LATE-WEICHSELIAN ICE SHEETS IN ARCTIC AND PACIFIC SIBERIA

Mikhail G. Grosswald
Institute of Geography, Russian Academy of Sciences, 29 Staromonetniy Street, 109017 Moscow, Russia

Interpretation of Space images coupled with field data on glacial geomorphology and glacial geology of Northern Eurasia have provided compelling evidence for a continuous Late Weichselian ice sheet covering the entire Arctic margin of the continent. In addition to the Scandinavian ice sheet, three ice sheets of the same order — the Kara, East Siberian and Beringian — are identified within the major Eurasian ice sheet. Also, there is evidence and other considerations suggesting a former ice sheet in the Sea of Okhotsk. Ice-spreading centers of the ice sheets were situated on the continental shelves off the Siberian coasts, thus we can term the ice sheets ‘Siberian’. So far, the conventional stratigraphic approach to the problem of Siberian glaciation has proven fruitless and yielded nothing but uncertainty, while geomorphological studies have discovered a wealth of glacial landforms in Arctic Siberia. It was these landforms and their spacing that made the existence of former Siberian ice sheets evident.

The hypotheses fall into three groups. One of them, still exceptionally strong in Russia, includes a variety of ‘antiglacialistic’, or ‘diluvialistic’ concepts; their followers deny ice-sheet glaciations of the high-latitude lowlands which suggests uniformity of the Arctic paleo-climates. As a result, much effort and resources are wasted on existing uncertainty and misleads Quaternary researchers. The basic premise of these concepts is the conviction that recent crustal movements and tectonically induced marine transgressions, not glaciations, played a leading role in past global changes in the Arctic. Another group, with the belief commonly referred to as the ‘concept of restricted glaciation’, admits some, but only minor, polar glaciations. According to that school of thought, the ice-age Arctic was dominated by ice-free environments, while ice caps were small and confined to the western peri-Atlantic part of the region. The third concept, which is defended in this paper, proposes a continuous system of marine ice sheets grounded on the Arctic continental margins, with a floating ice shelf over the deep Arctic Basin, and a chain of proglacial lakes integrated into a trans-Eurasian meltwater-drainage system alongside the southern margin of the ice sheets.

The hypothesis of vast Arctic ice sheets was proposed in the 1960s when evidence for a grounded marine ice sheet was discovered in the northwestern Barents Sea (Schytt et al., 1968). Later it developed into the theory of a marine Eurasian ice sheet. Initially, the latter appeared as a complex of two ice domes grounded on the Barents–Kara continental shelf (Grosswald, 1980). As more data were gathered, the limits of the reconstructed ice sheet were extended eastward to encompass the East Siberian shelf (Grosswald, 1988), and even further east- and southeastward to cover the Chukchi, Beaufort and Bering Seas (Hughes and Hughes, 1994; Grosswald and Hughes, 1995). A 1980 version of this theory was adopted by Denton and Hughes (1981) and CLIMAP Project Members (1981), and it gained support from certain glaciological
modeling (Lindstrom, 1990; Lindstrom and MacAyeal, 1989). That version was repeatedly used by paleoclimatologists as data on boundary conditions for climate sensitivity experiments. Since the early 1980s, a comprehensive program of geological studies has been undertaken by Norwegian scientists in the western Barents Sea. In the process, the glacialistic concept defended here was confirmed and substantiated by a wealth of new evidence of marine and terrestrial geology (Salvigsen, 1981; Elverhai and Solheim, 1983; Vorren and Kristoffersen, 1986; Vorren et al., 1988; Mangerud et al., 1992; Salvigsen et al., 1992; Sættem et al., 1992, and many others). These results turned the Arctic ice sheet hypothesis into a piece of common wisdom as far as the western Barents Sea was concerned. However, in Russia, it has not been acknowledged and accepted by the prevailing number of specialists (see: Biryukov et al., 1988; Velichko, 1993).

Up to now, it is generally believed that the available evidence for and against the ice-sheet glaciations in the rest of Arctic Eurasia is scant and incomplete, thus permitting a range of alternative reconstructions. This is no longer true. Today we are in a position to make a sensible selection from the existing alternatives, based on the facts of glacial geomorphology and geology. There are sufficient data to permit a single reconstruction. Moreover, the hypotheses which purport to pose as ‘alternative concepts’ do not stand even the elementary test: they fail to conform with the evidence provided by geological surveys and space image interpretations.

**THE KARA ICE SHEET**

During the last, Late Weichselian, glacial hemicycle, the Barents–Kara continental shelf and adjacent land were glaciated by the Kara ice sheet. Judging from end moraines, glacial striae, grooves and other ice-motion directional indicators, the ice sheet was centered on the western Kara Sea, merged with the Scandinavian ice sheet and spread out in all directions, invading the Barents Sea and northern coastal areas of the Russian Plain and Siberian mainland.

Despite the constant growth of corroborating evidence, the existence of the Kara ice sheet is still debated. In a number of recent reconstructions, the Kara continental shelf is indicated either as generally ice-free (e.g.: Biryukov et al., 1988), or as ice-free during the last glacial maximum (LGM) (Astagkov, 1992). Meanwhile, the bulk of evidence for the Late Weichselian Kara ice sheet has become impressive. It includes a single concentric end-moraine system on the northeastern Russian Plain, West Siberia and Taimyr Peninsula, centered in the Kara Sea; a number of prominent ice-shoved features; many sites with drumlins, flutes, glacial striae and grooves, all having the radial orientation compatible with ice spreading from a Kara-Sea center; similarly oriented through-valleys and boulder trains, as well as the traces of ice-dammed lakes and meltwater channels beyond the southern limit of ice.

Fig. 1 presents the most important geomorphological evidence for the west-central part of the last Kara ice sheet. Its components are adopted from such sources as ‘Geomorphological map of the USSR. Scale 1:2,500,000’ (1981), reports and maps of the State Geological Survey (Arslanov et al., 1987; Astakhov, 1979; Kind and Leonov, 1982; Lavrov, 1977, 1981; Voronov, 1951), and results of research projects of the Academy of Sciences (Arkhipov et al., 1980, 1986; Grosswald, 1979, 1980, 1988, 1993, 1994). Nearly all the elements comprising the map have been published elsewhere, in particular, by this author (Grosswald, 1993). The only difference is in areal coverage, the scale and, what is important, in the new, more easterly, position of the LGM-moraine in the basin of Northern Dvina. The map also shows a more precise relationship between the newly discovered end moraines of the Kola Peninsula (Grosswald, 1993, 1996b) and ice marginal formations of the North-Dvina and Mezen Basins.

