New constraints on the limits of the Barents-Kara Ice Sheet during the Last Glacial Maximum based on borehole stratigraphy from the Pechora Sea

Article *in* Geology · July 2000

DOI: 10.1130/0091-7613(2000)28<611:NCOTLO>2.0.CO;2

Leonid Polyak
The Ohio State University

New constraints on the limits of the Barents-Kara ice sheet during the Last Glacial Maximum based on borehole stratigraphy from the Pechora Sea

Leonid Polyak
Byrd Polar Research Center, Ohio State University, Columbus, Ohio 43210, USA
Valery Gataullin
Ol'ga Okuneva
Vilnis Stelle
Research Institute NIIMorgeo (Oil and Gas Research Institute), Riga, Latvia

ABSTRACT

A new, ^{14}C-verified borehole stratigraphy provides the first age-controlled reconstruction of the late Quaternary glacial history of the Pechora Sea (southeasternmost Barents Sea). A complete glaciation of the Pechora Sea is confirmed for middle Weichselian time, prior to ca. 35–40 ka. Composition of glacial erratics indicates that ice was moving from or across southernmost Novaya Zemlya and Vaygach Island. After a brief interstadial period with normal marine conditions, the Pechora Sea was affected by a drop in sea level and a drier climate. Subsequently, the late Weichselian Barents-Kara ice sheet occupied the northwestern part of the Pechora Sea, but did not reach the coast of the Pechora lowland, as previously believed. These data provide a new constraint on the Last Glacial Maximum (LGM) ice-sheet limits in the Eurasian Arctic. The inferred direction of the Last Glacial Maximum ice movement in the Pechora Sea was from the northeast, but with a stronger northern component than the penultimate glaciation. The ice sheet retreated early, ca. 13 ka, after which the shallow Pechora Sea was subjected to strong erosion during the postglacial sea-level rise.

Keywords: late Quaternary stratigraphy, Barents-Kara ice sheet, Pechora Sea, Eurasian Arctic.

INTRODUCTION

Although much progress has been recently made concerning the glacial history of the Arctic perimeter, both in North America and Eurasia (e.g., England, 1999; Svendsen et al., 1999), a significant uncertainty remains concerning the patterns and extent of Quaternary glaciations in the Arctic. The discrepancy between minimal and maximal models for the glaciation of northern Eurasia during the Last Glacial Maximum (LGM) exceeds 2×10^6 km^3, a volume larger than the present Greenland ice sheet (Lambeck, 1995; Siegert et al., 1999). This lack of knowledge about past Eurasian ice sheets significantly restricts our understanding of global sea-level variations and of Quaternary environmental change in the Arctic.

Numerous geologic data show that the lowlands south of the Barents and Kara Seas were repeatedly invaded by voluminous ice sheets centered on the continental shelf (see Astakhov et al., 1999, for review). However, the chronology of glacial events remains ambiguous over large areas. Most authors have associated a prominent belt of marginal glacigenic features mapped in the Pechora and West Siberian lowlands approximately along the polar circle with the last major glacial advance, which overrode marine deposits believed to be of Eemian age (Fig. 1) (e.g., Arkhipov et al., 1986; Svendsen et al., 1999). The fresh appearance of glacial geomorphic features has been cited as evidence for last advance during the LGM (Lavrov, 1977; Grosswald, 1994). However, new data employing modern chronostratigraphic techniques indicate that the Pechora and western Siberian coasts were likely not glaciated during the LGM (Mangerud et al., 1999; Forman et al., 1999a).

In contrast to the Pechora and West Siberian lowlands, data from the adjacent Barents Sea and at least part of the Kara Sea indicate the presence of a vast recent ice sheet (Landvik et al., 1998, and references therein). The termination of a subglacial depositional regime at various locations across the shelf is estimated to have been ca. 13 ka or slightly earlier (Fig. 1). Accordingly, the glacial sedimentary unit at these sites is believed to represent the LGM. Coupled with studies of glacial stratigraphy and glacioisostatic rebound on land, the marine data indicate that a continuous grounded late Weichselian ice sheet extended from Svalbard to at least the western Kara Sea and reached a thickness of as much as 2000 m in the north-central Barents Sea (Forman et al., 1995; Lambeck, 1995; Siegert et al., 1999). In the southwest, the Barents-Kara ice sheet likely coalesced with the Scandinavian ice sheet (Vorren and Kristoffersen, 1986; Sættem et al., 1992; Epshtein et al., 1999). The largest remaining uncertainty is how far the ice extended into the southeasternmost part of the Barents Sea (Pechora Sea) and the Kara Sea. A tentative southeastern ice-sheet limit was proposed by Svendsen et al. (1999) (Fig. 1). However, this reconstruction is mostly based on evidence from land and needs to be tested by marine data. Determination of the ice limit in the Pechora Sea will provide an important constraint on overall dimensions of the LGM Barents-Kara ice sheet.

