The Northern Pleistocene of Russia

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Edited by

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INTRODUCTION

This book consists of 26 research papers by the same first author and editor. They are selected by their relevance to the large geological object, namely the Northern Pleistocene of Russia. This object is a grey-coloured polymineral siliclastic formation up to 300-400 m thick mantling the great plains and neighbouring uplands of arctic and subarctic Russia. The papers describe geological results and paleoenvironmental inferences obtained by study of several decades.

The study was originally initiated from the practical needs of geological cartography and prospecting. They were in a great measure spurred by the incessant discussion of the age and mode of former glaciation which for decades haunted the Russian Quaternary literature and since the 1980s was also the theme of many research papers worldwide.

Fundamental knowledge of the recent geological history of continental terrains is based on studies of paleoclimatic cyclicity and its material manifestations. In this respect special attention has always been paid to the formerly glaciated regions of temperate and arctic lands where the cyclicity is most evidently expressed in the form of paleolandscape and sedimentological zonality.

The classical studies of the Pleistocene stratigraphy and paleogeography have been performed in North America and Western Europe relating the former Pleistocene Laurentide and Scandinavian ice sheets and mountain glaciers of the Alps. The general textbooks information is largely based on many decades of meticulous studies of these regions by hundreds of researchers (Elias & Mock, 2013). These works were mostly confined to the same geologic environment profoundly influenced by the permanent factor of the Atlantic Ocean.

However, the largest formerly glaciated area of Eurasia extending over 60 degrees of longitude south of the Barents and Kara seas and north of 59-60° parallels is much less known. Without understanding the peculiar surficial geology of this area, where the Atlantic influence is considerably weakened, our knowledge of the recent history of the dry lands would be incomplete and even deficient. The recent geological history of eastern subaerial and subaquatic lands with continental climates domineered by peculiar geological processes exhibits a considerable idiosyncrasy not readily understood within the frame of the classical models. Another feature of these terrains – the poor accessibility and scarce population – is an excuse for the gaps in the Quaternary science of the northern terrains.

The natural history interest in the Northern Pleistocene has been driven by its record of climatic fluctuations of the last million years. Without this record it is hardly possible to build the consistent global models of climate change and understand the development of the arcto-alpine biota, origin of great river systems, prehistoric human migrations and many other phenomena. This is the reason of the growing attention of the international community to the surficial sediments of the Russian North which resulted in several collaborative research projects lately performed on the Northern Pleistocene and partly reflected in my publications.

These papers were published during half-century in various journals and collections. Although almost all of them (except for the first one) were in English, their accessibility for an interested student is problematic: part of them was written in pre-digital times and can only be found in fairly obscure editions. These considerations inspired me to collect the disjointed publications into one easily accessible volume.

My first forays into the Barents and Kara seas catchment areas in the 1960-s were met with the cardinal controversy in popular ideas on the origin of the thick, predominantly diamictic sedimentary cover of the West Siberian Plain and the Pechora Basin. One group, basically geological, tried to apply the classical model of European glacials and interglacials to the thick, mostly diamictic Quaternary of the northern plains, whereas the other school insisted on the profound influence on the sedimentary cover of frequent transgressions of the Arctic Ocean with minor addition of alpine and Norwegian type glaciers from the highlands of the Urals and Central Siberia.

The last, so-called hypothesis of glacio-marinism, was bred by drift ideas of XIX century which were adapted to the northern lowlands. It was based on the fine-grained composition of the very thick diamicts which in places contained marine shells and microfauna. Accordingly, the northern diamicts were often interpreted as glaciomarine sediments even by those who maintained the European paradigm of Pleistocene climatic fluctuations and accepted former ice sheets (e.g. Arkhipov, 1971; Lazukov, 1971; Zubakov, 1972). The ideas of glacio-marinism, and sometimes even antiglacialism, were eagerly supported by permafrost workers without sedimentological background and by bedrock geologists who could not see anything glacial in the pre-Quaternary record.

A glimpse of the way out appeared in the 1970-s when the comprehensive glacial sedimentology was first applied to the key sections of the Quaternary on the Pechora and great Siberian rivers. It was found that most of so-called glaciomarine diamicts were lowland facies of glacial deposits left by huge continental ice sheets (Guslitser, 1973; Kaplyanskaya & Tarnogradsky, 1975; Astakhov, 1981). Simultaneously the progress in geological mapping with wide use of remote sensing methods firmly established the glacial nature of the surficial cover of Quaternary sediments and its origin not from mountain-based but from shelf-based ice sheets (Astakhov, 1974a, 1976, 1079; Astakhov, Fainer, 1975).

There was also the old problem of the extent and age of the last glaciation which was hovering in the background of the incessant discussion on the origin of the diamict formations. This problem was getting more acute with the growing number of radiocarbon dates which after the first enthusiasm of the 1960-70-s added a considerable uncertainty in the important correlation of the northern glacial and interglacial events with the Quaternary chronology of better studied Central Russia and Western Europe.

The classical concept, which domineered in the Russian literature in 1950-60-s, accepted the Saalian glaciation as the Pleistocene maximum ascribing a modest size to the early stage of the post-Eemian glaciation (Yakovlev, 1956; Ganeshin, 1976). With the advent of radiocarbon dating the revised classical chronology of the Late Pleistocene in the 1970-90-s was replaced by the popular concept of the Late Weichselian age of the last northern glaciation. At the same time the northern paleogeography was considerably influenced by the so-called maximalist idea of the huge Pan-Arctic ice sheet which during the last ice age presumably covered all arctic shelves and adjacent subarctic plains, i.e. was commensurate with Middle Pleistocene ice sheets (Grosswald, 1983, 1998).