Positions of the ice margins of both the Scandinavian and Kara ice sheets on the Russian Plain at the last glacial maximum-LGM-Sc and LGM-K have been established by Lavrov (Arslanov et al., 1987; Lavrov and Potapenko, 1993). The margins are shown as coincident with prominent systems of large end moraines which constrain-limit and confine-the areal extent of distal lacustrine terraces in the Mezen (145 m a.s.l.), Vychegea (130 m a.s.l.), and Pechora (150 m a.s.l.) basins. Neither the moraines nor the high terraces are directly dated. Nevertheless, for topographic reasons, only ice-dammed lakes related to those terraces were able to discharge meltwater southward to the Caspian Sea, accounting, at least partly, for its high stand at about 20 ka. The parts of the same basins lying upglacier of the moraines contain only terraces at 100–110 m and lower altitudes, which attest to the paleolakes draining to the west and southwest, not to the south. This fact should not be overlooked when trying different ice-margin positions for the LGM Kara ice sheet.

The ages of the younger moraines related to the Scandinavian ice are relatively well documented; they are marked on the map. As for ages of the moraines related to the Kara ice sheet, they are still viewed as uncertain. Not only the dates of moraines, obtained by Lavrov and others (Arslanov et al., 1987; Arkhipov et al., 1980), but also the very fact of their ice-marginal origin, are sometimes questioned (Mangerud et al., 1994; Zubakov and Borzenkova, 1990).

However, in this author’s opinion, the 14C-dates obtained on organic sediments contained in the low lacustrine terraces of the Pechora, Mezen and Ob river basins appear convincing. The dates span the intervals of 12.5–10.5 ka and 9.5–8.5 ka and thus suggest, broadly, the Late-glacial age of the second (from the south) major end-moraine belt and the Holocene age of the third belt. Corroborating evidence for these ages came from the Kola Peninsula–White Sea area, where Late-glacial collision of the two great ice sheets occurred, and a direct, physical relationship between the dated Scandinavian ice-marginal forms and the ‘Kara’...
moraines of problematic age can be observed and established.

Maps of glacial features of the Kola Peninsula based on putting together the data from older work (e.g. Rainio et al., 1995), bear little resemblance to reality. On the other hand, recent geomorphic analysis of air photos and space images, conducted by this author, clearly indicated that the main glacial landforms of the critical area, presented in Fig. 2, are: (1) two 'longitudinal' end-moraine belts, both facing southwestward, (2) the Tersky Keivy lateral-moraines, attesting, by their long profiles and the type of en echelon alignment, to the northeast-to-southwest ice flow along the adjacent Gorge of the White Sea, and (3) lateral moraines and meltwater channels related to a Kandalaksha lobe of the Younger Dryas Scandinavian ice sheet.

Of these, the 'longitudinal' end moraines deserve particular attention. The structure of the older (southern) one, with pronounced glaciotectonic slices thrust upon each other to form a pattern of fish scales, unmistakably attests to a vigorous ice-sheet advance from the northeast (Fig. 3a). The second 'longitudinal' moraine, having lower relief, is conspicuous by tongue-shaped lobes coincident with topographic saddles and projecting southwestward. Both the moraines are absent on published maps though they are easily distinguishable on space images. Why? I think this is because the moraines do not fit into existing concepts. It was for this reason that even the first moraine, which is a really huge ice marginal complex, perhaps the largest in Europe, was left unnoticed or when it was noticed it was misinterpreted — taken for an exposure of tectonically distorted bedrock (see, e.g. Punkari, 1993).

Fig. 3b makes evident the cross-cutting relationship between (2) and (3). This implies that the Tersky Keivy...
Moraines are younger than the lateral forms of the Kandalaksha lobe. Indeed, the subbasins of Lake Babozero are quite definitely contained in the ice-marginally eroded furrows of (3), and at the same time are as obviously impounded by the Tersky Keivy. Further, as the Kandalaksha lobe apparently is correlated to the Salpausselkä I Moraine of Finland and dates to 10.8 ka BP, the Tersky Keivy should be considered to have been formed after that date. This conclusion is consistent with and supported by 14C dates from the youngest lacustrine beds of the North Dvina and Vychegda valleys (Arslanov et al., 1984, 1987). The beds formed in a meltwater lake which was dammed by the ice lobe that intruded into the White Sea Gorge and transgressed up the valleys (Grosswald, 1993, 1996b).

On a broader scope, the Late-glacial (most probably, the late-to-post Younger Dryas) age of the ‘Kara’ ice encroachment upon the Kola Peninsula is clear from Figure 1, showing wide glacier lobes overlapping and eclipsing the ‘Scandinavian’ moraines dating back to 15 to 10.8 ka BP. Also, a readvance of the Kara ice sheet, having taken place at the time of Younger Dryas-to-

Preboreal transition, appears consistent with the chronology of the glaciomarine-sedimentation pulses in the eastern Barents Sea, discovered by Polyak et al. (1995). These workers demonstrated that sedimentation there occurred in two pulses which started at 12.7 and 10.5 ka BP, and were separated by an interval of nondeposition that lasted about 1.5 ka.

The resulting paleogeography is portrayed in the sketch-map (Fig. 4). The latter makes it manifest that a broad lobate margin of the Kara ice sheet, including the Gorge lobe, covered the Arctic coastal zone of the Russian Plain at the time of Late-glacial to Holocene transition. The areal extent of this readvance was among the largest on Earth, which appears consistent with specific ice-dynamic and glacio-climatic conditions in the Barents Sea at the end of the Younger Dryas time. The conditions were characterized by abrupt climate warming and increase in snowfalls (suggested by ice-core analyses from Summit Station, Greenland) and by dramatic destabilization of the Kara Sea ice sheet, as the latter, about 3000 m high, was left with no buttressing after its Barents Sea part collapsed between 14 and 11 ka. In style,
the discussed ice-sheet readvance resembled the Younger Dryas glacial event in southwestern Scandinavia (Björck and Digerfeldt, 1991), but occurred a few centuries later and was much more extensive, which appears consistent with its instability context.

Two consequences of the readvance are worth mentioning. First, that ice-dammed lakes formed along the ice front and were forced to drain into the Baltic Ice Lake, thus strongly increasing its catchment area. Second, the weight of evidence uncovered and presented by Lavrov and this author, as well as by Prokopchuk (1985), attest to advancing of the Late-glacial ice from the northeast, from the Kara ice spreading center. In this context, for physical reasons, the 'Kara' ice, being able to reach the Kola Peninsula and the White Sea, had to encroach upon the basins of Pechora and Mezen. Thus no reason can be conceived for arguing against the 'young' glaciation of the Pechora Basin, despite all attempts to uncover evidence for the contrary (Mangerud et al., 1994; Tveranger et al., 1995).

