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The Arctic Center of Quaternary ice and flood spreading: A deductive model

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Abstract. Early in the XIX century, the founders of glacial theory conceived of a "polar ice cap" centered on the North Pole and extending as far south as central Europe. However later this model was discarded. The deep Arctic Ocean, discovered in 1890s, was thought inconsistent with the model. Moreover, a belief took hold that the Arctic was not more severely glacierized than now, as polar snowfall seemed insufficient to nourish much bigger ice masses. So the reigning concept of the XX century suggested that the past great ice sheets of Northern Hemisphere had mostly located on the mid-latitude continents. This concept was first challenged in 1970s, when *Hughes et al.* [1977] put forth the model of an *Arctic Ice Sheet* (AIS) that had formed largely in the Arctic Ocean. A core *ice-shelf mechanism* of Arctic Ice Sheet formation was proposed, which suggested: first, an inception of ice shelves in confined cold-water seas; second, turning the ice shelves into marine ice domes grounded on the polar continental shelves; and third, amalgamation of the Arctic terrestrial, marine-based, and floating ice components into a single Antarctic-style dynamic system. Now, a marine ice transgression hypothesis is proposed which suggests that the Arctic marine ice domes and thick floating ice shelf would push outwards and transgress onto adjacent lands. The Arctic Ice Sheet was an unstable, threshold-like system, prone to generate nonlinear responses to gradual change in forcing. The responses materialized in glacial surges, Heinrich events, and megafloods. As a result of the Earth's rotation, the system developed a west-to-east asymmetry.

Introduction

An over-all portrait of the Ice Age world, in particular, of the Pleistocene Northern Hemisphere we conceive of, dramatically changes with time. Early in the XIX century, the founders of glacial theory envisaged a "polar ice cap" centered on the North Pole and extending as far south as central Europe. This picture, created by imagination of *Bernhardi* [1832], was supported by Venetz, Charpentier and Agassiz; the latter, when describing a "Great Ice Period", used to tell of "a vast sheet of ice extending from the North Pole to the Alps and to central Asia" [cit. from *Flint,* 1971, p. 13].

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However, later, Bernhardi's "polar ice cap" hypothesis, despite still appearing "attractively simple and the most plausible form of an ice sheet" [*Charlesworth,* 1957, p. 625], was found inconsistent with facts. One of such facts, inconsistent with the hypothesis, was Nansen's discovery of the deep Arctic Ocean. In addition, a belief took hold that the Arctic was not more severely glaciated than now, and that polar snowfall was insufficient to nourish much bigger ice masses. This scanty glaciation of the High Latitudes also seemed implied by their glacial geomorphology. For instance, the former ice movement, as given by striae and boulder trains, was found to have been not everywhere derived from the north, but rather from a number of terrestrial centers. As importantly, mapping of end moraines demonstrated that past ice sheets had not only southern, but also northern limits and, when shrinking, retreated both northward and southward [*Charlesworth,* 1957, p. 626]. These observations were broadly reflected on glacial maps of the world and continents, e.g., on the maps by *Antevs* [1929], *Flint* [1971], *Gerasimov and Markov* [1939], as well as on

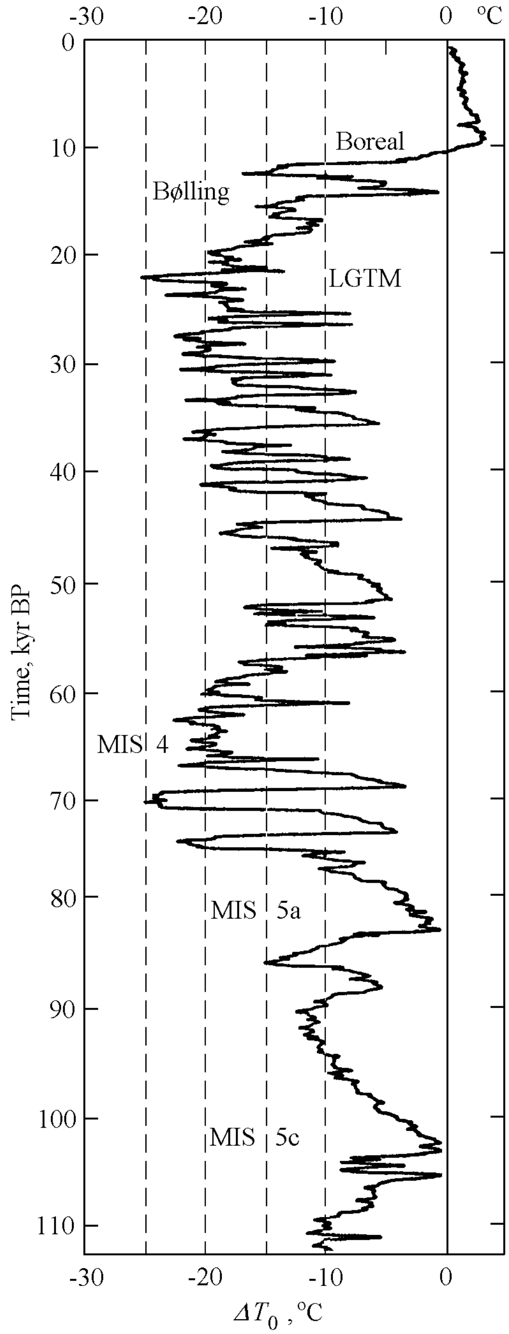

Figure 1. Paleotemperature curve from GRIP bore hole at Summit Station, Greenland, covering most of the Weichselian age (last 113 kyr). After *Johnsen et al.* [1995]. Note that mean annual temperatures between 75 and 10 kyr BP., i.e., during a time span of 65 kyr, were close to −15°C.

numerous regional maps of paleo-ice sheets.

Our knowledge of inception stages of glaciations was, and still is, incomplete, remaining scanty and spotty. Geomorphological traces of early-stage glaciers, such as initial end moraines and lineation swarms, have been largely erased by subsequent wet-based ice flow, so a lot had to be resolved by "common sense" of researchers. As for existing theoretical models of ice-sheet inception, they focus, nearly exclusively, on terrestrial mechanisms, such as the "highland origin and windward growth" by *Flint* [1971] and the "instantaneous glacierization" by *Ives et al.* [1975], and virtually not consider oceanic mechanisms of ice sheet formation whatsoever. The same can be said of modern computer reconstructions of the Northern Hemisphere's glaciations: nearly all of them do not simulate these mechanisms either [e.g., *Huybrechts and T'siobel,* 1997].

Thus the concept of a huge pole-centered ice cap was relinquished and replaced by a new model proposed that the great Northern Hemisphere's ice sheets had characteristically belonged to the mid-latitude continents [*Charlesworth,* 1957; *Flint,* 1971]. This idea, a ruling concept of the XX century, was first challenged only in 1970s, when *Hughes et al.* [1977] put forward the model of an *Arctic Ice Sheet* (AIS). The AIS model implied that the great past ice sheets in question had been built largely in the Arctic Ocean, not on the mid-latitude continents. In a way of explanation, an *ice-shelf mechanism* of Arctic Ice Sheet formation was proposed, which implied the following: first, an inception of ice shelves in confined cold-water seas; second, turning the ice shelves into marine ice domes grounded on the polar continental shelves; and third, amalgamation of the Arctic terrestrial, marine-based, and floating ice components into a single Antarctic-style dynamic system. Based on these, a *marine ice transgression hypothesis* was further developed which suggested, that under favorable conditions the marine ice domes would transgress onto adjacent lands [*Hughes,* 1986, 1998].

These favorable conditions occurred, when positive mass balance of the Arctic Ice Sheet coincided with initial and final stages of glaciations, as nearly ice-free land offered little resistance to ice transgressions from the north, as well as during the glacial maxima, when some of the terrestrial glaciers could not stand the ice transgressions.

The predominantly marine Arctic Ice Sheet was an unstable threshold-like system, prone to generate nonlinear responses to gradual changes in external forcing. As soon as the coupled marine ice sheet/ice shelf system was pushed across its stability threshold, glacial and hydrologic cataclysms went off. One type of the cataclysms was represented by gravitational collapses of marine ice domes; they ensued in dumping of big ice masses into the adjacent oceans, so that the dumped ice would squeeze ocean water sideways and upward giving rise to megafloods. The collapses would also set the Arctic ice shelf in a megasurge, so that huge slabs of ice would thrust upon each other and on adjacent continental shelves and coasts, the processes similar to the ones recently detected on Jupiter's Ganymede [*Schenk et al.,* 2001].

The Earth's rotation, having been superimposed on the existing distribution of northern continents and oceans, made the Arctic Ice Sheet develop a west-to-east asymmetry. As a result, its "western" (North American, Greenland and Barents-Kara) components, on the one hand, and the "eastern" (East Siberian and Beringian) components, on the other, had different morphologies and histories.

The Ice Age Arctic Ocean – Turning Into a White Hole?

A contention of this paper is to elaborate on the ice-shelf mechanism of marine ice-sheet inception by discussing its details and stages. Special regards will be paid to its implications for glacial history of Arctic Siberia, Alaska, and Beringia. Based on new evidence, it will be re-emphasized that a cradle of the great Northern Hemisphere's ice sheets was the Arctic Ocean: that it was in that ocean where the ice sheets incepted and gathered mass and energy before transgressing outwards.

The following facts are of immediate relevance.

First that the Late Weichselian cooling of the Arctic was much stronger than previously thought. As revealed by ice-core drilling in Greenland [*Johnsen et al.,* 1995], at two cold peaks dating to 22–23 and 70–72 thousand ^{14}C yr BP, the temperature lowering reached 25°C, while during the entire time interval of 75 through 10 thousand ^{14}C yr BP, the mean cooling amounted to about 15°C (Figure 1). In the rest of the Arctic, where climate-forming processes could be somewhat different, the ice-age cooling was only slightly less pronounced than in Greenland [*Broccoli,* 2000]. Compared to about 0°C summer temperature of the region today, this cooling indicates that there was no melting in the Pleistocene Arctic Ocean. Thus, whatever the ice accumulation, the mass balance of ice in the ocean was invariably positive.

