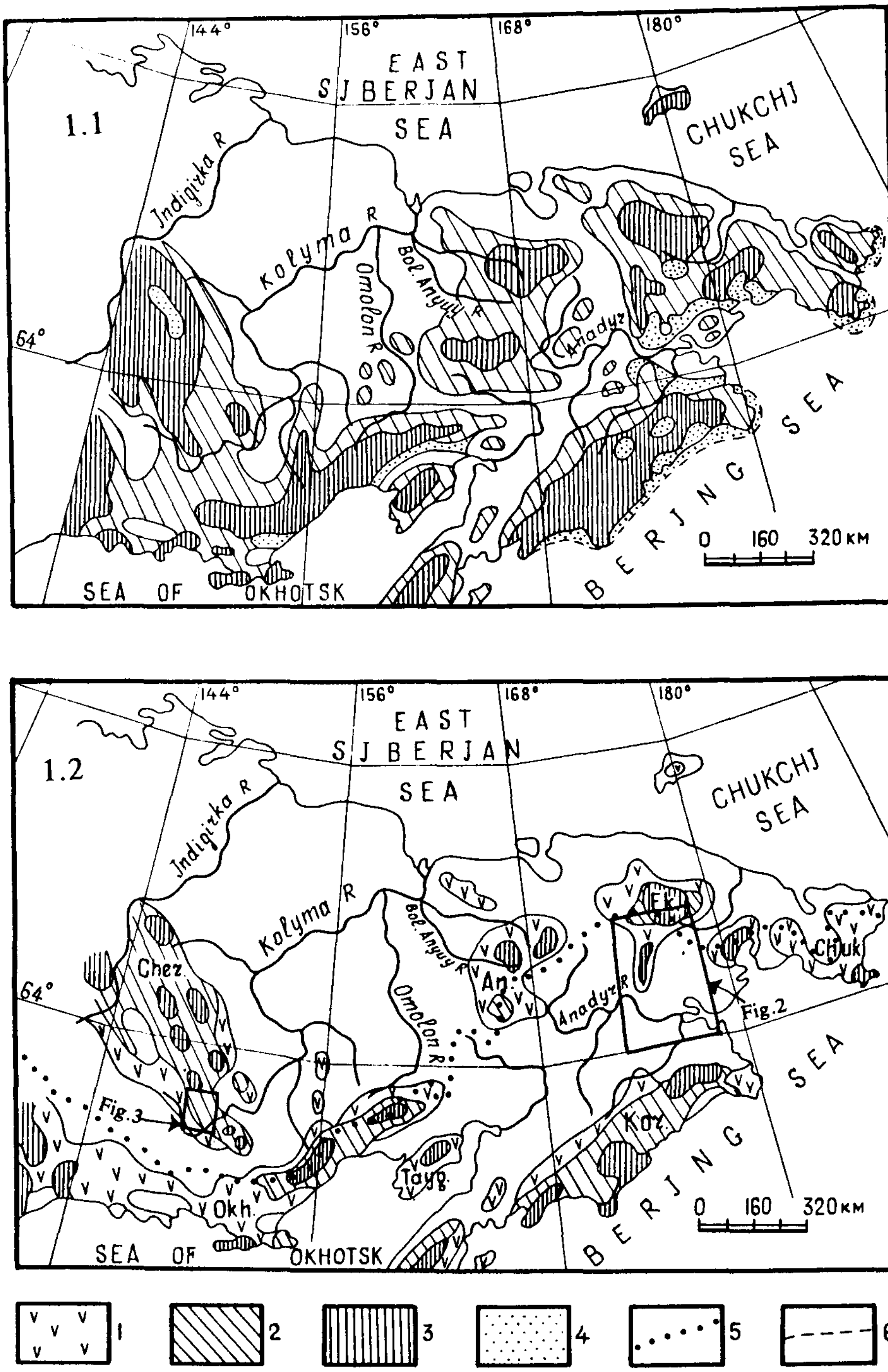

Fig.1. Areas of Late Pleistocene glaciations: 1.1-Zyryan, 1.2-Sartan. 1-4 - glaciation type: 1-mainly cirque, 2-mainly valley, 3-mainly reticulated and mountain-covering, 4-thick piedmont glaciers, 5-line of the Major Pacific-Arctic divide, 6-supposed glaciation boundaries on the shelf. Glacial regions: Chersky (Cher.), Anyui (An.), Ekityki (Ek.), Chukotsk (Chuk.), Okhotsk (Okh.), Taygonoss (Tayg.), Koryak (Kor.).