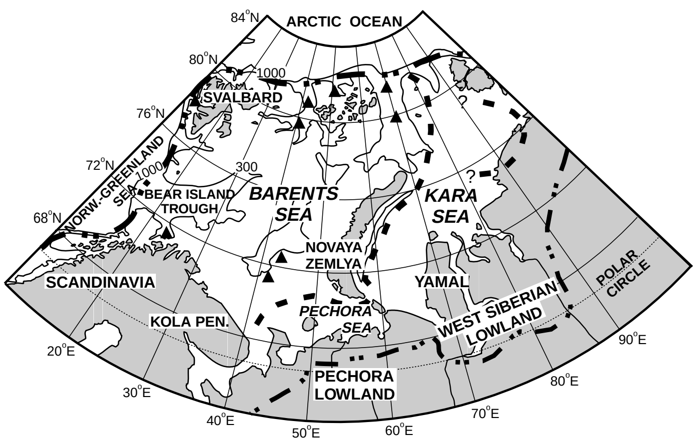

Figure 1. Map of Barents and Kara Seas with isobaths of 300 and 1000 m. Dashed-dotted and dashed lines show maximum post-Eemian glaciation limit and tentative southeastern Last Glacial Maximum (LGM) limit, respectively (Svendsen et al., 1999). Triangles show sites where postglacial sediments close to till surface have been dated between ca. 13 and 15 ka (Polyak et al., 1997; Landvik et al., 1998, and references therein).

PECHORA SEA BOREHOLE STRATIGRAPHY

The floor of the shallow (mostly <100 m) Pechora Sea is rather smooth, and has no obvious glacier-terminal features indicative of an ice-sheet margin (Epshtein, 1985). This topography likely reflects extensive seafloor erosion during the postglacial sea-level rise (cf. Piper et al., 1983). In the absence of a geomorphic expression of the ice-sheet terminus, a rigorous time control for sediment records from the potential ice-marginal zone is particularly important. By using a new series of ^{14}C dates (Table 1), we have reevaluated stratigraphic materials from boreholes drilled in the Pechora Sea (Fig. 2) (Krapivner et al., 1986; Onischenko and Bondarev, 1988; Okuneva, 1991; Gataullin, 1992). This reevaluation provides the first age-controlled stratigraphy for Quaternary sediments of the Pechora Sea. Together with a new analysis of seismic-reflection data (Gataullin et al., 2000), our study helps determine the extent of Weichselian ice sheets in this region.

The extensively dated boreholes 210–218 (a composite from four closely located wells with a nearly identical stratigraphy) and 234 are located in the southeastern part of the Pechora Sea adjacent to the Pechora lowland (Fig. 2). The remaining two boreholes, 3 and 104, are in the western Pechora Sea near Kolguev Island. To compare the Pechora Sea stratigraphy with that of the deeper southeastern Barents Sea, we also show the results from the closest dated boreholes 26 and 140 (Polyak et al., 1995, and this paper).

