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Paleoglaciology's grand unsolved problem

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ABSTRACT. The paleoglaciological concept that during the Pleistocene glacial hemi-cycles a super-large, structurally complex ice sheet developed in the Arctic and behaved as a single dynamic system, as the Antarctic ice sheet does today, has not yet been subjected to concerted studies designed to test the predictions of this concept. Yet, it may hold the keys to solutions of major problems of paleoglaciology, to understanding climate and sea-level changes. The Russian Arctic is the least-known region exposed to paleoglaciation by a hypothetical Arctic ice sheet but now it is more open to testing the concept. Implementation of these tests is a challenging task, as the region is extensive and the available data are controversial. Well-planned and co-ordinated field projects are needed today, as well as broad discussion of the known evidence, existing interpretations and new field results. Here we present the known evidence for paleoglaciation of the Russian Arctic continental shelf and reconstruct possible marine ice sheets that could have produced that evidence.

INTRODUCTION

Writing in *Nature*, Weertman (1976) stated "Over the past two decades, our understanding of the behavior of glaciers, ice shelves, and ice sheets has progressed and increased very nicely. We know enough now to recognize a grand glaciological problem that remains to be solved. The West Antarctic Ice Sheet is this problem." He then pointed out that it is a "marine" ice sheet grounded well below sea level, so its stability depends on a stable sea level. Yet, sea level has changed dramatically in the last 20000 years. He asked "How then did this ice sheet form? Why does it remain in existence? Is it growing or disintegrating at the present time?" He noted that the West Antarctic ice sheet is drained by ice streams, which are fast currents of ice similar to great rivers that drain the other continents. Ice streams supply the large floating ice shelves that fringe West Antarctica and, like surging mountain glaciers, ice streams may also be unstable. Several large-scale glaciological research programs are now addressing all of these questions.

In the nearly two decades since Weertman (1976) identified the marine West Antarctic ice sheet as "glaciology's grand unsolved problem", paleoglaciology has also advanced very nicely and we know enough now to recognize a grand paleoglaciological problem that remains to be solved. That problem is the possibility that a largely marine ice sheet formed, grew and collapsed in the Arctic during Quaternary glaciation cycles (Mercer, 1970). As an unsolved paleoglaciological problem, it is remarkably parallel to the modern Antarctic glaciological problem formulated by Weertman. Along with our colleague, G. H. Denton, we argued that this hypothetical former ice sheet, which we called the Arctic ice sheet, was an Arctic counterpart to the present-day Antarctic ice sheet, because it consisted of terrestrial ice domes grounded on land above sea level and marine ice domes grounded on continental shelves below sea level with marine ice domes drained by ice streams that supplied an ice shelf that floated on the deep part of the Arctic Ocean and calved into the North Atlantic (Hughes and others, 1977). We further suggested that the hypothetical Arctic ice sheet interacted vigorously with the ocean and behaved as a single dynamic system, as the Antarctic ice sheet does today.

As with glaciology's grand unsolved problem in the Antarctic, the grand unsolved problem of Arctic paleoglaciology translates into such questions as: "Did an Arctic ice sheet develop during Quaternary glaciation cycles? If it did, what was its specific extent and structure? In particular, did it include grounded marine ice domes and floating ice shelves? How long did it remain in existence? What was its disintegration history? Obtaining the answers and thus testing the hypothesis is a difficult task because evidence for the Arctic ice sheet is scattered over a huge, hardly accessible area and it is often obscured by active periglacial processes, or is concealed under permafrost-bound ice-rich sand and silt, or is submerged by the sea on continental shelves. The hypothesis of the Arctic ice sheet has not been subjected to concerted studies pointedly designed to test its predictions, although the critical region for this test, the Russian Arctic, is now open to international studies, and Russian components of an Arctic ice sheet may hold keys

to understanding global climatic and oceanographic changes.

A sense of urgency in addressing paleoglaciology's grand unsolved problem exists, in view of the contention by Miller and de Vernal (1992) that greenhouse warming in the decades ahead may initiate ice-sheet growth in High Arctic latitudes. They argued that greenhouse warming may duplicate the warmer winters and cooler summers in these latitudes that accompanied the onset of the last glaciation cycle. In particular, we suggest sea ice might not form in the Norwegian and Greenland Seas during warmer Arctic winters, thereby allowing greater precipitation over the permanent sea ice that does not melt during cooler Arctic summers. This would upset the precarious present-day mass balance in the High Arctic, so that sea ice would ground on shallow Arctic continental shelves and snowfields would grow on Arctic islands and uplands. This could impound the great rivers that drain into the Arctic from Eurasia and North America, creating a vast "White Hole" within which precipitation could accumulate but not escape. The area of this "White Hole" is shown in Figure 1 which is comparable to the maximum areal extent of Northern Hemisphere glaciation during the last glaciation cycle, including ice sheets in Eurasia and North America, and ice shelves or sea ice over the Arctic Ocean. The "White Hole" would account for the drop in sea level at the beginning of the cycle that was as rapid as the rise in sea level at its termination.

Fig. 1. The "White Hole" at inception of the Arctic ice sheet. Present-day and glacial maximum shorelines are solid and dotted lines, respectively. The heavy solid line encloses the Arctic ice sheet at inception. The heavy dashed line encloses watersheds of rivers flowing toward the Arctic ice sheet. Light solid lines are limits of glaciation at a Quaternary glacial maximum.

Figure 2 shows the hypothetical Arctic ice sheet just prior to termination. Note the extensive ice-dammed

Fig. 2. The proposed Arctic ice sheet during a Quaternary glacial maximum. Present-day and glacial maximum shorelines are dotted and solid lines, respectively. Black areas are ice-dammed lakes and glacier-fed lakes at the glacial maximum. For the ice sheet, solid lines are the maximum extent of glaciation and dashed lines are ice-shelf grounding lines.

lakes that drained into either the Sea of Okhotsk or the Mediterranean Sea, and that would influence the present-day arid climate of Central Asia. Figure 2 is based on the glacial geological, geomorphological and periglacial features reported in Russia by Grosswald (1993) and located in Figure 3, on a hypothetical marine glaciation of central Beringia proposed by Hughes and Hughes (1994), and on a glaciological interpretation of oriented lakes on the Arctic coastal plains of Siberia and Alaska. This evidence will by summarized under the headings: ice-dammed lakes, terrestrial ice sheets, marine ice sheets, ice streams and floating ice shelves. Figure 4 reproduces the glacial geological and geomorphological features on Arctic continental shelves and adjacent mainlands shown in Figure 3 and adds similar features in northeast Siberia and northwest Alaska, all of which were used to construct flowlines for the marine ice-sheet reconstructions in Figures 5 and 6.

ICE-DAMMED LAKES

An Arctic ice sheet would consist of an Eurasian ice sheet that was joined to the ice sheets of Greenland and North America by an ice shelf floating on the Arctic Ocean. The most conclusive evidence for an Eurasian ice sheet would be impoundment of the large Eurasian rivers that now flow into the Arctic Ocean, thereby creating Eurasian ice-dammed lakes during the last glaciation. These lakes constitute additional compelling evidence for the Eurasian ice sheet and their history constitutes a large-scale paleoglaciological problem in itself.

That a continuous Eurasian ice sheet, if it existed, had

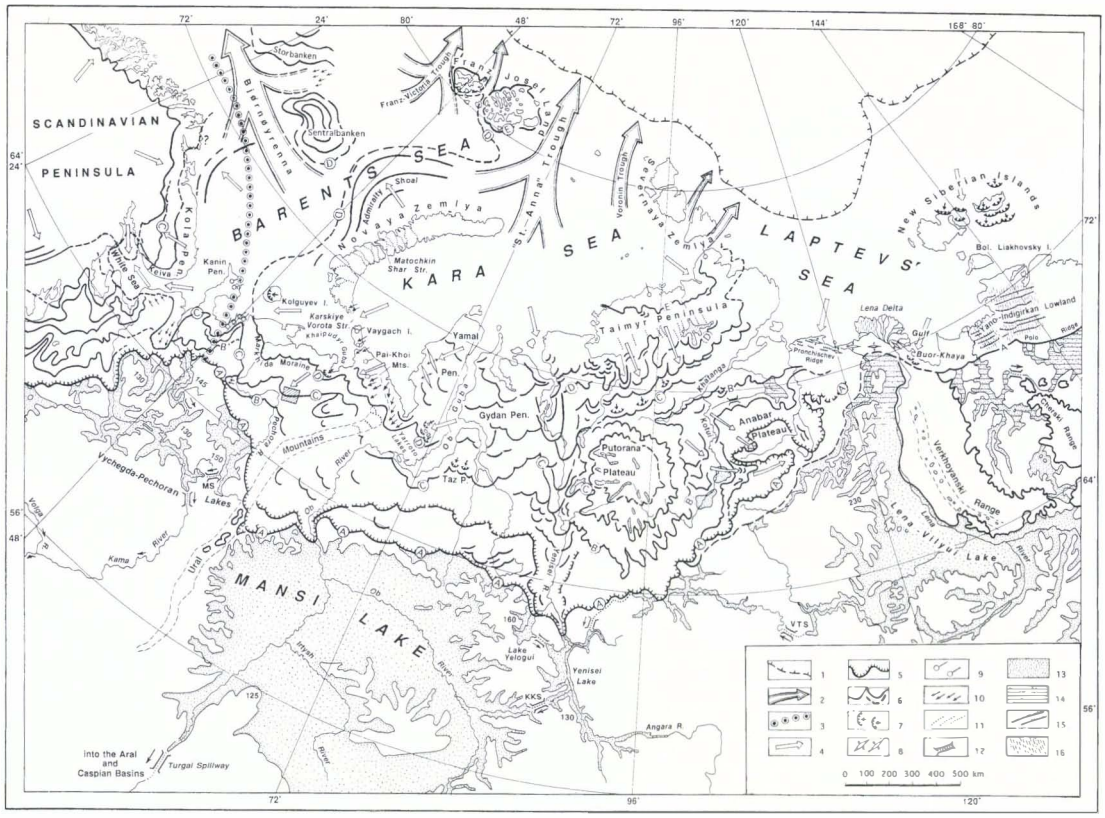


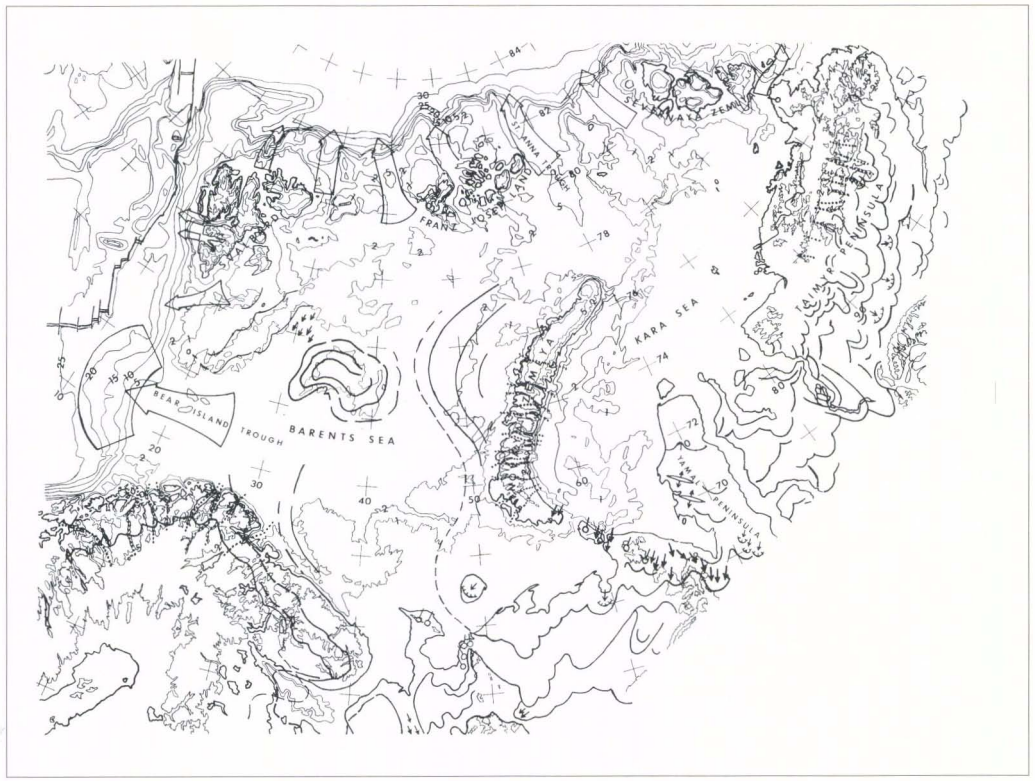
Fig. 3. Evidence for glaciation of Arctic Russia by a marine ice sheet. Symbols on the map are: 1. Brink of the continental shelf; 2. Directions and relative size of submarine troughs (channels); 3. Boundary of the Scandinavian and Kara ice sheets during the last glacial maximum; 4. Inferred directions of ice flow; 5. Outer limit of the Scandinavian and Kara ice sheets during the last glacial maximum (moraine belt A); 6. Ice limits, late glacial and Holocene stages (moraines B, C, D, E and intermittent); 7. Hill-and-hole pairs; 8. Ice-shoved folding in unconsolidated sediments; 9. Glacial grooves and striations; 10. Drumlins, drumlinoids, fluting and other lineations; 11. Glacial breaches (through valleys); 12. Major spillways, meltwater-overflow channels; 13. Ice-dammed lakes — their maximum extent at the Last Glacial Maximum; 14. "Yedoma" areas (accumulations of ice-rich silt and sand); 15. "Alas" valleys (parallel valleys created by melting of ground ice); 16. Direction of long axes of "oriented lakes".

