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The Late Weichselian Barents-Kara Ice Sheet: In defense of a maximum reconstruction

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Abstract. Extent of the Late Weichselian glaciation in western Arctic Russia is considered uncertain. Grosswald's model suggesting a continuous and long-lived Barents-Kara Ice Sheet centered on the Kara Sea is questioned by advocates of "restricted" models, including the QUEEN Program members. Based on sets of radiocarbon dates, they argue for a smaller and "diachronous" glaciation. However, the QUEEN reconstruction is inconsistent with the record of ice flow across the Kara-Barents divide, as well as with glacial geology of Kola Peninsula, Late Weichselian climate of the Arctic, Eurasian continental paleohydrology, and the entire paleogeographic context of northern Eurasia. As for the sets of radiocarbon dates, they appear erroneous (too old), these dating errors having been due to impeded ventilation of the Pleistocene Arctic Ocean and to recycling and contamination of the sampled materials. Destructive impacts of late-glacial ice-sheet surges and Eurasian megafloods upon the glacial sequences would also aggravate the situation. Thus we [*Grosswald and Hughes,* 1995, 2002] choose to ignore the dates until these problems are addressed. The rest of evidence supports extensive and continuous glaciation of the Barents-Kara continental margin at the last glacial maximum (LGM). Our reconstructions depict the Barents-Kara Ice Sheet before and after massive thawing of its bed that allows partial gravitational collapse of the overlying ice.

Introduction

In western Arctic Russia, a number of major problems related to reconstructing ice sheets during the Weichselian, especially during the last glacial maximum (LGM), remain unresolved. Distribution, extent and volumes of the ice sheets are still problematic in the region, as well as the pattern and chronology of deglaciation.

As proposed by *Hughes et al.,* [1977], during the Late Weichselian, the Arctic was glaciated by a continuous ice sheet composed of terrestrial ice domes grounded on land, marine ice domes grounded on continental shelves, and a floating ice shelf spreading across the deep Arctic Ocean. According to the hypothesis, all these elements amalgamated into an Arctic Ice Sheet – a single large glacier complex centered on the North Pole and behaving as a unified dynamic system, as is observed in the Antarctic today.

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Special research programs were initiated to address the problem. In the Northern Hemisphere the major debates centered on the possible existence of former marine ice sheets in the Kara and Barents Seas of Eurasia and the Queen Elizabeth Islands of northern Canada [*CLIMAP Project members,* 1981]. It was also unclear (and remained so until very recently) whether a thick floating ice shelf covered the deep Arctic Ocean. Despite all work done, the existing views still range from a complete denial of Arctic glaciation, to a model of "restricted glaciation" recognizing only local ice caps, to the reconstruction of an extensive Arctic Ice Sheet which included, as its largest Eurasian component, a single Barents-Kara Ice Sheet.

While initially two alternative versions of the Arctic Ice Sheet, "minimum" and "maximum" reconstructions, were considered, now we adhere to a single version that is some 30% larger than the "maximum" version of 1977 [*Grosswald and Hughes,* 1995, 2002]. Our recent interpretations suggest a larger Barents-Kara Ice Sheet and, in addition, the East Siberian, Beringian, and Okhotsk-Sea ice sheets. Thus, the Eurasian Ice Sheet, formerly depicted as a complex of two ice domes centered on the Barents and Kara Seas [*Denton and Hughes,* 1981; *Grosswald,* 1980, 1983], now appears broader and much longer.

New discoveries in the Arctic Ocean also suggest that the Arctic glaciation was extensive and continuous. Works by *Vogt et al.* [1994], *Jakobsson* [1999] and *Polyak et al.* [2001] provide evidence that a floating Arctic ice shelf impacted upon the tops of submarine Yermak Plateau, Lomonosov Ridge and Chukchi Borderland. So the ice shelf, the central element of the Arctic Ice Sheet, not only existed in the Arctic Ocean, but also was in excess of 1 km thick. This is of crucial importance to the model, as only with that ice shelf the Arctic Ice Sheet had been a continuous complex centered on the North Pole.

Until recently, the debates were focused on our controversies with the adepts of the "restricted glaciation". As of now, another minimalist reconstruction has been proposed by members of the QUEEN (Quaternary Environments of the Eurasian North) program, a project which is currently underway in western Arctic Russia. These members criticize our model, calling it controversial and ultra-maximalistic [*Astakhov et al.,* 1999; *Larsen et al.,* 1999]. Under the circumstances, I find it expedient to defend the reconstruction of Grosswald and Hughes and to further discuss the evidence for the maximum model of the Barents-Kara glaciation.

Newest Minimum Model

During the 1990s, the QUEEN Program members were conducting geological mapping and stratigraphic work in western Arctic Russia. Compared with existing knowledge [*Arkhipov et al.,* 1980; *Grosswald,* 1980, 1983; *Isayeva and Kind,* 1986; *Kind and Leonov,* 1982; *Lavrov,* 1973, 1977], their mapping did not result in new discoveries, but their stratigraphic work focused on collecting datable samples and their ^{14}C analyses has led to a new minimum reconstruction of the Weichselian glaciation. These are presented in an ample series of papers in *Boreas, 28,* (1–3), 1999, in which, after descriptions of field evidence and laboratory results, the principal conclusions are given, collectively referred here as "the QUEEN model". The model's main features are as follows.

(i) Late Quaternary (post-Eemian) glaciation reached its maximum in the western Arctic Russia during the Middle and/or Early Weichselian, not during the last, Late Weichselian. As for the Late Weichselian, it was represented here only by a Barents Sea, or a Svalbard-Barents Sea ice sheet, which was much smaller than the Middle and/or Early Weichselian ice cover.

(ii) At the LGM, the ice sheet in question was centered on the Barents Sea continental shelf, while the ice-sheet's margins reached the shelf edges in the north and the west, and crossed the barrier of Novaya Zemlya in the east, so that only a part of the Kara Sea was glaciated. The southern ice-sheet margin did not reach mainland Russia anywhere east of the White Sea (with a possible exception at the northern tip of Taimyr Peninsula), and did not impound the north-flowing rivers, as their normal drainage toward the Arctic Ocean was restored prior to 40,000 yr BP [*Mangerud et al.,* 1999; *Svendsen et al.,* 1999].

(iii) Accordingly, the Late Weichselian age of end moraines, drumlins, eskers and paleo-lake complexes of the mainland's coastal zone (except, perhaps, the "Isayeva Line" of Taimyr), advocated by Arkhipov, Grosswald, Isayeva, Lavrov, Volkov and others, was denied. Instead, all of these formations, including Markhida Moraine of the lower Pechora catchment, the Laya-Adzva and Rogovaya moraine lobes protruding for about 100 km to the south of the Markhida, as well as all their trans-Uralian continuations in West Siberia and Taimyr Peninsula, are now re-defined as belonging to the Early and Middle Weichselian.

(iv) Following *Astakhov* [1992] and based on radiocarbon dated sediments which overlay the youngest post-Eemian till sheet, the QUEEN Program members insisted that the last ice cover of the West Siberia and Pechora Lowlands disintegrated and became stagnant >40 kyr BP, and that the last merger of the Kara Sea ice sheet with the Putorana Plateau ice cap took place well before the Late Weichselian [*Svendsen et al.,* 1999].

The QUEEN members are confident that their reconstruction is perfectly coherent and non-controversial. Being based, as they stress, on the wealth of field geological data, it "resolves major uncertainties in assessing extent and volume of the last ice sheets of Eurasia". They also consider it "proven beyond any doubt" that the model of Late Weichselian glaciation worked out by Grosswald and Hughes in the 1990s is "incorrect and depicts ice sheets that are much too large", and that "the ice-sheet extent in the Eurasian Arctic during the Late Weichselian was less than half the size of Grosswald's reconstruction" [*Svendsen et al.,* 1999].

The QUEEN members claim that the maximum of Late Pleistocene glaciation in both north-central Siberia and the North Russian Plain was diachronous in regards to the rest of Eurasia, that it was out of phase with the global and West European glacial maximum of 18 kyr BP. Their maximum is found to be attained well before the Late Weichselian and probably not simultaneous throughout the entire study region. The members speculate that "this pattern indicates that the moisture supply from the west penetrated further to the east in Early-Middle Weichselian time than later in the ice age" [*Larsen et al.,* 1999]). The screening effect of a Scandinavian Ice Sheet, causing depleted snowfalls in the ice sheet's precipitation shadow, is invoked to account for this phenomenon [*Bolshiyanov and Makeyev,* 1995; *Svendsen et al.,* 1999].

Support for a Maximum Model

The evidence for an extensive and continuous Barents-Kara Ice Sheet centered on the Kara Sea, though often ignored or misinterpreted, has never been refuted. On the other hand, there are different datasets, in particular scores of radiocarbon dates, which have given rise to a number of minimum reconstructions, including the QUEEN model.

What shall be done under the circumstances? Apparently, there are two alternatives. One way is to keep gathering data, to pursue new research projects and programs, and to double the efforts in search for incontrovertible evidence. However, based on the history of glacial theory, this will hardly bring us anywhere, because new sets of "facts" will always be countered by other sets, apparently proving otherwise. And the facts themselves are mostly interpretations [*Chernyak,* 1986], which strongly depend on the theoretical concepts adhered to, and thus they are inherently ambiguous. So this approach offers little hope of breaking the impasse.

I have chosen to take a different approach – to by-pass, as much as possible, the ambiguous data and to directly examine "finished products" of the competing research programs, namely, their resulting reconstructions, and to see whether they fit into the broader paleogeographical context of Eurasia during the Late Weichselian. This approach is by no means my invention. It was put forth in the XIX century, when *William Whewell* [1840] expressed the notion of "colligation of facts" and its extraordinary role in "inductive" sciences. Present-day advocates of this approach contend that in geology, where testing hypotheses by physical experiments is not applicable, the arguments of internal coherence and external consistency step forward to assume paramount importance [*McMullin,* 1983]. According to *Baker* [2000], "the key element of the investigation is in the binding together of facts, and in the overall consistency and coherence of the working solution with the complex, developing web of interconnected clues and signs". Indeed, this kind of test can be an effective tool for checking the existing reconstructions and sorting out the wheat from the chaff. Thus our strategy is to demonstrate that the maximum model of Barents-Kara glaciation is perfectly consistent with glacial geomorphology, paleoclimate, continental paleohydrology and other paleogeographic elements of northern Eurasia established for the Late Weichselian, and to demonstrate that, by contrast, the alternative models don't.

Ice Flow Across the Kara-Barents Divide

As was shown above, according to the QUEEN model, the eastern margin of the last Barents-Kara ice sheet crossed the topographic barrier of Novaya Zemlya and Vaygach Islands and of Pai-Khoi Mountains from the west. In this, the model followed the reconstructions proposed by *Elverhøi et al.* [1993], *Forman et al.* [1995], and the *PONAM Project Members* [1995]. The PONAM authors argued in favor of a "Svalbard-Barents Sea ice sheet" as the largest member of a greater "multi-domed ice sheet", while *Forman et al.* [1995] emphasized the dominance of an ice sheet centered on the Barents Sea over a "diminutive glacier coverage of the Kara Sea".

However, there is no geological evidence supporting this west-to-east crossing. Just the opposite, all ice-flow directional indicators known from the barrier, i.e., from Novaya Zemlya, Vaygach Island, Yugorsky Peninsula and the Pai-Khoi Mountains, are oriented in the NE to SW and E to W directions. These indicators comprise assemblages of drumlins, crag-and-tails, flutes and other streamlined features, as well as larger landforms such as U-shaped saddles, straits, and through valleys [*Grosswald,* 1994]. These are features of first and second-order glacial geology, all showing an east-to-west and northeast-to-southwest glacial flow.

Hughes [1998] maintains that distinguishing between the two orders of glacial geological features is the key to correct interpretation of glacial landforms. First-order glacial features result from a prolonged, orderly glacier flow that is reinforced by each glaciation cycle and therefore places an increasingly dominant imprint on the landscape. Second-order glacial landforms are produced during deglaciation, when ice flow becomes unstable and chaotic, so the landforms are transient and easily erased, reoriented, or overprinted by short-lived ice advances and retreats. Hence, the second-order glacial features, being easily obliterated, always document the latest stage, or episode, of ice flow in a study area [*Lundqvist,* 1990].

Figure 1 displays the ice-flow indicators, and Figure 2 exemplifies the streamlined second-order glacial landforms of the Kara-Barents divide. Clearly, all the features were produced by outward ice flow from the Kara Sea and were not overprinted by any differently oriented flow. They are evidence for the latest episode of crossing the Kara-Barents divide by moving ice.

As for the first-order features of the Kara-Barents divide, they are the broad glaciated saddles, U-shaped transverse furrows and straits, and narrow through valleys that breaches the higher portions of the divide within the Polar Urals and central Novaya Zemlya. One of the breaches, the Strait of Matochkin Shar, was glacially eroded so deeply that it is now a seaway separating the two major islands of Novaya Zemlya. The rest of the breaches are some fifteen glacial troughs with hanging tributaries, broad bottoms and steep slopes covered by glacial polish reaching up to altitudes of 500–550 m. Long profiles of the troughs display no transverse divides, and are marked by alternations of concave sediment-filled basins and convex craggy sills with topographic relief of up to 40 m, while the ends of the troughs are submerged and have become fjords. Similar geomorphology is characteristic of the valleys breaching the Polar Urals. Ice flow through the glacial breaches of Novaya Zemlya proceeded to the west, and flow across the Polar Urals was to the southwest, so that both were directed outward from the Kara Sea [*Grosswald,* 1994]. This is clear from orientations of giant glacial grooves, stoss-and-lee sides of roches moutonnees, and boulder trains, and from configuration of related moraines [*Chernov,* 1936; *Liverovsky,* 1933].

Convincing evidence for the westward ice flow across Novaya Zemlya is the submarine Admiralty Ridge, an arcuate moraine in the eastern Barents Sea with its distal side facing to the west. This moraine with a relief of up to 200–240 m and a length of 400 km is located 150 to 300 km west of Novaya Zemlya, and is made up of a core of folded and faulted Mesozoic sandstone capped by 10 to 30 m of glacial till. The till is shoved to form several minor ridges, parallel to the major ridges [*Dunayev et al.,* 1995]. Judging by their geomorphology, the ridges were never overridden by ice moving from the west. *Dunayev et al.* [1995] believe that the sandstone cores of the ridge are anticline folds built by bedrock tectonism, however, to me they appear as typical ice-shoved features.