Second fact, a derivative of the first, is that the Arctic equilibrium line altitudes (ELA), that separates accumulation and ablation zones on the surface of ice sheets and now measures in a few hundred meters above sea level (asl), experienced enormous Pleistocene lowering. As established by climate studies, the ELA depends linearly on mean air temperature T, and the $\delta T/ELA$ ratio is close to 0.6° per 100 m of the ELA change, which is broadly used by paleogeographers [e.g., *Flint,* 1971; *Lowe and Walker,* 1997]. Thus, the 15°-cooling strongly suggests that the Pleistocene ELA lowering in the Arctic was on the order of 2.0–2.5 km, which turned the entire Arctic Ocean into a continuous area of positive mass balance of ice.

Third fact is that, as a result of ice-sheets' growth and sea level lowering, the Pleistocene Arctic Ocean was becoming a confined basin. All straits that presently connect it with the Atlantic and Pacific Oceans either became dry land, or got buried by glacier ice. This happened to Bering Strait and to all channels of Arctic Canada, including Nares Strait [e.g., *Dyke et al.,* 2002]. As for the Fram Strait, a wide sea gate between Spitsbergen and Greenland, it probably was blocked by ice also. The strait got about 70% narrower when the Greenland and Barents-Kara ice sheets expanded to the edges of respective continental shelves, while the strait's deep axial channel had to be filled by the ice masses converging on it from the west, north and east [*Grosswald,* 1999, 2001b]. Actually, north-Greenland outlet glaciers alone, having been commensurate with the channel's hollow, could have blocked it completely. This blocking was especially effective as, on entering the Norwegian-Greenland Sea, the outlet glaciers of NE Greenland got buttressed from the south by a thick floating shell of densely packed icebergs. This iceberg shell, although perfectly consistent with the ice mass balance computations [*Lindstrom and MacAyeal,* 1986], is generally thought doubtful. However, the sea's Pleistocene climate, oceanography, and physical setting make this phenomenon probable. On the one hand, the Norwegian-Greenland Sea was cold, getting abundant snowfall, and cut from inflow of the Atlantic warmwater [*Barash,* 1988; *CLIMAP Project members...,* 1981], on the other it was bordered on three sides by calving ice walls (Figure 2), and locked on the forth side by the Atlantic Sill carrying traces of a grounded ice shelf [*Belderson et al.,* 1973; *Vinogradova et al.,* 1959]. Hence, a complete lock up of the Fram Strait by an icy plug was probable and physically inevitable, so the strait was a Pleistocene analog of the Bentley Channel in Antarctica which, though being 2.5 km bsl deep, is presently buried by 4 km of glacier ice (Figure 3).

Figure 2. Directions and relative rate of ice inflow (bold arrows) into the Pleistocene Arctic Ocean, Norwegian-Greenland Sea and Baffin Bay from surrounding ice sheets. Modified from *Denton and Hughes* [1981]. Note the converging flow of the ice in the basins, and its resulting directions. N.P. – the North Pole; GIS – Greenland Ice Sheet; dashed lines – selected ice flowlines of floating ice shelves.

The above facts suggest, the Pleistocene Arctic Ocean along with its catchment area was becoming a completely closed basin with a positive mass balance of ice; in other words, it was a typical *White Hole.* The notion of White Hole was introduced to define the cold areas of the Earth in which all incoming ice – precipitated, imported and formed *in situ* – would accumulate but not escape [*Grosswald and*

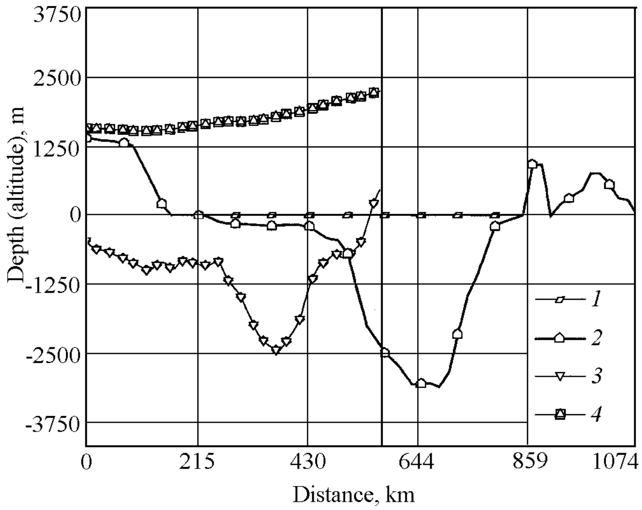

Figure 3. Transverse profiles of the Fram Strait (2) and subglacial Bentley Channel, West Antarctica (3). Horisontal line (1) stands for present-day sea-level, line (4) – for present ice surface in West Antarctica. Compiled by J. L. Fastook based on existing charts and the data of radio-echo sounding (not published). Note that the present-day ice, covering the Bentley Channel, is more than 4 km thick.

Hughes, 1995]. By contrast, the opposite notion *of the Black Hole* applies to the areas where all entering ice disappears, like the matter vanishing in the interstellar "black holes." Consciously or not, great many Quaternary scientists act on this Black Hole premise. In particular, most ice-sheet modelers, e.g., *Huybrechts and T'siobel* [1997], make their reconstructions on assumption that all floating ("calf") ice is lost, so that their models do not include coupled ice shelves enabling a dynamic interaction of ice sheets with sea level.

Two fundamentally different models of past glaciation come out of the above approaches. From the Black Hole approach that there could not be any floating glaciers in the Arctic, so there was no way for ice sheets to bridge submarine channels, let alone deep ocean basins. Only a few disconnected grounded ice caps appear on the maps based on this premise. Thus, with the Black Hole approach applied, only "minimalist" reconstructions would ensue.

As for the White Hole premise, its application predetermines that a continuous ice shelf would appear in the Pleistocene Arctic Ocean. As inevitably, this ice shelf would grow into an AIS, i.e., into a dynamically single system of terrestrial, marine-based and floating components [*Grosswald and Hughes,* 1999; *Hughes et al.,* 1977]. Hence, if there was an Arctic White Hole, there had to be extensive and continuous ice sheet around the North Pole.

Judging by Figure 1, the Arctic White Hole existed during the entire Late Weichselian/Late Wisconsin glaciation. This implies that the Arctic ice shelf had a positive mass balance, so that the ice-shelf's thickening was going on since about 75 kyr BP to 10 kyr BP, i.e., for a time span of about 65 thousand years. Rate of this thickening was probably close to 1 km per 5 kyr, this conclusion being based, first, on present-day Arctic precipitation and its assumed ice-age decrease by a factor of two, and, second, on an estimate of a solid-ice inflow from the adjacent marine ice sheets. Specifically, it was assumed that an average Late Weichselian snowfall amounted to about 15 g cm^{-2} in the west Arctic Ocean and 5–7 g cm^{-2} in the east Arctic Ocean [*Prik,* 1970], and that a solid-ice inflow was on the order of 10–15 g cm^{-2} [*Grosswald,* 1983, 1999; 2001a].

Given this rate, it would take only 20–25 kyr to build a 5-km thick single-dome Arctic Ice Sheet centered on the North Pole. Had this ice-sheet growth continued for the entire 65-kyr time interval, it would have become around two times thicker. Anyway, based on this and more temperate assumptions, a marine ice transgression hypothesis can be proposed suggesting that the Arctic marine ice domes and the thickening floating ice shelf would spatially expand, push outwards and transgress onto adjacent lands.

Of course, formation of such a giant single-dome pole-centered ice sheet could hardly be ever completed. The ice sheet had been underlain by a trapped ocean, it represented a coupled marine ice sheet/ice shelf system, thus had to be inherently unstable and prone to collapsing and surging [*Grosswald and Krass,* 1998; *Hughes,* 1998; *Weertman,* 1976]. These destructive processes would probably have prevented the system from reaching its "ultimate," high and convex, profile.

Ice Sheet Inception

As a result of the Arctic Ocean's negative radiation balance [*Atlas...,* 1970] and cessation of the Atlantic warm-water inflow, heat balance of the ice age Arctic Ocean was increasingly negative. Probably, this heat balance was caused by superposition of the abrupt cooling of 70-72 kyr BP upon this negative trend, that made temperature of the Arctic drop to one of its deepest Pleistocene minima, having brought about inception of the AIS.

First stage of this process, the inception per se, was started by formation of an Arctic floating ice shelf. It was initiated by abrupt freezing of sea-water, which created a perennial cover of sea-ice and prompted its rapid thickening (due to snow accumulation on its top and freezing of water on its bottom). A confined ocean with its shores preventing the ice from thinning by horizontal spreading was a favorable environment for the ice shelf forming. This mechanism was proposed and thermo-physically elaborated by *Crary* [1960]; and then used by *Denton and Hughes* [1981] and *Grosswald* [1983] for explaining of how the Arctic and Beringian ice shelves had incepted and developed.