ated lakes indicate that the glacier was divided into several lobes during its maximum advance. The thickest lobe filled the Tanyurer River valley. Glaciers formed in the central part of the Chukchi Upland and spread a maximum distance of about 330 km. In the Tanyurer River valley, there are eight inner arcuate end moraine belts and a series of small ridges. During the first three stages of glacial retreat, the Tanyurer glacier was multilobed with the first lobe, along the eastern slope of Pekul'ney Ridge, exhibiting the greatest thickness. The fourth stage of deglaciation is marked by a single morainal amphitheater, 40-80 m high, 1.5-4 km wide, and 15 km long, situated 60 km from the mouth of the Tanyurer River. Four lines of oriented lakes are divided by a series of recessional moraines, which mark the successive retreat of the glacier. Other arcuate end moraines cross the middle course of the Tanyurer River and are separated from each other by distances of 25-50 km. In this part of the river course the Tanyurer glacier was of the valley type. At the ice spreading centers in the mountain massifs of the Chukchi Upland and Pekul'ney Ridge, traces of the Zyryan glaciation were destroyed during the later Sartan glaciation. Zyryan age deposits were preserved only in deep trough valleys, at several levels on the shoulders of troughs, and in partially eroded cirques in the mountain regions.

As seen in Fig.1.1, ice-covered regions during the Zyryan glaciation generally followed the contours of mountain structures. In the west, the boundaries of these ice-covered regions coincided with the higher ridges and massifs. However, in the northeastern part of the region, low mountain plateaus and uplands were under glacial ice.

SARTAN GLACIATION

The Sartan glaciation was less developed than the Zyryan. Its glaciers occupied only 14 percent of the region. The Sartan glaciation was characterized by the irregular nodal glaciers, predominantly occurring in the highest mountain areas. There are seven distinct glacial regions: Chersky, Anyui, Ekityki, Chukotsk, Okhotsk, Taigonoss, and Koryak (Fig.1.2). Three glacial regions are distinguished according to their climatic-geomorphologic environment: (1) continental (Chersky, Anyui), (2) Okhotomorsk (Okhotsk, Taigonoss), and (3) Beringovomorsk (Ekityki, Chukotsk, Koryak). Glaciations were not continuous within the regions; most glaciers were concentrated in separate small knots.

Valley and cirque glaciers dominated the regional group with a continental climate. Reticulated glaciation appeared only in highlands; in the Chersky region at elevations higher than 1,800 m and in the Anyui region at elevations of 1,400-1,600 m. The extent and intensity of glaciation decreased from west to east, both within each region and from one region to the other. The average spreading distance of Sartan glaciers was 35-40 km in the highest glacial centers of the Chersky region (e.g., Buordakh, Mt. Pobeda, 3,147 m). Modern glaciers with lengths of 0.2-8.9 km are found within this area. Only the largest ice centers, such as Buordakh, had a length near 100 km (Nekrasov and Sheinkman, 1974). Glaciers terminated at elevations of 700-800 m, which are 800-1,000 m lower than their modern level.

The Bol'shoi Annachag glacial center is located in the southeastern part of the Chersky region and displays the complete range of glacial morphosculptures of the Sartan glaciation (Fig.3). The majority of alpine massifs in the Chersky region, such as the Bol'shoi Annachag Ridge (2,000-2,200 m), are formed by the intrusion of a large granitoid pluton into sedimentary strata of the Verkhoyansk complex. Ridges exhibit flat and gentle-salient divides with surface traces of glacial activity and horns. Ridge slopes are dissected by cirques. One hundred twelve cirques, exhibiting relative relief of 1,200 to 2,000 m, have been identified. Valleys have a typical troughlike cross section. The hilly relief of the main moraine is developed in areas around ridge axes. There are eskers, kames, arcuate end and recessional moraines, and many glacial lakes. The largest of these are Jack London and Elgenya lakes. The end moraine complex in the Jack London Lake region is large, consisting of four ridges of horseshoe form with widths of 0.3-0.7 km and heights of 80-90 m. The perimeter of the outer arc exceeds 15 km. There were several glacier types within this former ice center: glacial caps, reticulated glaciers, valley glaciers, and piedmont glaciers. The extension of Sartan ice varied from 10 to 30 km depending on slope morphology, valley size, the longitudinal gradients, and basin area. Degradation of glaciers occurred in several stages; the first was characterized by slow melting of ice fronts with fast melting in the final stages. Glacial development in other massifs of the Chersky region, such as Bokhapchin, Chyorgo, Okhandzha, was similar to Buordakh (Chanysheva and Bredikhin, 1981).