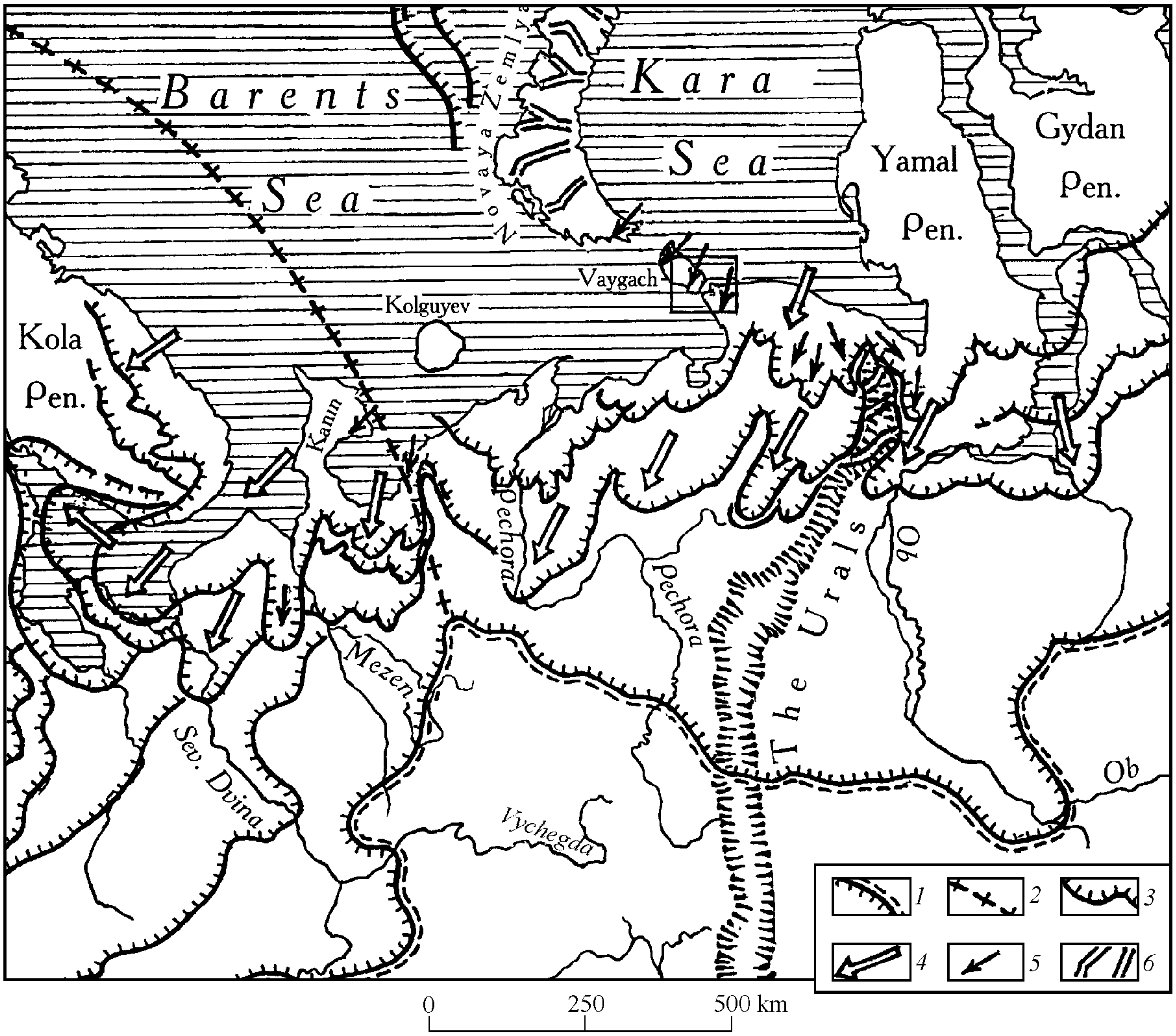

Figure 1. Late Weichselian ice margins and ice flow directional indicators, west-central Arctic Russia: 1 – ice margin during the LGM; 2 – confluence line of the Scandinavian and Barents-Kara ice sheets during the LGM; 3 – late-glacial and Holocene ice margins; 4 – generalized ice flow during the post-Younger Dryas glacial surge; 5 – ice flow directional indicators; 6 – glacial through valleys (breaches). Rectangle indicates locations of Figures 2A and 2B.

Great numbers of similar glaciotectonic landforms, notably ice pressure ridges, ice-thrust features, and hill-and-hole pairs, all facing west, were mapped in the eastern Barents Sea by oil prospectors. The prospectors also spotted peculiar asymmetric hills made up of glaciotectonic slices of till and sandstone thrust upon each other in the east-to-west direction (personal communication to M. G. Grosswald by V. N. Bondarev and N. A. Polyakova, Murmansk, 1993). Glaciotectonic features of this type, created by a NE to SW glacial pressure, were also recorded in Bolshezemelskaya Tundra, the SE Barents Sea coast, by *Lavrushin et al.* [1989].

Composition of erratics in the Upper Weichselian till blanketing the floor of the eastern Barents Sea also attests to the east-to-west flow of ice. The clasts of Paleozoic terrigenous and carbonaceous rocks originating from Novaya Zemlya, Vaygach Island, and Pai-Khoi Mountains are particularly abundant in that till [*Epshtein et al.,* 1999; *Gataullin et al.,* 1993].

Thus, all known directional indicators of past ice flow across the Kara-Barents divide, including those related to the last episode of such flow, make it obvious that the ice was spreading out of the Kara Sea center. The streamlined glacial landforms of Novaya Zemlya, Vaygach Island, and Yugorsky Peninsula are inconsistent with all "restricted glaciation" models, e.g., with the reconstruc-

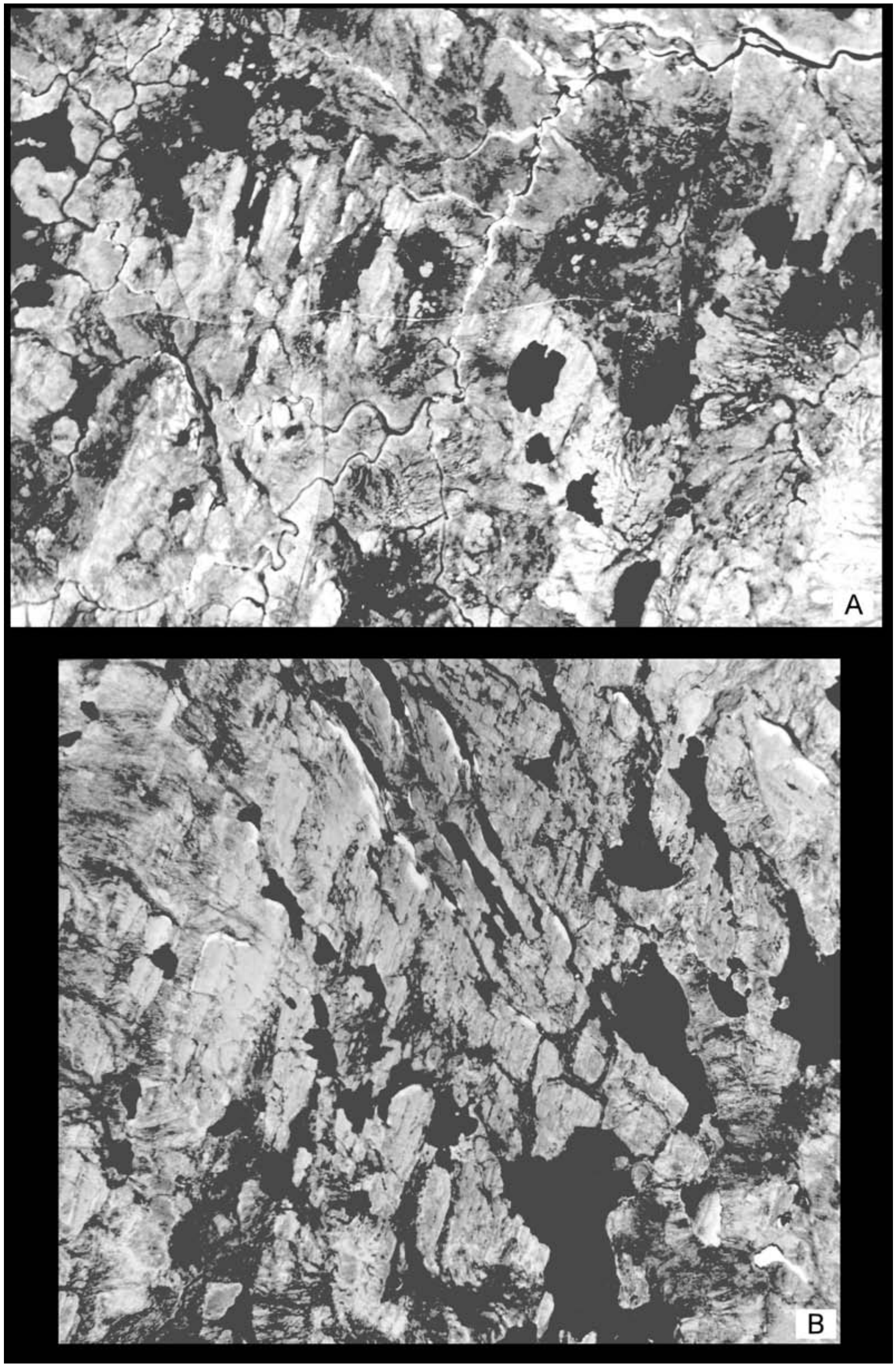

Figure 2. Examples of second-order glacial geomorphology: A – drumlins, SE Vaygach Island; B – giant fluting, NE Yugorski Peninsula. Mosaics of vertical aerial photographs. Courtesy of the Russian Geological Survey. For locations, see Figure 1.

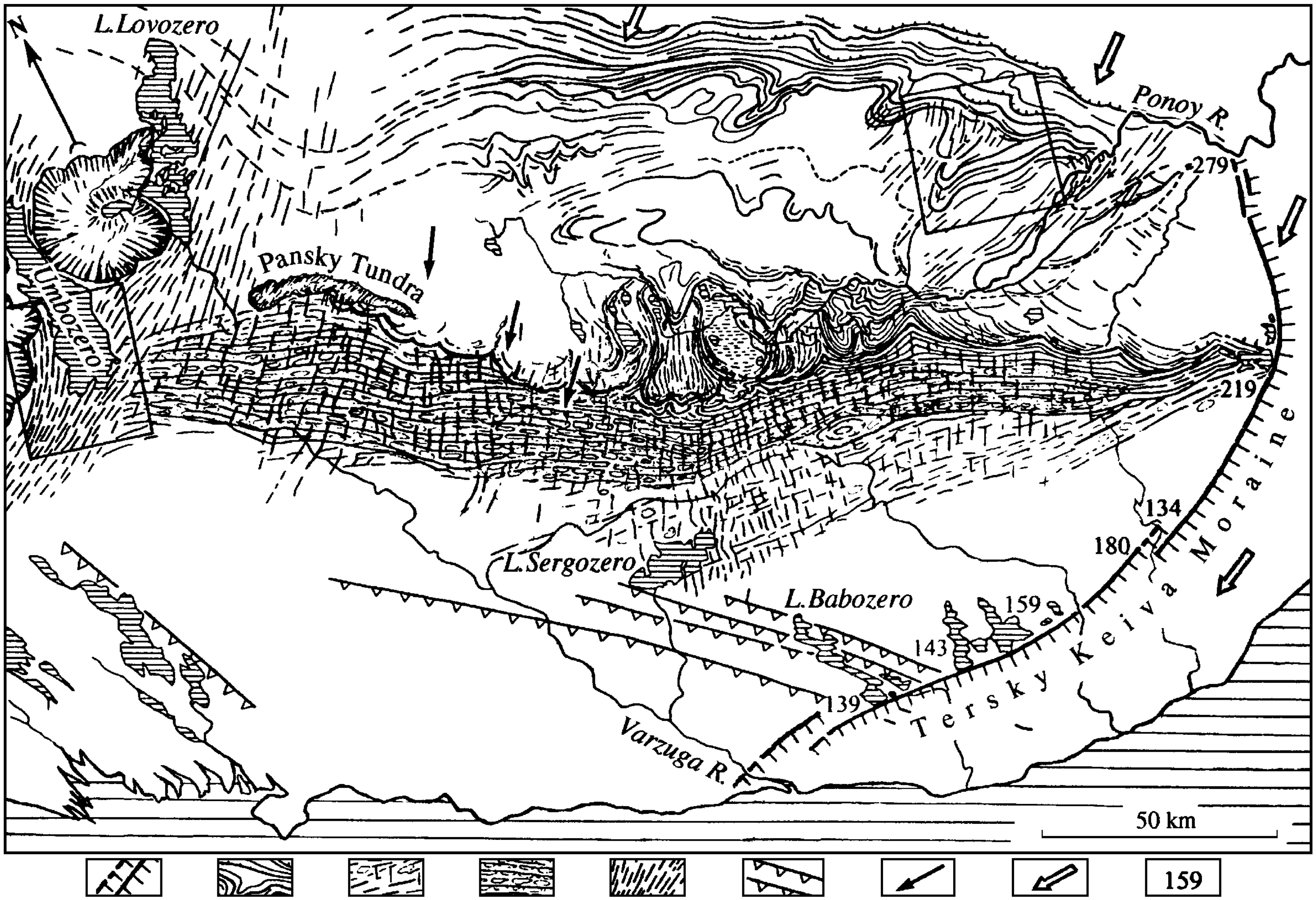

Figure 3. Second-order glacial geomorphology of Kola Peninsula [*Grosswald, Lapteva,* 2001]: 1 – lateral moraine of Tersky Keiva; 2 – moraines (partly ice-cored) of south-facing ice-marginal belts; 3, 4, and 5 – cataclysmic fluvial ridge-and-furrow complexes; 6 – lateral moraines and meltwater channels of the Kandalaksha outlet glacier; 7 – boulder trains directed southward; 8 – inferred direction of the youngest ice flow; 9 – elevations of the base of Tersky Keiva moraine. Rectangles indicate locations of Figures 4 and 5.

tions by *Biryukov et al.* [1988] and *Pavlidis et al.* [1997], in which ice flowlines diverge from the centers of their small ice caps.