The initial Arctic ice shelf was a huge floating formation with an areal extent of about 10 million km^2 extending across the whole Arctic Ocean. Perhaps the only exception was a narrow zone bordering East Siberia and Beringia, the shallowest part of the circumpolar continental shelf, where the ice shelf grounded at the very beginning. So, the Canadian, Greenland and Barents-Kara sectors were covered by a floating ice shelf which experienced a long stage of thickening and then got grounded on continental shelves, giv-

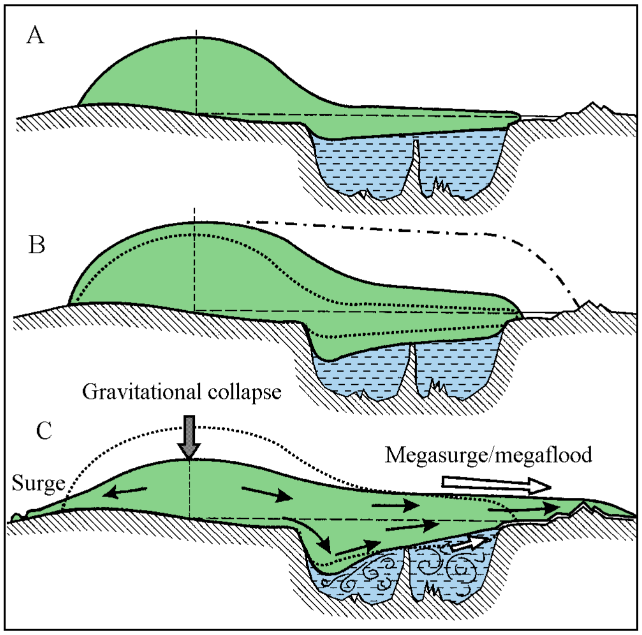

Figure 4. "Asymmetric" model of an Arctic Ice Sheet: principal stages: (A) initial stage: a coupled asymmetric system of a floating ice shelf and a grounded marine ice dome; (B) middle stage: the same coupled system after a few thousand years of further growth; (C) cataclysmic stage: collapsing of the ice dome and ensuing glacial surges and seawater eruption. Note that, due to ice-sheet asymmetry, the Atlantic-bound surging was moderate, while the Arctic-bound (poleward) surging was super-powerful. Fine dotted lines depict ice-sheet profiles of a previous stage; a bold dash-dotted line – an "ultimate", high and convex, profile of the AIS; the gray arrow indicates ice-dome lowering when it collapses, the black arrows – fast ice flow, and the white arrows – megasurge/megaflood and water eruption directions.

ing rise to respective marine ice domes. As for the East Siberian and Beringian continental shelves, their surfaces remained mostly covered by thin grounded ice, getting little snowfall on its top. Thus, in the course of its development, the single and uniform Arctic ice shelf became differentiated and asymmetric (Figure 4A). Specifically, a smaller ice shelf kept floating in the ocean's deep Central Basin, while, on its three sides, that ice shelf was bounded by grounded marine ice domes and, on the fourth side, turned out in juxtaposition to a slightly glaciated continental margin. Possibly, the latter thin ice cover could co-exist with permafrost and periglacial formations on continental margin of East Siberia and Beringia.

In the course of further ice-sheet buildup, this asymmetry would grow more and more pronounced (Figure 4B). For one, the marine ice domes had different regime and mass balance on their opposite sides; in particular, their northern slopes, buttressed by the Arctic ice shelf and having zero melting, outgrew their southern slopes that lost ice by melting and calving. As a result, the ice domes' divides were steadily and inexorably shifting polewards. For two, thickening of the ice shelf in its western (peri-Atlantic) segment was about 5 times faster than in its opposite (peri-Pacific) segment, as the first segment was getting twice as much snowfall than the second, and only the western segment was getting solid ice inflow.

Pattern of the ice inflow into the Arctic Ocean (see Figure 2) is a constituent of this asymmetry. The latter, having been expressed in differential nourishment and imbalanced profile of the ice sheets, makes it clear that a mainstream flow of the Arctic ice shelf had to proceed in the west-to-east direction. Lately, this shelf-flow direction was confirmed by orientation of stoss and lee sides on an ice-scoured crest of the submarine Lomonosov Ridge, surveyed by a geophysical mapping system of the SCICEX Expedition 1999 [*Polyak et al.,* 2001].

Gravitational Collapses, Surges and Megafloods

In the course of the Northern Hemisphere's ice-sheet buildup the thawed bed area widened, having reached its 50 to 70% [*Fastook,* pers.comm.]. Accordingly, the ice sheet instability kept increasing, so that sooner or later a fast purge had to come out of this growth. A sequence of cataclysmic events went off each time as the coupled Arctic marine ice sheet/ice shelf system crossed its stability threshold. As shown by *Hughes* [1998] and Krass [*Grosswald and Krass,* 1998], these sequences started with domino-like gravitational collapses of the marine ice domes, resulting in dumping (surging) of huge ice masses into adjacent oceans. In accord with the asymmetry of the ice domes, lesser portions of the ice would surge southward into the Atlantic Ocean where they produced Heinrich events, while much greater portions of the ice would debauch northward into the Arctic Ocean.

Predictably, the effect of the northward dumping could have been twofold.

On the one hand, the dumped ice would squeeze water from the western segment of the ocean and push it eastward, so that the water (or, more justly, ice-water masses) got erupted onto land surface (Figure 4C), cataclysmically flooding great areas of Eurasia and the North Pacific Region. In principle, this water's volume can be estimated based on probable amount of the dumped ice.

On the other hand, this dumping would set the floating Arctic ice shelf in fast motion of an eastward megasurge. A huge slab of ice, sliding on a pillow of sea water, would thrust upon the East Siberian, Alaskan, and Beringian continental shelves and coastal zones (Figure 5); and even force its way across Chukchi Peninsula and Beringia into the North Pacific, where it would spawn armadas of icebergs reaching as far south as southern Japan [*Okada,* 1980].

Given the above rates of the ice sheet growth, it can be inferred that even a fraction of cold Late Weichselian time would suffice to build a full-fledged AIS, and that quite a few, perhaps 4 to 5, ice-dome collapses and megasurge/megaflood events would occur during those 65 thousand years. The Heinrich events, which could ensue not only from complete

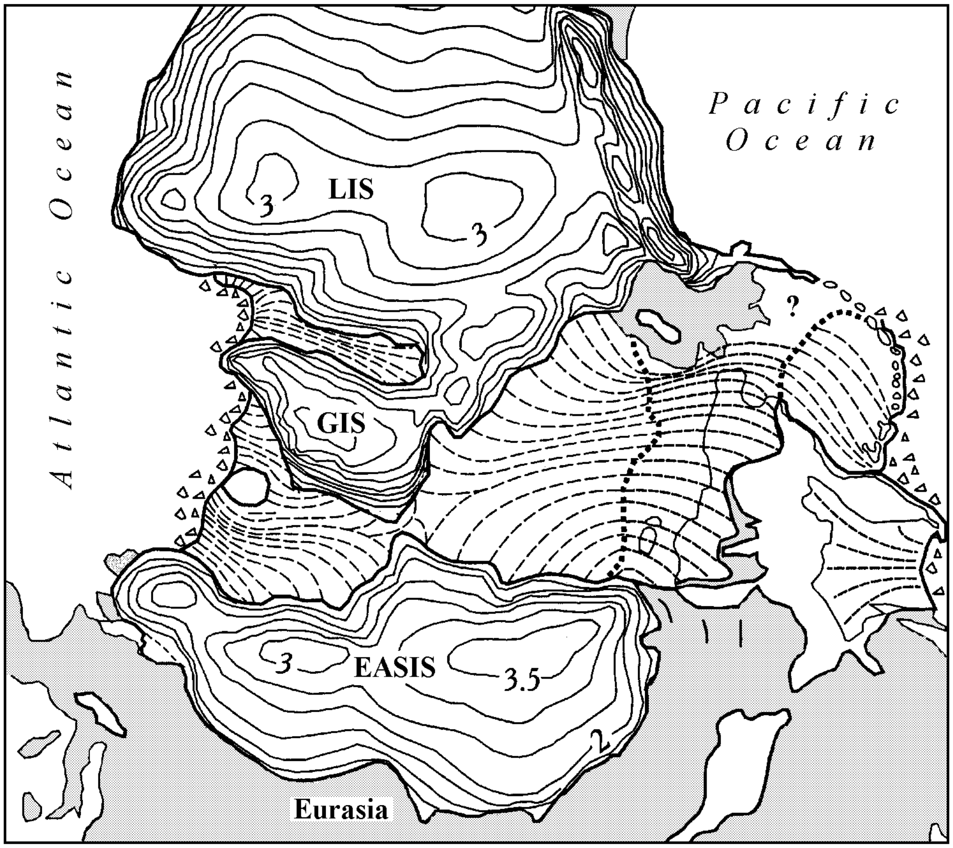

Figure 5. Schematic reconstruction of the AIS (a snapshot of a situation after the LGM episode of collapsing and surging). It shows: (a) the "western" – Laurentide (LIS), Greenland (GIS) and Eurasian (BASIS) – ice sheets; (b) the Arctic, Norwegian-Greenland and Baffin-Bay floating ice shelves (their ice flowlines are long-dashed); (c) the ice shelves that got thrust upon adjacent continental margins (their ice flowlines are short-dashed). Also shown: (d) some margins of continental shelves (by bold dotted lines), (e) intensely calving ice barriers (by small triangles scattered in front of the barriers). Ice shelves grounding on the Atlantic and other sills are not shown.

collapses of the ice domes, but also from partial (sectoral) ice-dome collapsings, might be more numerous. In this context, all speculations about pre-Late Weichselian age of the last Arctic ice shelf [*Polyak et al.,* 2001, 2002; *Spielhagen,* 2001] seem to make no sense whatsoever. Given the above rates of Arctic ice thickening, the last Arctic ice shelf could be only of Late Weichselian age.

The above mechanism gives grounds to believe that southward invasions of the Arctic ice, at least some of the invasions, were driven by ice-sheet instability; in other words, their rhythm was paced by life cycles of the ice sheet, and was independent of climate change.

New Theoretical Model

Our current model of Arctic glaciation [*Grosswald and Hughes,* 1995, 2002] comprises a continuous system of marine ice sheets grounded on the polar continental shelves, and an Arctic ice shelf confined within the ring of the ice sheets. This *circumpolar* model was first proposed in 1988, when, in addition to the data used by *Hughes et al.* [1977], the Late Weichselian glaciation of New Siberian Islands and surrounding seas was established [*Grosswald,* 1988a, 1988b, 1989]. Thereafter, the model was further "upgraded," and as of now, it includes not only Arctic and Norwegian-Greenland floating ice shelves and North American, Greenland, Scandinavian and Barents-Kara ice domes, but also marine East Siberian, Beringian and Okhotsk-Sea ice domes.