All of the boreholes contain glacial diamictons at the base of the Quaternary sequence, which unconformably overlies soft Mesozoic bedrock as demonstrated in composite borehole 210–218, consistent with seismic and lithostratigraphic data from the Barents Sea (Fig. 3; Gataullin et al., 1993; Polyak et al., 1995). Borehole 104 displays two stacked diamictons separated by a 30-m-thick marine sedimentary sequence. As observed elsewhere in the Barents Sea (e.g., Sættem et al., 1992; Gataullin et al., 1993), the Pechora Sea diamictons are composed of stiff sandy mud with coarse clasts (Fig. 4) and inclusions of soft bedrock to 1 m in diameter. The sturdiest clasts commonly have glacially polished and/or striated facets and mainly consist of Paleozoic mudstones and limestones originating from

TABLE 1. ACCELERATOR MASS SPECTROMETER ^{14}C DATES

Lab no.	Boring no.	Depth in core (m)	Material*	Mass (mg)	Uncorrected age (yr B.P.)
AA 27890	026	2.1	M, shell detritus	31.6	4795 ± 50
AA 27891	026	11.0	M, *Yoldiella* (?)	50.2	9855 ± 70
AA 25041	026	14.4	F, mixed	4.5	9907 ± 80
PL9802335A	003	12.0	M, shell detritus	11.6	9410 ± 80
AA 34296	104	25.7	M, *Ciliatocardium*	18.5	3960 ± 45
AA 34297	104	30.0	M, *Yoldia* (?)	27.8	6545 ± 50
AA 34298	104	41.0	M, *Buccinum*	28.3	6880 ± 70
PL9802336A	104	75.5	M, shell detritus	17.8	42100 ± 2700
PL9802338A	218	3.4	M, *Astarte*	18.5	5060 ± 80
AA 25041	212	5.5	F, mixed	5.8	6387 ± 68
PL9802339A	212	7.0	M, *Thyasira*, *Macoma*	13.0	6920 ± 80
PL9802340A	212	14.0	M, *Natica*	1000.0	8610 ± 80
AA 34299	215	15.5	M, *Natica*	82.0	9475 ± 60
PL9802341A	212	17.8	M, *Macoma*	8.8	10080 ± 80
AA 34300	215	19.1	M, *Macoma*	98.0	9930 ± 70
AA 25041	212	19.7	M, shell detritus	165.0	9675 ± 75
AA 34301	212	25.2	Plant detritus	8.1	23600 ± 400
AA 34302	210	35.3	Plant detritus	7.2	28330 ± 680
AA 34304	210	52.3	M, shell detritus	12.2	35540 ± 700
AA 12272	212	57.8	F, mixed	5.5	39765 ± 1275
AA 9449	210	59.5	F, mixed	5.3	36700 ± 900
AA 27894	210	99.0	F, mixed	5.8	37460 ± 990
PL9802342A	234	15.3	M, shell detritus	7.8	29650 ± 600
PL9802343A	234	20.1	M, *Yoldiella*	13.0	31310 ± 740
PL9802344A	234	25.2	M, *Yoldiella*	12.5	33000 ± 880
PL9802345A	234	29.7	M, *Yoldiella* (?)	13.5	39200 ± 1600

Note: Accelerator mass spectrometer laboratories: AA—Arizona AMS Facility, PL—Purdue University Laboratory.
*M—mollusks, F—benthic foraminifers.

Novaya Zemlya. Detailed studies of boreholes 210–218 and 234 show erratics with a high content of dark limestone from southernmost Novaya Zemlya and Vaygach Island (Epshtein et al., 1999).

Diamictons from the southeastern Pechora Sea (boreholes 210–218 and 234) and the lower diamicton from borehole 104 are overlain by indistinctly laminated, dark gray mud (Figs. 3 and 4). The lower 10+ m of mud contains abundant foraminifers, mollusks, and ostracodes; palynological spectra from this sediment are dominated by tree pollen. Upsection, gray mud includes rhythmically spaced silt laminae; marine microfossils nearly disappear, and pollen becomes increasingly dominated by herbs, mainly *Artemisia* (wormwood). This unit in the southeastern area is truncated by cross-bedded sands containing rounded rip-up clasts of underlying laminated muds; in composite borehole 210–218 these sands grade upcore into another interval of mud and then into cover sands. The sedimentary sequence above the truncation has variable amounts of marine fauna and tree-dominated pollen and is correlative to sediments overlying diamictons in boreholes 104 (upper diamicton) and 3. The top surface of the upper diamicton in borehole 104 has been washed out, as indicated by a coarse-clast pavement.