Second-order Glacial Geology of Kola Peninsula

According to the QUEEN model, all end moraines, drumlins, eskers and paleo-lakes of mainland Russia east of the White Sea, including the Markhida Moraine of the lower Pechora catchment, belong not to the Late Weichselian formation as previously inferred [*Arkhipov et al.,* 1980; *Arslanov et al.,* 1987; *Grosswald et al.,* 1974; *Lavrov,* 1973, 1977], but to the Early and/or Middle Weichselian [*Astakhov et al.,* 1999; *Mangerud et al.,* 1999; *Svendsen et al.,* 1999]. The concept of an early, pre-Younger Dryas, deglaciation of the Barents-Kara shelf [*Landvik et al.,* 1998; *Vorren et al.,* 1988] is also an element of the model.

However, these interpretations are incompatible with second-order glacial geology in the Kola Peninsula-White Sea region. During the height of the Late Weichselian glaciation, the region was overrun by the Scandinavian Ice Sheet; but during deglaciation, when the ice sheet retreated, it was reinvaded by a surging ice-sheet that transgressed from the northeast. The inference on this reinvasion came as a result of field studies and remote sensing of the Kola glacial geology [*Grosswald,* 1996; *Grosswald and Lapteva,* 2001]. Nevertheless, the majority of the Quaternary scientists still believe that it was the Scandinavian Ice Sheet that produced all the region's prominent landforms both glacial and deglacial [*Ekman and Iljin,* 1991; *Lundqvist and Saarnisto,* 1995].

The evidence for NE-to-SW glacial surging into the White Sea and onto Kola Peninsula consists of end and lateral moraines with associated ice-thrust features, boulder trains, and meltwater channels, all superimposed unconformably upon first-order glacial landscapes produced by the Scandinavian Ice Sheet (Figures 3, 4). The end moraines, partly glaciotectonic in origin, partly made up of sands and silts, and often retaining ice cores, form two ice-marginal belts facing south and southwest. The lateral moraine – en echelon Tersky Keiva – delineates the right-hand margin of a big ice lobe that advanced into the White Sea from the northeast. Assemblages of parallel ridges and furrows (Figures 3, 5), similar to geomorphic traces of the Eurasian megafloods [*Baker,* 1997; *Grosswald,* 1998a], are also conspicuous in second-order geomorphology of the Kola Peninsula.

The ice mass that impinged upon the Kola Peninsula-White Sea region from the Barents Sea continental shelf was a thin slab (about 300 m thick) with a gently, by about 1/1000 (Figure 6), sloping surface [*Grosswald,* 1996], indicating a surging ice mass which was probably underlain by a pillow of water.

This ice transgression is well dated. The Kola Peninsula dating is more reliable than any other dating in Arctic Russia. This is for the following reasons.

(i) The landforms that document the glacial surging from the NE overlap the glaciated landscape created by the Late Weichselian Scandinavian Ice Sheet. Thus, all overlapping landforms originated during the last (not the Early and/or Middle Weichselian) deglaciation.

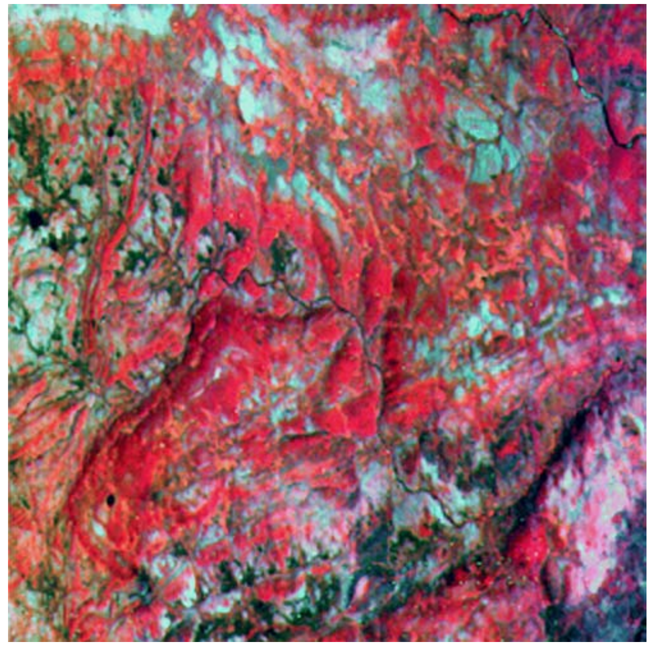

Figure 4. "Transparent" moraine loops in the Ponoy River basin. The loops are made up of silt and fine-grained sand, partly ice-cored. White arrows indicate orientation of the loops' axes. Fragment of a LANDSAT image, false colors. For location, see Figure 3.

(ii) Transgression of the Barents-Kara Ice Sheet took place after Scandinavian ice vacated the Kola Peninsula-White Sea region. Thus, in principle, the Barents-Kara moraines are datable here by their direct relationship to Scandinavian moraines, which have established ages. In particular, the Younger Dryas Salpausselka Moraine of Finland, which extends into the region via Karelia [*Ekman and Iljin,* 1991], can play the role of a critical benchmark in dating the invasion, as the age of Scandinavian moraines is determined not only by ^{14}C, but also by counting of varves, pollen analysis, and their relation to the paleo-Baltic terraces.

(iii) The ice lobe that entered the White Sea from the NE impounded the mouth of Severnaya Dvina River, creating a big ice-dammed lake in its valley. This lake was succeeded by another ice-dammed lake, which formed in the White Sea depression during the ice lobe's retreat. The sediment infills of these lakes formed synchronously with the corresponding ice invasion. Therefore dating of the lacustrine beds would yield the age of that glacial event. These beds were rich in pollen and other plant remains, so that the dating results could be compared with and verified by paleobotanical data. The age of the glacial surge from the NE is definitely post-Younger Dryas, or Early Holocene [*Grosswald,* 1996, 1998a]. This interpretation is supported by the following evidence:

(i) a cross-cutting relationship between the Tersky Keiva moraine (delimiting the surging ice lobe) and the lateral formations built by the Kandalaksha lobe of the Younger Dryas Scandinavian Ice Sheet correlated with the Salpausselka-2 Moraine of Finland. The Tersky Keiva moraine overlaps the

Figure 5. Scabland landscape south of Lake Umbozero. A piece of evidence for Kola megafloods. Fragment of a space image. Courtesy of the Russian Geological Survey. For location, see Figure 3.

formations [*Grosswald,* 1998a], hence it was built at or after 10.5 kyr BP;

(ii) the upper lacustrine beds deposited in the Severnaya Dvina ice-dammed lake are found, in the Vychegda Valley, to be underlain by a peat bog with the Younger Dryas pollen spectra and ^{14}C ages of 10.4–10.5 kyr BP and, near the Severnaya Dvina mouth, by a till sheet with crushed logs dating to 10.2–9.8 kyr BP [*Arslanov et al.,* 1984, 1987; *Grosswald et al.,* 1974];

(iii) a 25-m thick sequence of silt and fine sand beds that formed in a fresh- and brackish-water basin of the ice-dammed White Sea was found to overlay glaciated bedrock and to incorporate the Early Holocene pollen, spore, and diatom complexes, which are in turn overlain by the Middle Holocene marine deposits [*Voskresenskaya and Sobolev,* 1998].

Hence, a surging ice mass advanced upon the Kola Peninsula-White Sea region from the Barents-Kara continental shelf, and that this glacial event occurred immediately after 10 kyr BP. The event was coeval with the Pleistocene-to-Holocene transition, the time of abrupt climate warming. In Greenland, it was marked by a sudden 15–20°C temperature rise and a twofold increase in snowfall [*Alley et al.,* 1993; *Johnsen et al.,* 1995]. This change was favorable for collapsing of ice-sheets, especially of the Kara ice dome, which was marine and thus inherently unstable [*Hughes,* 1998; *Weertman,* 1974].

As evidenced by remote sensing, this ice-surging event was

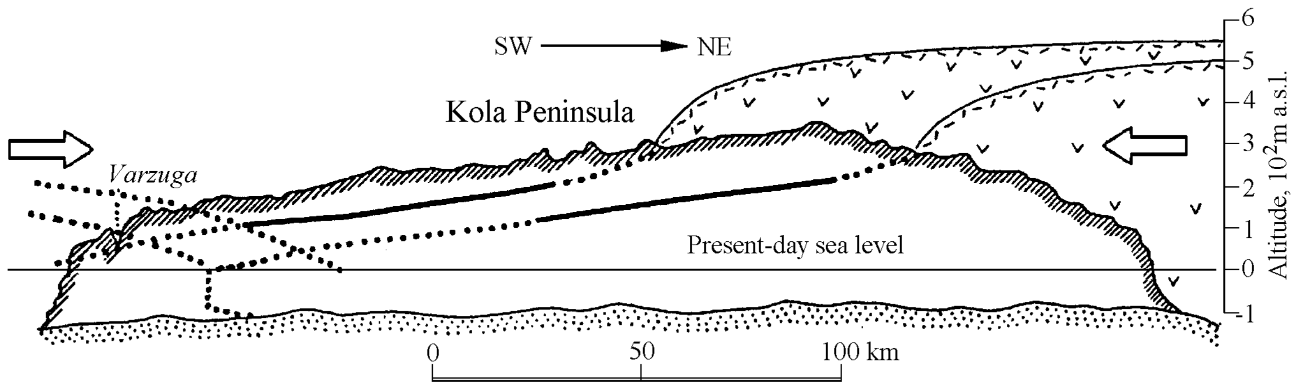

Figure 6. Long profile of the Tersky Keiva lateral moraines (bold lines) and their reconstructed continuations (dotted lines) between Ponoy River and Varzuga River. On the left, the Tersky Keiva moraine overlaps a lateral moraine of the Kandalaksha outlet glacier of the Scandinavian Ice Sheet. Note that the Tersky Keiva moraine is inclined in the NE-to-SW direction. Also note that the ice lobe was very thin, and its slope was extremely gentle.

coupled with a cataclysmic westward and southward flooding. Based on the above timing, we hypothesized [*Grosswald and Lapteva,* 2001], that the Kola megafloods, moving southward, would have cascaded into the Baltic Ice Lake, contributing to its catastrophic outburst at Billingen.

Obviously, these interpretations conflict with the QUEEN and "restricted glaciation" models. According to the QUEEN model, the Barents Sea continental shelf was ice free by about 12 kyr BP, while the Kara Sea shelf did not support any ice sheet even at the LGM, let alone during the Early Holocene. By contrast, the maximum model of the Barents-Kara Ice Sheet provides a source of ice for the young glacial advance upon the Kola Peninsula-White Sea region. Based on the geomorphology of northern Siberia and modeling experiments, we argued that the Kara Sea ice dome was among the longest-lived elements of the whole Arctic Ice Sheet, being the last to disappear in Arctic Russia [*Fastook and Hughes,* 1991; *Grosswald,* 1998a].

Implications of the Preboreal Kara ice Dome Collapse

Figure 7 is a sketch map of a residual Kara ice dome immediately after its collapse of about 10 kyr BP. This reconstruction is constrained by the facts (i) that the surging ice transgressed upon the Kola Peninsula-White Sea region, and (ii) that it crossed the barrier of Novaya Zemlya and Vaygach Island from the east. The conspicuous feature is the ice-spreading center located on the Kara Sea. Any other location is inconsistent with ice-flow indicators across the Kara-Barents divide and with second-order glacial landforms on Kola Peninsula. Another prominent feature is the ice margins, which are thrust up onto the coastal zones of mainland Eurasia. Obviously, the ice margins could not be placed in a different position, because they were predetermined by the dynamics and geometry of the collapsing ice sheet. When surging toward Kola Peninsula and the White Sea, the Kara ice dome, had to simultaneously, i.e., after 10 kyr BP, transgress upon the Pechora River catchment, northern West Siberia, and Taimyr Peninsula. Being coeval with the youngest Kola moraines, these ice margins had to be of the Early Holocene age also, which is a vital part of our model [*Grosswald,* 1998a; *Grosswald and Hughes,* 1995, 2002; *Hughes,* 1998].

The limit of ice expansion in Figure 7 coincides with a moraine belt, which was indicated in my previous papers as either a "Middle", or "Late-Glacial" moraine, and assigned the radiocarbon age of about 10 kyr BP. In NE European Russia, conspicuous elements of this belt are the Mid-Pechoran, Laya-Adzva, and Rogovaya moraine loops, while in Siberia their continuation is represented first by complex Salekhard and Yenisey moraine lobes, and second by a lobate Mokoritto Moraine of Taimyr Peninsula.

The "10 kyr BP moraine" is used here as a benchmark. Given that in concentric moraine systems the outermost moraine is always the oldest and the innermost one is the youngest, a prediction is justified that, in west-central Arctic Russia, all moraines located to the south of that "benchmark moraine" are older than 10 kyr BP, while all moraines located to the north of it are younger than 10 kyr BP.