This model became a fairly good approximation. It fits well into the context of Eurasia's Late Weichselian paleoglaciology [*Bintanja et al.,* 2002; *Grosswald and Hughes,* 2002], as well as was supported by several climate-based modeling experiments [e.g., *Budd et al.,* 1998]. Moreover, it goes along with new geological evidence, such as ice-shoved features of Tiksi area [*Grosswald and Spektor,* 1993; *Grosswald et al.,* 1992] and the Kolyma River-delta [*Grosswald,* 1996], with the assemblages of oriented lake-and-ridge landform of Arctic coastal plains [*Grosswald et al.,* 1999] and with submarine grooves and recessional moraines of Chukchi Borderland uncovered by *Polyak et al.* [2001]. Nevertheless, to me, the model looks somewhat “narrowminded”, it focuses on some facets of the Arctic ice age but disregards the others, as important facets. In particular, it elaborates on the peak of Late Weichselian glaciation and on the stages of its degradation, but considers neither the ways of their inception, nor differences in ice-sheet individual histories, including the system’s asymmetry.

Due to these shortcomings, this model cannot account for differences in submarine geomorphology of the Barents-Kara and East Siberian shelves, specifically, for the fact that the western shelf displays spectacular glacial troughs, while the eastern shelf is virtually devoid of them. It provides no explanation as to why, despite abundance of southward ice-flow indicators, there are no north-facing end-moraines on the Arctic coastal plains of East Siberia, and no record of recent glacio-isostatic crustal uplift there. The model appears, or seems to appear, inconsistent with available data on the depth and temperatures of submarine permafrost of the Laptev-Sea floor [*Romanovski and Hubberten,* 2001], with the age and distribution of rather numerous mammoth-bone finds on the Arctic margin of Siberia [*Sher,* 1995].

To some, these unsolved problems suggest that there was no ice sheet glaciation in Late Pleistocene East Siberia and Beringia whatsoever [*Brigham-Grette et al.,* 2001; *Svendsen et al.,* 1999]. However, the evidence that the mentioned regions were recently overridden by north-to-south moving ice is overwhelming [*Grosswald,* 1998; *Grosswald and Hughes,* 2002], and the objections to this glaciation by Svendsen, Sher and others refuted [*Grosswald,* 2001a]. Nonetheless, I took the above facts, partly convincing, partly doubtful or even spurious, for a message that our current circumpolar model needs rethinking, that it should be improved and reshaped in such a way that it accommodates and harmonizes all available evidence, especially those that appear controversial.

A new, *centrifugal and asymmetric,* model, resulting from this rethinking, seems to come over the controversies and to harmonize all the known evidence. This model suggests the following history of the great Arctic Ice Sheet during the last glacial hemicycle.

- An Arctic Ice Sheet formation started in the Arctic Ocean when air temperature dropped to one of its first Pleistocene minima, and the warm Atlantic water ceased to penetrate the ocean. According to the coupled ice sheet – ice shelf – bedrock model, forced by the GRIP-derived temperature records [*Bintanja et al.,* 2002], last ice sheet formation began at 118 kyr BP in the Barents and Kara Sea region, as well as over Baffin Island. Thus it was the Arctic Ocean where the last Northern Hemisphere’s glaciation incepted.

- The same model identified regions of farther Arctic Ice Sheet expansion by direct snowfall, ice flow and, what is of particular importance, by grounding of ice shelves on submarine uplands and shallow sea bottom, what resulted from ice-shelf thickening and sea-level lowering.

- As a result, the ice domes occurred in marginal seas off the Arctic Russia and Canada, West and Central Siberia, so that huge grounded masses of ice got stored off polar sides of the northern continents. These ice masses developed a west-to-east asymmetry with big ice domes in the west, floating ice shelf in the middle, and slightly (and perhaps only partly) glaciated continental margin in the east.

- The Fram Strait, the largest passage connecting the Arctic with the rest of the World Ocean, got plugged by converging ice masses. As all other polar channels had been closed earlier, the central Arctic Ocean became a completely isolated glaciological and hydrological system. This isolated system had a positive ice-mass balance, so its volume was building up, and therefore had a tendency to expand and push outward. Thus the western marine ice sheets and their north-flowing ice streams were buttressed from the north, while the slighter glaciated shelves and coastal zones in the east, presenting much weaker obstacles to the marine ice expansion, could have been deformed, shoved and overridden by the polar ice masses.

- A marine ice dome/ice shelf system was inherently unstable and prone to abrupt cataclysmic changes, i.e., to gravitational collapses of ice domes and ensuing glacial surges. So, when the system grew ripe, the collapsing and surging suddenly occurred. At that, due to the system’s asymmetry, only minor surges could reach the North Atlantic, while major surges went into the Arctic Ocean, forcing dramatic reorganizations in glacial and hydrologic environments of the entire Arctic White Hole (see Figure 4C).

- Having an estimate of 2 to 4 million km^3 of ice dumped into the confined Arctic Ocean, its water would be squeezed out and erupted onto adjacent land, and its floating ice shelf would be thrust upon the bordering continental margins. And again, due to the system’s asymmetry, these water and ice displacements would go in the west-to-east direction, toward East Siberia, Alaska and Beringia.

- The asymmetrical model suggests that the “western” (North American, Greenland, Scandinavian and Barents-Kara) and the “eastern” (East Siberian and Beringian) ice domes were of different origin and had different histories. The first domes developed in situ from grounded ice shelves and by a highland mechanisms, while the second ones, or great part pf them, grew out of allochthonous slabs of ice brought from the Central Arctic Ocean. Accordingly, the first were longer-lived formations, and their ice flowlines, diverging from ice-dome centers, partly entered the Arctic Ocean. As for the second ice domes, they were shorter-lived, intermittently existing features, the products of southward ice transgressions. During the latter, their ice flowlines just continued those of the adjacent ice shelf. In time-intervals between the ice transgressions, the "eastern" ice domes could behave as regular glacier formations.

It seems to me, that by adopting this centrifugal and asymmetric model, I am setting up a negotiating positions with opponents of the AIS concept. The model shows how the evidence, apparently inconsistent with the AIS concept, can be reconciled with it. For instance, my new interpretation of East Siberian and Beringian glaciation turns out compatible with permafrost parameters of the respective shelves, it accounts for peculiar features of their geomorphology and restricted range of glacio-isostatic rebound, provides new environmental frameworks for ice-age life in the region. In simpler words, why bother arguing with the opponents, if this new scenario leaves plenty of time for deep permafrost to develop on Arctic margin of East Siberia, and for mammoth hordes to thrive there between ice invasions from the north. Or why should we argue with geochronologists, if the ice transgressions and megafloods, at least some of them, were triggered by internal cycles in ice-sheet life, not by climate change.

Deductive Approach

With this theoretical model at hand, an attempt was made to solve the puzzle of East Siberian and Beringian glaciations by applying deductive mode of problem-solving. When the inductive mode, more common in geological sciences, tells the researchers "observe, and seek to explain", the deductive mode's motto is "predict, and seek to observe". Based on this new model, I have made the following major predictions.

First, hard evidence will be uncovered that, during Weichselian/Wisconsin time, the continental margins of East Siberia, Alaska and Beringia were recurrently overridden by extra-broad surging slabs of ice advancing from the north. Their mainstream hit Chukchi Peninsula and Bering Strait area (see Figure 5), thus, predictably, big glacial troughs and through valleys would cross the peninsula and cut its corners. There should be ice-shoved features on the continental margin, as well as evidence for north-to-south glacier sliding, such as parallel grooves and linear gulches.

Second, the evidence would be uncovered that enormous masses of Arctic ice, carrying erratics of East Siberian, Canadian and Beringian provenance, were periodically damped into the North Pacific. Specifically, there should be abundance of glacial boulders scattered on the North Pacific floor, and a record of regional climate cooling caused by expenditure of energy on melting the icebergs.

Third, there should be abundant evidence for powerful eruptions of the Arctic-Ocean water that were taking place concurrently with the ice-sheet collapses and ice-shelf megasurges. Specifically, widespread geomorphic complexes, produced by a series of massive megafloods, would be discovered in northern Eurasia.

Forth, there must be geochronologic data suggestive of the fact that all these cataclysmic events were controlled mostly by the rate of ice-sheet growth and the system instability, rather than by climate changes.

Acting as prescribed by the deductive mode, I sought to observe physical evidence for the predicted events, i.e., for glacial expansion from the Arctic Ocean, as well as for landward ice megasurges and traces of cataclysmic trans-Eurasian megafloods.

To make the long story short, I state that most of the above predictions have already come out justified. We are aware of a wealth of geomorphic evidence attesting to forceful glacial advances from the heart of the Arctic toward Central and East Siberia as well as to Beringia and further south into the North Pacific. In particular, there is aforementioned evidence for Pleistocene north-to-south ice thrusting in the wide area between the Kara Sea [*Polyak et al.,* 2002], the New Siberian Islands (Figures 6, 7) [*Grosswald,* 1988a, 1988b, 1989], Tiksi Harbour (Figure 8) [*Grosswald and Spektor,* 1993; *Grosswald et al.,* 1992] and the lower Yana, Indigirka and Kolyma River basins [*Grosswald,* 1996] (Figure 9). There is as conclusive evidence for glacial overriding of Chukchi Peninsula from the north as well [*Grosswald,* 1998; *Grosswald and Hughes,* 2002].

Especially impressive are New Siberian Islands, – a garland of horseshoe-like islands and shoals, which are, by their geomorphology and structure, very close analogs of the Massachusetts coastal end moraines of the NE United State [*Oldale and O'Hara,* 1984]. Both the Massachusetts moraines and the New Siberian Islands were definitely formed by a fluctuating late Wisconsin/Late Weichselian ice margins. However, judging by different orientation of their push and lee sides, those ice margins advanced in NE America from the west, i.e., from the North American continent, while in northern East Siberia – from the north, i.e., from the Arctic Ocean.

There are submarine north-to-south gulches, discovered on the East Siberian shelf in the course of a US Navy submarine special mission [*McLaren,* 1972], and parallel submeridional grooves on the coastal plains of north Siberia and Alaska, reworked by thermokarst and solifluction into chains of oriented lake-and-ridge complexes [*Grosswald et al.,* 1999].