to impound the northward-flowing rivers of Eurasia and cause formation of huge proglacial meltwater lakes was understood as early as the mid-nineteenth century. The lakes were first postulated and much later confirmed on the basis of scattered pieces of geological eviden
Recently, a late W
was published for European Russia (Kv
for west Siberia (Volkov
others, 1980; Grosswald, 1980). A sketch of the meltwater-drainage system at the Last Glacial Maximum, showing its status before erosional deepening of spillways, is included in Figure 3. This picture is based on all the available information on the occurrence of glacio-lacustrine sediments and shorelines studied and, in some instances, dated in the field. The rest was reconstructed by geomorphologic methods, with particular attention to the geography of flat expanses of paleo-lake terraces, *Urstromtäler* and spillways, as well as to spacing of *yedoma* accumulations. As a result, two transcontinental meltwater-drainage systems, western and eastern, were visualized.

The western system was the largest. It consisted of the Vychegda–Pechoran lakes of the northern Russian Plain, the Mansi and Yenisei lakes of west Siberia (of which the Mansi was the world's largest ice-dammed lake), Lena–Vilyui lake of East Siberia, as well as of the interconnected basins of the Aral, Caspian and Black "Seas". The catchment area of the system amounted to 21×10^6 km^2.

The eastern system was
Siberian part of the Eurasian ice sheet and was represented not so much by lakes but mostly by yedomas, which are thick accumulations of ice-rich silt and fine sand. Yedomas formed in ice-dammed proglacial deltas under very cold and dry conditions, when each summer's meltwater turned into ice during the following winter. Only a small proportion of the yedomas was formed during the Last Glacial Maximum. Most of it formed during the Late Glacial and Holocene ice retreat. The yedomas are still preserved on the Arctic coastal lowlands, where they apparently bury and conceal nearly the whole bulk of ice-marginal land forms.

The lakes experience drastic changes of their extents, outlines and levels, which were caused by the ice-sheet retreats and re-advances, by isostatic crustal rebound and by erosional deepening or sediment infilling of the spillw
changes. All we know is that, during the Last Glacial Maximum, the western system discharged meltwater into the eastern Mediterranean Sea and the eastern system



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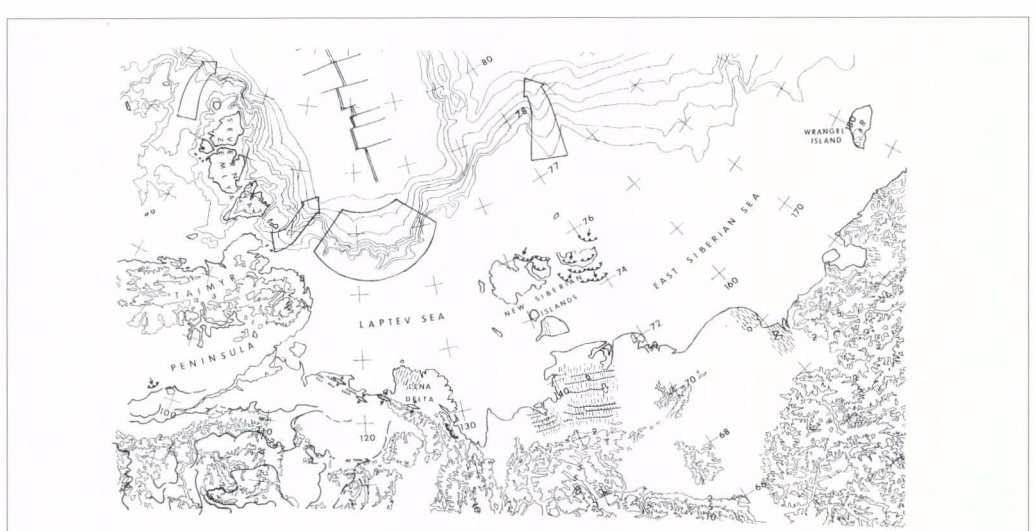

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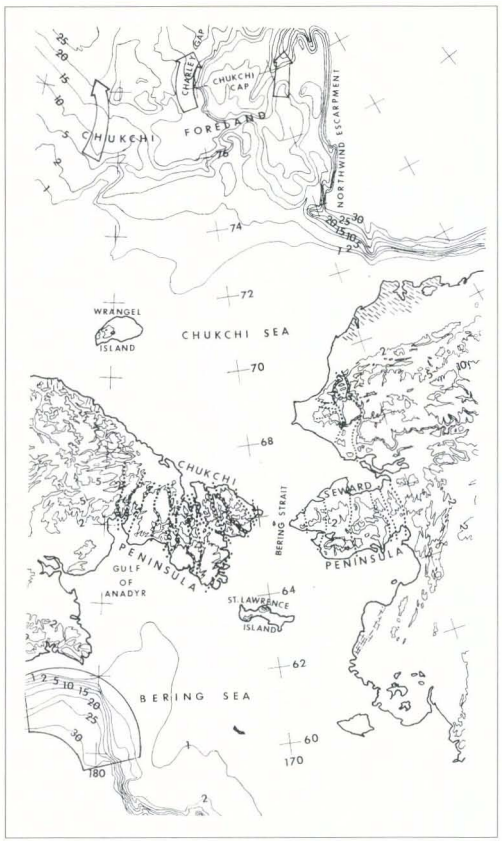

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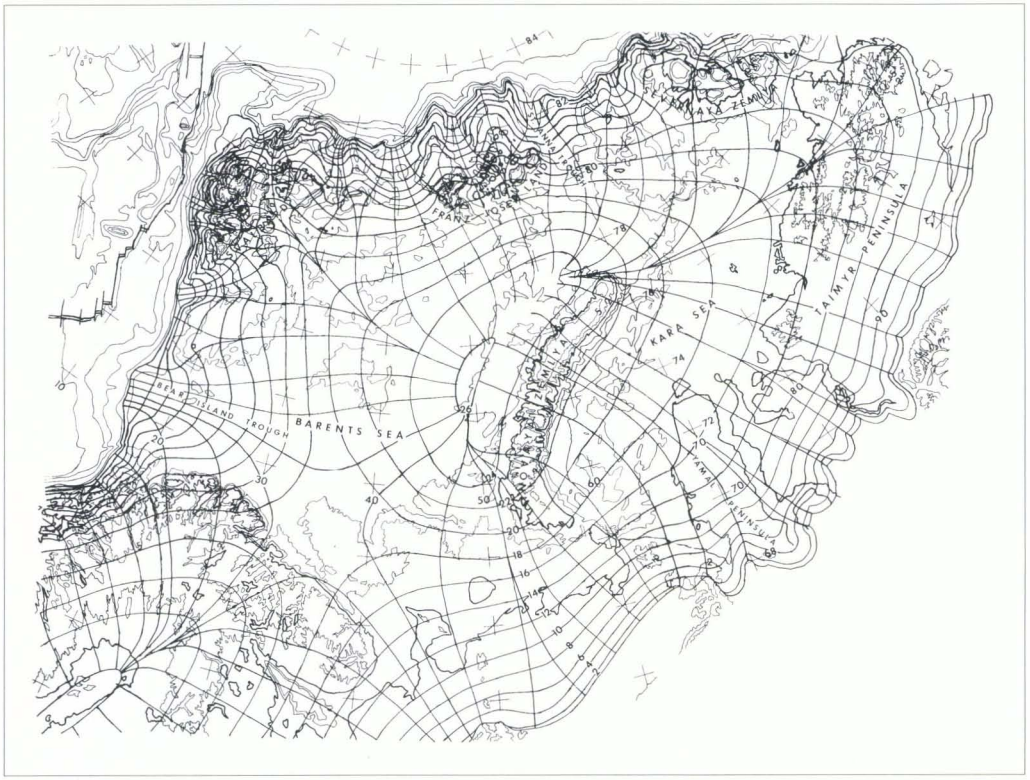
Fig. 4. Evidence for glaciation of Arctic Eurasia and Alaska by a marine ice sheet on the continental shelf. Symbols for the various kinds of evidence are defined in the caption to Figure 3. In addition, depositional fans are shown on the continental slope for the western Barents Sea, the northern Laptev Sea and the southwestern Bering Sea. Topographic contours (in hundreds of meters) are shown at 200, 500 and 1000 m. Bathymetric contours (in hundreds of meters) are shown at 100, 200, 500, 1000, 1500, 2000, 2500 and 3000 m. These contours are from the American Geographical Society Arctic region map, sheet 14 of the world 1 : 5 000 000 map series, divided into (a) the western Eurasian Arctic, (b) the central Eurasian Arctic and (c) the eastern Eurasian Arctic.



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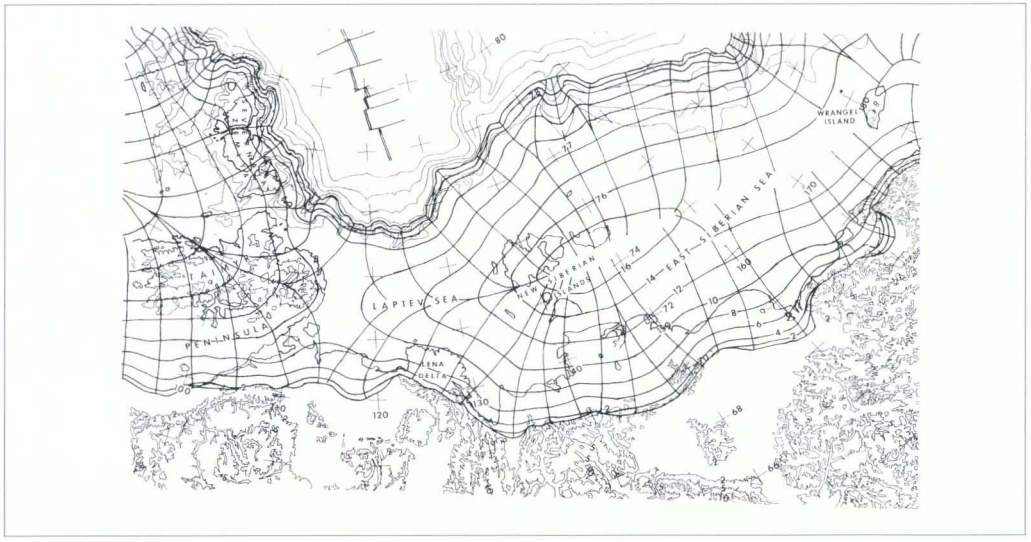