Motions to question the glacial, ice-marginal, nature of the landforms in question also appear groundless. These landforms were painstakingly surveyed in the field and carefully mapped by means of airphoto interpretation. The resulting map (Fig. 1), displaying the end-moraine belts with a variety of larger and smaller details, such as morainic lobes, ice-shoved features, fluted and drumlinized ice-tongue basins, is an objective portrait of a glaciated landscape (Lavrov, 1977, 1981). From my own experience, the discussed 'young' end moraines are, as a rule, easily discernible and identifiable on airphoto and space images. The pattern of moraines, with the spacing and character of the entire geomorphic complexes, provide convincing evidence for the glacial origin of both the landscape in general and of the smallest of its details in particular. Among other things, this concerns
Some additional questions should be addressed in the context of the morainic patterns. First; what interpretation of ice-sheet dynamics may be derived from it? The patterns suggest that the LGM moraine, which looks quite 'massive', was formed by thick and probably cold-based ice. By contrast, the younger moraines, appearing much more lobate (see also; Lavrov, 1981), and often associated with drumlins and flutings, could have been produced by much thinner and faster ice which was probably warm-based. In other words, the explanation for similar phenomena in southwestern Minnesota given by Patterson (1993) seems applicable to the ice-marginal features of the northeastern Russian Plain. Indeed, the Late-glacial and Holocene morainic lobes are typically long and narrow, such as the Rogovaya lobe, 120 km long and 25 km wide (marked by ‘R’ in Fig. 1), or fluted lobes entering the Mezen mouth from the north and the Pechora from the northeast. It is indeed possible that the ice was moving there on a deformable bed of water-saturated glacio-lacustrine deposits. The lobes commonly correspond to up-glacier passages, either to saddles of the Pai-Khoi Mountains or to inter-island channels of the Novaya Zemlya and Vaygach area. As well, the lobes stretch parallel to ice-sheet flowlines. This implies that their dynamics originated from somewhere in the ice sheet interior, which rules out the possibility that the lobes have been produced by collapses of dead-ice bodies. Also, given the nearly flat surface of the plain, the kind of lobation displayed by the map suggests that the ice-sheet margins were thin during Late-glacial and Holocene times. The probable age of the Late-glacial readvance was close to the end of Younger Dryas time, when air temperature and snowfall abruptly increased. This type of advance, which was suggestive of ice-sheet surging, is consistent with these climatic changes.

Second, where was the center of ice spreading? The ice-front position during the LGM and the orientation of younger ice lobes on the Russian Plain, as well as all known ice-motion indicators, strongly suggest that the ice flow there was invariably directed from the northeast. On the adjacent floor of the western and eastern Barents Sea, that direction turned to become east to west (Salvigsen et al., 1992; Gataullin et al., 1993). Judging from the evidence of giant glacial grooves, drumlins, flutes and glacial breaches from Novaya Zemlya, Vaygach Island and the Pai-Khoi Mountains, recently summarized by this author (Grosswald, 1994), the center of ice-spreading was located in the southern Kara sea. Figures 5, 6 and 7 show some signatures of ice flow across Novaya Zemlya, Vaygach Island and Yugorsky Peninsula. Given this evidence, all attempts to argue, mostly based on far-fetched considerations, in favor of a major ice-spreading center in the Barents Sea or on Novaya Zemlya, rather than on the Kara-Sea floor (Astakhov, 1992; Forman et al., 1995, and many others), appear dubious and hardly tenable.

Third, what does this imply for the ice-sheet reconstructions? The answer is obvious: continuous, south-
Late-Weichselian ice sheets in Arctic and Pacific Siberia

Ice flow direction

FIG. 5. Giant glacial grooves intersecting the outcrops of Paleozoic limestones and sandstones. Southern Novaya Zemlya, vertical airphograph.

facing end-moraine belts of Late Weichselian age

conclusively indicate that a marine ice sheet of that age

was grounded on the entire adjacent continental shelf.

Furthermore, this shows that ice-sheet thicknesses and

geometry can be resolved only by glaciological modeling,

not by manipulating the Holocene shoreline altitudes

which are virtually irrelevant. It is unfortunate that the

major evidence for the Kara ice sheet — its ice-marginal

formations — is too often ignored, while the pattern of

Holocene land-emergence is placed into focus (e.g.

Forman et al., 1995). Evidence of that pattern played a

role during the 1960s, when it provided the earliest hints of

marine glaciation. At the same time, it is fairly clear that

the pattern of residual isostatic uplift mainly reflects the

mode, chronology, and pattern of deglaciation, not the

LGM-distribution of ice thicknesses (Grosswald, 1980,

1983). As far as the absence of Late-glacial shorelines on

the Arctic coasts of Eurasia is concerned, this phenomenon

appears predictable and does not attest to the absence of

glacio-isostatic effects. The coasts of Siberia, being

landward of the marine Eurasian ice sheet, were protected

from the ocean. Thus their vertical movements were not

recorded by flights of shorelines. By contrast, in a majority

of glaciated regions, as in Scandinavia or Svalbard, the

coasts happened to lie seaward of a former terrestrial ice

sheet. These coasts were between ice margins and the

ocean, and were therefore easily sculptured by the latter

(Grosswald, 1983; Grosswald and Hughes, 1995).

Fourth, which end-moraine belts of West Siberia

correlate with the LGM, with Late-glacial, and with

Holocene moraines of the Russian Plain? A suggestion is

provided by Fig. 1. One can see, in the Late-glacial and

Holocene scenarios, an ice sheet spreading from the Kara

Sea divided into two broad lobes around the northern part

of the Polar Ural (about 1500 m a.s.l.), which played the

role of an ice-sunderer. For glacio-dynamic reasons, the

lobes had to be of commensurate lengths; thus, the

Salekhardsky-Uvaly Moraine of West Siberia (marked by

'S'), lying just south of the Gulf of Ob (taken by Arkhipov

et al. (1980) for a LGM-boundary), should be correlated

with the Rogovskaya lobe (see above) and assigned a Late-

glacial age. All Siberian moraines lying north of

Salekhardsky Uvaly appear to correlate with the Holocene

(Markhida) belt. In this context it is only natural to expect

that the Siberian LGM-boundary is located on the eastern

continuation of its European correlative. Presently, the

most likely candidate for this role is the limit suggested by

Goncharov (1986) — the limit which lies on that

continuation and is constrained by the evidence of

paleo-lake Yelogui. Further east, across the Yenisei into

Central Siberia, the LGM-boundary of the Kara ice sheet

probably extends along the end-moraine systems mapped

by Andreyeva and Isayeva (1988). Finally, in the north, the

ice sheet had to reach the outer edge of the Barents-Kara

shelf, which is clear from both data obtained by the

Norwegian marine geological surveys and glaciological

considerations by Weertman (1974).