Among other things, this explains the problematic Markhida Moraine of the lower Pechora River (Figure 8), which was discovered and sampled by A. S. Lavrov, ^{14}C-dated by K. A. Arslanov, and interpreted as evidence for a surge of the Barents Sea ice sheet, named "the Markhida Stage" [*Arslanov et al.,* 1987; *Grosswald et al.,* 1974; *Lavrov,* 1977, 1981]. Based on radiocarbon ages of lacustrine sediments underlying the Markhida till, this surge was inferred to have occurred at about 8.5 kyr BP. We keep sticking to this age for the following reasons:

(i) the Markhida Moraine lies north of the above "benchmark moraine", thus it must be younger than 10 kyr BP;

(ii) recent 14C-dating of the moraine, undertaken by *Tveranger et al.* [1995] twenty years after the dating by Arslanov, yielded ages of 8.69 kyr BP and 8.64 kyr BP;

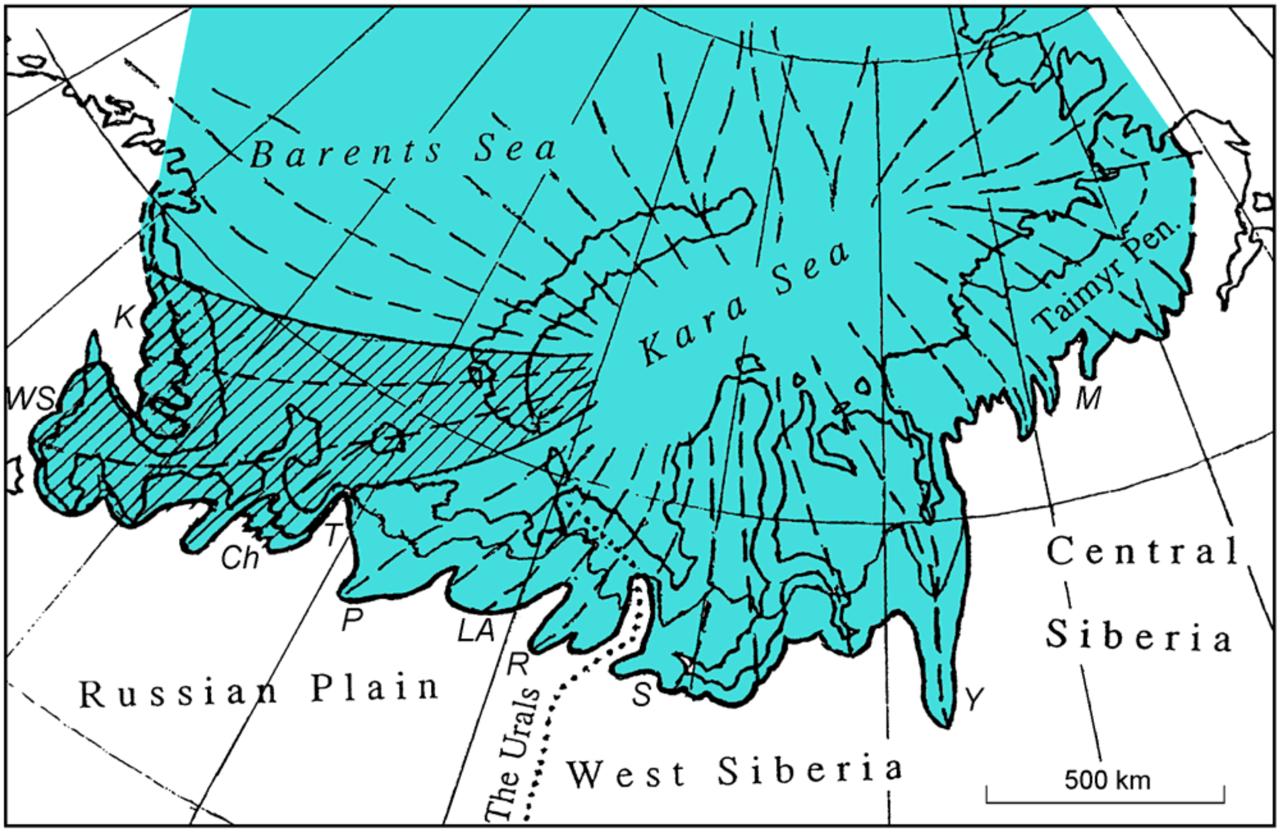

Figure 7. The Barents-Kara Ice Sheet following the Post-Younger Dryas (≤10 kyr BP) collapse of the residual Kara ice dome. The shaded sector is the portion of the collapsing ice dome that transgressed onto the Kola-White Sea region. Lettering: K – Kola Peninsula; WS – the White Sea; Ch – ice lobe of Chesha Guba; T – Timan Mountains; P – Pechora ice lobe; LA – Laya-Adzva ice lobe; R – Rogovaya ice lobe; S – ice lobe of Salekhard Uvaly; Y – Yenisey ice lobe, and M – Mokorittan lobate moraine.

(iii) the Markhida Moraine consists mostly of flow till, and was probably built by a thin ice sheet with a gently sloping surface [*Tveranger et al.,* 1995, 1999].

These facts suggest that our interpretation, which connects the moraine with a glacial surge, is correct. Indeed, in all regions with a history of great glacial surges, e.g., in North America, covers of flow-till prevail over other types of surface sediments [*Clayton et al.,* 1985], whereas a "flat, mobile and less than 200 m thick" ice sheet, like the one reconstructed by *Tveranger et al.* [1999] for the Kara Sea-Pechora Gulf area and inconsistent with an equilibrium ice dome, is typical of the dome that just experienced a gravitational collapse [*Hughes,* 1998].

Another moraine belt situated north of the "benchmark moraine" is the North Taimyr, or "Isayeva Line" moraine. Judging by its position relative to the "benchmark" Mokoritto Moraine, it is younger than 10 kyr BP. Its young age is also confirmed by radiocarbon dating – 20 kyr BP on a shell from inside the till and several dates of around 9.5 kyr BP on "plant material deposited in connection with deglaciation" [*Svendsen et al.,* 1999]. A correlation of the North Taimyr moraine with the Markhida Stage was often assumed [*Grosswald,* 1983; *Kind and Leonov,* 1982].

The QUEEN concept of the Markhida and North Taimyr moraines is different. The Markhida Moraine is "promoted" to a high-order ice-marginal formation and, despite its relatively small size, defined as a marker of the Middle Weichselian glacial maximum and assigned the age of 45 to 60 kyr BP [*Astakhov et al.,* 1999; *Larsen et al.,* 1999]. As for the North Taimyr moraine, it is assumed to represent a limit of the Late Weichselian glacial maximum. For the rest of the Taimyr moraine belts, including the Mokoritto "benchmark moraine", Early to Middle Weichselian ages are tentatively suggested, although a Late Saalian age is recognized as a possible alternative [*Möller et al.,* 1999].

Context of Continental Paleohydrology

According to the QUEEN model, the southern limit of the last Barents-Kara ice sheet, from the White Sea to Taimyr Peninsula, was located offshore of the Russian mainland, and was unable to interfere with the northward drainage of the Eurasian rivers [*Gataullin and Polyak,* 2000; *Svendsen et al.,* 1999]. However, there is inarguable evidence that the

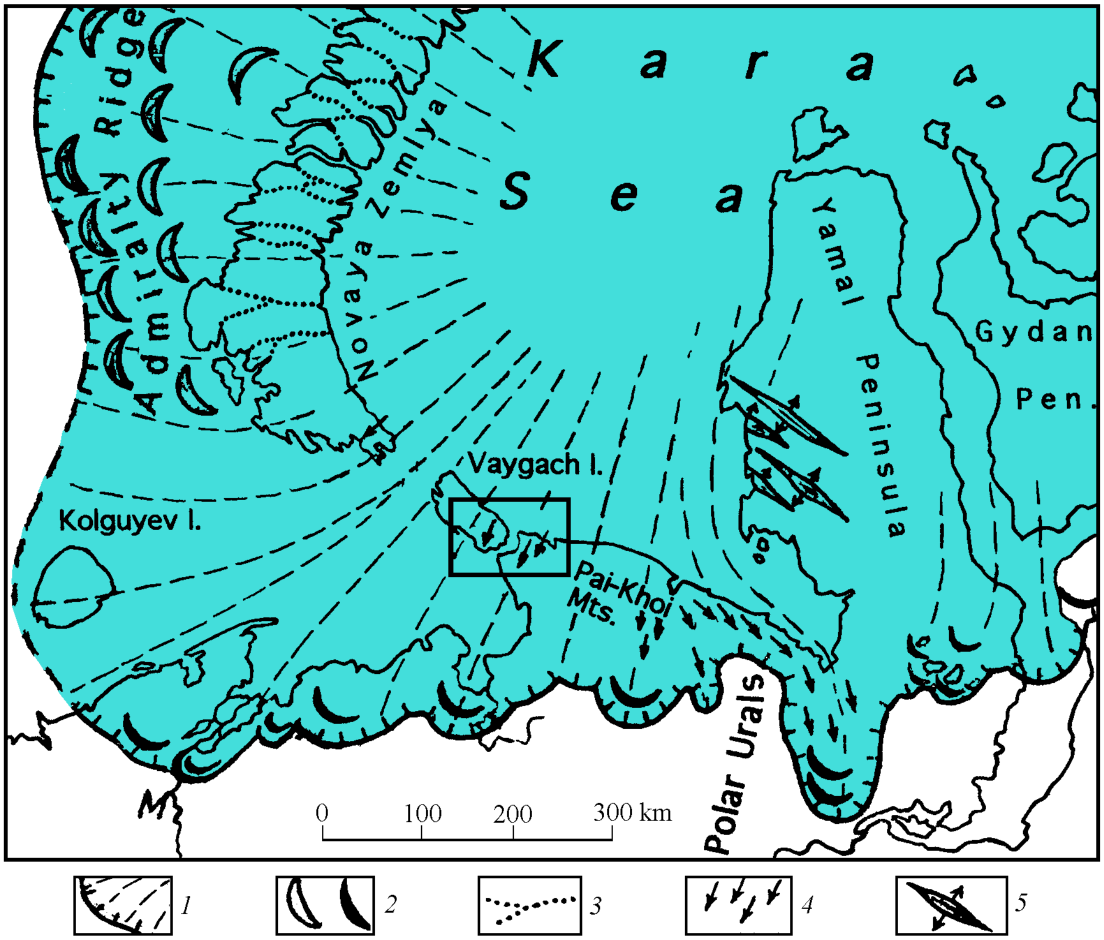

Figure 8. Extent of the Barents-Kara Ice Sheet following the Markhida-time collapse of a residual Kara ice dome at about 8.5 kyr BP: 1 – ice margin; 2 – moraine ridges, submarine (left) and terrestrial (right); 3 – glaciated through valleys; 4 – streamlined ice flow directional indicators; 5 – large glaciotectonic features. The Markhida Site is marked by M.

Barents-Kara ice sheet had a strong impact on the hydrological system of Eurasia. One of the pieces was formation of the Trans-Siberian drainage system, consisting of great meltwater lakes, Urstromtaler or pradolinas, and spillways. During the LGM, the system extended from the Verkhoyansky and Chersky Ranges in the east to the Caspian and Black Seas in the west, with meltwater runoff routed into the eastern Mediterranean Sea. The existence of this LGM meltwater drainage system, its latitudinal orientation, the locations of paleo-lakes, spacing and ages of the spillways, make it obvious that, during the Late Weichselian, all north-flowing rivers were glacially impounded and diverted. This strengthens the case for an extensive and continuous Barents-Kara Ice Sheet [*Grosswald,* 1983, 1998b; *Hughes,* 1998].

Another continental-scale paleohydrological phenomenon, the cataclysmic megafloods dated to 10 kyr BP and 12.2 kyr BP, would have remained inexplicable unless a continuous ice dam had formed on the Arctic continental margin during the last glaciation [*Grosswald,* 1999].

Interactions between the polar ice sheets and the paleohydrology of Eurasia were too complex to be all considered in this paper. Therefore I focus only on the causes and chronology of the Late Weichselian Caspian Sea transgressions, the episodes of major sea-lever rise – the Early ("Great") and the Late Khvalyn transgressions. During the first transgression, the level of the Caspian Sea rose by 76 m to 50 m asl (above sea level), its area expanded to a million square kilometers, and the Caspian water flowed via Manych Spillway into the Black Sea [*Svitoch et al.,* 1998]. This is confirmed by studies of the cores recovered by drilling in the central Strait of Bosp horus [*Tshepalyga,* 2000b]. During the second Khvalyn transgression, the Caspian Sea rose only by 26 m, and no discharge of the Caspian water was established [*Svitoch et al.,* 1998; *Tshepalyga,* 2000a].

Additional information on the timing and origin of these transgressions comes from the age of the Early Khvalyn transgression, which definitely postdated the LGM and was coincident with the first half of the last deglaciation, and from the age of the Late Khvalyn transgression which turned out much younger, although its ^{14}C dates display a scatter

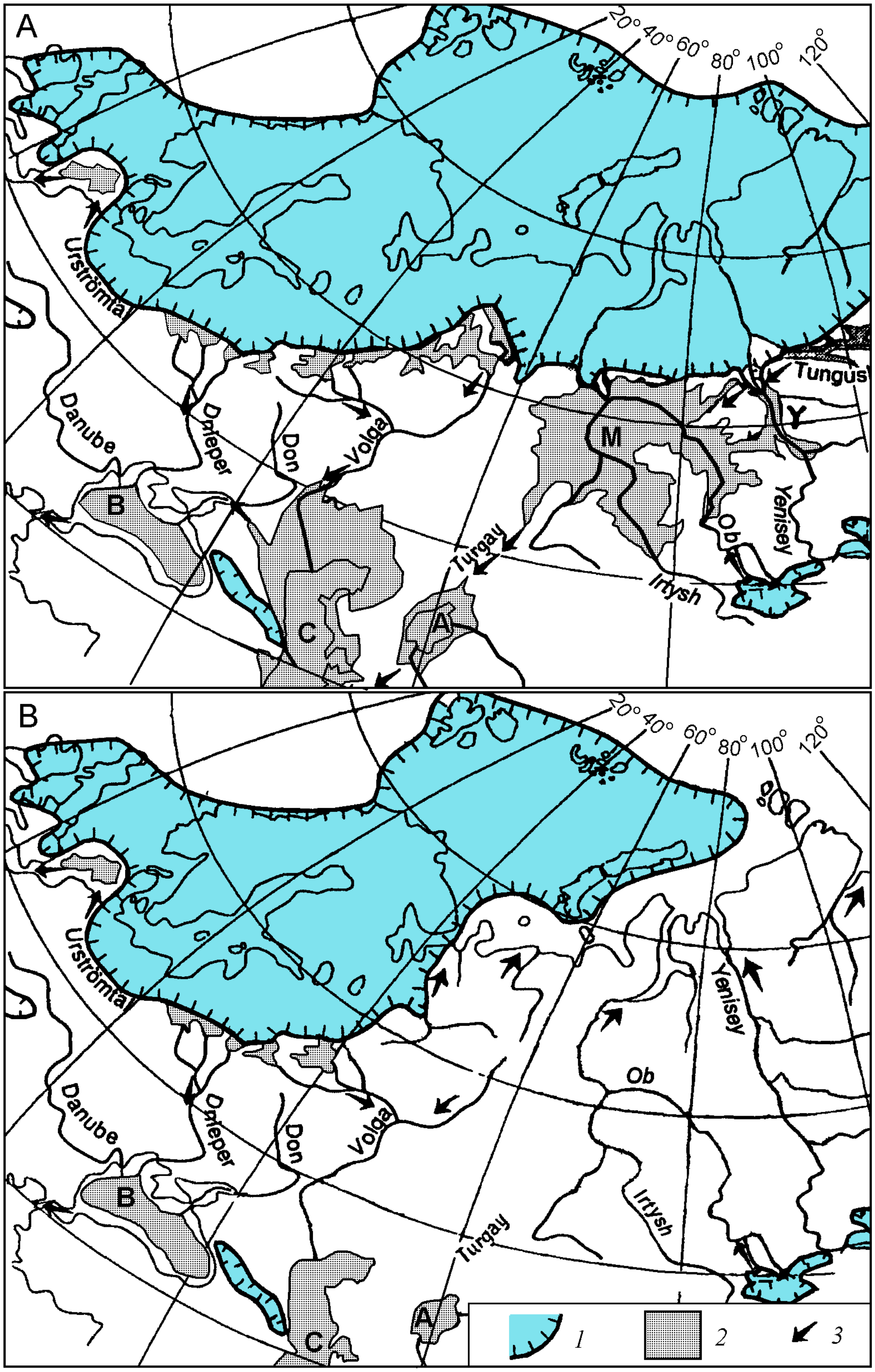

Figure 9. Paleohydrology of west-central northern Eurasia during the Late Weichselian glaciation, (A) controlled by an extensive and continuous Barents-Kara Ice Sheet and (B) simultaneous with a smaller Barents-Kara Ice Sheet predicted by the QUEEN model. Note the importance of whether or not the Pechora, Ob, and Yenisey Rivers were ice-dammed to distinguish between the two models: 1 – ice margin; 2 – ice-dammed lakes and other intracontinental basins; 3 – directions of water flow. Lettering: B – Black Sea, C – Caspian Sea, A – Aral Sea, and M – paleo-Lake Mansi.

of a few thousand years, the transgression is thought to be coeval with the Pleistocene-to-Holocene transition [*Svitoch et al.,* 1998]. *Tshepalyga* [2000a] bracketed the age between 10 and 9 kyr BP.