The maximalist model, an obvious replica of the North American paleogeography (e.g. Denton & Hughes, 1981), was fashionable in the West but in Russia was not that popular, especially among geologists dealing with ground truth. The analysis of the situation based on the knowledge of key sections, glacial topography, periglacial environments and statistics of conventional radiocarbon dates made me firmly reject the maximalist paleogeography and return to the classical idea of an early ice advance in the Late Pleistocene reinforced by the modern concept of shelf ice dispersal centres (Astakhov, 1992, 1998).

The problem of the age and volume of the last ice sheet of Eurasia is crucial for the solution of the global paleohydrological equation (Peltier, 1994). The last ice sheet of northern Eurasia is supposed to be responsible for 14 m of global sea level. As a result, a growing number of Pleistocene investigators from Western Europe and America have been over the last 25 years attracted to studies of the Russian Northern Pleistocene.

The modern research history started in 1993 with concerted field work by Norwegian and Russian scientists within the collaborative research project PECHORA (Palaeo Environments and Climate History of the Russian Arctic) supported by the Norwegian agencies and with the German-Russian project ‘Taimyr’. These efforts were followed by many other joint expeditions into the Russian Arctic with participation of Swedish, Danish and American geologists. The various international projects were coordinated by the programs QUEEN (Quaternary Environments of the Eurasian North) and APEX (Arctic Paleoclimate and its Extremes) supported by the European Science Foundation. The field works were supplemented by state-of-the-art means of remote sensing and analytical research in best laboratories of Europe.

The decisive contribution to the chronology of the latest Quaternary events was made by comprehensive dating programs which included radiocarbon, luminescence and cosmogenic exposure methods supported by paleontological and geocryological data (Svendsen et al., 2004). This author participated in all these studies from the beginning as an organizer, photointerpreter and field geologist.

I tried to organise the ingredient papers of this collection both thematically (in five Chapters) and chronologically (within each Chapter), but could not escape some repetitions of statements, and in rare cases even pictures. Replications are hardly avoidable in a book on the same subject embracing research efforts of several decades in different social and technological environments and published in disparate editions. However, the repetitions might not be too conspicuous because most readers would probably be interested in particular articles rather than in the entire collection. On the other hand, the repeated attempts to solve the same questions might be educating for those striving to understand the trend of reasoning and change of arguments over the decades.

It is my hope that the complicated story told in this book will be judged not only by its academic value but also by the persistent, if not always successful, efforts to unravel the glacial history of the huge area fascinating for students of paleoenvironments.

The papers appear in their original wording except for corrections of obvious grammar and terminological lapses, common for a not native English writer. Also Introduction and Summary are added. All references are assembled in the end of the book.

I am sincerely thankful to my coauthors named in the titles of papers 5, 8, 11-13, 15-17, 18, 19 and 25 for their assistance in the research and

permissions to use these reports of the collaborative work for the present publication. They cannot be blamed for possible linguistic or terminological errors since I have edited all the texts single-handedly.

My gratitude is also due to the publishers of the below mentioned journals and collections who originally dealt with the articles included into this book and only slightly modified for this edition.

CHAPTER I

MODE OF PLEISTOCENE GLACIATION

This chapter consists of four papers written in the 1970s (papers 1 and 2) and in 2003-2004 (papers 3 and 4). The old papers present my initial attempts to understand the fundamentals of northern ice sheets which for the first time were considered as basically originated in the low terrains and on the dry shelf and not as products of mountainous ice caps. The later papers 3 and 4 already took this new paradigm for granted and tried organize the data collected over the decades by many Russian geologists in a form accessible for external users. Paper 3 specially concerns indications of ice flow pattern and discrepancies in available proxies. Paper 4 presents the overview of geological mapping data which were used for estimates of shape and size of former ice sheets of different ages. This collection of Russian geological information was ordered by the INQUA project `Quaternary Glaciations: Extent and Chronology`– the first world-wide compendium published in 2004. The data described in this chapter, largely obtained by the Soviet Geological Survey, served as the cartographic and stratigraphic basis for several international research projects started in the 1990s which provided the bulk of results discussed in the following chapters.

1. Geological Evidence of Kara Sea Centre of Inland Glaciation

Valery I. Astakhov

Doklady Akademii Nauk SSSR 1976, Vol. 231, № 5,
(originally in Russian, translated by author)

The idea of centres of ancient glaciation in the West Siberian North was first put forward by V.A. Obruchev (1930). Later P.S. Voronov (1951) discovered Pleistocene ice advances from the low Yamal Peninsula onto the Pai-Hoi Ridge. Presently a Late Pleistocene ice sheet on the Barents Sea shelf is advocated by M.G. Grosswald. Lately structural analysis of the Middle Pleistocene Sanchugovka Formation has revealed its glacial origin. This led to a suggestion that the remains of arctic malacofauna in this formation were delivered from the shelf by a Kara ice sheet (Kaplyanskaya & Tarnogradsky, 1975). Nevertheless, the overwhelming majority of investigators of West Siberia have until now considered only influence of mountainous ice dispersal centres. The research of recent years has obtained decisive evidence of a Kara ice dome.

The crucial fact is the lately discovered traces of ice motion from lowlands onto the margin of the Central Siberian Plateau (Astakhov & Fainer, 1975). A large number of diamictic and sandy ridges is observed north of river Podkamennaya Tunguska where the convex distal slopes of these crescentic ridges face eastwards and south-eastwards upslope of the Plateau. Radial eskers and striae in the bedrock traced up to 450 m isohypse are orientated from north-west to south-east or west-east. The upslope ice motion is indicated also by mineral composition of the tills with predominant products of redeposition of Mesozoic sediments of West Siberia, mainly of quartz.