RESULTS AND DISCUSSION

It has been believed that the diamictons recovered in the southeastern Pechora Sea have a late Weichselian age (e.g., Okuneva, 1991; Epshtein et al., 1999), which implies a LGM ice-sheet margin south of the Barents and Kara Sea coasts. A different interpretation emerges with new ^{14}C dates (Fig. 3). In contrast to the open Barents Sea, where deposits above till are ubiquitously dated to ca. 13 ka, postglacial sediments in a seemingly similar stratigraphic position in boreholes 210–218 and 234 yield multiple ^{14}C dates older than 30 ka. Although these ages are near the upper limit of the ^{14}C technique, the downcore succession of postglacial ages (Figs. 3 and 4) suggests that deglaciation occurred during middle Weichselian time, ca. 40 ka or slightly earlier. This age is consistent with postglacial ^{14}C and luminescence ages from the coasts of the Pechora lowland and Yamal Peninsula (Mangerud et al., 1999; Forman et al., 1999a). A lens of foraminiferal-rich marine sediment incorporated into till in borehole 210 yields an age of 37 ka (Figs. 3 and 4) and might reflect a short-lived readvance of the ice-sheet margin during deglaciation.

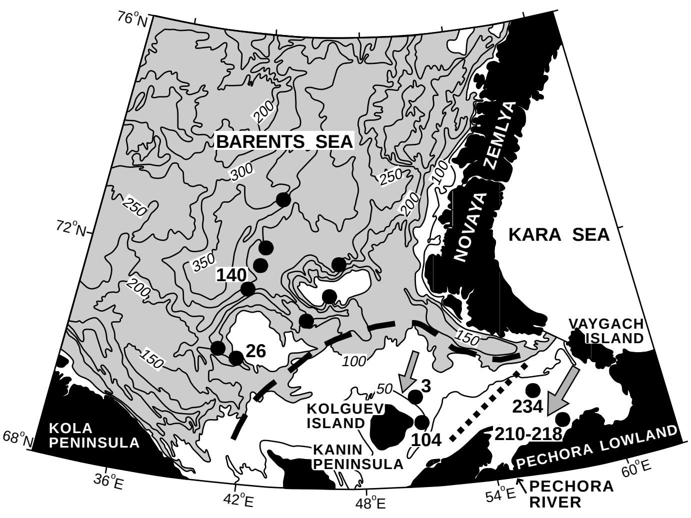

Figure 2. Southeastern Barents Sea with isobaths in 50 m intervals; area with depth >100 m is shaded. Filled circles are boreholes with ^{14}C-defined stratigraphy. Numbers are shown for boreholes discussed in this paper; others are discussed in Polyak et al. (1995). Dotted and dashed lines show approximate southeastern margin of Last Glacial Maximum (LGM) Barents-Kara ice sheet as suggested by this study and by Svendsen et al. (1999), respectively. Arrows show ice-sheet flows during middle Weichselian (larger arrow) and LGM (smaller arrow), inferred from composition of glacial erratics in tills.