This reconstruction is not yet fully substantiated by

geological evidence, but it is glacio-dynamically justi-

fied. It is consistent with the modeling experiments

by Fastook and Hughes (1991), and conforms well with

certain 14C-dates obtained in West Siberia and the

Taimyr Lowland from the beds underlying the upper till

sheet (Arkhipov et al., 1980). Paradoxically, it is

inconsistent with many other dates derived from sedi-

ments overlying the same till. Those dates, suggesting

ages 'older than 35–40 ka BP', are being pointedly used

as an argument against the concept of a Late Weichse-

lian Kara ice sheet; virtually, they are the main and

often the only argument on which minimum reconstruc-

tions base.

However, in my view, the evidence of 'old' dates is

unconvincing. As a rule it is at variance with the facts of

glacial geomorphology. Also, in many instances, the dates
themselves are suspicious, coming from recycled and displaced materials, and of being contaminated by ‘old’ carbon. This recycling and contamination are predictable consequences of the Siberian paleogeography, since the areas in question were recurrently overridden by ice or flooded by proglacial lakes transgressing southward from the Arctic continental shelf, so that massive spreading of sediments originating from distal environments had taken place.

The same should be said of mammoth bones coming from glaciated areas and dated at 14–24 ka BP. They do not present an unsurmountable obstacle to the concept of East Siberian glaciation, however strong the ‘mammoth argument’ may seem (Sher, 1995). The bones could be recycled, redeposited, and contaminated, too. After re-processing, they may yield quite different ages, as happened years ago in Scandinavia: there, several 19–24 ka dates, incompatible with the Scandinavian ice sheet, were also obtained on mammoth bones. However, after re-processing the samples, those dates turned out either much younger or much older. The same may happen to the ages of the ‘Russian’ mammoth. It wouldn’t be surprising because many of them are in striking contrast with the Arctic paleoenvironments. Could the mammoth fauna flourish in Severnaya Zemlya at the LGM, as suggested by the dates? Despite the dates, mammoth occupation is out of the question for an archipelago which is heavily (50% of its area) glacierized today. Quite obviously, a lot of additional work should be done concerning mammoth finds before employing their ages as a piece of evidence for or against the Siberian glaciations.

Considerable misunderstanding has sprung up from some erroneous interpretations. An example of such ‘errors of consequence’, leading to far-fetched inferences on ‘retarded deglaciation’ and ‘older-than-it-seems’ geomorphology of Siberia, has been demonstrated by a discussion of the Siberian site ‘Ice Hill’ (Astakhov and Isayeva, 1988). At this, special importance was assigned to a couple of 14C dates on wood fragments, namely 43.1±1 ka BP and more than 50 ka BP, originated from a debris bed overlying a thick tabular body of buried glacier ice. Judging by the authors’ description (and my own memories of the site), the overlying debris is typical ablation till reworked by the processes of slumping and redeposition in meltwater pools. Nevertheless, when inferring the age of the buried ice, Astakhov and Isayeva used the assumption that the wood incorporated into that ablation till is geologically younger than the underlying ice. But why? The ‘Ice Hill’ section is not a marine or lacustrine sequence, it is a remnant of a kilometer-thick ice sheet, the latter’s near-bottom part. Such parts are typically rich in debris produced by glacial scour of underlying rocks and incorporated into ice from below, along ice shear-plains or other near-bottom faults. The faults reach up to several tens of meters above glacier bed, and so do the masses of debris. And it was melting-out of that debris that first stopped the Late-glacial ice-sheet down-wasting by forming a protective cover of ablation till. Thus the datable materials contained in that till are typically derived from beneath the ice sheets, and are older, not younger, that the latter. In this context, Astakhov’s inference as to the Early Weichselian age of the buried glacier ice in the ‘Ice Hill’ locality (and elsewhere) appears groundless. Moreover, given the wide occurrence of buried glacier ice in Siberia, the above mechanism of how the older materials turned up on the surface of the younger ones may prove to be of more universal application, providing us with a clue to the long-debated problem of supra-till ‘old’ dates.

THE EAST SIBERIAN AND BERINGIAN ICE SHEETS

Until recently, all evidence for ice-sheet glaciation of the East Siberian shelves and coastal lowlands was sparse, indirect, and equivocal. The glaciation itself was considered highly problematic —especially since the ice-age climates of that part of Siberia were, and still are, broadly believed to have been too dry to enable initiation and growth of large ice sheets.

Conversely and quite paradoxically, recent computer simulations based on advanced climate models suggest the opposite. Specifically, they yield vast ice-sheet glaciation of the Siberian North East, which appears more extensive than the Scandinavian ice sheet (Verbitsky and Oglesby, 1992; Marsiat, 1994; Huybrechts and T’joobbel, 1995).

What can be learned from recent studies of the region? Judging from current publications (e.g. Biryukov et al., 1988; Velichko, 1993), only cirque and valley glaciers occurred in the north of East Siberia during the Quaternary. Even Hopkins (1972), who envisaged larger glaciers there, related them to the penultimate, not to the last glaciation. What is more important, he maintained that they were basically terrestrial features, restricted to highlands, and not marine ice sheets transgressing from continental shelves.

The first convincing geological signatures of vast East Siberian glaciations were uncovered during 1987–1990. Initially they comprised a complex of ice-shoved ridges, tunnel valleys, outwash plains and other glacial landforms of the New Siberian Islands and surrounding shelf. Their
Late-Weichselian ice sheets in Arctic and Pacific Siberia

geometry was indicative of former ice motion from the northeast. The tusks of *Mammoth primigenius* were found within ice-distorted beds of the northern Bunge Land Island, implying a late Weichselian age for the whole complex (Grosswald, 1988, 1990).

Another assemblage of ice-shoved features was found and mapped in the Tiksi area of North Yakutia a few years later. It is represented by well preserved ice-thrust forms (stacking orders of imbricate slices) coupled with glaciotectonically excavated basins (hill-and-hole pairs), as well of parallel rock-drumlin clusters carved from Paleozoic shales (Fig. 8). The glaciotectonic slices were found to be displaced southwestward, shale plates in drumlins were overturned in the same direction, and the drumlin-tails pointed to the southwest. Thus, there is little doubt that the geomorphology of the Tiksi area also implied the northeast-to-southwest direction of former ice flow (Grosswald and Spektor, 1993).