A number of large blocks of Cretaceous kaolin sands are found far to the east of their *in situ* occurrence. The flat summits of trapp mountains some 600 m a.s.l. are covered by alien tills full of Mesozoic pollen (Fainer, Mitachkina, 1974). Only east of the 92° E the Central Siberian

Plateau shows glacial features orientated downslope NE-SW with the tills predominantly consisting of trapp boulders, heavy minerals and feldspars in the matrix (Astakhov & Fainer, 1975).

Rose-diagrams of long axes of pebbles in tills with the West Siberian mineral association in the Middle Yenissei catchment area everywhere demonstrate prominent NW and WNW peaks. All these facts unanimously indicate a frontal advance of Middle Pleistocene glaciers from the north-west into the Yenissei valley and farther eastwards up to altitudes of at least 600 m.

Quite a similar pattern is observable at the same latitudes along the western margin of the lowland. The transportation of pebbles into the Urals from the lowland has been known for a long time (Sirin, 1947; Lider, 1964). Numerous sand and sand-gravel hillocks and west-east striking eskers cover the eastern slope of the Northern Urals up to 600 m (sources of rivers Lopsiya, Khuntynya, Mazapatya, Manya, Bolshaya and Malaya Sosva). Such landforms making in plan a huge arc with the convex side facing west are traced southwards up to Burmantovo settlement. In this area B.V. Ryzhov (1974) has described three formations of matrix-supported tills with numerous fragments of Mesozoic and Paleogene rocks of West Siberia at altitudes up to 500 m. Pebble long axes at the upstream river Severnaya Sosva indicated ice motion from NNE. Farther to the south in the area of Ivdel-Polunochnoye clast-supported till is practically devoid of boulders from the Central Uralian rocks (Rabinovich, 1961).

Scattered data from central West Siberia confirm the diffluent flow of Middle Pleistocene ice. The diagram of pebble orientation from the Samarovo Till near the city of Khanty-Mansiysk shows two distinct peaks: west-east (common for a marginal zone) and more pronounced north-eastern (Chernov, 1974b).

The sub-latitudinal orientation of the ice limits and of the accretion ridge of the Siberian Hills is most naturally accounted for by ice motion from the north and is hardly explainable by the assumed model of centripetal movement of mountain glaciers.

The pattern of linear parallel ridges which occur only in glaciated terrains is very significant (Fig. 1). In the Meso-Cenozoic succession they are represented by tight folds rapidly flattening downwards. Some investigators tried to explain these ridges by non-glacial factors such as permafrost, gravitation tectonism, etc. The only weak point of the glaciodynamic version of their origin was the orientation of the parallel ridges conflicting with the traditional paleogeography: the distal slopes of these arcuate ridges often face the presumed mountainous ice dispersal centres. Evidently this configuration of the glacigenic disturbances excellently agrees with the concept of a lowland ice dispersal centre in the West Siberian North (Fig. 1). These ridges should be considered as ice-pushed features. Their glacial origin is underlined by the reverse, i.e. downslope, orientation of parallel ridges in the area of piedmont glaciation of the Late Pleistocene. The pattern of the ice-pushed ridges is also conformable with the distribution of accretion hummocks such as kame plateaus (Fig. 1).

The diffluent motion of the lowland glaciers is evidenced also by the material composition of the Middle Pleistocene formations of the central part of the lowland. The north-south strip of the Taz Peninsula – Nadym-Pur interfluve is practically devoid of Uralian and trapp boulders. If the most resistant fragments of the Central Siberian trapps sometimes are noticed almost in the centre of the lowland, the amount of Uralian pebbles is negligibly small already in the southern Yamal and around Khanty-Mansiysk. Even in the Muzhinsky Urals the pebbles are mostly composed of Cretaceous clays and Paleogene opokas but not crystalline rocks of the Urals (Shumilova, 1974).

The base of the Pleistocene of the Taz Peninsula does not contain gravels at all. All investigators of northern West Siberia point out that the scarce fragments of crystalline rocks are mostly flint and quartz, obviously redeposited many times. The divergent transportation of terrigenous materials from the centre of the lowland is more evident from the matrix composition: the typical West-Siberia assemblage with dominant quartz and abundance of epidote and zoisite in the heavy crop is traceable at the eastern slope of the Urals as well as on the table summits of trapp monadnocks of Central Siberia (Ryzhov, 1974; Fainer, Mitachkina, 1974).

The thickness distribution agrees with the idea of the upslope ice dispersal: the relatively thin Quaternary of the central lowland thickens to the margins of the Plain together with the elevation growth. In parallel the Middle Pleistocene diamictons enriched with marine faunas are concentrated in the lower reaches of rivers Yenissei and Ob, whereas the Salemal (Sanchugovka) Formation of the central interfluve Nadym-Pur is practically devoid of marine shells.

Judging by the sub-concentric pattern of marginal features the Middle Pleistocene ice dispersal centre was located on the Yamal, Taz and Gydan peninsulas. However, the literary data and aerial images indicate a very young glacial topography there. Fresh kames, eskers, marginal canals, sandurs and initial valleys are especially characteristic for southern Yamal and Gydan. The lake-and-hummock relief around the lake Yarroto is built of sand with fragments of local rocks and practically devoid of Uralian boulders (M.N. Boitsov and S.G. Maksimenko, mapping report of 1953).

It is underlain by brecciated varved clay (probably of the Middle Pleistocene). From here fresh radial features (striae and eskers) were traced by aerial photos to the central Pai-Hoi Ridge, where transport of boulders and organic remains from north-east to south-west was documented (Voronov, 1951). In the south of the Taz Peninsula the margin of the last ice sheet is possibly outlined by festoons of parallel ridges, shallow upthrusts in the Paleogene rocks (data by Yu. F. Andreyev) and local gravitational maxima, presumably connected with minor flow-folding along the ice margin (Fig. 1).