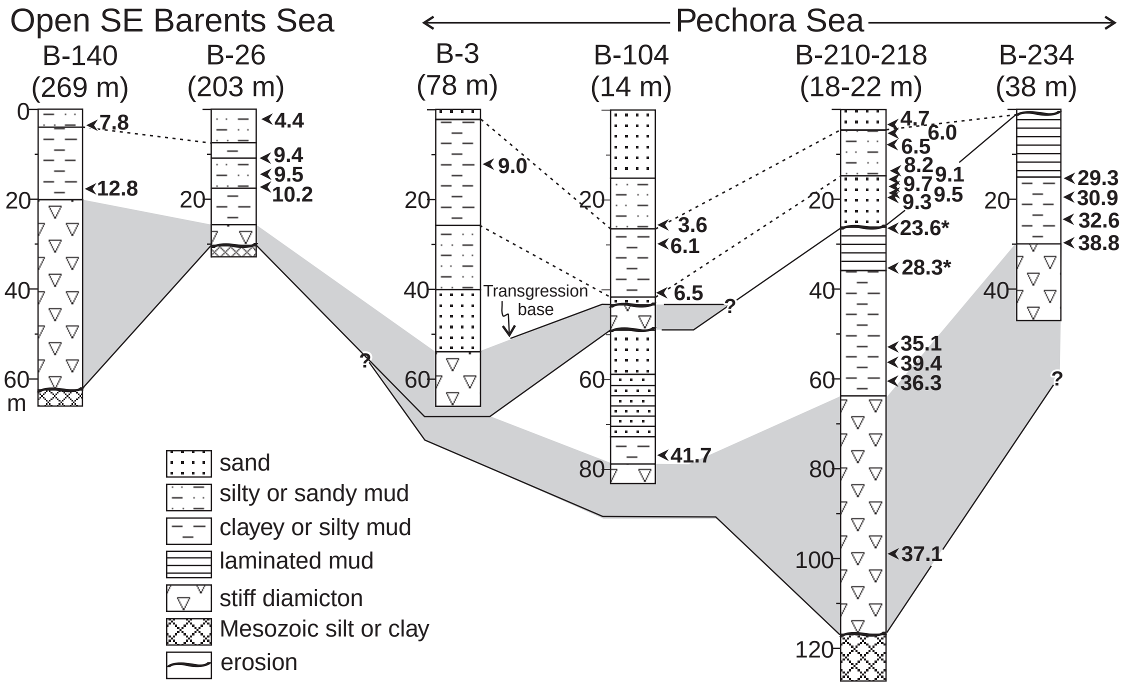

Figure 3. Borehole stratigraphy (see Fig. 2 for locations). Borehole numbers and water depths are shown at top. Solid lines connect major stratigraphic boundaries marked by hiatuses (glacial or wave erosion); dashed lines show other apparent correlations; shading highlights glacial diamictons. Arrows with numbers are ^{14}C ages (ka) with 400 yr reservoir correction for marine carbonates (Stuiver and Braziunas, 1993). Asterisks indicate plant-detritus samples.

Faunal assemblages in gray mud above the middle Weichselian diamicton indicate open-marine interstadial environments (Okuneva, 1991; Gataullin, 1992; Kupriyanova, 1999). The disappearance of marine microfossils and the emplacement of silt laminae after ca. 30 ka reflect a shift to shallow-marine, prodeltaic environments with a sea-level drop. A rising proportion of herbaceous pollen further indicates an increasing proximity to the coastline and/or the establishment of drier climate in the region, which is emphasized by the abundance of *Artemisia* (cf. Serebryanny et al., 1998). This interpretation is consistent with data from the Yamal Peninsula, where the interval 30–12 ka was characterized by cold and dry conditions (Forman et al., 1999a). The prominent hiatus between the Weichselian muds and the Holocene sands in the southeastern Pechora Sea (Figs. 3 and 4) reflects seafloor erosion during the post-LGM sea-level rise. No diamict remnants or rock clasts have been detected at the base of Holocene sands; instead, the base sands include rip-up clasts of soft Weichselian mud. This lithology strongly indicates that no glacial till was emplaced in the southeastern Pechora Sea during the Last Glacial Maximum.

In the western Pechora Sea, the borehole stratigraphy includes a second diamicton, which we correlate to the LGM till of the Barents Sea and to the hiatus in boreholes 210–218 and 234 (Fig. 3). The consistent presence of two or more superimposed diamictons separated by interglacial units in this region, exemplified by borehole 104, is observed in nearby Kolguev Island and Kanin Peninsula cliff sections (Baranovskaya et al., 1986; Epshtein et al., 1999), as well as on seismic lines in the western Pechora Sea (Krapivner et al., 1986; Gataullin et al., 2000). Preservation of older tills is common in a marginal ice-sheet zone where ice becomes thinner and less erosive, in contrast to the central zone of the Barents-Kara ice sheet, where pre-LGM Cenozoic deposits have been largely removed by glacial erosion (Sættem et al., 1992; Gataullin et al., 1993).

Available ^{14}C dates in the Pechora Sea are insufficient to precisely define the age of the last deglaciation. Nevertheless, correlation with boreholes from the adjacent Barents Sea (Fig. 3; Polyak et al., 1995) allows us to infer that deglaciation occurred ca. 13 ka. The actual deglaciation age in the Pechora Sea could be slightly older or younger than 13 ka, depending on the balance between a northwestward retreat of a land-based ice margin and a bathymetric-controlled retreat of an ice-sheet grounding line that propagated from the deep Bear Island trough to adjacent shallows (Polyak et al., 1995; Landvik et al., 1998). The top surface of the upper diamicton in borehole 104 was washed out by the post-LGM transgression, whereas the diamicton in borehole 3 is seemingly undisturbed, reflecting its position below the base of erosion. The deposition of relatively fine grained sediments with abundant fauna in the southern Pechora Sea commenced ca. 8.5–9 ka (composite borehole 210–218), indicating the end of extensive erosion of adjacent shallow areas and/or the landward migration of wave-base erosion with sea-level rise.