The Tiksi hill-and-hole pairs were AMS-14C dated. To this end, Wibjörn Karlen and his team visited the area in the spring, and drilled into the lake bottoms through the seasonal ice. The sediment samples were processed and dated at Uppsala University, Sweden, and yielded a Late Weichselian age of the whole Tiksi glacio-geomorphic complex (Grosswald et al., 1992).

Based on the evidence from the New Siberian Islands and Tiksi, a 400-km long ice flowband was reconstructed offering the first clue to solving the mystery of Siberian ice sheets. That flowband extended from the New Siberian Islands southwestward, reaching the foothills of the Verkhoyansky Range. With this accomplished, it was possible to take the following step and hypothesize the tentative southern ice boundary (Grosswald, 1988).

Further progress in establishing the ice sheet’s southern limits was achieved by mapping the oriented tundra landforms of the Yana-Indigirka, Lena delta and Bol. Lyakhovsky Island areas, including so called ‘oriented lakes’. Orientation of these tundra landforms within the entire region proved independent of wind directions or tectonic structures, but strikingly consistent with the flow pattern determined. The whole geomorphic continuum of the Yana-Indigirka Lowland and adjacent areas, including its ridge-and-lake complex, is sketched on Fig. 9. There, the ridges and lakes are clearly aligned along submeridional directions, and they radiate from the environ of the New Siberian Islands to form a fan-like pattern, diverging southward.

Another characteristic feature of the complex is the occurrence of a second, transversal, system of ridges and
valleys, oriented perpendicularly to the lake-and-ridge alignments (Fig. 10). Similar sets of intersecting tundra features are known from Ayon Island (see below) and Alaska (e.g. Rosenfeld and Hussey, 1958).

Both in Alaska and Siberia, the complexes occur on ice-rich sediments and are being interpreted as thermokarst features, while their elongation and regular orientation are traditionally accounted for by the effects of prevailing summer winds. However, we argued (Grosswald and Spektor, 1993; Grosswald and Hughes, 1995) that this explanation is inapplicable to Arctic Siberia. Instead, we suggested that the oriented tundra landforms had acquired their orientation and alignment from glacial drumlinization and large-scale fluting, produced by a marine ice sheet which transgressed from the adjacent Arctic shelf. Among other arguments supporting this hypothesis, Grosswald (1996a) pointed out *prima facie* drumlins occurring on continuations of the oriented tundra complexes (Fig. 11).

As far as the systems of transverse ridges and valleys are concerned, we interpreted them as ice-marginal features, akin to *Urstromtäler*, formed by meltwater streams and marking consecutive positions of a retreating ice margin. These features have been eroded into the thick blanket of specific ice-rich silts and sands, so-called 'yedoma', accumulated in proglacial (not subglacial, as Sher (1995) queried) environments during, mainly, Late-glacial and early Holocene times. Ice-sheet impoundment in the north was a vital prerequisite of their formation. At a number of sites the yedoma was $^{14}$C-dated to the Late-glacial (Kaplina and Lozhkin, 1982), and thus provided chronological limits for the oriented complexes.

All in all, we suggested that the landforms in question represent Late Weichselian glacial features that may be extensively used for ice-sheet reconstructions. Being carved from deeply frozen and ice rich sediments, the forms have been distorted and disfigured by following thermokarst, solifluction and other periglacial processes which are gathering speed under current climate warming. This disfiguring accounts for the systematic misinterpretation of the oriented landforms.

Based on the flowlines derived from both the ice-shoved features and oriented tundra forms (Fig. 9), a new, more advanced reconstruction of an East Siberian ice sheet was accomplished (Grosswald and Hughes, 1995). The spreading center of the ice sheet proved to be on the Arctic shelf, in the vicinity of the New Siberian Islands. It was coalescent with the Kara ice sheet in the west and

---

**FIG. 9.** Geomorphological complexes of the Yana-Indigirka Lowland and adjacent areas: 1 — large ice-shoved features; 2 — direction of horizontal glacial pressure; 3 — drumlins; 4 — direction of long axes of the tundra oriented forms; 5 — transverse tundra ridges; 6 — relic valleys of meltwater streams; 7 — inferred ice flowlines; 8 — mountains and highlands; 9 — areas discussed in the text; 10 — glacial and meltwater breaches. Areas: A — ice-shoved features, the New Siberian Islands; B — the same, Tiksi area; C — oriented forms, northwestern Lena delta, D — drumlins of the Bol. Lyakhovsky Island, E — field of oriented forms, Yana-Indigirka Lowland, F — site of washboard moraines, G — push-moraine of the Allaikha valley, J — Ogustakh drumlin field.
Evidence for the latter is currently being gathered and tested. A strikingly pronounced and large (12,000 km$^2$) field of push moraines of the Kholercha tundra, the lower Kolyma basin, and oriented tundra landforms of the Karchyk Peninsula and adjacent Ayon Island, west of the Chaun Guba, are among the evidence. Being identified on space images by Grosswald (1996a), both geomorphic complexes clearly attest to the iceflow directed southwestward, thus suggesting another ice-spreading center situated northeast of the Kolyma delta. Additional pieces of corroborative evidence include the Upper- and Mid-Pleistocene till sheets of the Vankarem Lowland, Chukchi Peninsula (Laukhin et al., 1989); accumulations of glacial erratics on Cape Serdtse Kamen; as well as abundant glacial erratics and Lappland-style geomorphology of Wrangel Island (observed by this author, 1991–1993).

Geomorphic evidence for ice flow through the Bering Strait and across the Chukchi Range of the Chukchi Peninsula, all directed from north to south, is of particular importance. Cape Dezhnev, bounding the strait from the west, turned out to be a 700-m high and steep glaciated wall with a truncated spur at its foot and a huge mass of coarse debris accumulated on its lee (southern) side. In turn, the Chukchi Range, on its entire 600-km-long part stretching between Bering Strait and the Pekulney Range,
is breached by dozens of U-shaped valleys oriented in a north-to-south direction. The same direction is implied by local oriented lakes and by large end moraines in the lower Anadyr valley. Ice moved there from the north and northeast, across the Anadyr Lowland and the adjacent shelf. Tabular bodies of relic glacier ice occur on the Anadyr coastal lowland, which contain marine fossils from that shelf (Kaplyanskaya and Tarnogradsky, 1978).