In the Anyui glacial region, cirque glaciation prevailed, where valley glaciers that extended for 10-15 km had existed earlier. Conditions in the Ilirney Ridge were conductive for glacier flow coalescence, which resulted in the increase of continuous glacial bodies that extended for 50-75 km. In the Okhotomorsk group, glaciation occurred in coastal mountains 600-800 m in altitude and at elevations of 1,600-1,800 m near the major divide. This region is characterized by an asymmetric distribution of Sartan glacial intensity, maximum on the southern slope and minimum from the area of the Kolyma Slope. Cirque and valley glaciers prevailed. The traces of 70 valley glaciers with the extension up to 30 km are identified in the massifs near Shelikhov Bay.

The Taigonoss glacier region coincides with the Tainynot Ridge, which forms the main mountain structure of Taigonoss Peninsula and contains the smallest mountains in the study area. Despite the small mountain height (1,200-1,400 m) of the Tainynot Ridge, favourable environments existed for the development of reticulated, valley, and cirque type glaciers. The largest number of valley and cirque glaciers were concentrated on the northern and northwestern slopes of the ridge. In the Beringovomor group, the Sartan glaciation was most widely developed in the Koryak glacial region due to both the large height of mountain massifs (2,000-2,500 m) and the proximity to the ocean.

Traces of thick valley glaciers, some of which reached the sea, are observed in the coastal ranges. Despite the high mountains, glacial intensity decreased; valley glaciers were replaced by cirque glaciers in the central part of the upland. Signs of Sartan glaciation are completely absent on the northwestern upland slopes. In the Ekityki region, the centers of glacial activity were concentrated in the Pekul'ney, Ekityki, and Chaantal' ranges. In lowland massifs of the Chukchi Peninsula, glaciers were formed mainly in the coastal ranges adjacent to Lavrenty and Krest Golfs.

CORRELATION OF UPPER-PLEISTOCENE GLACIATIONS

Paleogeographic reconstructions show that the extent of glacier spreading in Zyryan and Sartan epochs was different. In the mountains of Northern Priokhotye the extent of glacial spreading was two to three times greater in the Zyryan than in the Sartan epoch. Both linear ridges and separate plateaus were covered by ice of the Zyryan glaciation. Sartan glaciers formed mainly within a band 50-60 km wide along the coast, whereas the Zyryan glacial zone was 100-180 km wide. In the Verkhne-Kolyma Upland and contiguous Verkhoyan Ridge of the Chersky system (Kind et al., 1971), the area of Zyryan glacier ice only slightly exceeded Sartan glacial extent due to a generally symmetrical development of glaciers on western and eastern slopes.

In the Anyui Ranges and in the northern Kolyma Upland, the Zyryan glaciers exceeded by 10 times the distribution of Sartan ice. The southeastern and central parts of the Koryak Upland were covered by glaciers in Zyryan time. However, in Sartan time, glaciers generally formed in separate centers in the Chukchi Upland (except in the northern coastal regions and several lowland massifs, which constituted a single glacial region). The extent of Zyryan glaciers in the Chukchi Upland exceeded by 8 times the area of Sartan ice.

The most essential characteristics of Late Pleistocene glaciation were determined by topography and climate. Zyryan and Sartan glaciations were similar in scale in separated upland and mid-elevation environments. By contrast, the scale of glaciation and glacier types differed sharply in the eastern regions where uplands with plateaus and intermontane depressions prevailed. It is established that Sartan glacial intensity in the continental group of regions, both as a whole, and within each region, decreased from west to east in the Chersky and Anyui group and from coasts to the continent in the Okhotomorsk and the Beringovomorsk groups. On the contrary, in the same region during the Zyryan glaciation, ice increased in the same directions. The opposing effects are explained by the different reaction of mountain structures of different height and summit-level distribution to the rise and fall of the snowline. The average height of the snowline during Sartan time (Table 1) varied from 400 m in coastal ridges up to 1,600-1,700 m in the inner continental regions. However, in the central part of Ulakhan-Chistai Ridge, it reached 2,000 m. In comparison with the modern snowline (Krenke, 1982), the Sartan boundary was lower by 400-800 m. The Zyryan snowline was lower by 150-300 m than during Sartan time. Although differences in snowline level were not extreme,