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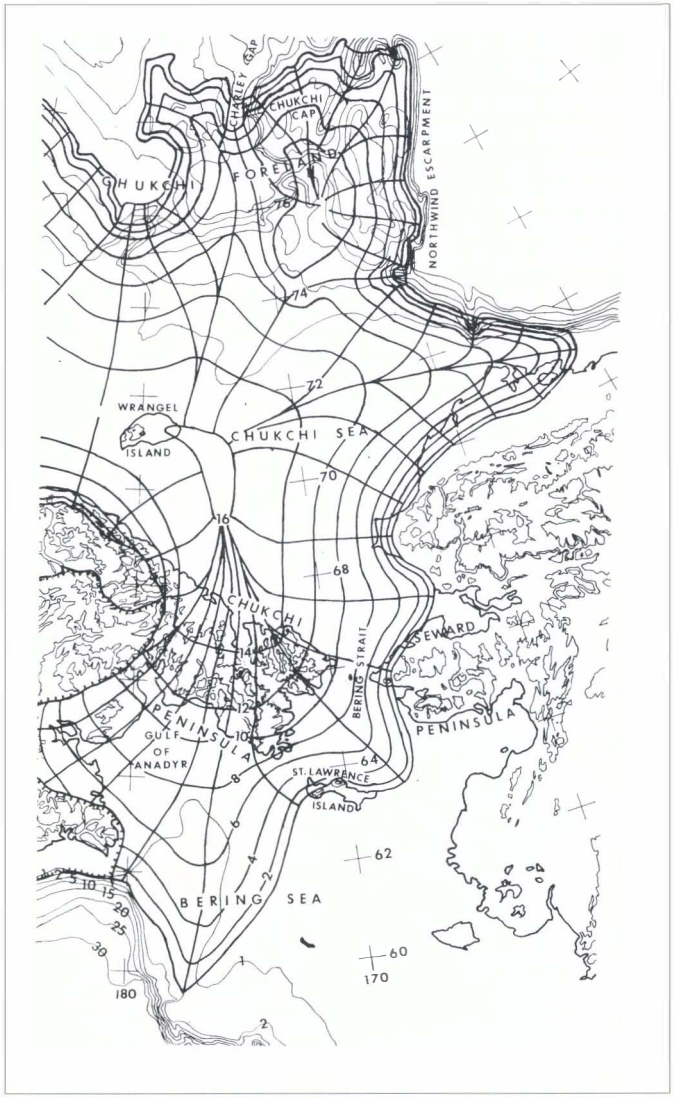

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Fig. 5. Flowlines and elevation contours at 200 m intervals for the Eurasian marine ice domes of an hypothetical Arctic ice sheet, based on the evidence in Figure 4 when present-day snow lines are lowered by 1000 m in (a) the western Eurasian Arctic, (b) the central Eurasian Arctic and (c) the eastern Eurasian Arctic.

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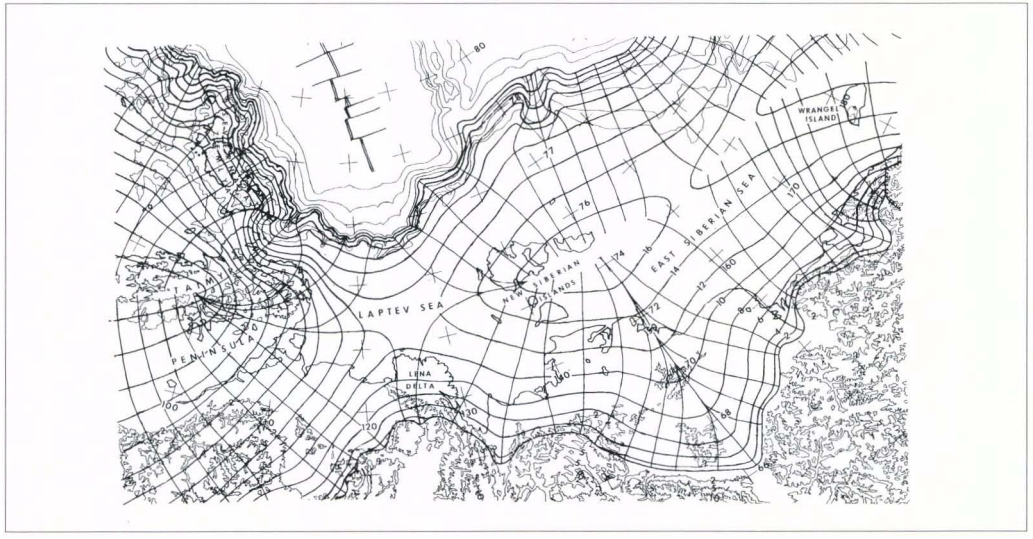

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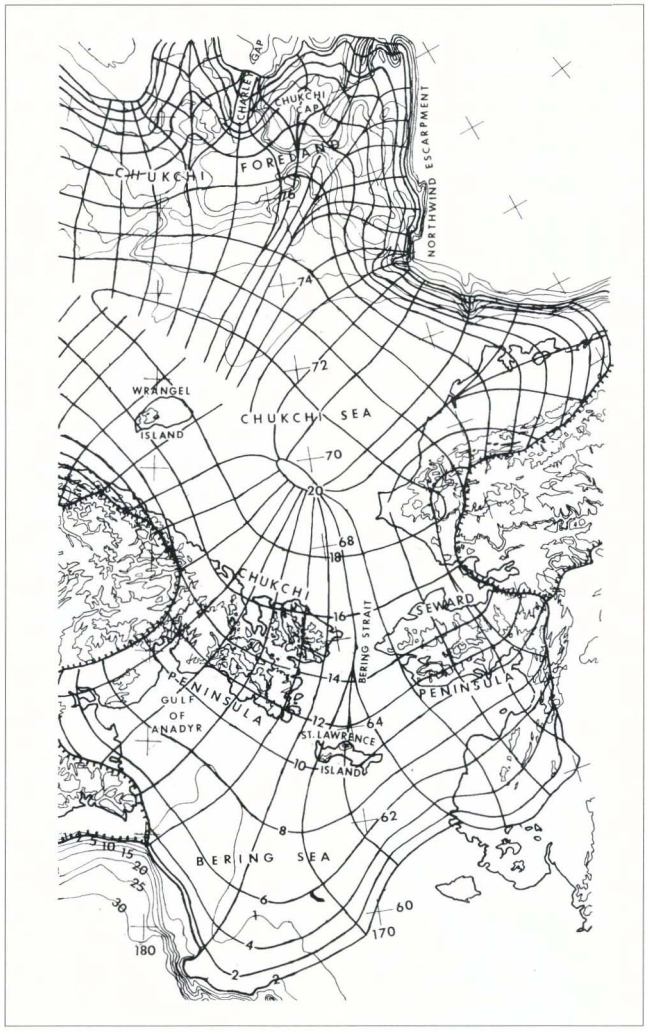

Fig. 6. Flowlines and elevation contours at 200 m intervals for the Eurasian marine ice domes of an hypothetical Arctic ice sheet, based on the evidence in Figure 4 when present-day snow lines are lowered by 1200 m in (a) the western Eurasian Arctic, (b) the central Eurasian Arctic and (c) the eastern Eurasian Arctic. The hachured lines in (c) show the extent of mountain glaciation in Siberia and Alaska that merged with the marine Chukchi ice dome.

discharged into the Sea of Okhotsk. At 14–13 ka BP, the western system turned latitudinal, flowing into the southern North Sea. During the warm Bolling–Allerod interval, when the Eurasian ice sheet was breached by an ice-free channel extending along the Bear Island Trough (Bjørnøyrenna in Figure 3) and the White Sea gorge, the system's water was dumped into the northern Norwegian Sea. The Younger Dryas cooling resulted in restoration of the system, which then probably resumed its flow v Caspian Sea into the Mediterranean Sea. The pre-Boreal warming entailed a new meltwater outburst from the northern Russian Plain and West Siberia into the Norwegian Sea.

These re-organizations in proglacial lake systems resulted in tremendous environmental changes. They account for modern distributions of fish and other ichthyo-faunas, some mammals (like seals), for the largest peat deposits and Arctic yedomas, and for many features of Eurasian geomorphology. Perhaps they can also explain, by outbursts of the Eurasian ice-dammed lakes, the massive meltwater spikes established in the Atlantic Ocean, which are now attributed to outbursts of the Agassiz paleo-lake in North America (Fairbanks, 1989).

TERRESTRIAL ICE SHEETS

Most of the terrestrial ice sheets in the Northern Hemisphere are relatively well documented (Flint, 1971; Denton and Hughes, 1981b; Lundqvist, 1986). This is true for the Laurentide ice sheet and the Cordilleran ice sheet of North America and for the Scandinavian ice sheet of Eurasia, but it does not hold for terrestrial ice sheets in Russia. For instance, the ice caps of Putorana Plateau, Anabar Plateau and Taimyr Peninsula, all located in central Siberia, are sometimes described as independent formations (Faustova and Velichko, 1992), but they could in fact be terrestrial parts of the major marine Kara ice dome, along with the glacier complex of the Ural Mountains (Arkhipov Leonov, 1982). Similarly, a terrestrial glacier complex envisaged by Hopkins (1972) and by Bespaly and Glushkova (Arkhipov and others, 1986) on the Chukchi Peninsula may have been part of a much larger marine ice sheet centered on the adjacent Chukchi Sea (Grosswald, 1988; Hughes and Hughes, 1994). The available data on the chronology of the Putorana ice cap and the glaciers of the Taimyr and Chukchi Peninsulas are meager, indirect and unreliable, permitting speculations as to whether the glacial land forms there represent the Last Glacial Maximum or one of the Late Glacial events. Accordingly, the maximum extent of the last glaciation in these areas is still unclear.

Two major problems arise if Quaternary glaciation cycles in the Northern Hemisphere are restricted to just terrestrial ice sheets. The first problem is that terrestrial ice sheets respond only to changes in snow-line elevations. Therefore, terrestrial ice sheets can nucleate only in mountains, according to the highland-origin, windward-growth hypothesis of Flint (1971), or on plateaux, according to the instantaneous glacierization hypothesis of Ives (1957), with glaciation being most extensive at high elevations near moisture sources. Computer simulations based on these hypotheses have Cordilleran ice sheet that formed sooner, grew bigger and lasted longer than the Laurentide ice sheet (Budd and Smith, 1981).

The second problem is that highland glaciation on Baffin Island, in Scandinavia, in Svalbard, in Franz Josef Land and in Novaya Zemlya would not be extensive enough to lower sea level sufficiently to allow these glaciers to cross the exposed floors of Foxe Basin, the Baltic Sea and the Barents Sea, and then transgress onto the mainlands of Canada and Russia to become the Laurentide and Eurasian ice sheets. Instead, the glaciers would calve into these seas and never reach the mainland. The numerous modeling studies that accomplish this island-hopping to the mainland do so by excluding calving dynamics in their models, thereby ignoring the dominant ablation mechanism; e.g. see Budd and Smith (1981). Only by invoking marine ice sheets and the marine ice-transgression hypothesis (MITH) can these vast late Quaternary ice sheets of North America and Eurasia be explained (Denton and Hughes, 1981b; Hughes, 1987; Grosswald, 1988).

MARINE ICE SHEETS

The first clues that a number of marine ice sheets existed on the Arctic continental shelves of Eurasia and North America came from such evidence as ice-motion proxies and dated raised beaches on the islands of the northwestern Barents Sea and Arctic Canada. As a result, a marine Barents ice sheet in the Barents Sea and a marine Innuitian ice sheet on Canada's Queen Elizabeth Islands were postulated (Schytt and others, 1968; Blake, 1970). The usual glaciological processes that produce prima facie glacial land forms and glacial deposits seem not to have been active in many areas of the High Arctic, probably because the ice was frozen to its bed over the islands and parts of the sea floor there. As a consequence, glacial land forms and deposits in such areas as the western Queen Elizabeth Islands or Severnaya Zemlya, an island group north of the Taimyr Peninsula (see Fig. 3), would be confined to the inter-island channels occupied by ice streams sliding on thawed deforming marine sediments. In these conditions, particular attention should be paid to the clues provided by geophysical studies and computer modeling, such as that by Clark (1980), who provided considerable support for the Innuitian ice sheet by showing that an ice dome over the Queen Elizabeth Islands was a necessary prerequisite for enabling an inverse computer model of glacioisostatic rebound to account for the raised beaches mapped and dated by Blake (1970).