Compelling evidence for a continuous glaciation of the Bering Sea, including its deep-sea basin, comes from the geomorphology of the southeastern Chukchi Peninsula and of some promontories jutting out into the sea. The first has become a fjordland (Sinyavino Maze of Fjords) by ice moving from the northeast, cutting and dissecting the land corner. As to the promontories, in particular, Cape Navarin and Cape Olyutorsky peninsulas, they also display intersection by glacial troughs (Fig. 12).

The phenomenon of 'ice-cut corners' seems ubiquitous on the shores abutting the former marine ice sheets. The Irish Sea ice sheet cut the promontories on both sides of St. George's Channel, between Ireland and Britain (Eyles and McCabe, 1989). Another marine ice sheet, that of the Kane Basin between Ellesmere Island and Greenland, overrode and dissected Cape Herschel Peninsula (Blake, 1992). The Central Arctic ice shelf overrode and eroded the Yermak Plateau 'corner' (Vogt et al., 1994). As to our example, it also strongly suggests that a marine ice sheet, this time confined within the Bering Sea, transgressed across the bounding headlands, such as Cape Dezhnev, the Sinyavino fjordland, and the above-mentioned capes. Incidentally, one of them, Cape Olyutorsky, lies quite close to the deep southern Bering Sea and, judging from this setting, was overridden by the edge of an ice shelf floating in this part of the Bering Sea. Furthermore, a triangle-shaped channel incised into the Shirshov submarine ridge just offshore of the cape looks similar to that of the Yermak Plateau. Based on this, it may be predicted that iceberg plowmarks of the kind described by Vogt et al. (1994) will be spotted offshore of Cape Olyutorsky in the years to come.

As it is, the 'hanging' troughs of Cape Olyutorsky are consistent with the ice shelf inferred earlier by Grosswald and Vozovik (1984) and Hughes and Hughes (1994). Additional piece of evidence for the ice shelf is provided by glaciated troughs crossing the Commander–Aleutian Ridge and its islands. In particular, Bering Island has been breached by several through valleys with U-shaped cross sections and striations on their slopes (Erlich and Melekestsev, 1974; Y. Muravyov, Petropavlovsk-Kamchatsky, oral commun.).

The hypothesis of a Beringian ice sheet consisting of grounded parts and of a floating ice shelf appears consistent with the evidence for a recent, post-Sangamon, episode of ice-overriding St. Lawrence Island (Benson, 1993). Also, it provides a first reasonable explanation for the giant submarine troughs deeply incised into the shelf margin—so called 'canyons' of Bering, Bristol, Prishlyov, Pervenets, Zhemchug and others—which were described, but virtually not accounted for, by Scholl and others (Scholl et al., 1970).

Moreover, the hypothesis is consistent with the results of deep-sea drilling in the North Pacific, undertaken in the course of Leg 145 of D/V JOIDES Resolution (Anonymous, 1992; Leg 145 scientific party, 1993). Analysis of the core sediments yielded by the drilling strongly suggested extensive glaciation of the ocean's coasts and shelves between 2.6 Ma and the very end of the Pleistocene. Variations in density of the sediments have

led to the inference that the last 95 ka of that period, including the Isotope Stage 2, was punctuated by a sequence of abrupt paleoceanographic changes similar to and simultaneous with Heinrich events and Dansgaard–Oeschger cooling cycles of the North Atlantic (Kotilainen and Shackleton, 1995). Pronounced traces of similar changes have been spotted in the Chinese loesses, also. In my view, they must have reflected glacial and climatic events in the 'nearby' North Pacific, although Porter and Zhisheng (1995), who discovered the traces, chose to ascribe them to atmospheric teleconnections with the North Atlantic.

The evidence for Beringian glaciation is constantly mounting. By now, it has gathered critical mass to warrant tentative reconstruction of an ice sheet. We may envisage a paleo-ice cover resting on the Chukchi and Bering shelves and periodically, in synchrony with Heinrich events of the North Atlantic, ejecting armadas of icebergs into the North Pacific. It has been this kind of scenario that was earlier suggested for the North Atlantic; now we are trying it on the North Pacific. The North Atlantic is known to have been bounded by huge ice sheets and ice shelves. Isn’t its paleoceanographic similarity to the North Pacific suggestive that the latter was characterized by the same paleo-glacial environment? The sketch-map in Fig. 13 portrays one of the possible versions of a Beringian ice sheet at the LGM.

AN ICE SHEET IN THE SEA OF OKHOTSK?

There is some evidence for Pleistocene glaciation of the Sea of Okhotsk, too. It comes from the data provided by paleoclimatic, geomorphological and marine geological studies.

Climate and paleoclimate of the Sea of Okhotsk and adjacent land is, and was, as cold as that of the Kara Sea, and rich in snowfall, thus favorable for initiation and growth of glaciers. Judging from recent modeling experiments, mountains and uplands bordering the sea were most susceptible to heavy glaciation during glacial hemi-cycles (Marsiat, 1994; Huybrechts and T’siobbel, 1995). Among other things, the experiments predicted that the Kolymsky, Suntar Khayata and Koryak Ranges, adjacent to the discussed sea, had been subject to extensive ice-sheet glaciation. This seems to come true as topographic maps and space images of the ranges display clear evidence for former glacier complexes of Cordilleran type.

Hence, the Sea of Okhotsk was semi-surrounded by large and continuous glacier complexes, which were most probably characterized by very low, close to the sea-level, equilibrium lines. This suggested that seaward margins of the complexes extended into the sea and invad its northern periphery. Actually, that event — past glacial invasion — has been well documented by the sea’s coastal and bottom geomorphology (Udintsev, 1957).

Even small-scale maps make it clear that big glaciated valleys enter the Penzhina and Gizhiga inlets and continue seawards at least as far as southern limit of the Shelikhov Bay. The southern exit of this bay is bounded, on both sides, by ‘ice-cut corners’ of the Utkholok and Pyagina peninsulas, thus suggesting a wide marine ice lobe moving outwards, in southwestern direction. At this, its left margin pushed sideways and impinged onto the western coast of Kamchatka Peninsula, where its position is marked by a chain of parallel end moraines, eskers and drainage channels (Grosswald, unpublished).

Further south, Shelikhov Bay opens up into the Tinro Basin of the Sea of Okhotsk, which is about 1000 m deep and U-shaped; its bottom topography is dominated by large longitudinal ridges of enigmatic nature (Udintsev, 1957; Volnev, 1983). A variety of explanations were advanced for the ridges, but, in my view, the ridges cannot be accounted for other than by impact of grounded ice and subglacial meltwater activity.