PATTERNS AND LIMITS OF THE LAST GLACIAL MAXIMUM AND PENULTIMATE GLACIATION

The absence of LGM till immediately north of the Pechora lowland (boreholes 210–218 and 234) is corroborated by seismic-reflection data showing that the youngest glacial unit does not extend into the southeastern Pechora Sea (Gataullin et al., 2000). We conclude that the LGM Barents-Kara ice sheet terminated northwestward of borehole 234 (Fig. 2), because extensive subglacial nondeposition is very unlikely in the marginal zone of a deformable-bed glacier (e.g., Boulton, 1996). On the basis of the upper diamicton in boreholes 3 and 104 and on Kolguev Island (e.g., Baranovskaya et al., 1986), we infer that these sites were occupied by LGM ice, which implies an ice margin ~200 km southeastward from that suggested

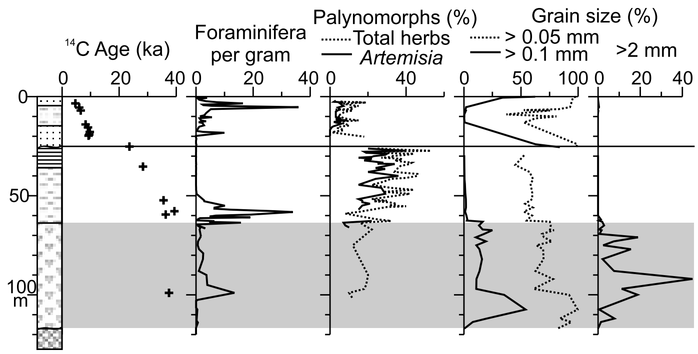

Figure 4. Distribution of ^{14}C ages, calcareous benthic foraminifers, herb pollen, and major granulometric classes in boreholes 210–218 (see Fig. 3 for lithology). Shading—glacial diamicton, solid line—erosional boundary between Weichselian and Holocene sediments.

by Svendsen et al. (1999). Further delineation of this margin is needed for a better assessment of LGM ice volume and for understanding the large difference in extent between the late Weichselian and penultimate ice sheets in Arctic Eurasia.

The common occurrence of dark-colored limestone erratics in the middle Weichselian diamicton suggests ice flow from or across southernmost Novaya Zemlya and Vaygach Island (Epshtein et al., 1999). This result is consistent with geomorphic and stratigraphic data from the adjacent lowlands indicating ice flow from the southern Kara Sea (e.g., Astakhov et al., 1999). In contrast, the upper (LGM) diamicton in the western Pechora Sea has common mudstones from more northerly Novaya Zemlya areas (Epstein et al., 1999); presumably, this difference reflects a more restricted distribution of the LGM ice into the southern Kara Sea.

The size difference between the penultimate and LGM glaciations in the Pechora Sea is emphasized by contrasting deglaciation styles. The lack of an erosional unconformity on top of the middle Weichselian diamicton indicates that the retreating ice-sheet front was well below sea level because of a glacio-isostatic depression of the seafloor and/or high global sea level, followed by a late Weichselian regression. In contrast, during the post-LGM deglaciation, most of the Pechora Sea was above sea level, as reflected in seafloor erosion during the subsequent transgression. These patterns are consistent with glacio-isostatic evidence from Novaya Zemlya (Forman et al., 1999b) indicating a substantially larger ice load during the penultimate glaciation.

ACKNOWLEDGMENTS

Boreholes were recovered by the Arctic Marine Geotechnical Expedition (AMIGE, Murmansk, Russia) and originally investigated at the Research Institute for Marine Geology and Geophysics (NIIMorgeo, Riga, Latvia) of the former Soviet Union. B. Romanyuk and I. Yakubovskaya assisted in lithological and palynological studies. Discussions with O. Epshtein and J.I. Svendsen, comments by D.J. Lubinski, and reviews by K. Lambeck and S.L. Forman helped to improve the manuscript. This project was supported by National Science Foundation grants OPP-9818247 and OPP-9725418. This is Byrd Polar Research Center Contribution 1180.