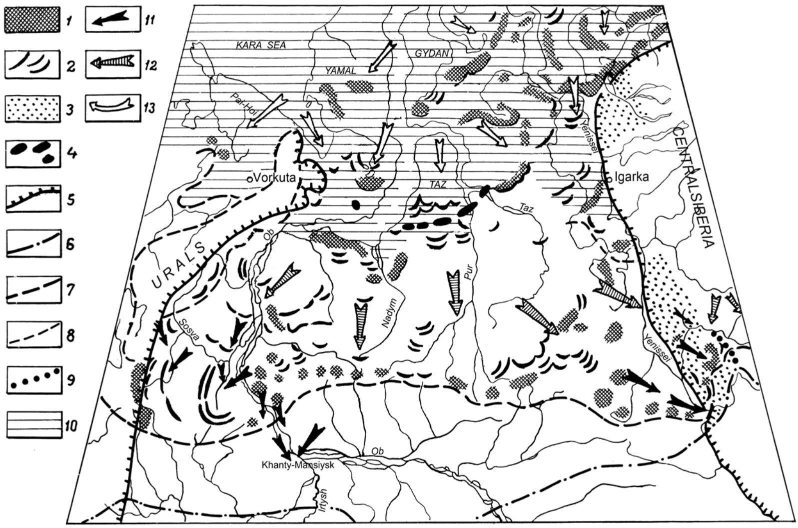

Fig. 1. Pleistocene glacial features in northern West Siberia.
Symbols: 1 – accretion hummocky terrains; 2 – parallel ridges of Meso-Cenozoic rocks (push moraines); 3 – area of Mesozoic erratics in Paleozoic Central Siberian Plateau; 4 – local gravitational maxima (after M.N. Boitsov and S.G. Maksimenko, 1957); 5 – 9 – limits of 5 – Mesozoic formations of West Siberia; 6 – maximum glaciation; 7 – Taz glaciation; 8 – Late Pleistocene piedmont ice sheet; 9 – Mesozoic and trapp mineralogical provinces in Middle Pleistocene tills of Central Siberia (after Yu. Fainer); 10 – provisional area of Late Pleistocene ice on the Plain. Ice flow directions of: 11– Middle Pleistocene glaciers (by orientation and composition of pebbles); 12 – Taz glaciers (suggested by marginal landforms), 13 – Late Pleistocene Kara Ice Sheet.

The paleoglaciologically estimated maximum ice thickness of the Late Pleistocene Barents Ice Sheet is up to 3.2-3.5 km (Grosswald & Chernova, 1972). The Middle Pleistocene ice of northern West Siberia must have been thicker. Direct measurements indicate its great thickness even in the marginal zone. Judging by the altitudes of foreign tills in the Urals and at the Yenissei Siberia marginal ice at 63° N was at least 0.8 km during the maximum glaciation and ~ 0.5 km thick in the time of the subsequent Taz glaciation. The great thickness of ice masses in the north of the Plain is indicated by boulders of igneous and metamorphic rocks of the Taimyr Peninsula scattered over the Putorana Plateau at altitudes over 1000 m (Urvantsev, 1957).

The occurrence of trapp and Uralian boulders in the West Siberian Plain is explained by the initial growth of ice sheets in the mountainous borderlands. Subsequently the ice dispersal centres shifted onto the shelf. As a result, glaciers moving upslope mixed originally deposited Uralian and Central Siberian material with products of assimilation of the Meso-Cenozoic rocks of West Siberia. This is the explanation of the meagre content of coarse fragments in the Middle Pleistocene sediments and its high concentration in the non-redeposited Late Pleistocene moraines of the Transuralia and Lower Yenissei area.

Apart from the landforms orientation and regularities of transport of terrigenous material the concept of the Kara ice dispersal centre is a logical explanation of the occurrence of arctic malacofauna in the diamicts of the Sanchugovka Formation and their evidently glacigenic structures (Kaplyanskaya & Tarnogradsky, 1974), transportation of bauxite fragments eastwards to the western slope of the Central Siberian Plateau (Fainer & Mitachkina, 1974), the southward displacements of crests of the local anticlines in the Meso-Cenozoic cover (Rudkevich, 1961), etc. More precise paleogeographic reconstructions in the coming years would demand detailed studies of the variations of the Quaternary sediments composition over the area and in the succession and careful analysis of accretion landforms in northern West Siberia.

2. New Data on the Latest Activity of Kara-shelf Glaciers in West Siberia

Valery I. Astakhov

International Geological Correlation Programme, Project 73/1/24 `Quaternary Glaciations in the Northern Hemisphere`, Rep. N 5, Šibrava V., Shotton F., eds, Prague: Czechoslovak Geological Survey, 1979, p. 22–31.

The hypothesis of centres of former glaciation on low coastlands of West Siberia was advanced by I.A. Molchanov and V.A. Obruchev around 1920-s but until recently it did not greatly influence research of the northern Pleistocene. Paleoglaciological speculations about a Middle Pleistocene ice sheet on the shelf (Voronov, 1968) were not substantiated by geologists because of lack of field data. The authors of the modern view on the former Siberian glaciation did not doubt the mountain origin of the Würm ice sheets of West Siberia and discussed only a hypothetical confluence of Uralian and Taymyr-Putorana glaciers on the Kara sea shelf (Arkhipov et al., 1976). Such conclusions were based on geological investigations between latitudes 50° and 60° which were rather detailed in the valleys and too scarce in the wide interfluvial terrains.