During the 1980s, Scandinavian geologists confirmed the existence of a Barents ice sheet at the Last Glacial Maximum and presented strong evidence that it was grounded on the floor of the western Barents Sea and coalesced with the Scandinavian ice sheet. Field data on which they based this conclusion consisted of isostatically raised beaches (Salvigsen, 1981) and the sedimentary record of the sea floor (Elverhoi and Solheim, 1983; Vorren and Kristoffersen, 1986; Elverhoi and others, 1992; Sættem and

others, 1992; Vorren, 1992). Subsequently, Russian marine geologists also presented strong evidence for the existence of this ice sheet in the eastern Barents Sea (Gataullin and others, 1993). Additional compelling evidence in the eastern Barents Sea, including data on a continuous sea-floor lodgement-till cover, hummocky and ridgy bottom topography and the widespread occurrence of glaciotectonic features, has been uncovered in the course of oil and gas prospecting (personal communication to M.G.G. from N.A. Polyakova).

It was also shown (Grosswald, 1980) that the terrestrial glacial geological record, notably the south-facing end moraines of northeastern European Russia (Lavrov, 1977), west Siberia (Arkhipov and others, 1980) and the Taimyr Peninsula (Kind and Leonov, 1982), all shown in Figure 3, can be explained only if marine ice domes occupied the Barents and Kara Seas, and transgressed landward from there onto the Eurasian mainland. Later, a revised model of the last ice sheet grounded on the Barents–Kara continental shelf was advanced (Grosswald, 1988). This model was based upon new evidence uncovered by Lavrov (Arslanov and others, 1987), Andreyeva and Isayeva (1988) and Gonchariv (1986) that pointed to a single major ice dome with its ice-spreading center located in the southwestern Kara Sea (see Fig. 3). Ice spreading from this Kara ice dome overrode Novaya Zemlya in an east-to-west direction, producing the glacial through valleys shown in Figure 3, and invaded the Barents Sea from the east as confirmed by the geological evidence of Gataullin and others (1993). Kara ice also encroached upon large areas of European Russia, west Siberia and central Siberia in directions shown by the glacial geology in Figure 3.

According to the model based both on the above geological data and the theoretical conclusion by Weertman (1974) that marine ice sheets expand until they become afloat, the Kara ice dome reached the outer edge of the Barents–Kara continental shelf; it covered 6×10^6 km^2 and was the largest dome of the Eurasian ice sheet. The ice dome was remarkably stable and long-lived, and its melting history was prolonged and stepwise; specifically, the ice-dome retreat was not completed before the mid-Holocene and was punctuated by the Younger Dryas and Boreal time re-advances of its ice margin (Grosswald, 1993). According to a computer simulation of the last glaciation cycle by Fastook and Hughes (1991), the Kara ice dome survived longer than any of the other major ice domes.

By contrast, Astakhov (1992) argued that the Kara ice dome did not exist during the Last Glacial Maximum, which seems to be consistent with "old" radiocarbon dates from surficial, not glacially disturbed, sediments of northern West Siberia. However, Astakhov's model disregards the evidence for recent ice flow directed outwards from the Kara Sea center shown in Figure 3 (Grosswald, 1993, 1994). Grosswald, in his turn, chose to ignore the "old" dates, considering them spurious and misleading as they appeared to have been obtained from materials which had been recycled, mixed and contaminated by older organics.

Epitomized in this controversy are two different approaches to paleoglaciological reconstructions for northern Eurasia. One emphasizes geological and geomorphological evidence. The other emphasizes dating results obtained from problematic materials. A parallel situation existed in the glacial geology of Arctic Canada during the 1970s and also resulted in "maximum" and "minimum" models of Laurentide glaciation (Mayewski and others, 1981). These differences eventually resulted in the two irreconcilable models of "continuous" and "restricted" glaciations in the Eurasian Arctic as well. Although we favor the first approach, we realize that the only possible way of resolving the controversy is by implementation of a special program targeted at dating and re-dating a number of carefully selected key sections of the Siberian Quaternary by means of the AMS–^{14}C method, surface exposure dating with cosmogenic nuclides and other advanced techniques. It is noteworthy that, when these techniques were applied to Arctic Canada, it was the maximum model of late Wisconsin glaciation that prevailed.

Most recently, geological signatures of a former marine ice sheet were also uncovered in areas of the Laptev, East Siberian and Chukchi Seas. At first, they were confined to late Weichselian ice-shoved features on the New Siberian Islands and in the Tiksi Harbour area, just east of the Lena River delta (see Figs 3 and 4). These glacial tectonics permitted reconstruction of the first flow band of a hypothetical east Siberian ice dome centered just north of the New Siberian Islands (Grosswald, 1988; Grosswald and others, 1992). Today, the supporting evidence also includes (1) upper and middle Pleistocene till sheets of the Vankarem Lowland (Laukhin and others, 1989); (2) glacial erratics on Cape Heart Rock; (3) north-to-south oriented fjords and U-shaped through valleys of the Chukchi Peninsula; (4) traces of southerly ice flow through Bering Strait, all located in Figure 4 (unpublished data of M.G. Grosswald and T.J. Hughes); and (5) post-Sangamon erratics and ice-shoved features on St Lawrence Island (Brigham-Grette and others, 1992; Heiser and others, 1992). This evidence implies that an ice sheet advanced southwards from the Chukchi Sea, as well as from the East Siberian Sea. Also, modern observations by Grosswald (unpublished) make clear that Wrangel Island, which lies between the East Siberian and Chukchi Seas, is characterized by strikingly glacial geomorphology which can be described as Lapland-style; that is, glacial geology produced beneath or near ice domes, as diagnosed by Kleman (1994) and Kleman and Borgström (1994) for northern Sweden. Also, the northern lowland of Wrangel Island is blanketed by marine sediments that could have been deposited prior to isostatic rebound after the ice dome collapsed and possibly prior to the Last Glacial Maximum.

We expect that further progress in establishing the extent of marine ice sheets in the Arctic will be reached by mapping "oriented lakes" on the Arctic coastal lowlands in northeastern Siberia and northern Alaska, and searching for buried glacial land forms. These lakes and associated elongated and parallel features are remarkably well oriented in sub-meridional directions (Figs 3 and 4). The prevailing view is that the lake orientations resulted from thermokarst processes operating under the strong impact of prevailing northeasterly winds (Rex, 1961; Carson and Hussey, 1962). This hypothesis seems to be

supported by hydrodynamic theory, mathematical models and field experiments. However, the geomorphology of the lakes suggests that the wind-affected thermokarst processes contribute not to orienting the lakes but rather to obscuring their orientation. Besides, the "wind" hypothesis is unable to account for both longitudinal and transverse alignments of the lakes and for the other linear features comprising the geomorphological complexes of the Arctic coastal lowlands. So far, all attempts to explain the complexes, not just the lakes alone, have resulted in a non-realistic hypothesis of "structural control". Instead, we propose that the linear complexes, of which oriented lakes are just one manifestation, inherited their orientations from former glacial land forms. Specifically, relative to long axes of the lakes, the longitudinal lineations are what remains of glacial drumlinization and fluting after the drumlins and flutes were disfigured by post-glacial thermokarst and solifluction processes, and transverse lineations are the remnants of land forms produced along the edge of the retreating ice-sheet margin. In addition, our hypothesis explains the origin and thermal properties of yedoma. These thick sequences of ice-rich sand and silt that blanket Arctic lowlands are sediments deposited by aggradation in ice-damming environments. Hence we argue that oriented lakes inherited their orientation from the grooves produced by a marine ice sheet transgressing on to the Arctic coastal lowlands from the adjacent seas. This seems to be paleoclimatically justified because northeastern Siberia and northern Alaska, with their "halfway-to-Ice Age" environments, were and are highly susceptible to easy and early glacierization (Verbitsky and Oglesby, 1992; Marsiat, 1994). Meanwhile, thousands of new ice flowlines can now be derived from the lake orientations, which therefore provide powerful tools for reconstructing marine ice sheets in the East Siberian and Chukchi Seas, where the usual glacial land forms have been either altered or buried, or never existed because the bed was frozen. This interpretation proved justified by the geomorphology of the Yana–Indigirka Lowland, where the alignments of oriented lakes and accompanying ridges are parallel to the former ice-flow directions derived from ice-shoved features on the New Siberian Islands and on the Siberian mainland around Tiksi Harbor (see Figs 3 and 4) (Grosswald and Spektor, 1993).

Still, we realize that nearly all the clues for a marine east Siberian ice dome are argumentative and therefore our reconstruction should be considered tentative. Nonetheless, climate modelers are increasingly placing marine ice domes on Arctic continental shelves, on the east Siberian continental shelf in particular, because meteorological conditions allow ice to thicken over time at these locations (Tushingham and Peltier, 1991; Deblonde and others, 1992).

Geologists, in their turn, should not overlook evidence from non-traditional sources. For instance, no one has yet acknowledged the paleoglaciological implications of the unusually large thickness of sedimentary sequences blanketing the deep Arctic Ocean floor and the peculiar features of their distribution (Sweeney, 1981). These sequences are normally over 2 km thick and grow thicker alongside the continental slopes off the Barents, Kara and East Siberian continental shelves. Is it not natural for the sequences to be a consequence of glaciological activity associated with former marine ice domes surrounding the deep Arctic Basin, namely by ice scouring the continental shelves and dumping the resulting debris into the basin?

ICE STREAMS

Figures 3 and 4 identify the sites of major ice streams that drained marine ice domes on the Arctic continental shelf of Eurasia and Alaska. The larger ice streams produced saddles on the ice divide by the down-draw mechanism, thereby leaving ice domes between the saddles. These ice domes are not mass-balance features created by precipitation patterns; they are dynamic features created by ice streams. Computer simulations of the Eurasian ice sheet that do not allow ice-stream dynamics, such as those by Lindstrom and MacAyeal (1989) and Lindstrom (1990), produce fewer ice domes, and those that are produced are in locations not compatible with glacial geology. Therefore, the glaciation cycles simulated by these models cannot replicate the full complexity and versatility of ice sheets, and exclude the ability of ice sheets to effect abrupt climatic change triggered by iceberg outbursts when internal ice dynamics activate ice streams, or triggered by outbursts of vast glacially impounded lakes when active ice streams collapse saddles along the ice divide. These outbursts may halt production of North Atlantic Deep Water, and thereby cause abrupt flip-flops from a glacial to an interglacial global climate. Such flip-flops have been proposed for the last termination, for example, by Charles and Fairbanks (1992) and by Broecker and others (1992). Ice saddles collapsed by ice streams could have produced outbursts of icebergs and impounded lakes in the Gulf of Saint Lawrence, the Labrador Sea, Baffin Bay, the North Sea, the Barents Sea, the Kara Sea, the Laptev Sea, the Chukchi Sea and the Beaufort Sea (Fastook and Hughes, 1991; Grosswald, 1993; Lindstrom and MacAyeal, 1993). Major marine ice streams would have occupied Cabot Strait in the Gulf of Saint Lawrence; Hudson Strait in the Labrador Sea; Lancaster Sound, Jones Sound, Nares Strait and Melville Bugt in Baffin Bay; the Norwegian Trough in the North Sea; Bear Island Trough and Franz–Victoria Trough in the Barents Sea; St Anna Trough and Voronin Trough in the Kara Sea; Boris Vilkitski Strait in the Laptev Sea; Charlie Gap in the Chukchi Sea; and Amundsen Gulf and M'Clure Strait in the Beaufort Sea.