REFERENCES CITED

Arkhipov, S.A., Isaeva, L.L., Bespaly, V.G., and Glushkova, O.Y., 1986, Glaciation of Siberia and northeast USSR, *in* Sibrava, V., et al., eds., Quaternary glaciations in the Northern Hemisphere: Oxford, Pergamon Press, p. 463–474.

Astakhov, V.I., Svendsen, J.I., Matiouchkov, A., Mangerud, J., Maslenikova, O., and Tveranger, J., 1999, Marginal formations of the last Kara and Barents ice sheets in northern European Russia: Boreas, v. 28, p. 23–45.

Baranovskaya, O.F., Grigor'ev, M.N., and Malyasova, E.S., 1986, Late Cenozoic stratigraphy of the Kolguev Island, *in* Zarkhidze, V.S., and Kulakov, Y.N., eds., Cenozoic deposits of the shelf and islands of the Soviet Arctic: Leningrad, Sevmorgeologia, p. 83–89 (in Russian).

Boulton, G.S., 1996, Theory of glacial erosion, transport and deposition as a consequence of subglacial sediment deformation: Journal of Glaciology, v. 42, p. 43–62.

England, J., 1999, Coalescent Greenland and Innuitian ice during the Last Glacial Maximum: Revising the Quaternary of the Canadian High Arctic: Quaternary Science Reviews, v. 18, p. 421–456.

Epshtein, O.G., 1985, Geotechnical conditions of the oil and gas prone areas of the Barents and Kara Sea shelf: Part I. Barents Sea: Latvia, Riga, NIIMorgeo Report, 300 p. (in Russian).

Epshtein, O.G., Romanyuk, B.F., and Gataullin, V.N., 1999, Pleistocene Scandinavian and Novaya Zemlya ice sheets in the southern part of the Barents Sea shelf and in the north of the Russian Plain: Byullyuten' Komissii po Izucheniyu Chetvertichnogo Perioda (INQUA Bulletin), v. 63, p. 132–155 (in Russian).

Forman, S.L., Lubinski, D., Miller, G.H., Matishov, G., Snyder, J., Korsun, S., and Myslivets, V., 1995, Post-glacial emergence and distribution of late Weichselian ice sheet loads in the northern Barents and Kara Seas, Russia: Geology, v. 23, p. 113–116.

Forman, S.L., Ingolfsson, O., Gataullin, V., Manley, W., and Lokrantz, H., 1999a, Late Quaternary stratigraphy of Marresale, Yamal Peninsula, Russia: New constraints on the footprint of the Eurasian ice sheet: Geology, v. 27, p. 807–810.

Forman, S.L., Lubinski, D.J., Zeeberg, J.J., Polyak, L., Miller, G.H., Matishov, G., and Tarasov, G., 1999b, Postglacial emergence and late Quaternary glaciation on northern Novaya Zemlya, Arctic Russia: Boreas, v. 28, p. 133–145.

Gataullin, V.N., 1992, Lithostratigraphic study of key geotechnical boreholes in the Barents and Kara seas: Latvia, Riga, NIIMorgeo Report, 363 p. (in Russian).

Gataullin, V.N., Polyak, L.V., Epstein, O.G., and Romanyuk, B.F., 1993, Glacigenic deposits of the Central Deep: A key to the late Quaternary evolution of the eastern Barents Sea: Boreas, v. 22, p. 47–58.

Gataullin, V., Mangerud, J., and Svendsen, J.I., 2000, The extent of the late Weichselian ice sheet in the southeastern Barents Sea: Global and Planetary Change (in press).

Grosswald, M.G., 1994, The drumlin fields of the Novaya Zemlya–Urals region and the Kara center of glaciation: Polar Geography and Geology, v. 18, p. 15–32.

Krapivner, R.B., Gritsenko, I.I., and Kostyuhin, A.I., 1986, Seismostratigraphy of recent deposits of the southern Barents Sea region, *in* Zarkhidze, V.S., and Kulakov, Y.N., eds., Cenozoic deposits of the shelf and islands of the Soviet Arctic: Leningrad, Sevmorgeologia, p. 7–14 (in Russian).