The situation changed in the seventies as the All-Union Corporation `Aerogeologia` began areal investigations and mapping of glacial topography of North Siberia and the Urals using small-scale aerial photos and also satellite images. The starting point for revival of the shelf-centres concept was the discovery of extra-local moraines in the area of the right bank of the Middle Yenissei. These data proved the frontal advance of Middle Pleistocene ice masses south-eastward onto the Central Siberian Plateau (Astakhov, Fainer, 1975).

New data on the glacial topography of Peri-Yenissei Siberia and the Northern Urals combined with a revised interpretation of published literature reestablished the concept of the Kara-shelf as a centre of former glaciation (paper 1). The main proofs are as follow:

1) `Anti-orographic` configuration of end moraines of the Middle Yenissei and Northern Urals: the convexities of the morainic ridges face mountain ranges, not the lowland.

2) Numerous West Siberian erratics found in the Urals and in the Central Siberian uplands.

3) Glacial landforms in the West Siberian Plain including accretion hummocks and parallel-scalloped ridges in the Arctic area of the latest glaciation which are parallel to the Kara Sea coast.

4) Orientation of the long axes of pebbles, commonly normal to the terminal moraines.

5) Lowland, i.e. West Siberian, composition of the tills which occurs not only in the central part but also at the margins of the Plain.

6) Definite areal coincidence of West Siberian erratics and `anti-orographic` morainic amphitheatres.

7) Drift thickness which increases from the central part of the lowland towards the mountain margins.

8) Absence of topographic evidence of downslope ice movement except for the youngest moraines in the Norilsk region and on the Trans-Uralian piedmont of the Polar Urals.

9) Absence of crystalline pebbles in the breccia-like till of the Kara Sea floor covered by Holocene marine sediments (Astakhov, 1977).

Further photogeological mapping in West Siberia has provided the opportunity of a practical examination of the Kara glacial centre concept, particularly relating to the terminal formations in the Arctic area of the latest glaciation. New satellite and high-altitude aerial images have revealed more push moraines concentrically orientated around the Kara Sea coast. The interpretation of high-altitude aerial photos of the Gydan Peninsula found amphitheatres of parallel ridges opening northward and bordered by outwash plains from the south and by lacustrine depressions from the north.

Such a ridge of a mixed push and accretion origin, 30-60 m high, was recognized in the Taz-Messo interfluve. Landsat imagery showed also horseshoe-shaped parallel ridges about 80 km long on the Yenissei west-bank area stretching out from the Muram Lake across the upper Turukhan River up to the Osetrovaya-Pokoinitskaya interfluve. The axes of these amphitheatres indicate late Pleistocene ice movement from the Ob Estuary south-eastward (the first case) and from the Yenissei Estuary southward (the second case).

The most distinct glacial end formations were investigated in 1977-1978 in southern Yamal and Polar Trans-Uralian piedmont. Two chains of parallel ridges joining at an acute angle were recognized from high-altitude photos of the area. The first one stretches out northward in the Yuribey left bank area. It consists of crescentic festoons of interfluve hills 60-100 m above sea level which form the western borders of the biggest lake basins of the Yamal Peninsula – Yarroto 1st, Yarroto 2nd, Mengakoto and Tetanto (Fig. 1). These lakes, with water levels about 25-35 m a.s.l. are placed in a sandy plain of 40-50 m a. s. l. This plain was considered to be a Kazantsevo (Eemian) marine terrace (German et al., 1963; Trofimov et al., 1975). The `Kazantsevo terrace` comprises light-grey, inclined quartz sands rhythmically interbedded with silt, lenses of redeposited peat, fragments of driftwood and thin beds of fine gravel. According to the author's observations (together with K.E. Simonov) these sands form also festoons of parallel ridges rising10-50 m above the `Kazantsevo terrace` level.

The most detailed investigations were made at the Handy-Hoi Ridge which is 20 km long and 3 km wide. The ridge bounds the Tetanto Lake basin from the west (H and 6 in Fig. 1). The internal structure of the ridge was studied at numerous natural exposures along the consequent valleys. Angles of dip of the `Kazantsevo` sands increase from 0-5° on a flat foot to vertical ones at the crest of the ridge in pace with the increasing elevation (Fig. 2). Along the axis of the ridge the sands are always crumpled into steep, sometimes isoclinal folds. Dark grey fissile silt layers 3-8 m thick containing very scarce pebbles of crystalline rocks and balls of underlying sand and varved clay appear there together with lenses of coarse gravel.

Extreme contortion is registered along the westward shifted crest of the asymmetric ridge where the exogenous-tectonic structure becomes actually of alpine type: uneven ferruginated thrust planes dipping eastward divide blocks of tilted sand beds at almost every outcrop. Layers of incompetent till-like silt sometimes form shear dykes and tongues which are concordant with the general direction of lateral pressure (Fig. 3). Where distinct blocks are absent, in these sections one can see disharmonic folding of at least two structural stages divided by sharp angular unconformity. The upper sands are crumpled with dips from 20-40° of the lower sands up to 50-90°. The beds at the foot of the western steep slope of the ridge abruptly flatten to the angles of 3-10° and become conformable to the wavy surface of the `Kazantsevo terrace`. The flat crest of the ridge is topped with deflation armors consisting of pebbles and boulders sometimes 1-1.5 m in diameter. Along the crestline small gravel cones 1-5 m high are scattered. Numerous (more than 150) measurements of bedding showed strike coincidence of the steep-dipping beds with arcuate stripes on the aerial pictures bounding Tetanto Lake from the west.

Such ridges were formerly regarded by investigators either as end moraines of the Uralian glaciers (Strelkov, 1959) or as coastal bars of a retreating sea (Trofimov et al., 1975). The inadequacy of these explanations can be seen from Fig. 2 which shows an asymmetric diagram of the dip of the internal strata conformable to an asymmetric profile of the ridge itself. This means that the arcuate ridge (H in Fig. 1) was formed simultaneously with contortion of the beds and by the same process. The dominant eastward dip of the bedding and the crescentic form of the parallel ridge-and-groove features clearly indicate severe lateral pressure from Tetanto Lake, i.e. from the east.