Although the glaciological mechanisms that activate and deactivate ice streams are unclear, they probably thaw and refreeze till or sediments in inter-island channels and submarine troughs where these deposits accumulate and are either ice-cemented or water-saturated. Upon thawing, the deposits no longer provide basal traction to the overlying ice, which then converts from sheet flow to stream flow as it funnels into the channels and troughs. Therefore, ice streams would be activated by climatically warmed surface ice that is advected downward, by frictional heating from ice shearing over the bed and by geothermal heating of basal ice. Conversely, ice streams would be deactivated by climatically cooled surface ice that is advected downward, by converting sensible heat into latent heat as basal

meltwater refreezes and by conducting basal heat upward more rapidly through ice that has been thinned by being down-drawn into ice streams. Although climatic warming and cooling at the ice surface is a factor, the effect of the bed can be delayed for millennia, whereas basal melting and freezing that turn ice streams on and off can be virtually instantaneous. Therefore, ice sheets have a capacity for abrupt change that is largely independent of exerted climatic forcing.

On the other hand, changing sea level is external forcing that can have an immediate effect on marine ice streams such as those located in the inter-island channels and submarine troughs in Figures 3 and 4. As shown by Weertman (1974) and applied to marine ice streams by Thomas (1977), Thomas and Bentley (1978), Stuiver and others (1981) and Fastook (1984), the grounding line of an ice shelf with a marine ice sheet can advance or retreat irreversibly for small changes in sea level if the bed slopes downward up ice streams, due to isostatic depression beneath the marine ice sheet. Since ice streams are the dynamic links connecting a marine ice sheet to its floating ice shelves, grounding-line advance and retreat occur along the inter-island channels and submarine troughs occupied by ice streams. Collapse of ice saddles along the ice divides of marine ice sheets are caused by irreversible retreat of ice-shelf grounding lines along marine ice streams. Floating ice shelves are therefore an important dynamic component of a hypothetical Arctic ice sheet.

FLOATING ICE SHELVES

With terrestrial and marine ice domes grounded along nearly the whole circumference of the Arctic, only one additional interconnecting element, an ice shelf floating over the deep Arctic Ocean basins, would have been required to produce an Arctic ice sheet at the Last Glacial Maximum. The idea of a floating ice shelf on the Arctic Ocean is not new. Thomson (1888) and Crary (1960) postulated the same ice shelf on thermophysical grounds, considering it a consequence of Ice Age changes in the ocean's heat balance. Mercer (1970) postulated the same ice shelf on mechanical grounds, citing it as an important counterbalance capable of buttressing a marine ice dome grounded on the Barents Sea floor, checking its instability and preventing the dome from collapsing. Broecker (1975) and Williams and others (1981) proposed an Arctic ice shelf on the basis of oxygen-isotope ratios and sea-level records. Lindstrom and MacAyeal (1986, 1989) modeled floating ice shelves in the Arctic Ocean and the Norwegian–Greenland Sea, based on mass-balance computations in a finite-element computer simulation. With reasonable assumptions, they found that a dynamic finite-element ice-sheet model produced an ice shelf 1000 m thick north of Fram Strait, up to 1500 m thick further into the Canadian Basin and 1000–500 m thick in the Norwegian–Greenland Sea as far south as Iceland. Their ice shelf was supplied by marine ice domes grounded on the Arctic continental shelf of Eurasia.

There is compelling evidence for abiotic conditions in the central Arctic Ocean during the Last Glacial Maximum, which is consistent with a continuous floating ice shelf between 33 and 13 ka BP (personal communication from G. Jones, 1993). Also, numerous parallel plowmarks have been recorded on the southern Yermak Plateau, near the "exit" of the central Arctic Ocean between Greenland and Svalbard, at water depths of 850–1000 m, perhaps even up to 2000 m (Vogt and others, 1994). These marks seem to be the first-known signatures of the thick floating ice shelf or rather giant icebergs either incorporated into the ice shelf or calved from it and carried across Yermak Plateau by southward flow of the ice shelf. Marine biological activity north of Yermak Plateau began shortly after the Last Glacial Maximum (Stein and others, 1994). Perhaps this coincided with progressive disintegration of the ice shelf after the calving front breached the ice-shelf bottle-neck in Fram Strait. As for the Norwegian–Greenland Sea, there is microfaunal evidence that deep-sea life did not cease there during the Last Glaciation. However, this is not an unsurmountable hindrance to the concept of a Norwegian–Greenland Sea ice shelf, especially if the ice shelf thinned as it moved southward, interacted with the continental margins and entering ice streams, and adjusted its shape to conform to inter-island passages, all of which had to result in a multitude of crevasses and rifts. The thinner the ice, the more likely top and bottom crevasses could meet and open rifts. Perhaps, the periodically forming crevasses and chasms provided enough open water for initiation and development of deep-sea life recorded by oceanographers. Marine organisms live under the Ross Ice Shelf in Antarctica 450 km from the calving front but only 70 km from rifts through the ice shelf in the lee of Crary Ice Rise, a local pinning point (Stockton, 1982).

RECONSTRUCTING MARINE ICE SHEETS

Most of the glacial geological evidence in Figure 4 supports transgressions of marine ice sheets from the Arctic continental shelf of Eurasia southward on to the Russian mainland and northward into the Arctic Ocean. If an Arctic ice sheet developed during late Quaternary glaciation cycles, a major component would have been marine ice domes on the broad, shallow continental shelves of the Barents, Kara, Laptev, East Siberian and Chukchi Seas. In the marine-ice-transgression hypothesis (MITH), marine ice sheets began when sea ice thickened from snow accumulating on its top surface and water freezing onto its bottom surface, until it grounded on shallow Arctic continental shelves. Thereafter, continued snow accumulation on the top surface produced ice domes that spread onto adjacent coastal lowlands, where marine ice may have merged with terrestrial ice from ice caps on coastal highlands, and spread to the edge of the continental shelf, where marine ice either calved into the ocean or became a floating ice shelf.

Initial sea-ice thickening rates have been given by the formula (Crary, 1960)

$$\frac{\mathrm{d}h_\mathrm{I}}{\mathrm{d}t} = \dot{a} + \frac{(D/h_\mathrm{I})\Delta T - Q}{\rho_\mathrm{I} H} \qquad (1)$$

where h_I is ice thickness, t is time, $\dot{a}$ is the ice-accumulation rate on the top surface of sea ice, D is the

thermal conductivity coefficient for sea ice, ΔT is the temperature difference between the mean annual air temperature on the top surface and the freezing temperature of sea water on the bottom surface, Q is the rate at which heat is supplied to the bottom surface by Arctic rivers and ocean currents, ρ_I is ice density and H is the latent heat of freezing for sea water. Integrating Equation (1) for constant $\dot{a}$, ΔT and Q

$$t = \left[\frac{\rho_I H h_I}{\dot{a}\rho_I H - Q}\right] - \left[\frac{\rho_I H D \Delta T}{(\dot{a}\rho_I H - Q)^2}\right] \ln\left[1 + \frac{(\dot{a}\rho_I H - Q)h_I}{D\Delta T}\right]. \tag{2}$$

Taking $\dot{a} \approx 10\,\mathrm{cm\,a^{-1}}$ and $\Delta T \approx 15^\circ\mathrm{C}$ for present-day conditions and $Q \approx 0$ for the "White Hole" in Figure 1, Equation (2) predicts that sea ice would ground in water 100 m deep or less in 500 a or less. As seen by the 100 m bathymetric contour in Figure 3, this would allow marine ice domes to grow in all the seas of the Arctic Eurasian continental shelf.

Orographic effects increase $\dot{a}$ as the marine ice domes get higher, thereby offsetting the cessation of ice thickening by bottom freezing after sea ice becomes grounded. Eventually, the marine ice domes will become high enough so their gravitational potential energy becomes kinetic energy of motion and they will then creep in directions having the greatest ice-surface slope. Initially, the Arctic continental shelf of Eurasia would be frozen, except in the western Barents Sea, as is the case today (Gavrilova, 1981; Bigl, 1984). As marine-ice domes thicken and spread, however, more of the bed will become thawed and glacial sliding will then begin to produce the glacial erosional and depositional features shown in Figure 4.

Glacial erosional and depositional features that reveal the pattern of flowlines from the interior ice divide to marine and terrestrial margins of a former ice sheet are produced by traction between moving ice and its bed. If the bed is frozen, these features are rare and consist primarily of glacial tectonics, such as thrust sheets and hole–hill pairs. If the bed is thawed, these features are ubiquitous and result primarily from areal scouring that produces glacial lineations ranging in scale from striated pavements to fluted landscapes. If the bed is freezing or melting, these features are mostly confined to thawed parts in a mosaic of thawed and frozen patches where freeze–thaw quarrying produces a pitted landscape of lakes and hills elongated in the direction of ice flow. If sheet flow becomes stream flow towards the ice margin, selective linear erosion produces fore-deepened troughs beneath ice streams and the eroded material is deposited along grounding lines beyond which marine ice streams become afloat or is deposited as lobate moraines where terrestrial ice streams end on land. Sugden and John (1976) described these various glacial landscapes in detail and the mechanisms that produced them.

Basal traction that produces glacial landscapes is represented by basal shear stress τ_0 defined as the product of ice density ρ_I, gravitational acceleration g_z, ice thickness h_I and ice-surface slope α for a coordinate system in which x is horizontal along flowlines and z is vertical

$$\tau_0 = \rho_I g_z h_I \alpha\,. \tag{3}$$

Ice elevations along surface flowlines of an ice sheet can be computed from Equation (3) by writing it in the following numerical form

$$h_{i+1} = h_i + \left(\frac{\tau_0}{h_I}\right)_i \frac{\Delta x}{\rho_I g_z} = h_i + \left(\frac{\tau_0}{h - h_R}\right)_i \frac{\Delta x}{\rho_I g_z} \tag{4}$$

where $\alpha = \Delta h/\Delta x$, $\Delta h = h_{i+1} - h_i$ is the change in ice elevation in constant step length Δx along a flowline of length L divided into $L/\Delta x$ equal steps from the ice margin to the ice divide, integer i denoting the step, bed elevation $h_R = h - h_I$ and $[\tau_0/(h - h_R)]_i$ must be specified at each step. Glacioisostatic depression of the bed lowers the surface from elevation h to elevation h^* above sea level and lowers the bed from h_R to $h_R{}^*$ above or below sea level. Taking r as the ratio of the lowered surface to the lowered bed

$$r = \frac{h^* - h_R}{h_R - h_R{}^*}\,, \tag{5}$$

it can be shown that Equation (4) becomes (Hughes, 1985)

$$h_{i+1}{}^* = h_i{}^* + \left[\frac{\tau_0}{(1+r)h^* - (1+r)^{\frac{1}{2}}h_R}\right]_i \frac{\Delta x}{\rho_I g_z} \tag{6}$$

and that $h_R{}^*$ is linked to h_R for present-day topography or bathymetry by the expression

$$h_R{}^* = (1+r)^{\frac{1}{2}}h_R - rh^*\,. \tag{7}$$

If $\rho_I = 917\,\mathrm{kg\,m^{-3}}$ for ice density and $\rho_R = 3600\,\mathrm{kg\,m^{-3}}$ for the mean density of the Earth's mantle, isostatic equilibrium requires that

$$r = r_0 = \frac{\rho_I}{\rho_R - \rho_I} \approx \frac{1}{3}\,. \tag{8}$$

Taking t_0 as the time constant for glacioisostatic compensation beneath an ice sheet, the value of r for an ice sheet advancing over time t is

$$r = r_0[1 - \exp(-t/t_0)] \tag{9}$$

and the value of r for an ice sheet retreating over time t is

$$r = r_a \exp(-t/t_0) \tag{10}$$

where r_a is the value of r in Equation (9) when advance ends and retreat begins.