Kupriyanova, N.V., 1999, Biostratigraphy of upper Cenozoic sediments of the Pechora Sea by ostracodes: Berichte Polarforschung, v. 306, p. 62–79.

Lambeck, K., 1995, Constraints on the late Weichselian ice sheet over the Barents Sea from observations on raised shorelines: Quaternary Science Reviews, v. 14, p. 1–16.

Landvik, J.Y., Bondevik, S., Elverhøi, A., Fjeldskaar, W., Mangerud, J., Salvigsen, O., Siegert, M.J., Svendsen, J.I., and Vorren, T.O., 1998, The last glacial maximum of Svalbard and the Barents Sea area: Ice sheet extent and configuration: Quaternary Science Reviews, v. 17, p. 43–75.

Lavrov, A.S., 1977, The Kola-Mezen, Barents-Pechora and Novaya Zemlya-Kolva glacier flows, *in* Chebotareva, N.S., ed., Structure and dynamics of Europe's latest ice sheet: Moscow, Nauka, p. 83–100 (in Russian).

Mangerud, J., Svendsen, J.I., and Astakhov, V.I., 1999, Age and extent of the Barents and Kara ice sheets in Northern Russia: Boreas, v. 28, p. 46–80.

Okuneva, O.G., 1991, Methods of development and substantiation of the proposed regional stratigraphic scheme for the upper Quaternary deposits of the Pechora Basin shelf: Riga, Latvia, NIIMorgeo, 68 p. (in Russian).

Onischenko, S.V., and Bondarev, V.N., 1988, Stratigraphy and paleogeographic environments of sedimentary sequences from the Pechora Sea, *in* Matishov, G.G., and Tarasov, G.A., eds., Quaternary paleoecology and paleogeography of the northern seas: Moscow, Nauka, p. 142–150 (in Russian).

Piper, D.J.W., Letson, J.R.J., De Iure, A.M., and Barrie, C.Q., 1983, Sediment accumulation in low-sedimentation, wave-dominated glaciated inlets: Sedimentary Geology, v. 36, p. 195–215.

Polyak, L., Lehman, S.J., Gataullin, V., and Jull, A.J.T., 1995, Two-step deglaciation of the southeastern Barents Sea: Geology, v. 23, p. 567–571, 767.

Polyak, L., Forman, S.L., Herlihy, F.A., Ivanov, G., and Krinitsky, P., 1997, Late Weichselian deglacial history of the Svyataya (Saint) Anna Trough, northern Kara Sea, Arctic Russia: Marine Geology, v. 143, p. 169–188.

Sættem, J., Poole, D.A.R., Ellingsen, K.L., and Sejrup, H.P., 1992, Glacial geology of outer Bjørnøyrenna, southwestern Barents Sea: Marine Geology, v. 103, p. 15–51.

Serebryanny, L., Andreev, A., Malyasova, E., Tarasov, P., and Romanenko, F., 1998, Late glacial and early-Holocene environments of Novaya Zemlya and the Kara Sea region of the Russian Arctic: The Holocene, v. 8, p. 323–330.

Siegert, M.J., Dowdeswell, J.A., and Melles, M., 1999, Late Weichselian glaciation of the Russian High Arctic: Quaternary Research, v. 52, p. 273–285.

Stuiver, M., and Braziunas, T., 1993, Modelling atmospheric ^{14}C influences and ^{14}C ages of marine samples to 10,000 BC: Radiocarbon, v. 35, p. 137–189.

Svendsen, J.I., Astakhov, V.I., Bolshiyanov, D.Y., Demidov, I., Dowdeswell, J.A., Gataullin, V., Hjort, C., Hubberten, H.W., Larsen, E., Mangerud, J., Melles, M., Möller, P., Saarnisto, M., and Siegert, M.J., 1999, Maximum extent of the Eurasian ice sheets in the Barents and Kara Sea region during the Weichselian: Boreas, v. 28, p. 234–242.

Vorren, T.O., and Kristoffersen, Y., 1986, Late Quaternary glaciation in the southwestern Barents Sea: Boreas, v. 15, p. 51–59.

Manuscript received December 17, 1999
Revised manuscript received April 7, 2000
Manuscript accepted April 24, 2000