The structure and topography of the ridge are identical to ice-pushed ridges well known on the plains of North America and Northern Europe (Flint, 1971) and described in Bielorussia as `glaciotectonic garlands` (Levkov, 1978). The largest lakes of the Yamal Peninsula, located in the rear of the glaciotectonic garlands, are most likely remnants of dead tongues of ice that advanced from the Ob Estuary and Gydan Peninsula. These sandy ice-pushed ridges formed by frontal contortion of the proglacial outwash are the reason why the whole terminal formation of the lake district of Yuribey River has been termed the `Sandy Belt`.

West of the Sandy Belt the glacial ridges acquire another orientation. At the upper Yorkuta River festoons of ice-pushed ridges with their front facing eastward stretch out south-westward along the right bank of the Tanlova River. This system is traced farther along the left bank of river Heyaha towards the west-east orientated length of river Shchuchya where it transforms into the thick till ridges of the Sopkay amphitheatre (Fig. 1). The latter was always considered to be a typical end·moraine of the Uralian glaciation (Trofimov et al., 1975). ·

Yet photointerpretation data do not support this idea. Zones of hummock-and-lake landscape do not fringe the Polar Urals as is shown on all the maps of Quaternary deposits but they are perpendicular to the mountain front (Fig. 1). To clear up the origin of the hummocky ridges the author in 1975 traced them from the eastern front of the mountains to the middle course of river Heyaha, i.e. about 100 km from west to east. It was thus established that the uplands about 100-300 m a. s. l., barring the former lake of the Shchuchya River basin from the north, are not till ridges but ice-moulded Paleozoic bedrock forming roches moutonnées. The flat late-glacial lacustrine depression of the middle course of river Shchuchya, about 50 m a. s. l., occupies the lowest central part of a Paleozoic ring structure filled with Jurassic deposits.

Typical terminal moraines are situated along the south and east perimeter of the ring where they cap narrow ledges of Paleozoic basement and form hummocky till ridges 30-60 m high. As the altitude of the bedrock surface declines eastward, so do the levels of the accretion ridges from 200-300 m at the mountain foot to 100 m farthest east at the Sopkay Ridge. The whole system of end moraines on the right bank of the Shchuchya River strikes in a W-E direction except for the longitudinal part of the Sopkay Ridge·about 15 km long.

The hummock-and-lake topography of the Sopkay amphitheatre is analogous to the landscape of the Valday Ridge but the composition makes an important difference. There is a striking lack of crystalline boulders in the drift of the Sopkay Ridge despite its being much nearer to an assumed mountain source of ice than the Valday Ridge. Surficial boulders are scattered over the ridges only in the piedmont area where the moraines rest immediately on the bedrock basement. A small amount of gravel is concentrated in little kames that occupy inter-moraine hollows.

The terminal moraines as seen in natural outcrops consist of dark-grey silt and clay with lenses of laminated lacustrine sediments. Immediately east of the last outcrops of Paleozoic rocks at about 68° E coarse fragments in till are so scarce that measurements of pebble orientation usually run into insurmountable obstacles. Crystalline fragments are practically lacking at the base of the Sopkay till. The basal till 1-3 m thick is a viscous breccia consisting of small pieces of varved clay and Mesozoic-Paleogene siltstone. Upwards in the succession the clayey fragments crush into crumbs and then grade into surrounding till which incorporates very scarce well rounded pebbles of Uralian rocks and balls of underlying quartz sand.

The basal clayey till is observed almost everywhere at the exposures along the W-E stretch of the Shchuchya River. The terminal ridges prolongating the Sopkay Ridge north-eastwards along the right bank of the Heyaha River also consist of clayey till, with practically no pebbles. The whole chain of high accretion ridges stretching out from the Polar Urals to the upper river Yorkuta (Fig. 1) may be called the \`Clayey Belt\`.

Moraines of the Clayey Belt extend to the Baydarata Estuary basin from the south and probably join the glacial disturbances on the right bank of river Yuribey. Pebble orientation diagrams for 5 sites in the Shchuchya river valley show a regular strike of long axes normal to the strike of the morainic ridges. A north-west strike of the long axes of pebbles extending to Laborova settlement and still farther along the eastern slope of the Polar Urals, dominate at the Sopkay Ridge which faces south-eastwards. Orientation diagrams with northerly peaks varying to north-east prevail at the transverse stretch of river Shchuchya. This indicates ice movement from the south-east coast of the Baydarata Estuary.

Orientation of abundant stoss-and-lee features of Paleozoic limestone to the north from the transverse stretch of river Shchuchya agrees with the orientation diagrams (Fig. 1). The stoss slopes dip northwards between 350 and 20°. The same orientation is common for polished rocks and longitudinal grooves that can be seen in aerial photographs of the eastern slope of the Urals; for instance, in the Big Hadata-Little Hadata interfluve, and around the Laborova settlement. Farther north the traces of moving ice extend north-westwards round the Polar Urals to Mt. Konstantinov Kamen (Fig. 1).

Signs of longitudinal ice movement such as eroded summits, grooves, and blocks of northern dunite are observed along the eastern slope of the Urals up to 500 m above sea level. Typical alpine topography made by valley glaciers can only be seen at a higher altitude. Mountain gravel moraines are sometimes located at the foot of the Polar Urals, but they are obviously connected with the late glacial transverse troughs dissecting the longitudinally eroded surfaces. Large morainic amphitheatres of local valley glaciers joining the extra-local moraines of the Clayey Belt are recognised on aerial photos only in the Longot-Yegan valley much farther south (Fig. 1).