New insight into the nature of the Caspian transgressions is gained by climatologists. They prove that the events cannot be accounted for by changes in the precipitation/evaporation balance of the Caspian catchment, as was previously thought, and demonstrate that changing water balance explains only short-term fluctuations of 2–3 m in the Caspian-Sea level [*Kislov and Surkova,* 1996; *Meleshko et al.,* 1998]. This suggests that the major transgressions required massive water inflows from outside. As there is no other source imaginable for these inflows except glacial meltwater from the Arctic, and no other mechanism of its routing into the Caspian Sea except by ice-damming of the north-flowing rivers and their southward deflection, the transgressions had to be coupled with a continuous ice sheet across northern Eurasia.

It should be also noted that, given the topography of European Russia, only an ice margin rising to 130–150 m asl is able to dam the north-flowing rivers and cause southward runoff into the Caspian Sea, since any lower ice dam would have let the meltwater drain to the west, not to the south [*Grosswald,* 1998a]. Finally, the water flowing into the Black Sea and the Bosp horus was isotopically light, characterized by δ^{18}O of five to nine per mille, which suggested that this water had been "drained from glacial and periglacial environments" [*Tshepalyga,* 2000a, 2000b].

This discussion is summarized in Figure 9, which strongly suggests that the Late Weichselian river-damming had been produced by a continuous Barents-Kara Ice Sheet. In order to divert both the Ob and Yenisey Rivers, the ice dam was to reach at least as far east as Taimyr Peninsula. These phenomena could not be brought about by the QUEEN ice sheet, let alone by disconnected ice caps of the "restricted glaciation". The only sensible explanation of the Caspian transgressions are provided by the model of a continuous Barents-Kara Ice Sheet, while the transgressions in turn confirm that the ice sheet was continuous and Late Weichselian in age.

Hence, it is easy to see that a long-lived and fully developed Early Khvalyn transgression was caused by a near-equilibrium LGM ice sheet, while the short-lived and less extensive Late Khvalyn event probably resulted from the damming by a residual Kara Sea ice dome, after it had collapsed and surged (see Figure 7). It is noteworthy that both this Late Khvalyn transgression and the Kara ice-dome collapse occurred simultaneously, taking place between 10 and 9 kyr BP.

Context of Late Weichselian paleoclimate

Comparison of the "restricted glaciation" and QUEEN models with a variety of climate-based ("top-down") reconstructions of the Northern Hemisphere's ice sheets, such as the ones by *Fastook and Hughes* [1991], *Verbitsky and Oglesby* [1992], and *Budd et al.* [1998], shows that they contradict each other. By contrast, our "bottom-up" (based on glacial geology) reconstruction of the Barents-Kara Ice Sheet [*Grosswald and Hughes,* 1995, 2002; *Hughes,* 1998] and the results of computer simulations by *Budd et al.* [1998], using an ice sheet model linked to an energy-balance climate model, look like twins. Other top-down modeling invariably yields similar results, no matter who does it, whether impartial mathematicians or the QUEEN program members themselves. For instance, of six simulations of the last glaciation by *Huybrechts and T'siobel* [1997], all six yielded a continuous ice sheet over the entire Barents-Kara continental shelf. Similarly, modeling experiments by the QUEEN program members also produced a continuous ice sheet on that shelf [*Siegert et al.,* 1999; *Svendsen et al.,* 1999].

A test for the extent of glaciation by using simple physical notions was also conducted. To this end, the lowering of the Arctic ELA (equilibrium-line altitude) during Late Weichselian time was estimated, and the probable impact of this lowering on the extent of polar glaciation evaluated. The ELA, separating accumulation and ablation zones on the surface of alpine glaciers and ice sheets, depends linearly on mean air temperature T, and the δT/δELA is about 0.6°C per 100 m of ELA change, the ratio which is broadly used by paleogeographers [e.g., *Lowe and Walker,* 1997]. The actual rate of the Late Weichselian ELA lowering can be calculated based on paleotemperatures from ice cores, e.g., from the Greenland Ice Sheet drilling. The peak LGM cooling in Greenland amounted to about 25°C, and over an interval from 75 to 10 kyr BP the average temperature lowering was about 15°C [*Johnsen et al.,* 1995; *Jouzel,* 1999]. Consequently, the Late Weichselian depression of ELA in Greenland had to be on the order of 2.0–2.5 km.

The top of the Greenland Ice Sheet retained both its interglacial altitude and perennial snow cover, so it did not amplify the climatic cooling. One can assume that a commensurate ELA depression was characteristic of the rest of the Arctic, even if climate-forming processes were somewhat different beyond Greenland. Indeed, as suggested by an atmosphere-mixed layer ocean model simulation, the LGM cooling over the region was only slightly less pronounced [*Broccoli,* 2000].

As a consequence of 2.0–2.5-km ELA lowering, the entire Arctic Ocean would become a continuous area of ice accumulation. In this respect, it would be like Antarctica. However, unlike Antarctica, it was confined by the circum-Arctic continents, so that the ice input into the Arctic ice-accumulation basin would not be counter-balanced by ice export into the adjacent oceans. Thus the ice would be building up in the Arctic Ocean over a long period [*Grosswald and Hughes,* 1999; *Hughes,* 1998].

The ensuing environmental changes are easy to envisage. If, as predicted by the mass balance calculations, ice in the Arctic Ocean thickened at a rate of 1 km per 5000 years [*Grosswald,* 2001], then it must have expanded and pushed outward to fill every ice-free gap on its periphery, and the circumpolar continental shelves would have been the first areas to have been overrun. So from a paleoclimatic standpoint, it is improbable that any portion of that shelf remained ice-free during the Late Weichselian. Moreover, on reaching a certain threshold, the thickening floating ice would transgress far to the south of the continental shelves and coastal lowlands, following the scenario predicted by the marine ice transgression hypothesis [*Hughes,* 1986, 1998].

Thus, clearly, the "restricted glaciation" and the QUEEN models are inconsistent with the established cooling of the Arctic and the inferred drop in the Arctic ELA. For instance, whatever the ^{14}C dates on mammoth bones from Severnaya Zemlya, they do not prove that, during the LGM, the local glaciers were no larger (or even smaller) than today, or that these animals were living on the islands at the LGM, as believed by *Svendsen et al.* [1999]. Neither this favorite argument of minimalists [*Bolshiyanov and Makeyev,* 1995; *Makeyev et al.,* 1979], nor the claim of *Serebryanny and Malyasova* [1998] that the last glaciation of Novaya Zemlya was "no more extensive than nowadays", could make sense unless one assumes that Late Weichselian climate of the Arctic was warmer, not colder, than today. Small ice caps of "restricted glaciation" models [*Biryukov et al.,* 1988] are also inconsistent with the paleoclimate, as they imply only a 300–500-m range of the ELA lowering.

A hypothesis of "diachronous glaciation" is also climatically weak. The QUEEN model suggests that the Weichselian ice sheets of Arctic Russia peaked well before 40 kyr BP, out of phase with the global glacial maximum of 18 kyr BP, and a precipitation shadow effect of the Scandinavian Ice Sheet is invoked to account for this non-synchronism [*Möller et al.,* 1999]. However, this non-synchronism looks like an artifact of erroneous dating (see below), and explaining it by the "precipitation shadow" is inconsistent with the ice-age atmosphere circulation over the Northern Hemisphere [*CLIMAP Project Members,* 1981; *Kutzbach and Wright,* 1985]. In Eurasia, the ice-age storm tracks shifted some 20° equatorward relative to the "interglacial" tracks and, instead of crossing the major ice sheets, they proceeded south of them, giving rise to snowfall by unimpeded SE cyclonic winds.

Context of West Siberian Geothermometry

The Late Weichselian climate cooling was to imprint upon the Siberian permafrost. In West Siberia with its flat topography and thick sequence of non-lithified water-saturated rocks, the cooling was recorded by both ground temperature lowering and downward shift of the lower "phase boundary", and the subsequent warming – by restoration of the interglacial geothermal conditions. This restoration is a gradual, retarded process, so that, depending on depth and thermophysical properties of the rocks, some information ("memory") on the previous cooling would be preserved and discernible in geothermal curves.

Today, there are hundreds of thermograms, heat flux records and other measurements from deep drill-holes across the Siberian lowlands. Based on geothermal curves from the holes, *Balobayev* [2000] accomplished a reconstruction of the Sartan (Late Weichselian) paleo-permafrost parameters for some 20 sites in West Siberia. This reconstruction demonstrates that a considerable warming has occurred in the region over the last 18,000 year resulting in a considerable degradation of the permafrost. What is particularly notable, this whole process was strikingly different in southern and northern zones: in the first zone, south of the Polar Circle, range of warming was 8–12°C and that of permafrost thinning – 100 to 170 m, while in the second zone, north of the Circle, the temperature rise was either restricted to 1–5°C or, like on Yamal Peninsula, did not occur at all.

Thus, some 18,000 yr ago, the sedimentary rocks blanketing the vast flat lowland were much warmer in the north than in the south. To account for this abnormal paleogeography, *Balobayev* [2000] could not find any alternative to the hypothesis that, during the last (Late Weichselian) glacial maximum, the entire zone north of the Polar Circle was overlain, and thermally insulated, by a rather thick ice sheet. It is needless to say, that this hypothesis goes along perfectly well with this author's glaciation model.

The Context of Timing

The QUEEN reconstruction resulted from a field program focused on collecting and processing datable samples. When the program members refer to "field geological evidence", only ^{14}C dates are meant. More specifically, their arguments are as follows:

(i) scores of dates in the range of 35 to 12 kyr BP, from the sediments overlying the upper till in northern West Siberia and the Pechora Lowland, including peat bogs dated to 32 through 40 kyr BP [*Astakhov,* 1992; *Astakhov et al.,* 1999; *Mangerud et al.,* 1999]. Based on these, they inferred that these regions had been ice-free during the Late Weichselian, northward drainage of rivers had not been impeded [*Svendsen et al.,* 1999], and the latest ice-dammed lakes of the Pechora, Ob and Yenisey basins had been of the Middle and/or Early Weichselian age;

(ii) sets of dates on sediment cores from the Barents and Kara Seas that led QUEEN marine geologists to infer that the southern margin of the last Barents-Kara ice sheet had not reached the mainland of Eurasia [*Gataullin and Polyak,* 2000; *Knies et al.,* 1999];

(iii) dates on marine organics from the Barents Sea floor that had led to the concept of an early, pre-Younger Dryas, deglaciation of the sea [*Landvik et al.,* 1998; *Vorren et al.,* 1988];

(iv) reconsidered age of the Markhida Moraine made *Larsen et al.* [1999]. *Mangerud et al.* [1999] believe that the corresponding ice margin was much older than the 8.5 kyr-age inferred by *Grosswald* [1983], and that it had formed within the interval of 45–60 kyr. In this context, the age of a Lake Komi, dammed by the Markhida ice, was bracketed between 55 and 80 kyr BP [*Astakhov et al.,* 1999];

(v) ^{14}C dates from the marine terraces of Severnaya Zemlya, raised up to 120 m asl and revealing ages between 21 and >50 kyr BP, gave rise to an inference that the dates had recorded the crustal rebound following the Early or Middle Weichselian glaciation [*Bolshiyanov and Makeyev,* 1995]. This led to a speculation that the Late Weichselian ice load on the Kara Sea and Taimyr Peninsula had been negligibly small [e.g, *Möller et al.,* 1999]. No wonder, isostasy-based models relying on post-glacial relative sea level changes, predict little or no ice on the continental shelf of the Kara

Sea [*Forman et al.,* 1995; *Lambeck,* 1996; *Tushingham and Peltier,* 1991];

(vi) some ages of sediments in a few sites of the central and southern Taimyr Peninsula, in particular in Lake Lama, Lake Levinson-Lessing, and Ledyanaya Delta (west of Lake Taimyr), suggested that this area had been ice free during the last 40 to 60 thousand years [*Bolshiyanov and Hubberten,* 1996; *Melles et al.,* 1996, 1997; *Möller et al.,* 1999]. As all attempts to date the lacustrine beds by ^{14}C and pollen stratigraphy failed, the dating was conducted by extrapolating present-day rates of lake sedimentation downward, so the ages of 30 to 50–60 kyr for the drill-hole bottoms appeared;

(vii) chronology of the paleo-Lake Taimyr at the Cape Sabler site was particularly important. This 25 m thick sequence consisting of laminated to massive silt, rich in organic detritus (moss, twigs, seeds, and leaves), was first located by Isayeva and dated by Sulerzhitsky [*Kind and Leonov,* 1982]. After it was re-studied by the QUEEN members, an inference was reached that the sequence attested to a continuous, undisturbed lacustrine sedimentation in the central Taimyr Peninsula from 39 kyr BP into the Holocene [*Melles et al.,* 1997; *Möller et al.,* 1999], and that Late Weichselian glaciation had not occurred in this region. A ice-free long period was suggested, resulting in deep soil weathering, slope development, and fluvial incision [*Melles et al.,* 1997];

(viii) trump argument of minimalists consisting of ^{14}C-dates on mammoth bones from Severnaya Zemlya, some of which yielded the ages of 25 to 19 kyr BP. The finds were first made by *Makeyev et al.* [1979], *Bolshiyanov and Makeyev* [1995], and then extensively used by other advocates of "restricted glaciation". *Svendsen et al.* [1999] also agree with Makeyev's interpretation that "[these] imply that when the dated animals were living, the local glaciers on these islands were no larger than they are today. In fact, some bones were found so close to the present-day glaciers that it suggests the glaciers may have been smaller than today."