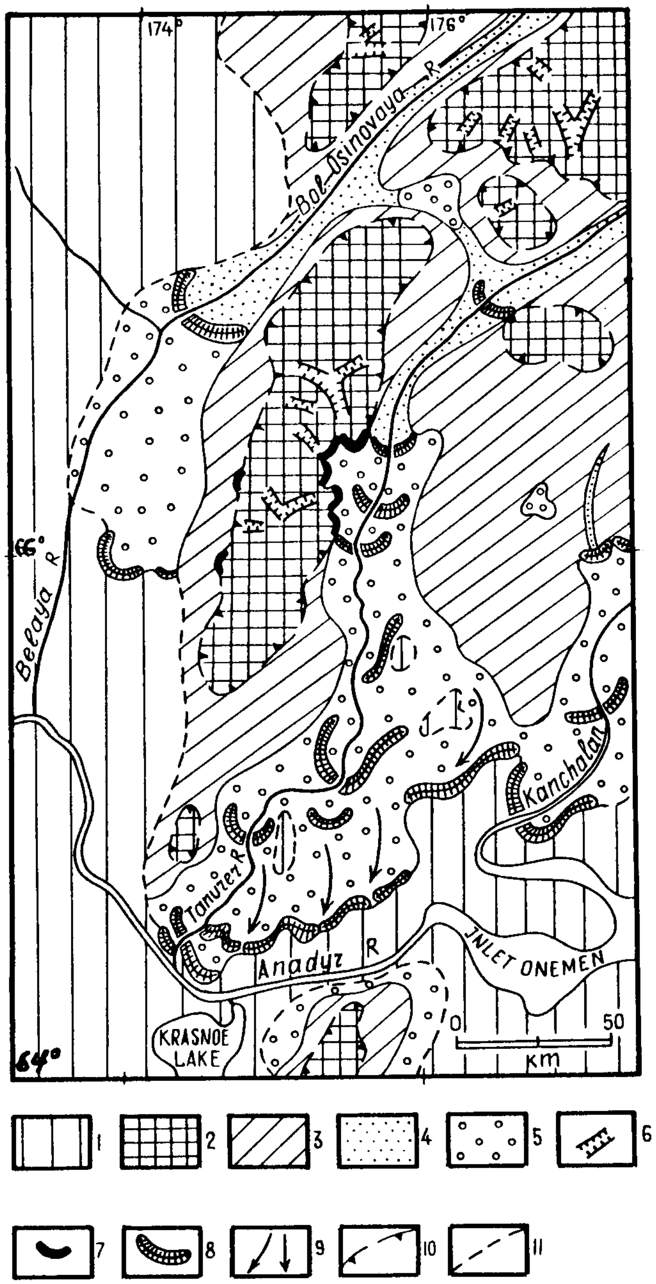

Fig.2. Correlation scheme of Zyryan and Sartan glacial complexes in the Pekul'ney Ridge region. 1-extraglacial regions, 2-regions of development of valley and cirque glaciers in Sartan time, 3-5-Zyryan glaciation: 3-regions of the main development of the glaciation of reticulated and valley cirque types, 4-regions of development of the thick valley glaciers, 5-regions of piedmont glacial development, 6-8-some forms of the glacial relief: 6-valleys-troughs, 7-Sartan end moraine arches, 8-Zyryan arcuate end moraines and amphitheaters, 9-direction of the glacial flows, 10-boundary of maximum spreading of Sartan glaciers, 11-boundary of maximum spreading of Zyryan glaciers.

they nevertheless influenced the scale of glaciation. The higher position of the Sartan snowline resulted in vast ice-barren plateaus and poorly separated lowland massifs in the eastern regions that were beyond the glacial ice. Ice sources for glaciers were greatly reduced. The rise of the snowline was due to an increase in sea ice and the weakening of moist Pacific air masses. In western alpine