Also, there is older evidence that a former ice sheet encroached upon Alaska's North Slope from the north, in particular the data on spacing of the Flaxman erratics [*Leffingwell,* 1919; *McCarthy,* 1958]. These erratics clearly imply that giant ice streams originated in Arctic Canada were deflected to Alaska and pushed up its North Slope [*Grosswald and Hughes,* 1999].

As for the dumping of Arctic ice into the North Pacific, it appears evident in the light of new discoveries by marine geologists and oceanographers, especially by ODP *Leg 145 Scientific Party* [1993]. This party's work, as well as research by *Conolly and Ewing* [1970], *Okada* [1980] and *Kotilainen and Shackleton* [1995], made it clear that vigorous sedimentation of ice-rafted debris was among leading features in depositional environment of the Pleistocene North Pacific. Another facet of the ice dumping events, spells of regional climate cooling due to energy losses on melting the Arctic icebergs, have been evidenced in Japan and Southeast China by pollen, oceanographic and glacial records [*Grosswald,* 2002; *Kazakova,* 1955; *Kozarski,* 1963; *Lee,* 1947].

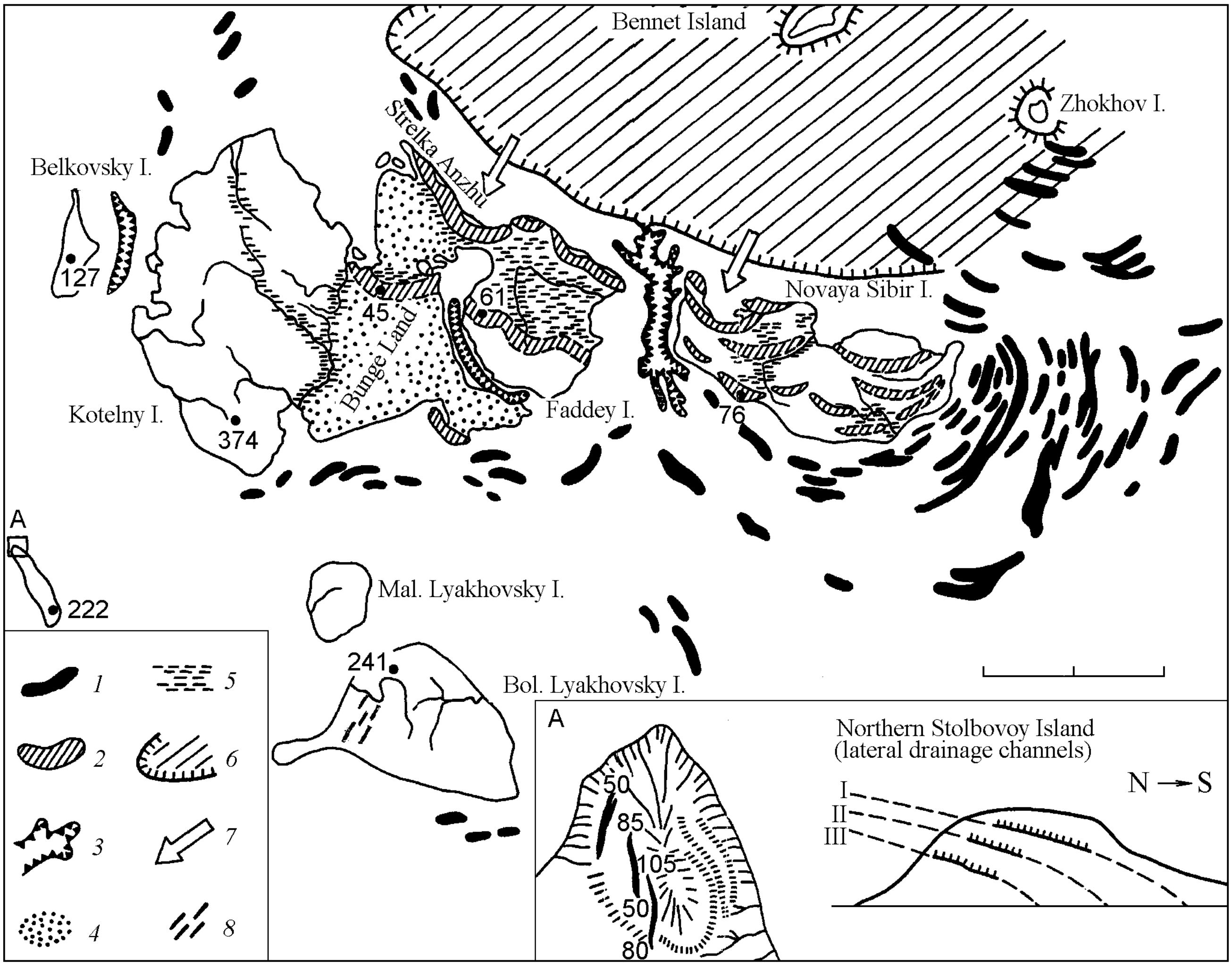

Figure 6. Glacial geologic features of the New Siberian Islands and adjacent continental shelf [*Grosswald,* 1988b, 1989]: (1) submarine glaciotectonic ridges; (2) terrestrial glaciotectonic ridges; (3) tunnel valleys; (4) sandy outwash plains; (5) wet terrains; (6) flat-bottom basin of glacial excavation; (7) direction of horizontal ice pressure; (8) complex of parallel lakes and ridges.

Second prediction, the one concerning cataclysmic trans-Eurasian megafloods concurrent with the megasurges, has also been justified. A huge, thousands of kilometers long, field of parallel ridge-and-furrow landforms, extending from NE Siberia due SW, has been described and mapped in North Eurasia (Figures 10, 11). Judging by its geomorphological analysis, it turned out to be a piece of incontrovertible evidence for the megafloods. Extent of this field, specific parameters of its components, their relation to land topography and some other arguments, generally considered by *Baker* [1997] as megaflood-related, suggest that amount of water involved in individual flooding events was on the order of 10^6 km^3, and floodstream discharges measured in 10^8–10^9 m^3/s. The water velocities had to be also very high: the westward (right-hand) flow deflection and the curvatures of former watercourses, clearly visible on my maps [*Grosswald,* 1999; *Grosswald and Hughes,* 2002], appear suggestive of Coriolis Force having been applied to the floodstreams.

Finally, as predicted, there is a stratigraphic evidence that timing of these major cataclysmic events in East Siberia and Beringia did not fit into the framework of traditional geochronology of glacial peaks. For instance, *Brigham-Grette et al.* [2001] reported that a major glacial advance in Chukchi Peninsula, "not a local event but part of a general, pan-Arctic pattern of glaciation", took place within marine isotope stage 5, not during stages 2 or 4, as elsewhere.

Conclusions

During the Pleistocene ice ages, the Arctic Ocean was becoming a completely confined and very cold basin, so it turned into a White Hole, meaning that all entering ice would neither melt in it, nor escape, so that the ice would inexorably build up in the ocean.

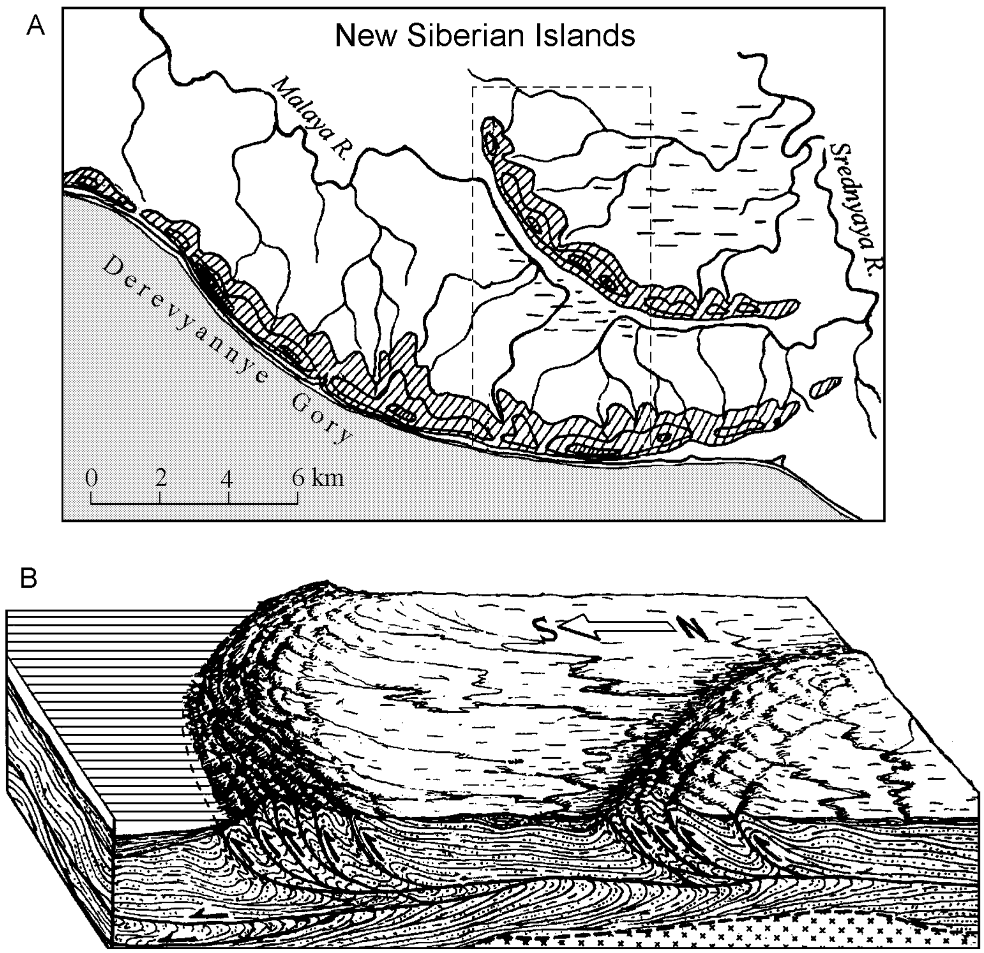

Figure 7. Examples of ice-shoved (glaciotectonic) features of New Siberian Islands produced by glacial pressure from the north. (A) asymmetric ice-thrust ridges of Novaya Sibir Island; and (B) a block diagram showing inferred Pleistocene structure of the island: glaciotectonic slices thrust upon each other and entraining mammoth tusks [*Grosswald,* 1989]. The features are analogous to Massachusetts coastal moraines of NE USA [*Oldale and O'Hara,* 1984], but instead of facing seaward as in USA, they face landward.