The rest of the Sea of Okhotsk falls into two different parts, of which one lies north of 47–49°N, where I envisage a shelf break. The other is confined between that break and the Kuril submarine ridge. The second part, no doubt, is a piece of deep ocean akin to the deep Bering Sea basins, while the first, though extraordinary deep, looks to me very much as a continuation of a continental shelf. The basins and sills of that part, including Deryugin Basin with its depth of about 2 km, thus are intra-shelf formations, which strongly suggest, at least to me, that they are of glacial origin. In other words, I hypothesize that the basins in question have been excavated by a marine ice sheet, and the submarine ridges bearing the names of Academy of Sciences and of Institute of Oceanology, as well as other similar forms are glacial sills, or riegels.

I am fully aware that, according to the currently prevailing view, the edge of the shelf lies farther north, and the area of the above basins and ridges is underlain by the crust of transitional, not continental, type. Not only those big submarine forms, but also many smaller troughs and sills, are believed to have been produced by faulting and folding of the crust (Udintsev, 1957). However, this concept has not been proven, either, and also needs to be tested.

I did not mention that the floor of the Sea of Okhotsk is commonly covered, even far from the coasts, by coarse sediments, including boulders (Bezrukov, 1960). A field of lodgement till, a sheet of unsorted solid boulder clays, 3 to 8 m thick, was found under 15 m of late- and postglacial sediments by drilling off the coast of southwestern Kamchatka (Kuzmina and Yeremeeva, 1990). On the northern and western sides of the sea, all ‘corners’ seem to have also been glacially cut, and the lower reaches of the Amur River exhibit clear indications of former impoundment.

We cannot say how far south the Okhotsk ice sheet extended, and what its morphology was like. But it hardly was just an icy apron attached to the foot of the coastal mountains, though the ice sheet could be shaped like this at the beginning of its growth. Later its ice spreading center had to shift to the shelf, in the southeasterly, windward direction. At this stage, the ice sheet would move centrifugally, in all directions, including landwards,
impinging upon some of the intra-montane saddles from the sea. As of now, we only know of fairly clear traces of ice-sheet pressure against Taigongos Peninsula, between the Penzhina and Gizhiga inlets, directed to the northeast, from the sea landwards.

The southern margin of the ice sheet most probably graded into a floating ice shelf which, in the same way as the Bering ice shelf, was buttressed by a submarine ridge, in this case by the Kuril one. This ridge is also breached by a number of deep U-shaped straits. Some of the latter, like the Bussol, are quite deep, up to 2.5 km. So it is not unlikely that the straits played the role, in concert with the Commander-Aleutian straits, of conduits for the icebergs supplying into the North Pacific.

All in all, judging from paleoclimate of the Sea of Okhotsk, the modeling experiments, and some geomorphic and marine geological data, this sea may turn out to be an additional center of former Siberian glaciation. The marine Okhotsk ice sheet, if confirmed, would further strengthen the stance of the Leg 145 scientific party (Leg 145 scientific party, 1993; Anonymous, 1992) who argued in favour of similarity, as opposed to antagonism, of the ice-age North Atlantic and North Pacific. A few decades ago, a visionary geologist proclaimed this similarity. It was Okamoto (1972) who used his till finds in Japan to argue that ‘...glaciations on the eastern side of Asia were large and comparable on size to those in Atlantic North America, due to maritime climate with strong precipitation, the low mean yearly temperature at about the same latitudes and the wide distribution of alpine regions’. This quotation sounds quite up to date. And Okamoto’s inference looks sensible and consistent with the latest developments.

CONCLUDING REMARKS

About 20 years ago Hughes et al. (1977) advanced a hypothesis of a huge and continuous ice sheet of the Arctic, behaving as a single dynamic system. A grand problem was posed by the title of the paper: ‘Was there a late-Würm Arctic ice sheet?’. Today, we can answer that question: yes, there was. Moreover, it was larger than was suggested by our ‘maximum version’ of 1977.

A continuous Eurasian ice sheet impounded northward-flowing rivers, causing the formation of large proglacial lakes and their integration into transcontinental meltwater drainage system. The lakes experienced drastic changes in their extent, outlines, and levels, resulting from retreat and re-advances of the ice sheet, from consequent isostatic rebound, and from erosional deepening or sediment infilling of spillways and over-flow channels. So far, the drainage systems are not properly studied; however, the very fact of their existence, documented by a number of spillways, paleo-lake terraces and other features, constitutes a strong and independent argument confirming a continuous ice sheet in the Arctic.

Here, although I am not discussing the lakes and their history, a couple of remarks seem appropriate. The first one concerns the erosional incision crossing the Laptev Sea shelf just east of Taimyr Peninsula. As hypothesized in a report edited by Fütterer (1994), the feature was eroded on emerged shelf by the ice-age Lena River, which implied that the last East Siberian ice sheet had not existed. In our concept, however, the incision in question and an ice sheet in the north were quite compatible: the erosional form was produced by a Late-glacial flood, or floods, resulted from outbursts of a meltwater Lena paleo-lake, dammed by the East Siberian ice sheet.

The second remark concerns the Turgay Valley of southern West Siberia. The role of this valley as a huge late Weichselian spillway, draining Siberian meltwater into the Aralo-Caspian basin, was questioned by Astakhov (1992). However, an analysis of the newest space images by V. Baker, coupled with older information on the geology and age of the spillway (Grosswald, 1983), left little doubt that it has been a morphologically young formation eroded by powerful and turbulent streamflow from West Siberian ice-dammed lakes. The same was found to be true for another major spillway, the Manych Valley, which connected the ancient Caspian Sea, or the Khvalyn meltwater basin, with the Black Sea (V. R. Baker, pers. commun.). These young spillways are hardly compatible with Astakhov’s position in the dispute over the Eurasian proglacial lakes.

I am not discussing here the problem of a giant Central-Arctic floating ice shelf, either. However, it is hard not to mention that new discoveries in the Arctic Ocean have provided compelling evidence for such an ice shelf. Specifically, they are huge iceberg (or crushed ice shelf) plowmarks detected on the Yermak Plateau at the depths of 500–850 m, perhaps even at 2 km (Vogt et al., 1994); and also, facts providing new insights about ecological conditions of the ice-age Arctic Ocean. In particular, when crossing the ocean aboard the US and Canadian icebreakers, and ‘...studying the box core sediments for evidence of biological life, researchers found nothing in the layers dated to between 13,000 and 26,000 years ago. This abiotic zone suggests that during that glacial period the Arctic Ocean was covered by an ice shelf hundreds of meters thick that killed off all life in the waters below... Thus the Central Arctic was locked up’ (Travis, 1994). This discovery is particularly remarkable, as some of our opponents, e.g. Zubakov and Borzenkova (1990), repeatedly emphasized that the ‘fact (fact?) of uninterrupted, continuous evolution of organic life in the Arctic Ocean presented strong evidence against the ice shelf and the whole Arctic ice sheet’.