Equation (6) is an initial-value finite-difference recursive formula. The initial value is grounding-line ice thickness h_0 for $i = 0$ at a marine ice margin for which the condition for ice just becoming afloat in water of density ρ_W and depth h_W is

$$h_0 = h_W(\rho_W/\rho_I)\,. \tag{11}$$

The initial value is ice thickness h_1 at $i = 1$ for the first Δx step in from a terrestrial ice margin for which $h_1 = h_I = \Delta h$ and Equation (3) can be integrated for $\alpha = \Delta h/\Delta x$ and constant τ_0 to give

$$h_1 = (2\tau_0 \Delta x/\rho_I g_z)^{\frac{1}{2}}\,. \tag{12}$$

The finite difference is Δx. The recursive feature of Equation (6) is that, once the initial h_i is specified by either Equation (11) or Equation (12), h_{i+1} for the next step is calculated readily and becomes h_i for calculating h_{i+1} in the following step, a process that recurs along a flowline of length L until step $i = L/\Delta x$ at the ice divide. Modified Euler or Runge–Kutta solutions of Equation (6) are available to reduce the dependence of h on the length Δx of steps. These solutions introduce a correction factor that depends on Δx and that can be applied to Equation (6) if it is solved directly using a pocket calculator and a given Δx.

With values of h_R at each Δx step obtained from topographic or bathymetric maps of the deglaciated landscape and values of r obtained from Equations (9) and (10) for specified times of glacial advance or retreat, only τ_0 must be specified at each Δx step in Equation (6) in order to reconstruct ice elevations along flowlines of former ice sheets. Values of τ_0 depend on ice velocity and on how frozen and thawed areas are distributed over the bed. Since τ_0 is a measure of bed traction, τ_0 is nil beneath ice divides where ice is barely moving and beneath ice streams where a layer of basal water or muck greatly reduces traction. In between, τ_0 increases from the ice divide to the ice stream, because ice velocity must increase in order to transport ice accumulating on the ice-sheet surface. If sheet flow continues to the ice margin, τ_0 will increase in the accumulation zone and decrease in the ablation zone, because ice velocity increases and then decreases as ice is gained by accumulation or lost by ablation.

Theoretical variations of τ_0 for sheet flow along an ice flowline have been derived for variable accumulation and ablation rates, variable convergence and divergence of flow, and variable frozen and thawed basal conditions along the flowline (Hughes, 1985). Using accumulation and ablation rates for marine ice domes on the Eurasian Arctic continental shelf specified by Hughes (1985), and using the glacial geology in Figure 4 to specify convergence or divergence of flow and frozen or thawed basal conditions, these theoretical τ_0 values can be calculated and used to compute flowline-elevation profiles in Equation (6) for sheet flow.

For stream flow along length L_S of a flowline of length L, the counterpart of Equation (6), using an improved version of the analysis by Hughes (1992b), is

$$h_{i+1} = h_i + \left[\left(1 - \frac{\rho_I}{\rho_W}\right)\left(\frac{P_W}{P_I}\right)^2\right] \cdot \left[\frac{\dot{a}(h-h_R)_i - (h-h_R)_i^2 (R_{xx}{}^{*\,n-1}/A^n)_i (\sigma_{xx}{}')_i^n}{\dot{a}x + h_0 u_0}\right]\Delta x + \left[\frac{2}{\rho_I g_z}\left(\frac{\Delta\sigma_{xx}{}'}{\Delta x}\right)_i + \frac{(\tau_0)_i}{\rho_I g_z (h-h_R)_i} + \frac{2(\tau_s)_i}{\rho_I g_z w_i}\right]\Delta x \qquad (13)$$

where $\dot{a}$ is the ice-accumulation rate, h_0 and u_0 are ice thickness and velocity (negative for x positive upstream) at the foot of the ice stream, w is the width of the ice stream, $R_{xx}{}^*$ represents the stress field, $\sigma_{xx}{}'$ is the longitudinal deviator stress, $\Delta\sigma_{xx}{}'/\Delta x$ is longitudinal deviator stress gradient, τ_0 is the basal shear stress, τ_s is the side shear stress, A and n are the hardness parameter and the viscoplastic parameter in the Nye (1953) flow law of ice, $\sigma_{xx}{}'$ is given by

$$\sigma_{xx}{}' = \frac{\rho_I g_z (h - h_R)}{4}\left(1 - \frac{\rho_I}{\rho_W}\right)\left(\frac{P_W}{P_I}\right)^2. \qquad (14)$$

τ_0 is given by

$$\tau_0 = \tau_v \left(1 - \frac{P_W}{P_I}\right)^{4m/(2m+1)}. \qquad (15)$$

τ_s is given by

$$\tau_s = \tau_v \left(\frac{P_W}{P_I}\right)^{4m/(2m+1)}. \qquad (16)$$

ρ_I is ice density, ρ_W is water density, P_I is basal ice pressure, P_W is basal water pressure, τ_v is the viscoplastic yield stress of ice and m is the viscoplastic parameter in the Weertman (1957) sliding law of ice, modified to include sliding on soft water-soaked sediments or till.

Equations (13) and (14) are results of the mass balance and the force balance. Equation (15) assumes that bedrock bumps which control the sliding velocity for sheet flow over bedrock become progressively drowned by basal meltwater or blanketed by easily deformed sediments or till for stream flow. Equation (16) assumes that side shear increases in proportion to the decrease in basal shear. A solution for these equations is obtained by assuming the following variation of P_W/P_I along normalized length x/L_S of the ice streams

$$\frac{P_W}{P_I} = \frac{\rho_I g_z h_W}{\rho_I g_z h_I} \approx \left(1 - \frac{x}{L_S}\right)^c \qquad (17)$$

where h_W is the height to which P_W would raise basal water in an imaginary borehole through ice of thickness h_I, and $0 < c < \infty$ represents the spectrum of basal buoyancy along length L_S of stream flow that converts sheet flow ($c = \infty$) to shelf flow ($c = 0$), with $x = L_S$ at the head and $x = 0$ at the foot of the ice stream. For active ice streams, $0 < c < 1$. For inactive ice streams, $1 < c \ll \infty$.

In applying Equation (13) along flowlines determined by the glacial geology in Figure 4, the $\Delta\sigma_{xx}{}'/\Delta x$ term can be ignored because, except near the grounding line, it is small compared to the other terms when $\sigma_{xx}{}'$ is given by Equations (14) and (17), the τ_s term can be ignored except in the fjords of Norway and Svalbard, where $(h - h_R)_i$ is not insignificant compared to w_i, $R_{xx}{}^* \approx 1$ if w_i does not vary greatly along L_S, $\tau_v \approx 100$ kPa for viscoplastic yielding in shear, L_S for active ice steams is the length of an inter-island channel or a submarine trough formerly occupied by an ice stream, c is chosen to give the same elevation at the ice divide for flowlines down opposite flanks of the ice divide, and u_0 is obtained from the mass flux of ice having thickness h_0 and width w_0 at $x = 0$, as specified by the mass balance for ice converging on the ice stream.

The glacial geology in Figure 4, and the ice-sheet reconstructions in Figures 5 and 6 that are based upon it, are added to the map of the Arctic Region, sheet 14 of the world 1 : 5 000 000 series of topographic and bathymetric maps produced by the American Geographical Society. The isostatically depressed topography and bathymetry

beneath terrestrial and marine components of the reconstructed ice sheets are obtained for $r = r_a$ at $t = t_a$ in Equation (9). Upper and lower limits of t_a may be $15\,\mathrm{ka} > t_a > 5\,\mathrm{ka}$, since this brackets the spacing of Heinrich events for glacial unloading of Laurentide ice in the North Atlantic (Bond and others, 1992). Sea level began to rise rapidly about 14 000 years ago (Fairbanks, 1989), after which marine ice domes on the Eurasian continental shelf would have begun to collapse if their ice streams became afloat on a bed that sloped upward seaward (Thomas, 1977). If the ice streams became afloat on a bed that sloped downward seaward, the marine ice domes would have remained stable despite rising sea level and t_a would be longer. Any t_a values are tenuous, since they assume complete rebound following complete collapse of earlier marine ice domes. This condition exists only at the beginning of glaciation cycles.

For an Arctic ice sheet, the Arctic Ocean would be covered by an ice shelf rather than by thick sea ice. The best evidence for an ice shelf is an abiotic Arctic Ocean from 32 to 13 ka BP (personal communication from G. Jones, 1993) and linear ice plowmarks across the submarine saddle between Yermak Plateau and Svalbard (Vogt and others, 1994). The plowmarks are parallel, trend southward and are at water depths from 850 to 1000 m. We therefore put the ice-shelf grounding line at the 1000 and 750 m bathymetric contours north and south of Yermak Plateau, respectively, with the thickness change being caused by compressive converging flow becoming extending diverging flow as the ice shelf moved through Fram Strait between Greenland and Svalbard. These depths place ice-shelf grounding lines on the Arctic continental slope, a bed that slopes downward seaward, and therefore would stabilize marine ice domes and increase t_a. Also, the spacing of Bond cycles tends to be longer earlier in the last glaciation cycle, so marine ice domes earlier in the cycle may have had more time to grow.

The glacial geology in Figure 4 allows two reconstructions of marine ice domes on the Eurasian Arctic continental shelf. The reconstructions in Figures 5 and 6 are obtained for respective snow-line lowerings of 1000 m for the Last Glaciation and 1200 m for the maximum Pleistocene glaciation (Péwé, 1975; Broecker and Denton, 1989; Pelto, 1992). Both reconstructions are obtained from present-day precipitation rates, with $t_a = 20\,\mathrm{ka}$ in Equation (10), allowing 20 000 years of growth to conform with the high-latitude hemi-cycle of insolation dominated by the 41 ka cycle of the Earth's axial tilt. Insolation is assumed to control snow lines. Snow-line lowering expands existing island ice caps in the eastern and northern Barents Sea. However, these ice caps cannot advance into the central Barents Sea until sea ice grounds in water over 100 m deep. Even then, the size of ice caps over Svalbard and Franz Josef Land is limited by ice streams that develop in fjords, inter-island channels and submarine troughs on nearly all sides. These ice caps are continuously down-drawn by the ice streams so they never expand much beyond these island groups. In contrast, ice caps on the islands of Novaya Zemlya, the New Siberian Islands, Wrangel Island and, to a lesser extent, the islands of Severnaya Zemlya, are much less vulnerable to down-draw by marine ice streams, so they can be nuclei for major marine ice domes.

GLACIATION FOR SNOW LINES 1000 m LOWER

Figure 5 shows the extent of marine Eurasian glaciation after 20 000 years for present-day precipitation rates when present-day snow lines are lowered by 1000 m. According to the highland-origin, windward-growth hypothesis (Flint, 1971), the present-day ice cap on Novaya Zemlya is the most probable nucleus for a marine ice dome in the Barents Sea. Moisture-bearing westerly winds, along with shallow water on the west and deep water on the east, would allow this ice cap to advance into the Barents Sea but not into the Kara Sea. A marine ice dome would then develop in the eastern Barents Sea and merge with a smaller ice dome over Svalbard and with the Scandinavian ice sheet at the Last Glacial Maximum. Ice from this Barents ice dome would flow into the Kara Sea, following glacial through valleys across Novaya Zemlya and then fanning out, flowing northward as ice streams in Saint Anna Trough and Voronin Trough, flowing eastward across Severnaya Zemlya and flowing southward in glacial through valleys on the Taimyr Peninsula and in the estuaries of the Yenisey River and the Ob River. Most of the ice moving westward from the Barents ice dome would enter a giant ice stream in Bear Island Trough. Ice moving to the northwest would enter ice streams in the submarine troughs and inter-island channels of Franz Josef Land and Svalbard. Ice moving to the southwest would transgress on to the north Russian Plain and, after retreat of Scandinavian ice, onto the Kola Peninsula. Figure 5a shows these flow patterns, for comparison with the glacial geological flow indicators in Figure 4. The poorest match is near the Ural Mountains, where the glacial geology shows ice moving southwestward from the Kara Sea, not from the Barents Sea. The depositional wedge on the continental slope of the western Barents Sea in Figure 4 was supplied by the large ice stream in Bear Island Trough.