This implies that the great Northern Hemisphere's ice sheets were incepted in the Arctic Ocean, not on the middle latitude continents, and that the Arctic Ocean was a major source of ice which glaciated the continents. This also implies that an "ice shelf" and a "marine ice transgression" mechanisms developed by Denton and Hughes were largely involved in the inception, and that ice buildup in the Arctic White Hole would, as inexorably, result in formation of a continuous Arctic Ice Sheet centered on the North Pole. In the light of the White Hole concept, all alternative models of Arctic glaciation, such as "minimal" and "restricted", stand out as totally inconsistent.

A "centrifulal" and "asymmetric" model of the Arctic Ice Sheet is now proposed instead of our previous "circumpolar" model. It suggests that the "western" (North American, Greenland and Barents-Kara) ice domes emerged *in situ* (partly due to grounding of the ice shelf and its landward transgression) and were longer-lived formations, while the "eastern" (East Siberian and Beringian) ice sheets would have resulted from cataclysmic occupations of respective continental margins by allochthonous ice from the Arctic Ocean. By contrast to "western" ice-dome formations, these occupations were probably transient and short-lived events. So for some fractions of glacial time, the "eastern" region was only slightly glacierized and partly ice-free, thus favorable for preservation of permafrost, for terrestrial vegetation, and survival of big animals, such as mammoth, as well as for burial of tabular bodies of dead ice. This opens a way for resolving, at least partly, of the long-lasting controversies in East Siberian and Beringian paleogeography.

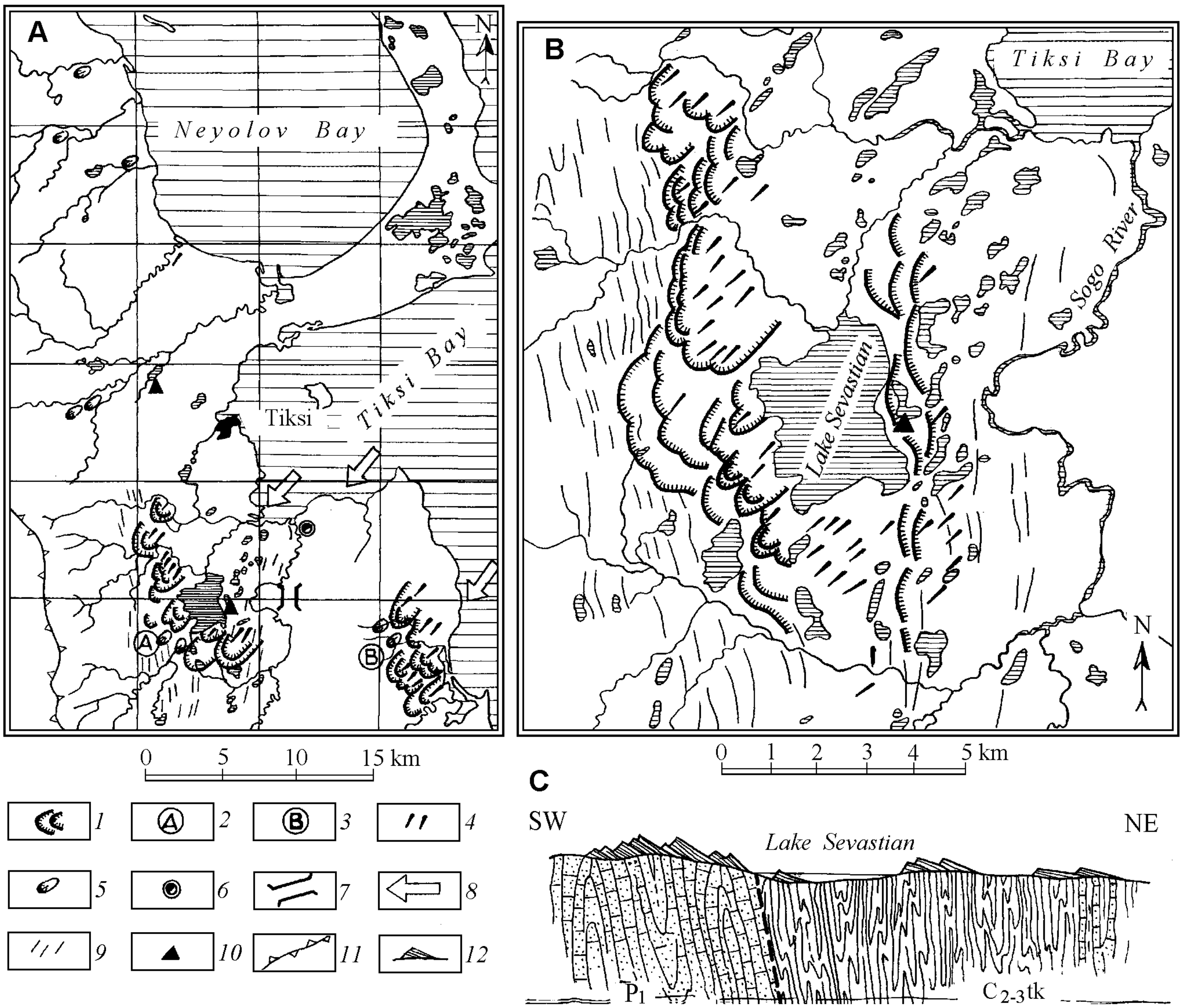

Figure 8. (A), major glacial features of the Tiksi Harbor and surrounding area of northern Yakutia; (B), large-scale map of glaciotectonic landforms in the vicinity of Lake Sevastian, and (C), a latitudinal cross-section of Lale Sevastian area [*Grosswald and Spektor,* 1993].
(1) glaciotectonic thrust features; (2) glacially tectonized area of Lake Sevastian; (3) the same of Belugalakh; (4) rock drumlins; (5) sites with striated boulders; (6) folded and faulted beds of Tertiary rocks; (7) meltwater overflow channel; (8) inferred direction of ice flow; (9) structural lines (strikes) in Paleozoic beds; (10) site of core drilling; (11) crest of Kharaulakh Range; (12) blocks of Paleozoic rocks (on the cross-section) upthrusted by ice in SW direction.

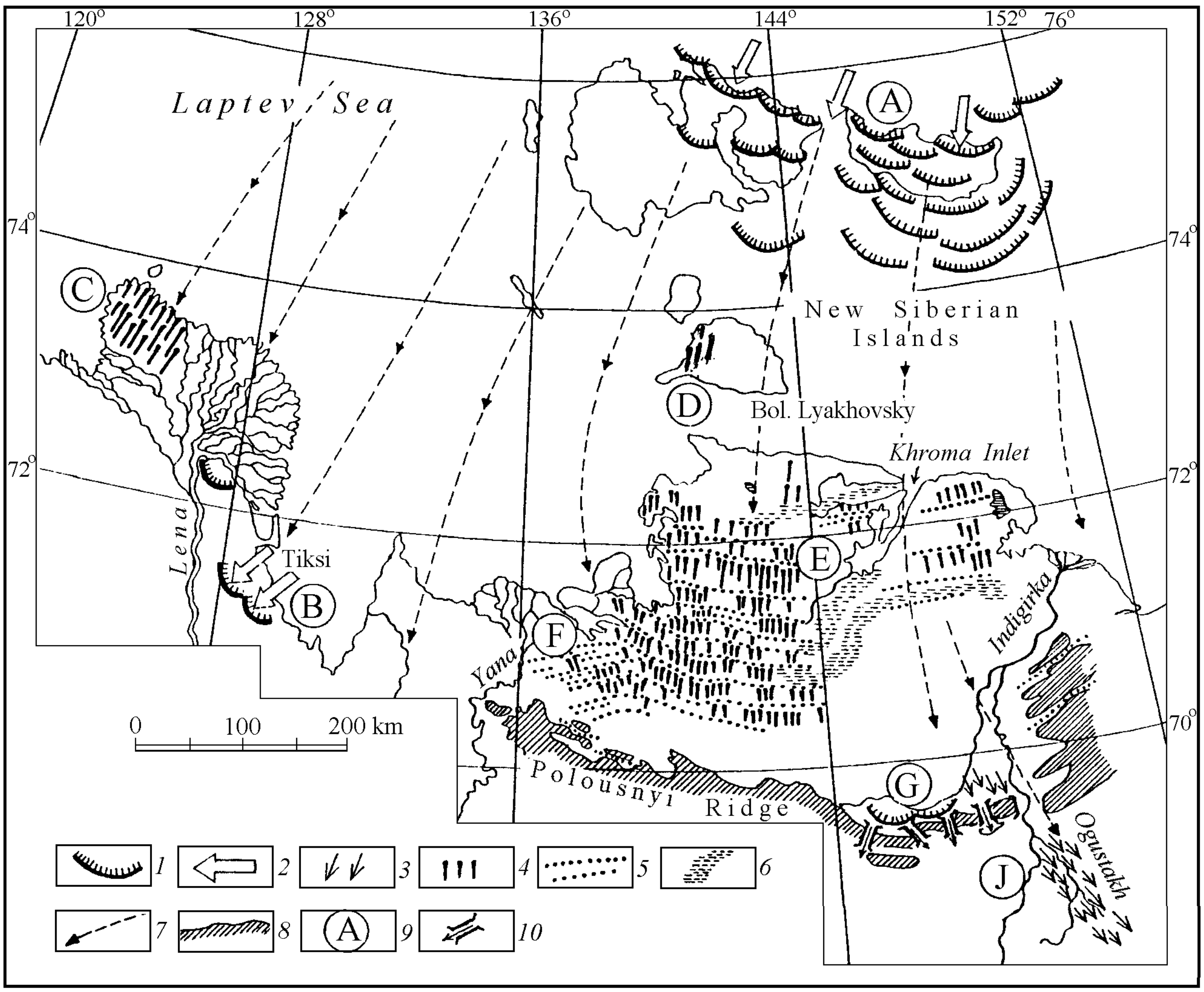

Figure 9. Spatial organization of glaciotectonic features, oriented lake-and-ridge assemblages, drumlins, and drainage channels on Arctic coastal plain between the lower Lena and Indigirka rivers, NE Siberia. The areas: (A) New Siberian Islands, (B) Tiksi area, (C) NW Lena Delta, (D) Bol. Lyakhovsky Island, (E) Yana-Indigirka Lowland, (F) Yana River delta area, (G) piedmont of the eastern Polousnyi Ridge, (J) Indigirka-Ogustakh basin. The symbols: (1) ice-shoved features, (2) ice flow directions, (3) drumlins and drumlinoids, (4) orientation of longitudinal lakes and ridges, (5) orientation of transverse ridges, (6) former pradolinas, (7) ice flowlines, (8) uplands, (9) the areas described above, (10) glacial through valleys (breaches).