The characteristic properties of glacial topography studied in the field can be easily extrapolated to the western slope of the Urals where high altitude aerial photographs also show signatures of exclusively longitudinal movement of the last ice sheet. Such features are represented by the sub-longitudinal lobe basin of the Kara River. The basin is bounded in the south by a zone of fresh-looking hummock-and-lake landscape stretching against Mt. Khoidype (Fig. 1).

Thus, modern data on the glacial topography of the Arctic Trans-Uralian region definitely testify to southward movement of the latest ice masses from the Baydarata Estuary round the adjacent high massifs of the Polar Urals. Marks of south-westward ice-movement discovered in 1951 across the NW orientated Pai-Hoi Ridge should obviously be referred to the Baydarata Ice Stream, not to a hypothetical upland ice-cap at the Yamal Peninsula as proposed by P.S. Voronov. Moraines of the Clayey Belt are most likely formed by ice-masses of the West Kara Sheet moving south-eastward and by excavation of clayey Cenozoic deposits of the Baydarata glacial depression.

As can be deduced from the altitudes of ice eroded surfaces on the slopes of the Urals, the thickness of the ice of the Sopkay Stage, even taking into account a postglacial uplift of the Urals of about 100 m, may amount to 300 m in the Kara and Shchuchya river valleys and a minimum of 500 m in the Baydarata Estuary. The ice-eroded surfaces at 500 m

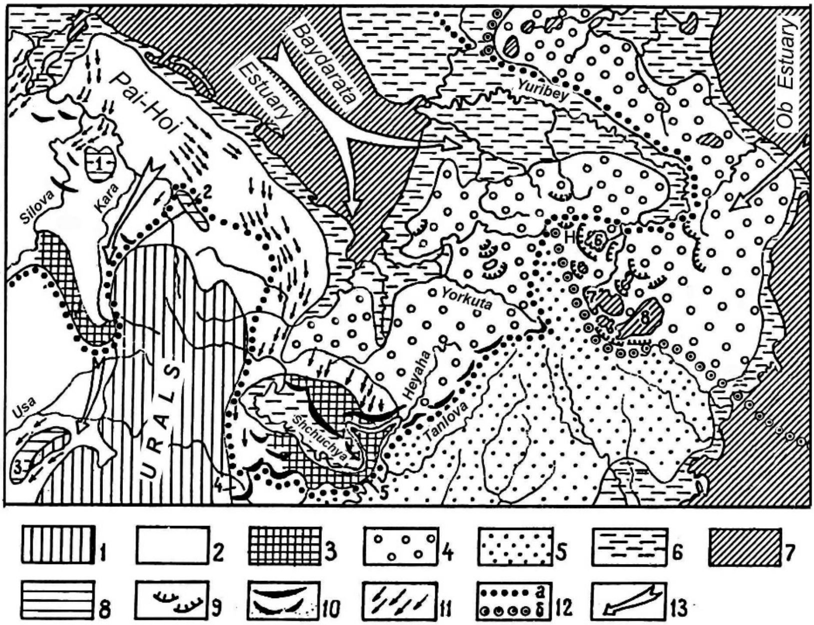

Fig. 1. Glacial features of the Polar Urals and south of the Yamal Peninsula. Symbols: 1 – alpine mountain massifs; 2 – piedmont and low mountains graded by continental ice; 3 – hummock-and-lake landscape of terminal moraines; 4 – accretion plains with Upper Pleistocene till and outwash; 5 – outwash plains; 6 – flat plains of late glacial lacustrine basins; 7 – present reservoirs; 8 – large glacial monadnocks; 9 – push moraines= glaciotectonic garlands; 10 – end moraines=. push-and-accretion till ridges; 11 – orientation of stoss-and-lee features and grooves; 12 – assumed boundaries of: a – West Kara and b – Central Kara ice streams; 13 – ice flow. The figures indicate: 1 – Mt. Yeduney and 2 – Mt. Konstantinov Kamen in the Pai-Hoi Range; 3 – Mt. Yenganape; 4 – glacial amphitheatre of river Longot-Yegan; 5 – Sopkay Ridge; 6 – Tetanto Lake east of Handy-Hoi Ridge (H); 7 – Yarroto 2nd Lake; 8 – Yarroto 1st Lake.

above sea level, and up to 600-700 m on the northern end of the Urals, may refer to a preceding larger glacial stage.

The terminal formation of the Sandy Belt should be considered as a result of ice movement from the Ob Estuary and Gydan Peninsula. It may be traced south-eastward via the push garlands of river Hadutte on the Taz Peninsula that were discovered during geological mapping, and by the above mentioned ridges in the Taz-Messo interfluve. All of them mark the southern margin of the Central Kara Ice Sheet. The distinctive push style of the Sandy Belt moraines and the relatively thin basal till are probably connected with a short duration glacial advance and maybe with a second advance of a thinner ice sheet of the latest glaciation on the Taz and Gydan peninsulas correlated with the West Kara Ice Sheet.