Discussion

Two Approaches to Glacial Chronology

To many, the QUEEN model and its chronology appear convincing. Nevertheless, there are two points to note. First, all the evidence just summarized depends, completely and solely, on ^{14}C dates. If these dates change, the whole model tumbles. Second, there are other sets of dates which were previously used by *Arkhipov et al.* [1973, 1980], Isayeva [*Kind and Leonov,* 1982], *Grosswald* [1980, 1983], *Goncharov* [1986], Lavrov [*Arslanov et al.,* 1987], as well as by Astakhov and Gataullin themselves, and clearly indicated to the Late Weichselian age of the Barents-Kara glaciation. These sets neither disappeared nor got refuted, they are simply ignored.

My approach to glacial chronology is different. Instead of exclusively relying on ^{14}C dates, I use correlations with independently dated events in glacial geomorphology, paleohydrology, ice-sheet dynamics, and in climate and environmental change. For instance, I pay special attention to reconciling our glacial chronology with the range and timing of the Arctic cooling, with lowering of the Arctic ELA, and with dated episodes of impoundment of Russia's north-flowing rivers and their re-routing into the Caspian Sea. These events recorded in north-Eurasian glacial geology (Figures 1, 10–12) appear inconsistent with the QUEEN glacial chronology. Additional inconsistencies in that chronology are listed below.

(i) The episode of a Kara ice- dome collapse recorded by the second-order glacial landforms on Kola Peninsula. The Kola dates are inconsistent with the ages inferred by the QUEEN for major moraines in west-central Arctic Russia, in particular, with the Early/Middle Weichselian age assumed for of the Laya-Adzva, Rogovaya, and Mokoritto moraines (which are ca. 10 kyr-old in our model), as well as with assignment of a 45–60 kyr age to the Markhida Moraine and Lake Komi.

(ii) The ages of lacustrine beds of Taimyr Peninsula obtained by extrapolating present-day rates of lake sedimentation into the past, which resulted in the inference that the central peninsula remained ice free throughout the last 40 to 60 kyr. This technique is justified only in case of uniform sedimentation proceeding under uniform climate and environmental conditions, which was not the case in Lake Lama, Lake Levinson-Lessing, and neighboring lakes. During Late Weichselian time, the lakes were buried by an ice sheet [*Isayeva and Kind,* 1986; *Kind and Leonov,* 1982], so their glacial, deglacial, and postglacial rates of sedimentation had to differ by orders of magnitude, rendering this part of the QUEEN chronology misleading.

(iii) The QUEEN Cape Sabler chronology is equally misleading. Although based on extensive studies yielding numerous ^{14}C dates, the QUEEN interpretation of the Cape Sabler section is strikingly incoherent. It assumes that Lake Taimyr's environment, even though located in juxtaposition to a large ice sheet, managed to remain uniformly lacustrine over a time span of about 30 kyr that included an interstadial, a high-glacial, and post-glacial intervals. For a geologist knowledgeable in impacts of climate upon sedimentation process, this kind of a steady-state near-glacial basin is all but impossible. By contrast, the stratigraphy based on a 10 kyr-old "benchmark" moraine provides a more realistic scenario. Whatever the QUEEN dates, the fact remains that the 25-m-thick Cape Sabler sequence would not start its formation before the Mokoritto ice lobes vacated that hollow, i.e, not before 10 kyr BP, and that lacustrine deposition would terminate as soon as the ice retreated from the "Isayeva Line", probably, at 8 to 7 kyr BP (Figure 10). Thus, a maximum time span of 2 to 3 kyr was available for undisturbed lake deposition at Cape Sabler, not a full 30,000 yr offered by the QUEEN model.

Many uncertainties would be resolved if the role played by Eurasian megafloods [*Grosswald,* 1999] were acknowledged. The megafloods were capable of destroying moraines, coastal terraces, till sheets, and bodies of interglacial deposits. They would rework freshly glaciated terrains into geomorphic landscapes having an appearance of the land affected by "long-lasting weathering, slope and fluvial processes" [*Melles et al.,* 1997]. The flood-scoured rocks would become scablands that look like deeply weathered surfaces.

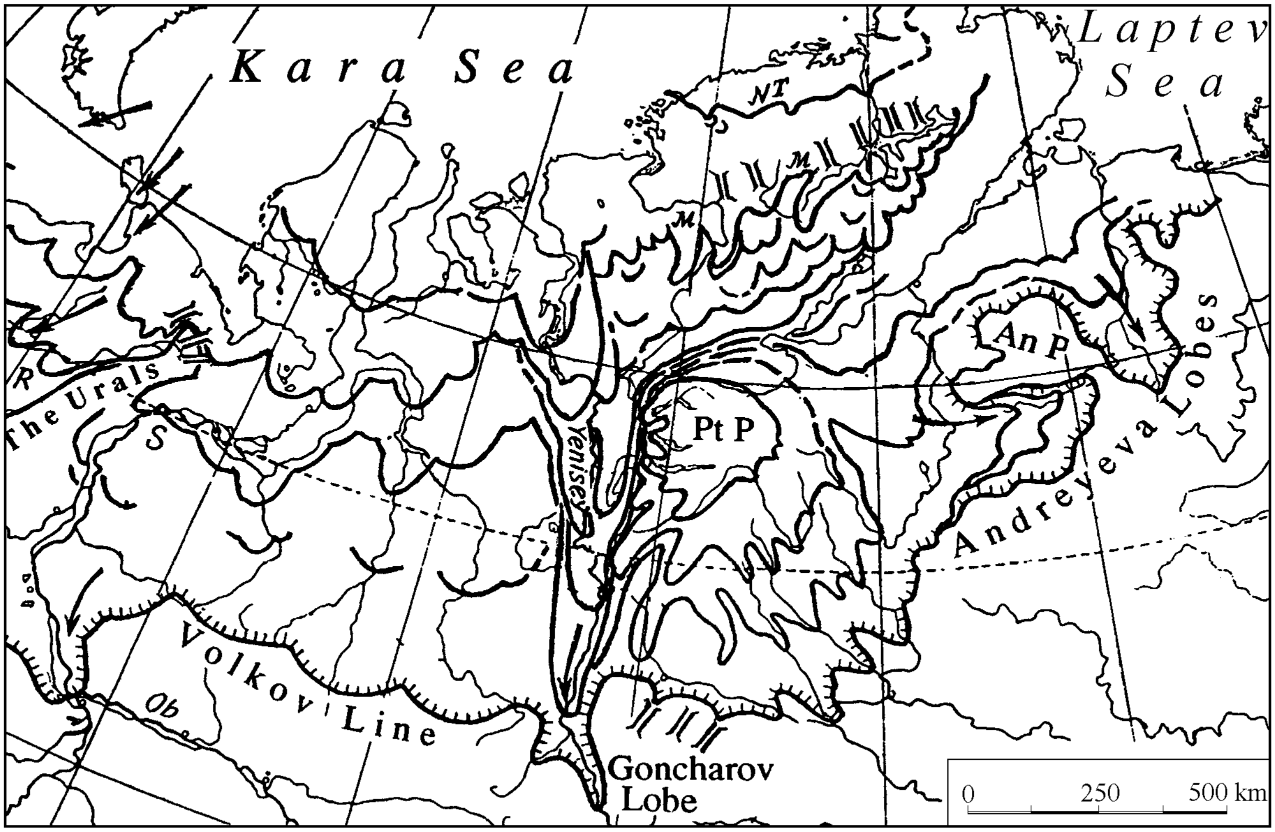

Figure 10. Late Weichselian end moraines in northern West and Central Siberia. New terms: "Volkov Line," as mapped by *Volkov* [1997]; "Goncharov Lobe," as surveyed by *Goncharov* [1986]; and "Andreyeva Lobes," as mapped by S. M. Andreyeva [*Andreyeva and Isayeva,* 1988]. Lettering: Pt P – Putorana Plateau, An P – Anabar Plateau, NT – North Taimyr moraine ("Isayeva Line"), M – lobate Mokorottan Moraine. Note that the Putorana glacier complex was assimilated by the Barents-Kara Ice Sheet during the LGM, and was subject to strong pressure by Kara ice throughout the late-glacial time.

Flood-reworked glacial deposits would look like products of prolonged fluvial action. The glacial landforms, whether superimposed upon a flood-scoured terrain or by-passed by flood streams, would appear much younger that those directly impacted by megafloods. This creates an illusion of great age difference between two groups of glacial landforms, which in fact is not the case. Some landforms, such as the Mokoritto moraine of Taimyr Peninsula and Khadutte moraine of the Taz Peninsula, though very young, have been flood-scoured to the ground, and only their roots, glacially distorted Cretaceous and Paleogenic beds, reveal their locations [*Arkhipov et al.,* 1980; *Kind and Leonov,* 1982].

Flood-scoured surfaces of known age can serve as markers for relative age determinations. For instance, judging by Figure 10 in *Astakhov et al.* [1999], the "Halmer moraine" of the Polar Ural foothills overlaps a ridge-and-furrow landscape produced by megaflooding (though called there "a surface heavily striated by an old ice flow from the NNE"). This relationship suggests its <10 kyr BP, age, not a Middle/Early Weichselian age assumed by Astakhov. Another example comes from the images of Central Siberia, displaying a piedmont of Putorana Plateau. This piedmont is clearly scoured by megafloods and overlapped by morainic lobes protruding out of troughs that are now partly occupied by lakes Lama, Keta, and Khantaiskoye. The youngest megafloods occurred 10 and 12.2 kyr ago [*Grosswald,* 1999], hence those morainic lobes are geologically young landforms, created after 10–12 kyr BP.

Thus, there are two approaches to dating glacial landforms of Arctic Russia: the one, which makes use of all known physical interrelations, glacial dynamics, and environmental transformations, and the QUEEN's approach, which doesn't.

Radiocarbon Dates

As demonstrated above, the "field geological data" which constrain ice limits in the QUEEN model are mostly sets of radiocarbon dates. So the whole model hinges on ^{14}C dates and, if the dates change, the model tumbles. On the other hand, dismiss the misleading dates – and all above inconsistencies disappear, all pieces in the Eurasian paleogeographic puzzle fall into place.

Today, Quaternary scientists come to understand limitations of the ^{14}C method. For example, the account of Late

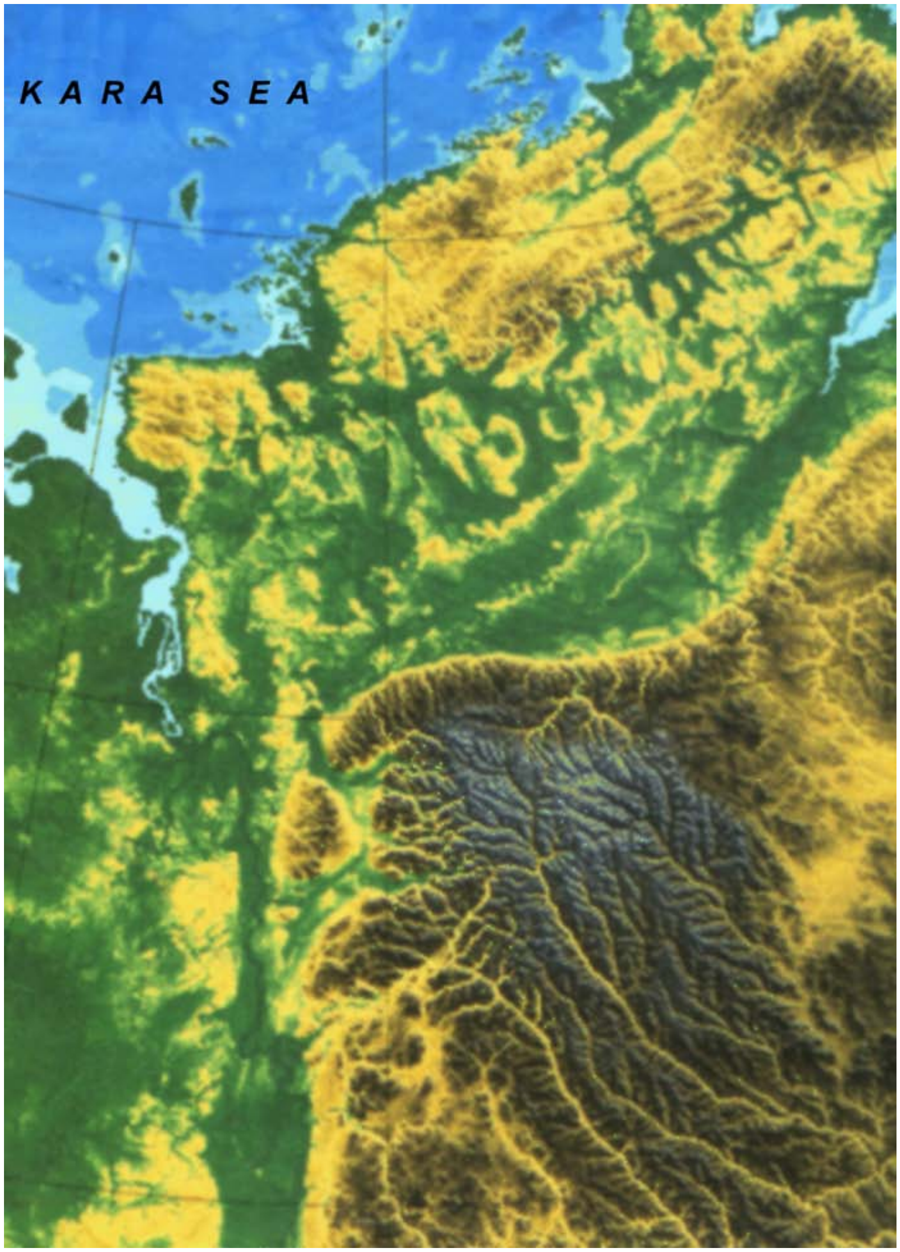

Figure 11. Shaded relief of Taimyr Peninsula and NW Central Siberia, a fragment of the "Shaded relief of the Arctic Ocean and adjacent continents", a map compiled by *Jakobsson* [2000]. Note end moraines and large fluvial features attesting to an ice sheet advancing from the Kara Sea, especially geomorphic evidence for the West Siberian, Yenisey, and West Taimyr (Pyasina) ice lobes.