The paper by Hughes et al. (1977) provoked a surge of critical papers targeted at refuting the concept of the Arctic ice sheet, and presented similar ‘facts’ and considerations appearing to disprove it. However, the elapsed time interval has been sufficiently long to confirm Bacon’s observation that time is the greatest innovator. New trends in the thinking of ice-age researchers become discernible, revealing a slow but steady progress towards adopting our concept. Virtually all new discoveries in the region, let alone modeling experiments, bring increasing support for the Arctic ice sheet. So, virtually, we no
longer need to defend the case: rapid development of Arctic science is doing the work.

ACKNOWLEDGEMENTS

My participation in the Stockholm workshop on the Siberian sheet was sponsored by Marcus Wallenberg’s Foundation for International Scientific Cooperation, as well as by the Royal Swedish Academy of Sciences and the Stockholm University. This paper was written while I was visiting the Scott Polar Research Institute (SPRI), Cambridge, U.K., and I thank the Institute and its Director John Heap for provision of resources. My thanks are also due to Robert Headland, SPRI, and Chalmers Clapperton, University of Aberdeen, who critically read the manuscript. This research was supported in part by Grants N4Y000 and N4Y300 from the International Science Foundation.

REFERENCES


Hopkins, D.M. (1972). The paleogeographic and climatic history of Beringia during Late Cenozoic time. Inter-Nord, 12, 121–150.


Patterson, C.J. (1993). Mapping glacial terrain, southwestern Minnesota,

Mangerud, J., Bolstad, M., Elgersma, A., Helliksen, D., Landvik, J.Y.,


Lavrov, A.S. (1981). Subglacial deformation moraines produced by the


Laukhin, S.A., Drozdov, N.I., Panychev, V.A. and Velichko, S.V.

Kuzmina, N.N. and Yeremeeva, G.P. (1990). New data on the origin and


Kuzmin, N.N. and Yeromenova, G.P. (1990). New data on the origin and

age of the boulder clay from the shelf off West Kamchatka. Doklady

Akad. Nauk SSSR, 310, 1425–1428.

Laukin, S.A., Drozlov, N.I., Fyndichev, V.A. and Velichko, S.V.

(1989). The last glaciation in northern East Chukotka. Izvestiya

AN SSSR, Ser. geol., N3, 136–140.


Zemlya-Kolvan paleo-ice streams. In: Chebotarova, N.S. (ed.),

Structura et Dinamika Poslednego Evropeiskogo Ledovikovo Pokrov-

va [Structure and Dynamics of the Last European Ice Sheet], pp. 81–

100. Moscow, Nauka.

Lavrov, A.S. (1981). Subglacial deformation moraines produced by the


1–60.


Leg 145 scientific party (1993). Paleoceanographic record of North

Patterson, C.J. (1993). Mapping glacial terrain, southwestern Minnesota,

OK.


and Arctic Ocean glaciation: effect of Holocene atmospheric CO2


Mangerud, J., Bolstad, M., Elgersma, A., Heltiksen, D., Landvik, J.Y.,

Lonne, I., Lykke, A.K., Salvigsen, O., Sandahl, T. and Svendsen, J.I.

(1992). The last glacial maximum on Spitsbergen, Svalbard. Quaternary


PECHORA: Paleo environment and climatic history of the Russian


Luleå. Abstracts of lectures and posters, 132.

Marisait, I. (1994). Simulation of the Northern Hemisphere continental

ice sheets over the last glacial-interglacial cycle: experiments with a

latitude-longitude vertically integrated ice-sheet model coupled to a

ice sheets for thick calving ice fronts and a possible marine ice sheet in

the south-western Barents Sea. Geomorfologiya, 22, 403-408.

Okamoto, Y. (1972). Piedmont glaciation in the taiga forests of ice ages

in Japan and Northern Italy similar to those now present in Southern


Congress, Montreal, pp. 175–186.

Patterson, C.J. (1993). Mapping glacial terrain, southwestern Minnesota,

OK. In: Aber, J.S. (ed.), Glacioclimatices and Mapping Glacial Deposits,


events in the North Atlantic and China during the last glaciation.


University of Regina.


moraines in Finland and NW Russia. Quaternary International, 28,

179–192.


problem of oriented lakes. Proceedings of the Iowa Academy of

Science, 65, 279–287.


Land, Svalbard, and their consequences for the glacial history of the


Salvigsen, O., Adrisselon, L., Hjort, C., Johansson, K., Kelly, M.,


Svalbard. In: Möller, P., Hjort, C. and Ingólfsson, O. (eds),


Glacial geology of outer Bjørnøyrenna, southwestern Barents Sea.

Marine Geology, 103, 15–51.


The structure and origin of the large submarine canyons of the Bering


Schytt V., Hoppe G., Blake W., Jr and Grosswald, M.G. (1968). The


Sher, A. (1995). Is there any real evidence for a huge shelf ice sheet in


last Barents-Kara ice sheet at Markhida, northern Russia. Quaternary

Research, 44, 328–340.


Bezrukov, P.L. (ed.), Geoligiftskie issledovanija v Dalnevoostoch-


Publ., Moscow.

Velichko, A.A. (ed.). (1993). Evolution of Landscapes and Climates of

Northern Eurasia. Late Pleistocene-Holocene. 1 — Regional

Paleogeography, Nauka, Moscow.


carbon dioxide concentration on continental glaciation of the

Northern Hemisphere. Journal of Geophysical Research, 97,

5395–5909.

Vogt, P.R., Crane, K. and Sundvor, E. (1994). Deep Pleistocene iceberg

plowmarks on the Yermak Plateau: sidescan and 3.5 kHz evidence

for thick calving ice fronts and a possible marine ice sheet in the

Arctic Ocean. Geology, 22, 403–408.

Volnev, V.M. (1983). On the origin of the ridgy topography in the

Tiro Basin, the Sea of Okhtoks. Geomorfologiya, N3, 66–75.

Voronov, P.S. (1951). New data on glaciation and Quaternary deposits

of the Central Pau-Khooi. In: Collected Papers on the Arctic Geology,

Vol. 2, pp. 84–92.


Verren, T.O. and Kristoffersen, Y. (1996). Late Quaternary glaciation in


the Late Cenozoic. Elsevier, Amsterdam.