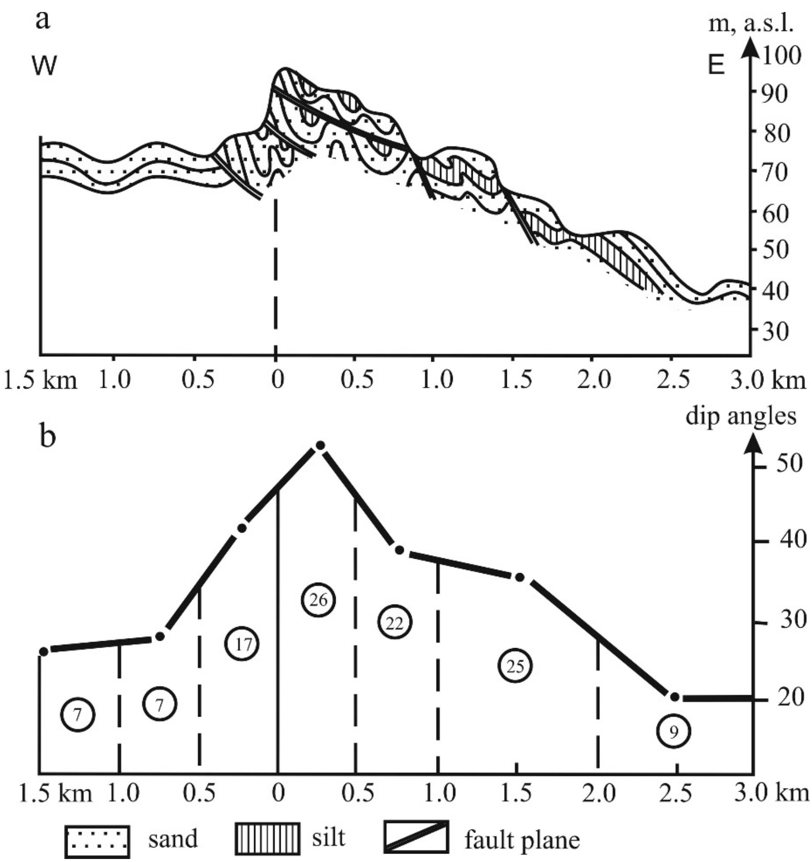

Fig. 2. Glaciotectonic structure of Handy-Hoi Ridge west of Tetanto Lake. Symbols: a – simplified cross-section; b – diagram of average angles of dip. The figures in the circles indicate number of measurements for calculation of average dip within the intervals of 0-0.5, 0.5-1.0, 1.0-2.0, and 2.0-3.0 km from the crest of the ridge.

Little is known on the absolute chronology of the described glacial stage. Moraines of a preceding advance in the Salehard region, i.e. about 50 km south, lie on deposits with radiocarbon dates of 25-28 000 years BP (Arkhipov et al., 1977). These investigators are inclined to consider the Sopkay Stage to be about 13-15 000 years BP. A date of 15 000 years was recently obtained from the second terrace of the upper river Yuribey which is enclosed in the described morainic belt (A.I. Spirkin, personal communication). This date would not permit the Sopkay stade to be younger than 17-18,000 years BP but the question must remain open until additional dates from the Sopkay deposits are received.

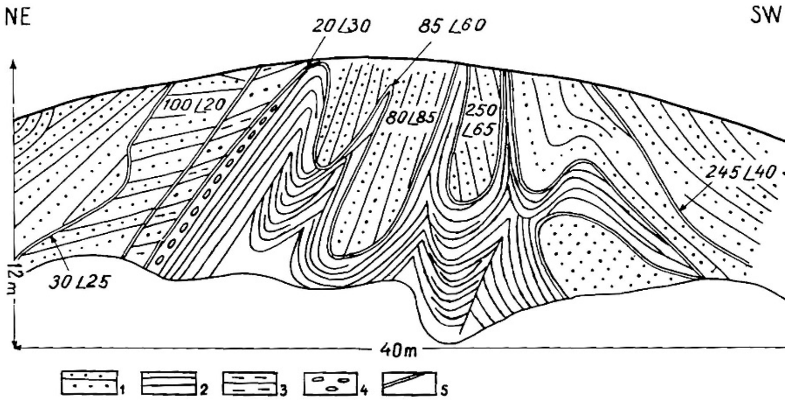

Fig. 3. Deformed Quaternary deposits near the crest of Handy-Hoi Ridge in exposure at 7 km WSW from the mouth of Tetan-Tanyo creek.
Symbols: 1 – sand; 2 – silty till; 3 – fine silty sand; 4 – gravel; 5 – thrust line.

In any case the modern photogeological research demonstrates quite clearly that the northern lowlands of West Siberia in the Late Würm-Wisconsin were attacked by continental glaciers approaching from the north.

3. MIDDLE PLEISTOCENE GLACIATIONS OF THE RUSSIAN NORTH

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Introduction

The volume and extent of Middle Pleistocene ice sheets exceeded those of the Late Pleistocene by far, especially on the eastern flank of glaciated Eurasia (e.g. Ganeshin, 1976). Accordingly, their impact on the geological structure and environments of the arctic and subarctic regions was more profound. However, geological research within the QUEEN framework has largely been focused on the Late Pleistocene history of the Russian North. Only a few sections of Middle Pleistocene drift have been studied by QUEEN members on the Russian mainland. Hence the bulk of data discussed below is derived from Russian literature.

Over the last half-century various attempts have been made to synthesize data on Middle Pleistocene glaciations collected by hundreds of Russian researchers. The only work in which all Quaternary of the Russian Arctic and Subarctic is discussed – the monumental volume by Sachs (1953). Another outstanding contribution is a stratigraphic monograph with a Quaternary map of European Russia by Yakovlev (1956). In the 1960-70s the huge influx of data, especially from geological surveys, led to graphical generalisations in the form of synthetic Quaternary maps for the entire Soviet Union (Ganeshin, 1976) and separately for each of the superregions of northern Eurasia such as the Russian Plain, the Urals, West and Central Siberia. These maps are principal sources of hard data about the size of former ice sheets obtained by generations of mapping geologists. Lately they were used to compile the digital map of Pleistocene ice limits as part of the INQUA project (Astakhov, 2004b).

After Sachs and Yakovlev numerous articles and regional monographs were dealing with the Middle Pleistocene glacial deposits of the North in terms of stratigraphy (Arkhipov & Matveyeva, 1964; Lazukov, 1970;