Weichselian glaciation in Arctic Canada used to be confused and constantly changing, which was due to unreliable dates and poor stratigraphic control – until G. H. Denton weeded out the unreliable dates, so that a clear picture of the last glacial maximum and the subsequent deglaciation emerged [*Denton and Hughes,* 1981]. The QUEEN model may also be an artifact of erroneous dates, especially because Arctic Russia is particularly vulnerable to dating errors, which is for the following reasons:

(i) dating errors are inherent due to the peculiar position of northern Eurasia relative to the main ice divide of the Eurasian Ice Sheet. Unlike anywhere else on Earth, this ice divide extended north of and parallel to the present-day shoreline of continental mainland. For this reason, southward flow of the ice sheet affected parts of continental shelves and the zone of coastal terraces, coastal plains, and coastal uplands. In the course of this southward flow of ice, huge masses of Mesozoic, Tertiary, and interglacial Quaternary rocks, including brown coal, wood, marine organics and amber, were entrained, transported, and redeposited. With

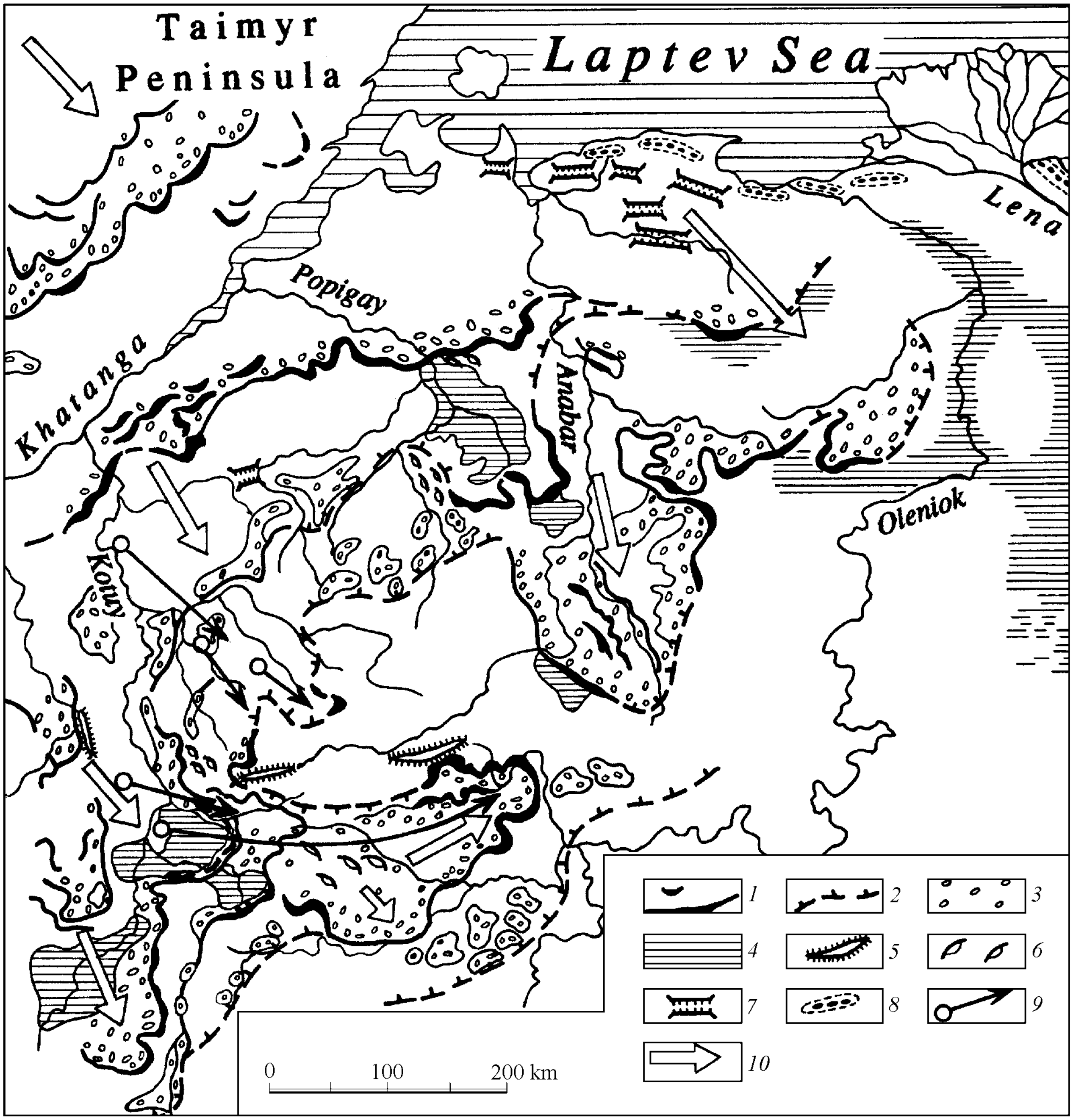

Figure 12. Glacial geomorphology in NE Central Siberia. After *Andreyeva and Isayeva* [1988]. Ice-marginal features (end moraines) outline two big surging lobes of the Late Weichselian Barents-Kara Ice Sheet: 1 – end moraines; 2 – inferred ice margins; 3 – areas of ridge-and-hill topography; 4 – glacial paleo-lakes; 5 – eskers; 6 – drumlins; 7 – meltwater channels; 8 – glaciotectonic features; 9 – boulder trains; 10 – directions of ice motion.

these cycles repeated dozens of times, all datable material of the north-Eurasian regolith has been repeatedly recycled, mixed, and subjected to carbon-exchange reactions, and thus contaminated by older materials [*Grosswald and Hughes,* 1995];

(ii) specific limitations on the validity of ^{14}C dates are predictable for the polar oceans. The Pleistocene Arctic Ocean seems to be characterized by a particularly large reservoir effect. *Mangerud and Gulliksen* [1975] drew our attention to this phenomenon. However, having not been aware of a continuous ice shelf that had floated over the Arctic basin, they could not offer an adequate quantitative estimate of the effect. Now that the existence of this ice shelf is confirmed [*Polyak et al.,* 2001], time is ripe for reconsidering the whole issue.

The real scope of the reservoir effect in glaciated polar basins can be shown by the examples from Antarctica. *Sikes et al.* [2000] estimated the surface and deep-water reservoir effects in the New Zealand region of the Southern Ocean for the last glaciation using volcanic tephras deposited in both marine and terrestrial sediments, and demonstrated that the glacial surface-to-deep-water age differences reached 3000–5000 years. Another example comes from Antarctica itself, where *Hall* [2000] compared $^{234}U/^{230}Th$ and ^{14}C ages of the same samples taken from a closed-basin Lake Vida in the Dry Valleys, and determined that, due to the lack of aeration, the former lake-bottom reservoir effect was 3500 years at 9500 years ago, with this lack of aeration resulting from the perennial ice cover and density stratification in the lake. In Miers Valley, at the former grounding line of the Ross Ice Shelf, where water contained not-yet-diluted old CO_2, this age offset was found to be ca. 20,000 years.

As considerable reservoir effects can be predicted for the Arctic Ocean, which would render the dates obtained from its fossils unreliable and too old. This casts doubt on accepted deglacial chronology of the Barents and Kara Seas, suggesting that their deglaciation took place not 15–12 kyr BP, as is believed now [*Landvik et al.,* 1998; *Vorren et al.,* 1988], but at least 3 to 5 kyr later. With this correction, the ages of un-recycled material in undisturbed sea floor and coastal deposits would correspond to the timing we advocate;

(iii) uncertainty has sprung up as a result of assigning an Early Weichselian age to giant tabular bodies of ground ice that are widespread in Siberia. These bodies are composed of relic glacial ice left over in permafrost as a result of incomplete decay of the last ice sheet [*Kaplyanskaya and Tarnogradsky,* 1978], their age, being the age of the extinct ice sheet itself, is crucial for glacial chronology of northern Eurasia. *Astakhov and Isayeva* [1988] believe that the bodies belong to the Early Weichselian formation, which has led them to an inference on "retarded deglaciation" and "older-than-they-seem" glacial landforms of Siberia. However, this inference draws from erroneous considerations.

It is based on the fact that, in the well known "Ice Hill" section of the Middle Yenisey River, two ^{14}C dates on wood fragments collected from a debris layer overlying a thick body of glacial ice yielded the ages of ca. 43 and >50 kyr BP. It is assumed that the debris layer was geologically younger than the underlying ice. However, what was observed in the "Ice Hill" section was not a marine or lake sequence, but a remnant of a former ice sheet, its near-bottom portion. Such near-bottom parts of ice-sheets are typically rich in debris incorporated in the process of scouring the underlying rocks. The debris layer is typical ablation till melted out of the underlying ice. The debris was entrained into the ice from below, along englacial shear-plains or other faults, that reach up to 20–40 m above the glacier bed, and so do the debris. Subsequently, as the ice sheet wasted down, the melt-out debris formed a protective cover of ablation till, that stopped the downwasting a few tens of meters short of reaching the glacier bed.

Thus the datable materials of the ablation till overlying the ground ice are typically derived from beneath the ice sheets, and are older, not younger, than the relic glacial ice, thus the inferred age of the buried glacier ice at the "Ice Hill" site is incorrect. Moreover, given the wide occurrence of buried glacial ice in Siberia, the above mechanism for concentrating older materials on the surface of younger ice may prove to be of more universal application.

(iv) Dating of transported shells having mixed ages and of fossils formed in the ^{14}C-depleted sea water invariably yields ages that are much too old, and thus lead to the false conclusion that glaciation was less extensive at the LGM than during the earlier glacial stages. In order to avoid this mistake, the trustworthy radiocarbon ages need to be separated from the spurious dates. Denton's method of "weeding out" bad dates is not applicable in the study area because of reworking and for other reasons discussed above, so we test the radiocarbon ages for their consistency with the geomorphologic, paleohydrologic and other paleogeographic evidence. This strategy has been applied by some of our predecessors to practice.

For instance, evidence from geology, paleontology, paleoecology and archaeology was used by *Hughes et al.* [1981] in order to defend a Late Pleistocene age of the last glaciation in eastern Beringia. Like in Arctic Russia, this age was challenged based on ^{14}C ages of some correlative deposits suggesting an older age. An even better example comes from northern Europe, where Quaternary scientists chose to ignore a large number of ^{14}C dates that, if taken at their face value, would preclude existence of the Scandinavian Ice Sheet. Among these dates, I cite mammoth bone dates of 13 to >30 kyr from Sweden [*Berglund et al.,* 1976], bone dates of 15 to >45 kyr from Finland [*Donner et al.,* 1979], dates of 19 to 32 kyr from Norway [*Follestad and Olsson,* 1979], some 50 dates of 12 to 32 kyr from Denmark [*Aaris-Sørensen et al.,* 1990], and more that 20 dates of 11 to 38 kyr from Britain [*Coope and Lister,* 1987; *Stuart,* 1991]. By contrast, based on these dates, Vasil'chuk argues that the concept of Late Pleistocene ice sheets in northern Europe is untenanble even for Scandinavia, and proposes instead, as a "realistic alternative", a ubiquitous development of thick permafrost [*Vasil'chuk and Kotlyakov,* 2000].

As already stated, the above researchers, except Vasil'chuk, did not hesitate to dismiss the dates as erroneous and misleading, and kept adhering to the concept of a Late Weichselian ice sheet centered on Scandinavia. However, when considering the veracity of a coeval ice sheet in the Kara Sea, the QUEEN members use another standard, taking the mammoth-bone ages from Severnaya Zemlya and Taimyr Peninsula as incontrovertible evidence that no Kara Sea ice sheet existed.