In the East Siberian Sea, a marine ice dome developed over the New Siberian Islands. It met ice from the Barents ice dome in the Laptev Sea, producing a low saddle on the ice divide. East Siberian ice moved southward across the Lena River delta and the Yano–Indigirka Lowland as far as Pronchischev Ridge and Polousny Ridge, according to oriented lakes and glacial tectonics (see Fig. 3). The East Siberian dome extended to the edge of the continental shelf in the north and formed a saddle with the Chukchi dome in the east. Figure 5b shows the ice-flow pattern, for comparison with glacial geological flow indicators in Figure 4. Features we attribute to glacial tectonics are southward about an ice dome north of the New Siberian Islands and imply northward retreat of the ice dome during deglaciation. If confirmed, this is further evidence for stable grounding on the continental slope. The depositional wedge on the continental slope of the Laptev Sea may be formed as the sediments of the Lena River ice-dammed lake were released when the ice saddle collapsed, and the valley crossing the Laptev Sea shelf could be eroded by outburst floods of that lake, not by the Lena River itself, as suggested by Fütterer (1993).

The Chukchi dome probably originated as an ice cap on Wrangel Island but at the Last Glacial Maximum it was centered in the Chukchi Sea, having grown in the direction of moisture-bearing winds from Bering Strait in

the general circulation-model simulation by Manabe and Broccoli (1985). Marine Chukchi ice spilled over Chukchi Peninsula and through Bering Strait to produce glacial tectonics on St. Lawrence Island and to end as a calving ice wall along the edge of the continental shelf in the southwestern Bering Sea. Field studies by Heiser and others (1992) and by Brigham-Grette and others (1992) show that the snow line during the Last Glaciation rose from 150 m high on St. Lawrence Island to 300 m high on Seward Peninsula and a submarine ridge, possibly a moraine, extended northeastward from St. Lawrence Island. These results limit the transgression of Chukchi marine ice to the western Bering Sea and to coastal Alaska north of Seward Peninsula, perhaps as far as Point Barrow, according to oriented lakes. Ice from the Chukchi dome may have spread over the Chukchi foreland, where it would have entered ice streams in submarine troughs to the north and ended along the Northwind Escarpment to the east. Figure 5c shows the ice-flow pattern for comparison with glacial geological flow indicators in Figure 4. The depositional wedge on the continental slope in the southwestern Bering Sea in Figure 4 may have been supplied by the calving ice wall in Figure 5c. Transgression of the marine Chukchi ice dome onto the northwestern Alaskan coast should isostatically depress the coastline. Raised beaches 10–12 m high are widespread along this coast and are ^{14}C dated as older than 40 ka (Hamilton and Brigham-Grette, 1991).

GLACIATION FOR SNOW LINES 1200 m LOWER

Figure 6 shows the extent of Eurasian glaciation after 20 000 years for present-day precipitation rates when present-day snow lines are 1200 m lower. This allows the marine ice dome in the eastern Barents Sea to continue expanding eastward into the Kara Sea and southward on to the central Siberian mainland, even after its expansion westward and northward had halted at the edge of the Eurasian Arctic continental shelf. Therefore, the Barents ice dome migrated southeastward into the Kara Sea to become a Kara ice dome that was much larger and was able to engulf highland ice caps on Taimyr Peninsula, Putorana Plateau and Anabar Plateau (see Fig. 3). Island ice caps on Severnaya Zemlya, nourished by moisture-bearing westerly winds, could expand westward and thereby contribute to forming a marine Kara ice dome. Kara ice could then spread eastward across Severnaya Zemlya and through Boris Vilkitski Strait into the Laptev Sea. Kara ice could also spread westward in through valleys across Novaya Zemlya and cross the Barents Sea, ending as an ice stream in Bear Island Trough, as ice streams in submarine troughs and inter-island channels in the northwest Barents Sea and as ice lobes following river valleys on the north Russian Plain. Kara ice moving northward would have entered ice streams in Saint Anna Trough and Voronin Trough. Kara ice moving southward would have followed the Ob and Yenisey River estuaries into the central Siberian Lowland and followed glacial through valleys in Taimyr Peninsula to continue across the Putorana Plateau and the Anabar Plateau. Figure 6a shows these flow patterns for comparison with glacial geological flow indicators in Figure 4. There are no major discrepancies.

The marine ice dome over the New Siberian Islands in the East Siberian Sea would have advanced southward to the foothills of mountains in northeastern Siberia if snow lines were 1200 m lower. Therefore, we located the southern margin of this ice dome along the edge of these foothills. In particular, we assumed that the Kolyma River was ice marginal at the glacial maximum, so that its course today marks the former ice margin, and we assumed that ice lobes occupied the valleys of the Indigirka River and the Yana River. If true, the glacial geology produced by this advance is now buried under yedoma deposited in ice-dammed lakes during ice retreat. In the Laptev Sea, the ice saddle between the Kara ice dome and the East Siberian ice dome was both higher and broader when marine ice advanced to the southern foothills. For ice flowing northward from the East Siberian dome, we located the grounded ice margin at the 1000 m bathymetric contour west of Lomonosov Ridge and at the 1500 m bathymetric contour east of Lomonosov Ridge, since an ice shelf 1500 m thick in the Canadian Basin of the Arctic Ocean could not cross Lomonosov Ridge without thinning by 500 m. Figure 6b shows these flow patterns for comparison with glacial geological flow indicators in Figure 4. Discrepancies are minor and are the same as those noted for Figure 5b.

The Chukchi dome is enlarged by moisture-bearing winds from the North Pacific and it expands in that direction, if snow lines are lowered by 1200 m. Mountain glaciation in northeastern Siberia and Alaska is also expanded. In particular, glaciation of the Anadyr Range and the Koryak Mountains in Siberia and the Brooks Range in Alaska allow marine Chukchi ice pouring over Chukchi Peninsula, through Bering Strait and over Seward Peninsula to be unusually thick because marine and mountain ice merged, thereby eliminating lateral ablation zones in this region. Marine Chukchi ice would then have been able to advance further southward across the Bering Sea. Judging from glacial troughs cutting "the corners" of southeastern Chukchi Peninsula, as well as of the Navarin, Olyntorskiy and Govena Peninsulas (all three the seaward promontories of the Koryakskiy Range), that ice probably invaded the deep basin of the Bering Sea, ending as an ice shelf that calved into the Pacific Ocean along the Aleutian–Commander Islands. It is worth mentioning that this fundamentally new concept of the North Pacific glaciation is consistent with the sensational discoveries made on leg 145 of the "Joides Resolution" Ocean Drilling Program (Anon., 1992). If longitudinal lakes and transverse ridges in the southern Yukon delta reveal glacial lineations, the lower Yukon River would have been ice marginal. In northern Alaska, Chukchi ice may have occupied glacial through valleys in the DeLong Mountains, entered the Beaufort Sea and transgressed onto the Alaskan North Slope as far as the Colville River, which would have been ice marginal. A larger Chukchi dome may have advanced to the 1500 m bathymetric contour in the Chukchi foreland. This flow pattern is shown in Figure 6c for comparison with the glacial geology in Figure 4. Oriented lakes in the southern Yukon delta are from the Black and Kwiguk Quadrangles of the United States Geological Survey (USGS) topo-

graphic maps of Alaska, whereas other oriented lakes depicted in Figure 4 are from satellite imagery. We have more confidence in giving a paleoglaciological interpretation to oriented lakes in satellite imagery, because the associated geomorphology is more evident. Through valleys in the DeLong Mountains and across Seward Peninsula are also from USGS topographic quadrangle maps, so our interpretation that these are glacial through valleys is questionable. With these reservations, the flow indicators in Figure 4 are in reasonable agreement with the flowlines in Figure 6c. Raised marine shorelines up to 60 m high on the northern and northwestern Alaska coasts, and of apparent Pliocene age (Brigham-Grette and Carter, 1992), would be compatible with glacioisostatic depression by the Chukchi ice dome in Figure 6. We propose that these raised shorelines represented rebound after collapse of the cosmogenic nuclides may identify these shorelines as Pleistocene features.

FUTURE RESEARCH GOALS

Paleo-ice sheets controlled by present-day precipitation rates for snow lines either 1000 or 1200 m lower and growing for 20 000 years are, of course, not the only possibilities. Obvious alternatives are to confine growth of paleo-ice sheets to other time spans and to allow different precipitation rates and other snow lines. More realistic reconstructions would allow precipitation rates to change as an ice sheet gets larger and it increasingly creates the surrounding meteorological conditions, because it becomes the dominant geographical feature. It is also possible that, except for the Barents Sea, there was no extensive glaciation of the Eurasian Arctic continental shelf, especially during the Last Glacial Maximum, so there was no Arctic ice sheet. This possibility has the advantage of freeing us from the task of reconstructing paleo-ice sheets in the Russian Arctic but it makes no contribution toward stimulating Quaternary research in these remote regions, in the hope that keys to understanding global climatic change will be found there.

We expect that future research related to the Arctic ice sheet will provide new insights into the very basics of paleoglaciology. It will involve mapping the maximum extent of marine ice domes on Arctic continental shelves, mapping and dating the stages of their deglaciation, determining the dynamics of iceberg and lacustrine outbursts as ice domes collapsed and ice-dammed lakes were drained, establishing whether the ice domes were connected across the Arctic Ocean by a floating ice shelf, locating the major ice streams that linked them dynamically to the ice shelf, and determining how changes in one sector of a unified Arctic ice sheet affected ice dynamics in other sectors. On a more general scale, we will learn whether existence of the ice sheet compels recasting our knowledge and understanding of Quaternary glacial history. In fact, the pay-off may be a scientific revolution in understanding global climate and sea-level changes, especially abrupt changes.

Lessons learned from studying glaciology's grand unsolved problem in the Antarctic can be applied directly to understanding paleoglaciology's grand unsolved problem in the Arctic. Do ice streams have life cycles longer than but comparable to surge cycles of some mountain glaciers? Preliminary studies suggest they do (Clarke, 1987). Can these life cycles produce iceberg outbursts in the North Atlantic that correlate with "Heinrich events" of glaciomarine sedimentation that may date cessations of North Atlantic Deep Water production and shut-downs of overturning circulation? This possibility exists (MacAyeal, 1993) and the cessations may trigger abrupt global climate change (Hughes, 1992a). How was the dry interglacial ecological regime of Central Asia transformed by major changes in atmospheric circulation and water-vapor transport ensuing from the Arctic ice-sheet formation? What role in these changes was played by the vast proglacial lakes impounded by the ice sheet, especially by their outbursts during deglaciation? On theoretical grounds, one may expect profound ecological and geomorphological reorganizations.

What are the archeological implications for peopling the Americas if the Bering Land Bridge between Siberia and Alaska was periodically blocked by a marine ice lobe extending across Bering Strait from a marine ice dome in the Chukchi Sea? Our finite-element ice-sheet model produces this lobe with only modest changes of present-day climate in Beringia (Hughes and others, 1991). Finally, how rapidly and how soon could an Arctic ice sheet form again?

Answers to these compelling questions are hidden in the Arctic, foremost in Arctic Russia. With Russia now more open to international co-operative scientific investigations than ever before, definitive answers to these questions are within reach but time may be running out as we enter a new and perhaps a warmer century. In particular, one can speculate that if "greenhouse" warming eliminated winter sea ice in the Low Arctic, allowing greater winter precipitation in the High Arctic, thickening sea ice in the High Arctic might ground on shallow Arctic continental shelves and impound rivers flowing into the Arctic Ocean. The "White Hole" might form almost instantaneously in the decades ahead and enclose an area comparable in size to that covered by an Arctic ice sheet at its maximum stage (see Fig. 1), causing sea level to drop almost as fast as it rose during termination of the last glacial cycle. Paleoglaciology's grand unsolved problem may be answered much sooner than we expect and by Nature herself, not by us.

IMMEDIATE RESEARCH GOALS

We do not need to wait until Nature answers paleoglaciology's grand unsolved problem. Much can be done to determine whether or not an Arctic ice sheet existed in the past and what are its implications for understanding Quaternary climatic changes, including changes triggered by "greenhouse" warming and abrupt changes.

Datable materials, including tusks and teeth of woolly mammoths, are widespread on the Arctic coastal plains of Siberia and its offshore islands, and they are typically associated with both glacial and marine deposits. So far, these materials are only sporadically dated and some of the samples used for

dating appeared to be contaminated and thus yielded spurious, misleading chronologies. Obviously, these chronologies should be subjected to scrupulous revision, based upon systematic dating and re-dating of Siberian samples, taken in stratigraphically clear situations, combining AMS–^{14}C dating and surficial dating of cosmogenic nuclides whenever possible. A history of marine ice-sheet transgressions onto the Arctic coastal plains can be unraveled by this chronology-establishing program.