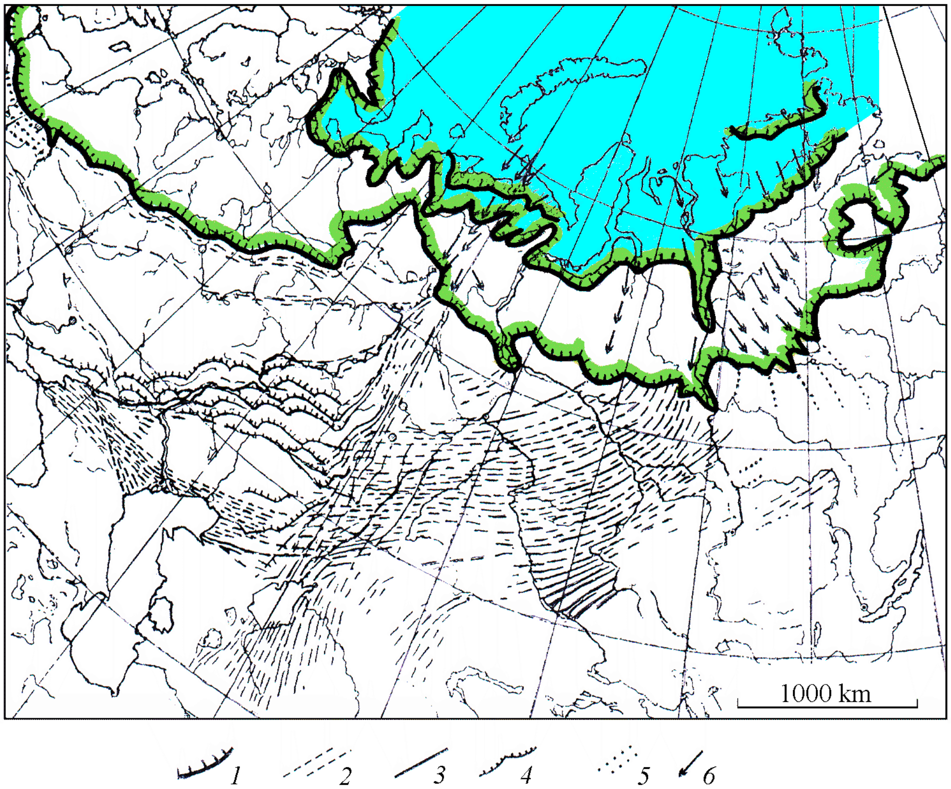

Figure 10. Geography of ridge-and-furrow complexes ("Baer's mounds") in northwestern and north-central Eurasia [*Grosswald,* 1999]. (1) Maximum and recessional end moraines of the Late Weichselian, (2) zone of ridge-and-furrow landforms, (3) giant straightline channels, (4) "skirting" valleys of northern Caspian Lowland, (5) inferred continuations of cataclysmic water flow, (6) furrows of subglacial streams.

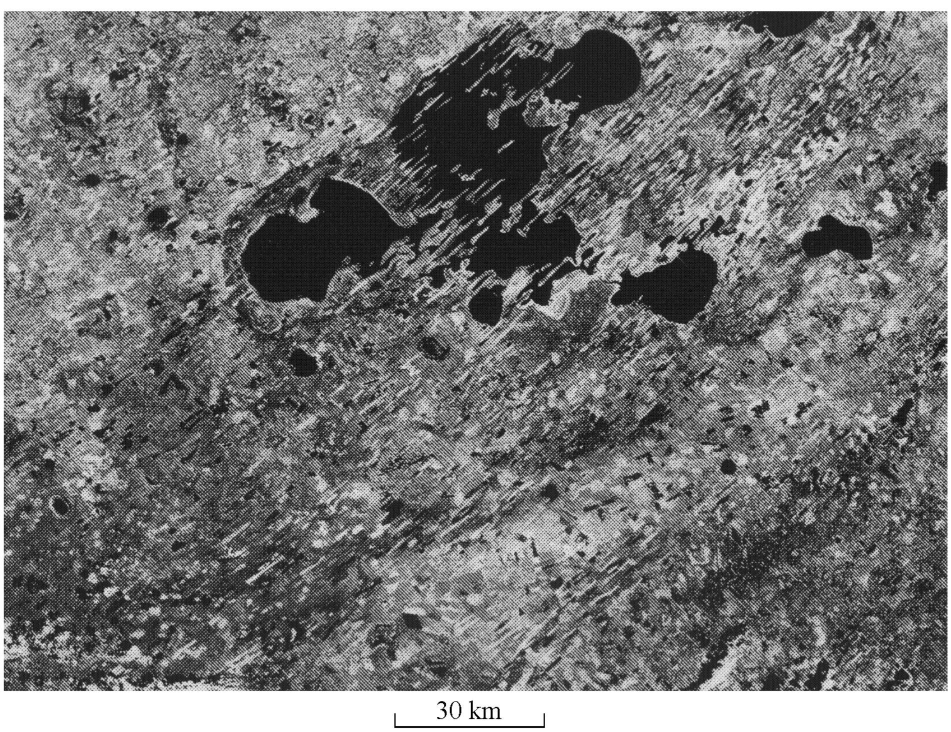

Figure 11. An example of ridge-and-furrow topography produced by trans-Eurasian megafloods: a Landsat mosaic of space images, Baraba Lowland of central West Siberia.

For instance, the model suggests that the arguments of Grosswald-Hughes vs. Brigham-Grette and others are, in some respect, missing the point: while according to our concept East Siberia and Beringia were heavily glaciated by transient, *alien* ice, our opponents keep focusing on an indigenous glaciation, which could be not only smaller, but also of different age, than "ours".

Buildup of ice in the Arctic Ocean, its expansion upon surrounding continents were the primary inception mechanisms of the Northern Hemisphere's glaciation. Recurrent gravitational collapses of the unstable "western" ice domes accompanied this expansion, causing abrupt cataclysmic events, such as north-to-south ice-sheet transgressions, dumping of Arctic ice into the North Pacific and the North Atlantic, and massive eruptions of water out of the Arctic Ocean, resulting in transcontinental megafloods.

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References

Antevs, E., Maps of the Pleistocene glaciations, *Bull. Geol. Soc. Amer., 40,* 631–720, 1929.

Atlas of the energy balance of the oceans, 52 maps, 32 pp., Sevastopol, Mar. Hydrophys. Inst. Acad. Sci. USSR, 1970.

Baker, V. R., Megafloods and glaciation, in *Late Glacial and Postglacial Environmental Changes* (I. P. Martini, Ed.), pp. 98–108, New York-Oxford, Oxford Univ. Press, 1997.

Barash, M. S., *Quaternary paleoceanography of the Atlantic Ocean,* (in Russia), 272 p., Nauka, Moscow, 1988.

Belderson, R. H., N. H. Kenyon, and J. B. Wilson, Iceberg plough marks in the northern Atlantic, *Palaeogeogr., Palaeoclimatol., Palaeoecol., 13,* 215–224, 1973.

Bernhardi, A., Wie kamen die aus dem Norden stammenden Felsbruchstucke und Geschiebe, welche man in Norddeutschland und den benachbarten Landern findet, an ihre gegenwartigen Fundorte? *Jahrbuch Mineralogie, Geognosie, Petrefaktenkunde, 3,* (Heidelberg), pp. 257–267, 1832.

Bintanja, R., R. S. W. van de Wal, and J. erlemans, Global ice volume variations through the last glacial cycle simulated by a 2-D ice-dynamical model, *Quatern. Internat., 95/96 (C),* 11–23, 2002.

Brigham-Grette, J., D. M. Hopkins, V. F. Ivanov, et al., Last Interglacial (isotope stage 5) glacial and sea-level history of coastal Chukotka Peninsula and St. Lowrence Island, western Beringia, *Quatern. Science Reviews, 20,* (1–3), 419–436, 2001.

Broccoli, A. J., Tropical cooling at the last glacial maximum: an atmosphere mixed layer ocean model simulation, *J. Climate, 13,* (5), 952–976, 2000.

Budd, W. F., B. Courts, and R. C. Warner, Modelling the Antarctic and Northern Hemisphere ice sheet changes with global climate through the glacial cycle, *Annals Glaciol., 27,* 153–160, 1998.

Charlesworth, J. K., *The Quaternary era with special reference to its glaciation,* Vol. 2, pp. 595–1700, Edward Arnold, London, 1957.

CLIMAP Project members, Seasonal reconsructions of the Earth's surface at the last glacial maximum, U.S. Geol. Soc. Map and Charts Series, MC-34, 1981.