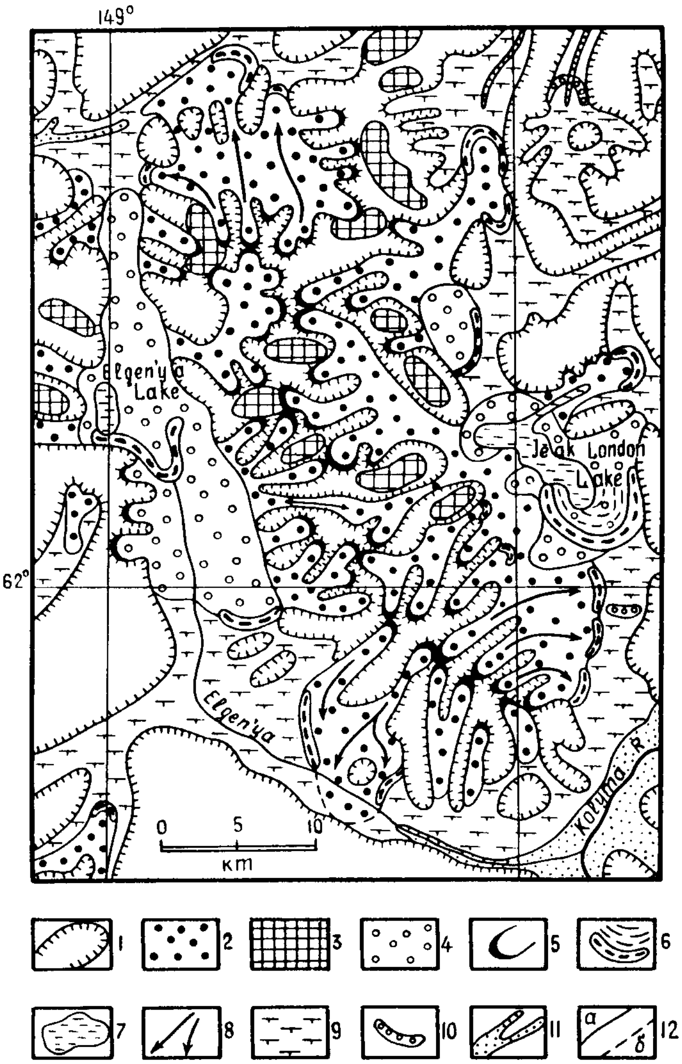

Fig.3. Glaciation scheme of Bol'shoi Annachag Ridge. 1-extraglacial regions, 2-8-Sartan glaciation: 2-regions of spreading of the valley and cirque glaciers, 3-regions of the glacier spreading of the plain tops, 4-regions of spreading of piedmont glaciers, 5-cirques, 6-arcuate end moraines and ridges, 7-glacial lakes, 8-movement direction of the glacial flows, 9-12-Zyryan glaciation: 9-regions of Zyryan glacier development, 10-arcuate end moraines, 11-alluvial complex, 12-boundaries of glaciation regions: a) established, b) supposed.

areas, the higher snowline in the deeply separated mountains insignificantly influenced the area of snow accumulation. The tops of many mountains laid within the snow accumulation zone during Sartan time.

CONCLUSIONS

Paleogeographic reconstructions confirm that in northeastern Asia, about 18,000-20,000 years ago, the climate was not the coldest but the driest during all of Pleistocene time. This arid climate resulted in a high Sartan snowline and correspondingly small glaciation. It also gave rise to a periglacial zone, which exhibits specific landscapes that have no modern analogues.

The character of glacier development shows that

Table 1. Snowline of Sartan epoch in glacial regions of northeastern Asia.

Glacial region	Glacial knot	Absolute height (m) interfluve	end moraines	Height of snow line according to Gepher's formula	cirques
Chersky	Bokhapchin	1900-2000	500-600	1200-1400	1400-1600
	Okhandzha	1920-2000	1100-1210	1510-1690	1500-1700
	Chyorgo	1770-2000	880-1320	1450-1700	1500-1600
	Annachag	1800-2500	800-1000	1450-1600	1500-1700
Anyui	Ilirney	1300-1500	420-500	860-1000	800-1100
Ekityki	Ekityki	980-1400	400-750	720-900	700-900
	Chaantal'	1100-1300	400-500	920-1050	900-1000
	Pekul'ney	1050-1220	160-500	600-830	600-800
Chukotsk	Iskaten'	900-1450	0-800	150-1100	200-1100
	Tenian	800-950	0-450	100-700	200-650
Priokhotsk	Maimandzhin	1160-1600	250-620	760-1100	700-1100
	Momoltykis	1050-1470	350-630	700-1050.	700-900
	Bilibin	1060-1400	290-600	720-1000	800-900
Taigonoss	Tainynot	1100-1300	120-520	610-800	600-800
Koryak	Meinypil'gin	850-1050	50-370	500-560	500-700
	Kenkeren	780-950	90-120	400-500	450-550
	Pakhachin	1300-1600	150-300	720-950	600-1100

glacial intervals in this region were different from those in Europe. European glaciers reached their maximum extent in the second half of the Late Pleistocene, whereas, in northeastern Asia, glaciation reached a maximum during the first half of the Late Pleistocene.

ACKNOWLEDGMENTS

The author is deeply grateful to V.N. Smirnov for the review of the paper, and also to V.I. Rachinskaya, Ye.P. Burak, and M.A. Trumpe for the graphic constructions, translation, and computer work, respectively.

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