Dating lacustrine deposits of the former Yelogui ice-dammed lake in the Yenisey Valley and a youngest moraine on the northern Taimyr Peninsula are of highest priority, as their ages would shed light on the maximum extent of the last Kara ice dome and the final stages of its history.

Russian geologists, especially those working in Siberia, have accomplished impressive work on glacial and Quaternary lithology, stratigraphy, paleontology, archeology and geocryology. However, glacial geomorphology, which is most important for paleoglaciological reconstructions, has not similarly advanced. Hence, a special glaciogeomorphological program should also be considered. Specifically, the existing maps of end moraines, ice-shoved features and ice-motion-directional proxies, such as giant glacial grooves, drumlins and flutes, should be verified and improved on the basis of air-space images and field reconnaissances. We suggest that special attention be paid to the Arctic "oriented lakes" as a particularly promising tool of ice-sheet reconstructions for Siberia.

Marine scientists are on the verge of a major breakthrough in studies of the deep Arctic Ocean. We expect that the studies of unusually thick sediments blanketing the ocean floor would yield evidence for past glacial–interglacial cycles. In this context, we should be ready to correlate the glacial records from the Arctic continental shelves of Eurasia and the Eurasian mainland with those of the ocean, especially in Arctic basins just beyond troughs on the Arctic continental shelf that are the most probable sites for ice streams that drained the marine ice domes.

The origin of the ice-rich unconsolidated sediments blanketing the Arctic coastal lowlands in northeastern Siberia and northern Alaska is still unclear and debatable. Meanwhile, these sediments, containing erratics and taken either for signatures of eustatic marine transgression or for lacustrine sequences formed in ice-dammed lakes, may testify as to whether these lowlands developed under dominance of marine oceanic transgressions and regressions ("diluvialistic" scenario), or experienced recurrent glaciations by a marine ice sheet grounded on the Arctic continental shelf. The latter "glacialistic" scenario seems more predictable for the High Arctic, which even today is just half-way between Ice Age and interglacial conditions, especially the broad continental shelves and glaciated islands of the Russian Arctic.

The nearly continuous raised marine shorelines along the northwest Alaskan coast are older than 40 ka BP (Hamilton and Brigham-Grette, 1991). This coastline should be dated using exposure dating with cosmogenic nuclides to determine whether ice from the marine Chukchi ice dome transgressed on to the Alaskan mainland during the Last Glaciation.

Holocene raised beaches are low or absent on Russian Arctic islands but are high and widespread on Canadian Arctic islands. This implies that either marine ice domes were low or absent on the Russian Arctic continental shelf but not on the Canadian Arctic continental shelf during the Last Glacial Maximum, or a floating ice shelf or perennial sea ice prevented the wave action needed to form beaches in the Russian Arctic until the late Holocene. The second explanation is the case in Antarctica, where the late Wisconsin marine ice sheet on the Ross Sea continental shelf reached 700 m above present-day sea level on Ross Island and along the nearby Transantarctic Mountains, and was over 1300 m thick in McMurdo Sound yet raised beaches are low or absent (Stuiver and others, 1981). This region lies just north of the calving front of the Ross Ice Shelf, which has retreated during the Holocene and perennial sea ice extends to most shorelines even today. Systematic gravity measurements should be made in the Russian Arctic to see whether a pattern of negative anomalies exists that is compatible with the marine ice domes in Figures 5 and 6. If it is, these ice domes probably existed during the Last Glacial Maximum and ice grounded along Holocene shorelines prevented beaches from forming during post-glacial isostatic rebound.

DISCUSSION

We have avoided assigning times to the marine ice sheets reconstructed in Figures 5 and 6. These reconstructions are constrained by geomorphology and not by dates. Both reconstructions allow the ice sheets to grow for 20 000 years for snow lines lowered by 1000 and 1200 m, respectively. We expect the marine ice sheets to form whenever these conditions prevailed during the Quaternary. Specifically, since oxygen-isotope records during the last 800 000 years reveal glaciation cycles lasting about 100 000 years each, with no great differences in ice volume from one glacial maximum to the next if oxygen-isotope ratios are a reliable ice proxy (Hays and others, 1976), we believe that either reconstruction is possible for any Pleistocene glacial maximum. Furthermore, neither reconstruction has attained a steady state for our specified mass balance. If time was sufficient, a snow line 1000 m lower would convert the Figure 5 reconstruction into the Figure 6 reconstruction, and a snow line 1200 m lower would make the Figure 6 reconstruction even larger, so that ice in Figure 6a would advance into the Ukraine, and ice in Figure 6b would reach the Sea of Okhotsk. The geomorphology in Figure 4 indicates that time was not sufficient to produce a steady-state ice sheet in Arctic Eurasia. The actual limits of glaciation, especially during the last glaciation cycle, will be

established not by computer models but by careful and sustained field work using the latest dating methods. However, our model simulations alert us to the possibilities.

The ice-sheet reconstruction in Figures 5 and 6 are based on the view that snow precipitation borne by westerly winds was heavy on the western side of Novaya Zemlya and light on the eastern side, and an ice dome would migrate eastward over Novaya Zemlya if the regional snow line were lowered by an additional 200 m. This view requires that a single high ice dome developed in the Barents Sea. However, ice spreading from a single high Kara Sea ice dome provides a better fit to glacial geology, near the Urals and elsewhere, than ice spreading from a single high Barents Sea ice dome. During deglaciation, retreat of ice margins would leave a single ice dome over Novaya Zemlya in Figure 5 and over the Kara Sea in Figure 6. Glacial geology shows ice moving westward into the Barents Sea and there is no evidence that an ice dome ever existed over Novaya Zemlya. We conclude that Novaya Zemlya did not cast a long precipitation shadow over the Kara Sea, as that contradicts the field evidence for the last deglaciation. If the Barents Sea ice dome depicted in Figure 5 never existed, then the Kara Sea ice dome depicted in Figure 6 developed in situ, not as a result of eastward migration of a hypothetical Barents Sea ice dome.

One could conclude that no flights of raised beaches along the coast of the north Russian Plain proves that no marine ice sheet existed in the Barents Sea during the Last Glacial Maximum. However, high raised beaches on the islands of Svalbard and widespread glacial geology on the floor of the Barents Sea and on the north Russian Plain prove that a marine ice sheet did exist, without producing flights of raised beaches on the north Russian Plain. The same is true of the Kara Sea. Further east, the marine ice sheet would form in situ on a frozen bed, so little glacial geology would be produced. The lack of widespread glacial geology or flights of raised beaches on the coastal plains of Siberia and Alaska is not, in itself, proof that the frozen continental shelves and adjacent coastal plains of the Laptev, East Siberian, Chukchi and Beaufort Seas were not covered by a marine ice sheet during the last glaciation.

A solution to this dilemma lies in recognizing the distinction between glaciated coastal zones of the Norwegian type and of the Siberian type. The Norwegian coastal zone, which included Svalbard, lay between the ice divide and the seaward margin of the ice sheet, so retreat of the seaward ice margin was immediately accompanied by isostatic rebound of a coastal zone that was in continuous contact with the open sea. Therefore, flights of raised beaches full of contemporary marine fauna would be produced, one beach for every increment of retreat, and radiocarbon dating of faunal shells would yield a clear and precise chronology of deglaciation.

In sharp contrast, the Siberian coastal zone lay between the ice divide and the landward margin of the ice sheet, so retreat of the landward margin was accompanied by isostatic rebound of land that was not in contact with the open sea, and marine beaches would not form. Instead, ice-dammed lakes along the retreating landward ice margin would form and be a load on the bed that partly replaced the former ice load. Spillways draining these lakes would be continuously relocated during ice retreat, so the isostatic response to deglaciation would be irregular both temporally and spatially. The ice margin would respond to these instabilities with advances that were superimposed on a general retreat, such as occurred along the landward margin of the marine ice sheet in the Barents and Kara Seas, where a thawed bed existed and so glacial geology was produced.

Because the bed was thawed, basal sliding was continuously transporting marine shells landward and each advance and retreat of the landward ice margin was accompanied by dumping this mix of marine shells in proglacial lakes or as glacial outwash. The mixed shells would have the ages of all the Pleistocene interglaciations and many interstadials within glaciations. This is why radiocarbon ages of marine deposits on the Siberian lowlands are often non-finite or "over 40 ka". These bogus dates and low raised beaches underpin the view that the Kara Sea was not the site of a major ice dome during the last glaciation. However, raised marine beaches would form only after the terrestrial ice margins had retreated enough to allow ice-dammed lakes to be discharged directly into the open sea. Raised beaches are often present but they are low. This is consistent with final collapse of the Eurasian marine ice domes late in the Holocene, when isostatic rebound was nearly complete and the coastlines were seasonally free of sea ice.

The concept that when marine ice sheets are grounded on polar continental shelves and coasts, so that ice moves over preglacial marine sediments which are then eroded, entrained and transported landward, to be dumped into ice-dammed lakes or added to glacial outwash, provides an explanation for the huge lowland areas of Siberia that are blanketed with old-age fossil-rich sediments having marine geochemistry. After many Quaternary glaciation cycles, contamination of surficial sediments by non-contemporary organics and inorganics is now so overwhelming, so omnipresent and so diverse that even the AMS–^{14}C dating technique may be unable to untangle the stratigraphic puzzles, let alone conventional radiocarbon dating. Ignoring deposition by a marine ice sheet has led some Russians to embrace neodiluvianism as an explanation for widespread marine sediments of "old" age in the lower Pechora Basin and in the west Siberian Lowland.

The Dry Valleys of Antarctica were invaded by marine ice lobes when the marine West Antarctic ice sheet advanced across the Ross Sea during the last glaciation. These ice lobes dammed lakes in the Dry Valleys just as we propose for the Siberian Arctic coastal plain. The confusing stratigraphy of the Dry Valleys revealed a deglaciation history of the marine ice sheet only after the lacustrine shorelines were mapped and organics in their associated deltas were dated (Stuiver and others, 1981). This history placed glacial erratics over 600 m above raised beaches only 6 m high on nearby Ross Island. Therefore, we point to Antarctica to support our view of the glacial history of the Arctic. We note, however, that 30 years of sustained field research were spent before the record of the last deglaciation in the Dry Valleys, a tiny area, was understood. We cannot expect the Russian

Arctic, which spans 11 time zones, to reveal its deglaciation history without a correspondingly larger effort.

Of more glaciological interest than the extent of former Eurasian glaciation is the expanded horizon for ice dynamics when Eurasian glaciation combines with North American and Greenland glaciation to complete the circuit of marine ice domes on Arctic continental shelves. Then the domes could sustain an ice shelf floating on the Arctic Ocean, so that an Arctic ice sheet existed as a unified dynamic system, just as does the Antarctic ice sheet today. The heartbeat of the Arctic ice sheet would be cycles of thawing and refreezing of the bed under the major ice domes, with the concomitant reduced and restored basal traction causing the southern ice margins to advance and retreat, and sea level to rise and fall. The arteries through which this heartbeat pumped ice were the major ice streams radiating from the major ice domes and flanking the ice saddles between ice domes. With an Arctic ice sheet behaving as a single dynamic system, the heartbeat of each ice dome communicated with the heartbeats of all other ice domes through their ice streams, since they pumped ice into the sea through these arteries and sea level directly affected the marine margins of all ice domes. Marine ice domes expanded as sea level fell and contracted as sea level rose, creating another heartbeat that became a secondary harmonic superimposed on the primary heartbeat of basal thawing and refreezing. In addition, ice streams may have life cycles of their own, thereby adding even higher harmonics (Hughes, 1992a, b). The prospect of a Quaternary symphony orchestrated by the harmonics of an Arctic ice sheet quickens the heartbeat of every glaciologist. The search to find that ice sheet, and then to read its musical score, is paleoglaciology's grand unsolved problem.

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