Conolly, J. R., and M. Ewing, Ice-rafted detritus in northwest Pacific deep-sea sediments, *Geol. Soc. Amer. Memoirs, 126,* 219–231, 1970.

Crary, A. P., Arctic ice island and ice shelf studies, Part 2, *Arctic, 13,* 32–50, 1960.

Denton, G. H., and T. J. Hughes (Eds.), *The last great ice sheets,* 484 pp., Wiley-Interscience, New York, 1981.

Dyke, A. S., J. T. Andrews, P. U. Clark et al., The Laurentide and Innuitian ice sheets during the Last Glacial Maximum, *Quatern. Science Reviews, 21,* 9–31, 2002.

Flint, R. F., *Glacial and Quaternary geology,* 892 pp., New York et al.: John Wiley and Sons, 1971.

Gerasimov, I. P., and K. K. Markov, *Quaternary Geology,* 364 pp., Uchpedgiz Press, Moscow (in Russian), 1939.

Grosswald, M. G., Late Weichselian ice sheet of northern Eurasia, *Quatern. Res., 13,* 1–32, 1980.

Grosswald, M. G., *Ice sheets of the continental shelves,* 216 pp., Nauka, Moscow, 1983.

Grosswald, M. G., Antarctic-style ice sheet in the Northern Hemisphere: toward a New global glacial theory (in Russian), *Materials of Glaciol, Studies, 63,* 3–25, 1988a.

Grosswald, M. G., Evidence for ice-sheet glaciation of New Siberian Islands and adjacent continental shelf (in Russian), *Doklady Akad. Nauk SSSR, 302,* (3), 654–658, 1988b.

Grosswald, M. G., Ice-sheet glaciation of the East-Siberian continental shelf during the Late Pleistocene, in *Pleistotsen Sibiri, Stratigrafiya I mezhregionfl'nye korrelyatsii* (N. A. Skabichevskaya, Ed.), pp. 48–57, Nauka, Novosibirsk, 1989.

Grosswald, M. G., Evidence for transgression of a marine ice sheet from the Arctic continental shelf toward the coast of NE Siberia (in Russian), *Doklady Akad. Nauk, 350,* (4), 535–540, 1996.

Grosswald, M. G., Late Weichselian ice sheets in Arctic and Pacific Siberia, *Quatern. Internat., 45/46,* 3–18, 1998.

Grosswald, M. G., *Cataclysmic megafloods in Eurasia and the Polar ice sheets* (in Russian), 120 pp., Scientific World, Moscow, 1999.

Grosswald, M. G., The Late Weichselian Barents-Kara Ice Sheet: In defense of a maximum reconstrustion, *Russian J. Earth Sciences, 3,* (6), 427–452, 2001a

Grosswald, M. G., The Arctic "White Hole" as a factor of the Ice-Age Earth System (in Russian), *Izvestiya Akad. Nauk, Seriya Geogr,* (6), 32–41, 2001b.

Grosswald, M. G., Large-scale global change in Japan (as revealed by glaciohydrological evidence), in *Vergletscherungen in japanischen Gebirgen und ihr Einfluss auf die Entwicklung des Biwa-Sees* (Shoji Horie, Ed.), pp. 306–335, Universitätsverlag Wagner, Innsbruck, 2002.

Grosswald, M. G., and T. Hughes, Paleoglaciology's grand unsolved problem, *J. Glaciol., 41,* (138), 313–332, 1995.

Grosswald, M. G., and T. Hughes, The case for an ice shelf in the Pleistocene Arctic Ocean, *Polar Geogr., 23,* (1), 23–54, 1999.

Grosswald, M. G., and T. Hughes, The Russian component of an Arctic Ice Sheet during the Last Glacial Maximum, *Quatern. Science Reviews, 21,* 123–146, 2002.

Grosswald, M. G., and M. S. Krass, Last deglaciation of the Barents-Kara shelf: role of gravitational collapses and surges (in Russian), *Materials of Glaciol. Studies, 85,* 205–218, 1998.

Grosswald, M. G., and V. B. Spektor, Glacial landforms of the Tiksi Region (western coast of Buor-Khaya Bay, north Yakutia) (in Russian), *Geomorfologiya,* (1), 72–82, 1993.

Grosswald, M. G., T. Hughes, and N. P. Lasca, Oriented lake-and-ridge assemblages of the Arctic coastal plains: glacial landforms modified by thermokarst and solifluction, *Polar Record, 35,* (194), 215–230, 1999.

Grosswald, M. G., W. Karlen, Z. Shishorina, and A. Bodin, Glacial landforms and the age of deglaciation in the Tiksi area, East Siberia, *Geogr. Annaler, 74A,* (4), 295–304, 1992.

Huybrechts, P., and S. T'siobel, A three-dimensional climate-ice-sheet model applied to the Last Glacial Maximum, *Annals Glaciol., 25,* 333–339, 1997.

Hughes, T. J., G. H. Denton, and M. G. Grosswald, Was there a late Würm Arctic Ice Sheet? *Nature, 266,* 598–602, 1977.

Hughes, T. J., The marine ice transgression hypothesis, *Geograf. Annaler, 69A,* (2), 237–250, 1986.
Hughes, T. J., *Ice sheets,* 343 p., Oxford University Press, New York, Oxford, 1998.
Ives, J. D., J. T. Andrews, and R. G. Barry, Growth and decay of the Laurentide ice sheet and comparison with Fenno-Scandinavia, *Naturwissenschaften, 62,* 118–125, 1975.
Johnsen, S. J., D. Dahl-Jensen, W. Dansgaard, and N. Gundesrup, Greenland palaeotemperatures derived from GRIP bore hole temperature and ice core isotope profiles, *Tellus, 47B,* (5), 624–629, 1995.
Kazakova, N. M., Some data on the former glaciation of China, in *Problems of geomorphology and Paleogeography of Asia* (I. P. Gerasimov, Ed.), pp. 243–255, Izd. AN SSSR, Moscow, 1955.
Kotilainen, A., and N. J. Shackleton, Rapid climate variability in the North Pacific Ocean during the past 95,000 years, *Nature, 377,* (6547), 323–326, 1995.
Kozarski, S., Problem of Pleistocene glaciations in the mountains of East China, *Zeitschr. für Geomorphol., N.F., 7,* (1), 48–70, 1963.
Lee, J. S., *Quaternary glaciations in the Lushan area, central China,* Acad. Sinica. Institute of Geology Nanking. Man. Ser. B. V. 2, 37 pp., 1947.
Leffingwell, E. d. K., *The Canning River region, Northern Alaska,* US Geol. Survey Profes. Paper 109, 251 pp., 1919.
Leg 145 Scientific Party, Paleoceanographic record of North Pacific quantified, Eos, Transactions, Amer. Geophys. Union, 74, (36), pp. 406, 411, 1993.
Lindstrom, D. R., and D. R. MacAyeal, Paleoclimatic constraints on the maintenance of possible ice-shelf cover in the Norwegian and Greenland Seas, *Paleoceanography, 1,* (3), 313–337, 1986.
Lowe, J. J., and M. J. C. Walker, *Reconstructing Quaternary Environments,* 2nd edition, Hong-Kong, Longman, 1997.
McCarthy, G. R., Glacial boulders on the Arctic coasts of Alaska, *Arctic, 11,* (2), 71–85, 1958.
McLaren, A. S., *USS Queenfish's 1970 Polar Expedition,* 10 pp., Unclassified manuscript, 1972.
Okada, H., Pebbles and carbonate nodules from Deep Sea Drilling Project Leg 56 cores, *Initial Reports of the Deep Sea Drilling Project,* Vols 56, 57, pp. 1089–1105, Washington D.C., 1980.
Oldale, R. N., and C. J. O'Hara, Glaciotectonic origin of the Massachusetts coastal end moraines and a fluctuating late Wisconsinan ice margin, *Geol. Soc. Amer. Bull., 95,* (1), 67–74, 1884.
Polyak, L., M. H. Edwards, B. J. Coackley, and M. Jakobsson, Ice shelves in the Pleistocene Arctic Ocean inferred from glacigenic deep-sea landforms, *Nature, 410,* (6827), 453–457, 2001.
Polyak, L., V. Gataullin, V. Gainanov, V. Gladysh, and Yu. Goremykin, Kara Sea expedition yields insight into LGM ice sheet extent, *Eos, Transactions, Amer. Geophys. Union, 83,* pp. 525, 529, 2002.
Prik, Z. M., Climate [of the Arctic], in *The Soviet Arctic. Seas and islands of the Arctic Ocean* (Y. Y. Gakkel, and L. S. Govorukha, Eds.) (in Russian), pp. 108–149, Nauka, Moscow, 1970.
Romanovski, N. N., and H. W. Hubberten, Formation and evolution of permafrost within continental shelves and coastal lowlands (example of the Laptev Sea) (in Russian), *Izvestiya Akad. Nauk, Seriya Geogr.,* (3), 15–28, 2001.
Schenk, P. M., W. B. McKinnon, D. Gwynn, and J. M. Moore, Flooding of Ganymede's bright terrains by low-viscosity water-ice lavas, *Nature, 410,* 57–60, 2001.
Sher, A., Is there any real evidence for a huge shelf ice sheet In East Siberia? *Quatern. Internat., 28,* 39–40, 1995.
Spielhagen, R., Enigmatic Arctic Ice sheets, *Nature, 410,* 427–428, 2001.
Svendsen, J. I., V. I. Astakhov, D. Yu. Bolshiyanov, et al., Maximum extent of the Eurasian ice sheets in the Barents and Kara Sea region during the Weichselian, *Boreas, 28,* (1), 234–242, 1999.
Vinogradova, P. S., A. G. Kislyakov, V. M. Litvin, and L. S. Ponomarenko, Results of the 1955-1956 oceanographic investigations in area of the Iceland-Faroes Sill (in Russian), *Proc. Polar Res. Inst. Marine Fishery and Oceanography, 2,* 106–134, 1959.
Weertman, J., Stability of the junction of an ice sheet and an ice shelf, *J. Glaciol., 13,* (67), 3–11, 1976.

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