In fact, clinging to this sort of dates is more precarious in Arctic Russia than in northern Europe and Arctic Canada, because the processes that invalidate them are more pervasive there. Marine ice sheets advanced landward repeatedly, producing glacial tectonics and megafloods with each glaciation cycle, and marine dates were systematically too old due to a great reservoir effect of the Arctic Ocean. We avoid these problems by tying our "benchmark moraine" in Arctic Russia to the accurately dated Younger Dryas moraine in

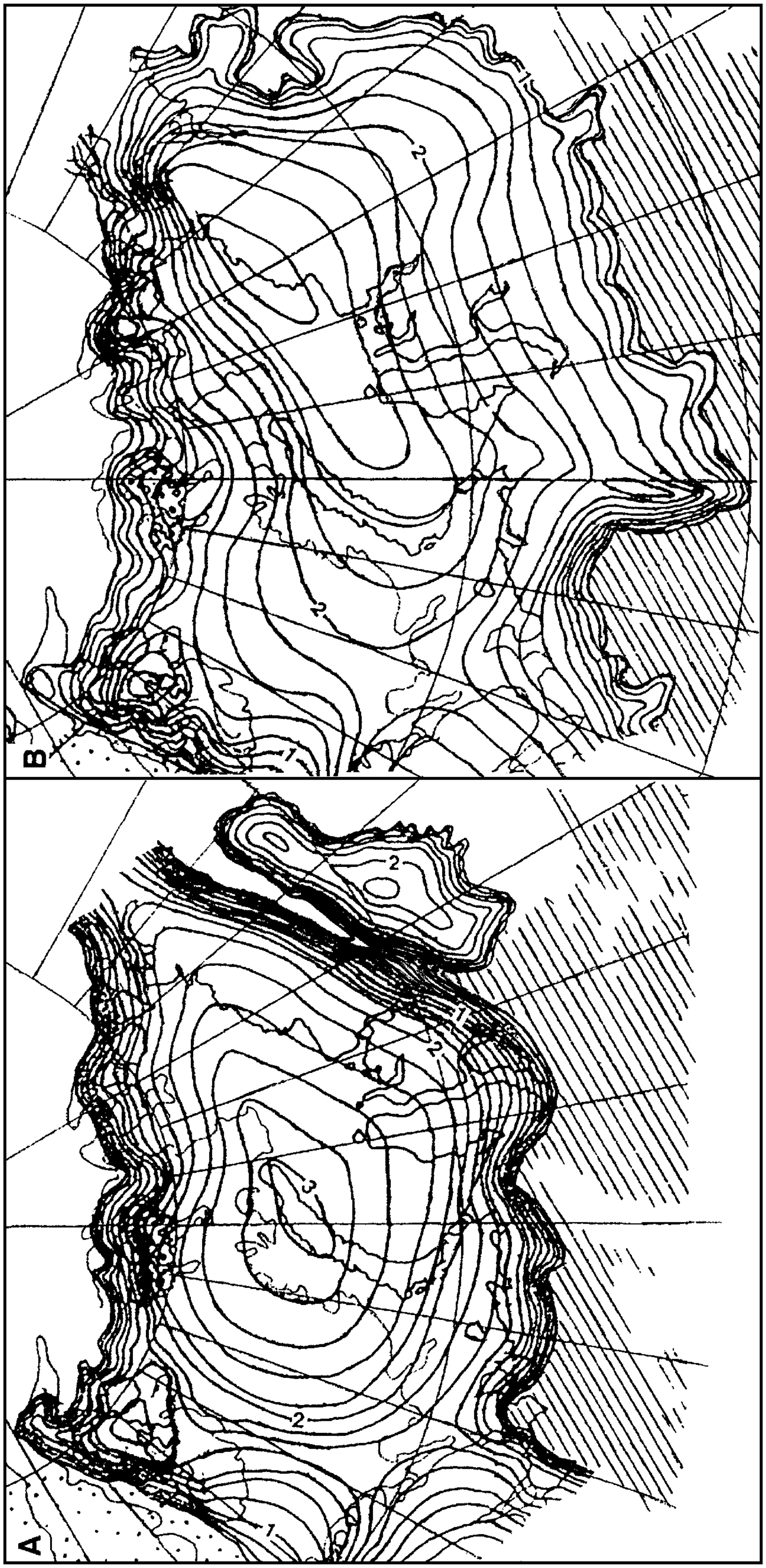

Figure 13. The Barents-Kara Ice Sheet during the LGM as reconstructed over a frozen bed (A) and over a thawed bed (B). The collapsed ice sheet on a thawed bed largely conserves the ice volume of the ice sheet reconstructed over a frozen bed. Ice elevations are contoured in 0.2 km intervals. Parallel-lined areas are lakes dammed by ice sheets.

Scandinavia, using second-order glacial geology and geomorphology, and then applying deductive logic that fits the separate data sets for glaciation, climate, and hydrology within a coherent understanding of the LGM.

The QUEEN glacial chronology is unreliable because it is based on radiocarbon dating of organics that are alien to glacial deposits and landforms and, in the case of marine dates, have a large and unknown reservoir error. In such cases, direct hightech-methods, such as cosmogenic exposure dating, should replace radiocarbon dating, especially because these dating methods have already invalidated raiocarbon dates elsewhere [*Marsella et al.,* 2000; *Zreda et al.,* 1999].

The Barents-Kara Ice Sheet

Two different modeling strategies are employed in computer reconstructions of Pleistocene ice sheets. The top-down strategy places primary emphasis on obtaining accurate temperature and mass balance data on the ice-sheet surface. These surface boundary conditions are then used to calculate basal thermal conditions, specifically basal temperatures where the bed is frozen and basal melting or freezing rates where the bed is thawed. The bottom-up strategy places primary emphasis on deducing basal thermal conditions from interpretations of glacial geology and geomorphology, relating these conditions to the degree of ice-bed coupling they allow, and then calculating ice elevations that could be supported by a given pattern of coupling.

Both strategies were employed in reconstructing the Barents-Kara Ice Sheet at the LGM, notably in the *Fastook and Hughes* [1991] top-down reconstruction and the *Grosswald and Hughes* [1995] bottom-up reconstruction. These two strategies, each based on entirely different data sets, ultimately yielded substantially the same paleo-ice sheet.

Bottom-up modeling was employed to reconstruct a Barents-Kara Ice Sheet during the LGM and after the Younger Dryas. The model, as described in detail [*Hughes,* 1998], allows smooth transitions from sheet flow to stream flow to shelf flow along ice sheet flowbands, and calculates the degree of ice-bed coupling as ice crossed frozen, thawed, freezing, and melting basal thermal zones. The model allows variable surface accumulation and ablation rates, basal topography, and isostatic adjustments to the changing ice load. The most important variables were the thawed fraction of the bed for sheet flow, the ratio of basal water pressure to ice overburden pressure for stream flow, and the buttressing stress for an ice shelf. Each variable is a measure of the degree of ice-bed coupling for sheet flow, stream flow, and shelf flow. Sheet flow extended over 90% of the glaciated landscapes, but stream flow discharged 90% of the ice.

In the ice-sheet reconstructions [*Grosswald and Hughes,* 2002], the primarily interest was in how much surface lowering and areal spreading takes place as the ice sheet loses substantial coupling to its bed when a frozen bed becomes thawed. The modeling, allowing this ice lowering and spreading with minimal change in ice volume, was meant both to reproduce a scenario that actually took place during the LGM and after the Younger Dryas, and to investigate the consequences of such a sudden and widespread change in the basal boundary conditions.

Figure 13 shows the Barents-Kara Ice Sheet before and after the LGM basal thawing event, and Figure 14 – the ice sheet before and after the Younger Dryas basal thawing event. When the bed is a crystalline shield, thawing lowers the ice surface between 20% and 25%; when it is ice-cemented permafrost, thawing can lower the ice surface much more, depending on the ice fraction and the composition of the sediments or till. Stream flow is transitional from sheet flow to shelf flow [*Hughes,* 1998]. Therefore, changes of the ice sheet depicted in Figures 13 and 14 were accomplished by ice streams.

The farthest surge from the collapsing Younger Dryas Kara ice dome was to the west and southwest, crossing southern Novaya Zemlya and Karskiye Vorota Strait, and transgressing onto the Kola Peninsula-White Sea region. It also transgressed onto the Russian Plain, West Siberia, and Taimyr Peninsula. The westward surge creates a short-lived ice sheet in the Barents Sea that diverts ice onto the Russian Plain, with ice streams ending as ice lobes in the valleys of the Pechora, Mezen, and Severnaya Dvina Rivers. A surge to the south ended as ice lobes in the valleys of the Ob, Nadym, Pur, Taz, and Yenisey Rivers. Probably this surge is responsible for the Late Khvalyn transgression of the Caspian Sea at about 10 kyr BP.

Based on geological evidence and on modeling, using both top-down and bottom-up techniques, a conclusion is reached that, at the LGM, the Late Weichselian Barents-Kara Ice Sheet covered the entire Barents and Kara Seas, along with considerable areas of adjacent land. It had a shape of a single asymmetrical dome centered on the Kara Sea. Its after-collapse LGM extent was close to 6 million km^2, and its central dome had an elevation of 2900–3000 m.

In the southwest, the LGM Barents-Kara Ice Sheet merged with the Scandinavian Ice Sheet, and in the east – with the grounded marine East Siberian Ice Sheet. Thus it was a constituent part of a larger Eurasian component of the Arctic Ice Sheet.

At about 10 kyr ago, after its post-Younger Dryas collapse, the residual Kara Sea ice sheet still stands out as a single ice dome centered in the Kara Sea (Figure 14B). Its areal extent was in excess of 2 million km^2, and central dome had an elevation of 1900–2000 m. Even the Markhida-time after-collapse ice sheet had an areal extent of about 1.5 million km^2.

Both the LGM and post-Younger Dryas ice sheets seem to be much more consistent with the modern sea-level records inferred for the Late Pleistocene and Holocene, than all minimum reconstructions. Specifically, the post-Younger Dryas ice sheet in Figure 14 and the Markhida-time ice sheet in Figure 8 account, at least partly, for the considerable amount of residual ice suggested by the sea-level records from Barbados [*Fairbanks,* 1989] and the NW shelf of Australia [*Yokoyama et al.,* 2000].

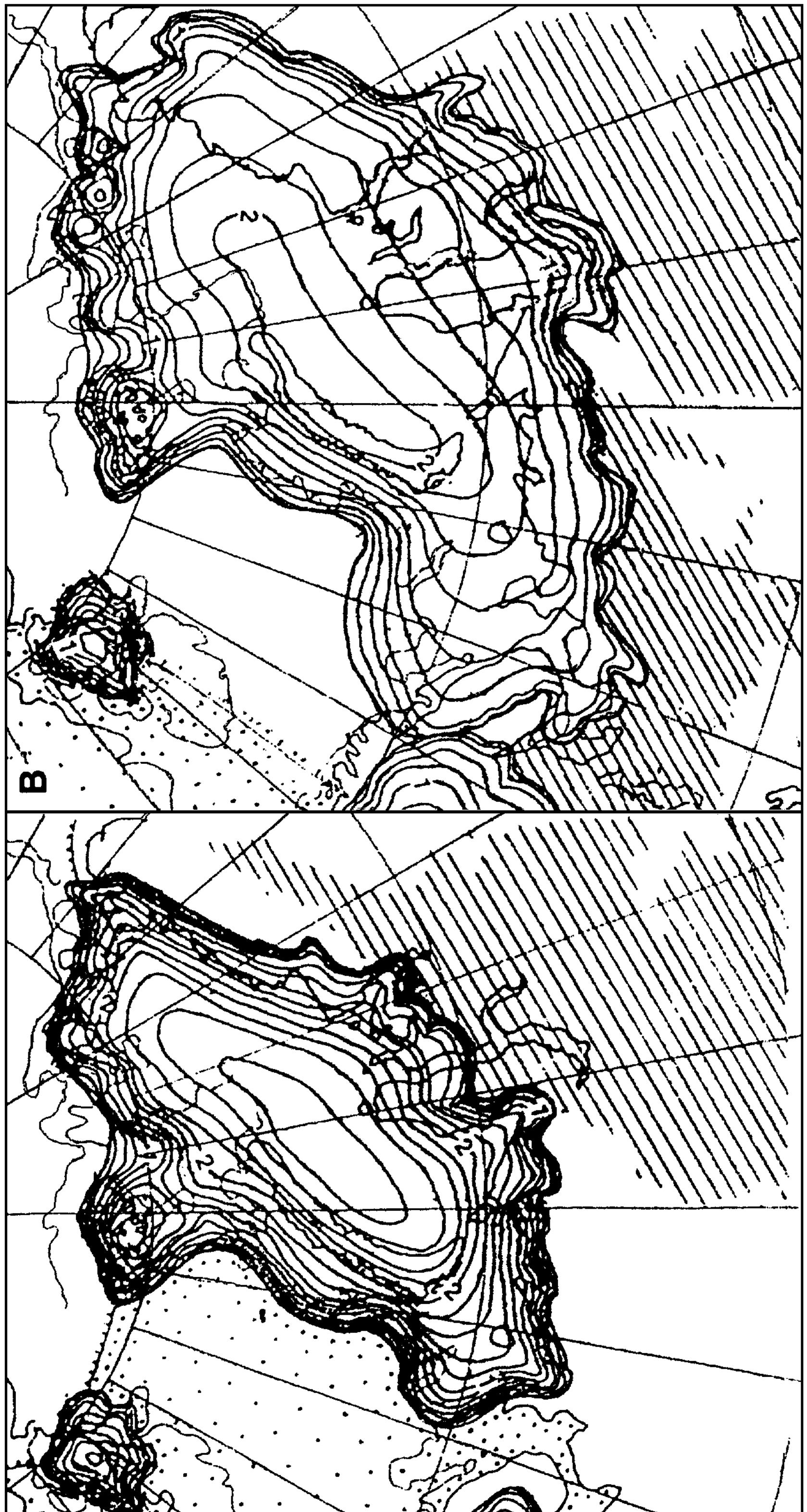

Figure 14. The Barents-Kara Ice Sheet during and immediately after the Younger Dryas cold event. The Younger Dryas ice (A) is reconstructed over a frozen bed, while the colllapsed ice sheet (B) – over a thawed bed.

Conclusions

Today, there are two rival models of Late Weichselian glaciation in western Arctic Russia. The first model is an extensive and continuous Barents-Kara Ice Sheet. Its reconstruction is consistent with directional indicators of ice-flow across the Kara-Barents divide; with second-order glacial geology on Kola Peninsula and the ensuing paleoenvironments; with the pattern of end moraines in north-central Arctic Russia that are aligned in circles centered on the Kara Sea; with the continental paleohydrology of Eurasia, including the Trans-Siberian drainage system, the Eurasian cataclysmic megafloods, and major transgressions of the Caspian Sea; with the Late Weichselian paleoclimate of the Arctic, including the results of climate-based modeling experiments. In addition, it is consistent with new evidence for glaciation of submarine ridges and plateaus in the Arctic Ocean showing that the circum-Arctic ice domes were joined to an Arctic ice shelf to produce an Arctic Ice Sheet that behaved as a single Pole-centered dynamic system; and with the Arctic Ice Sheet discharging icebergs into both the North Atlantic and the North Pacific at the LGM. At the same time, this model is inconsistent with certain sets of ^{14}C dates from the Arctic continental shelf and adjacent coastal lowlands of Eurasia.

Another model is the QUEEN interpretation, which suggests that Late Weichselian glaciation of western Arctic Russia was discontinuous, diachronous, and much smaller than in the first model. The QUEEN model is based on and consistent with several sets of ^{14}C dates. However, it is inconsistent with the entire paleogeographical context of Late Weichselian Eurasia.

All inconsistencies in the QUEEN model seem to be accountable for by erroneous dating. This conclusion is hard to avoid, especially by those who employ the tests for internal coherence and external consistency as a standard practice of research. Based on these tests, it can be shown that the Late Weichselian Barents-Kara Ice Sheet had the shape of an extensive asymmetrical dome centered on the south-central Kara Sea. The ice sheet's LGM extent was close to 6 million km^2, and its central dome rose to about 3000 m. This ice sheet merged with the Scandinavian Ice Sheet in the southwest, and with the marine ice dome grounded on the East Siberian continental shelf in the east. Thus it was part of a larger Eurasian component of the Arctic Ice Sheet.

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