Quaternary Research
doi:10.1006/qres.2001.2256, available online at http://www.idealibrary.com on IDEAL®

Holocene Relative Sea-Level History of Novaya Zemlya, Russia, and Implications for Late Weichselian Ice-Sheet Loading

JaapJan Zeeberg

Department of Earth and Environmental Sciences (M/C 186), University of Illinois at Chicago, 845 West Taylor Street, Chicago, Illinois 60607-7059

E-mail: jzeebe1@uic.edu

David J. Lubinski

Institute of Arctic and Alpine Research (INSTAAR), 1560 30th Street, Boulder, Colorado 80303

and

Steven L. Forman

Department of Earth and Environmental Sciences (M/C 186), University of Illinois at Chicago, 845 West Taylor Street, Chicago, Illinois 60607-7059

Received September 19, 2000

We present six new radiocarbon-dated emergence curves that provide a detailed record of postglacial emergence of northern Novaya Zemlya and ages which constrain the emergence of Vaygach Island in the southern archipelago. Radiocarbon ages on *Hiatella* sp. from a lateral moraine in Russkaya Gavan' and abundances of foraminifea in a marine core from Nordenskiold Bay, 300 km south of our study area, indicate that coastal deglaciation occurred prior to ∼10,000 cal yr B.P. However, postglacial emergence commenced ∼7000 cal yr B.P., with stabilization of global sea level. The total emergence is 13–11 m above sea level (asl) with apparent uplift rates of 1–2 mm/yr for the past 2000 yr, indicating modest glacier loads (<1 km), early (>11,000 cal yr B.P.) deglaciation, or both. The isobase pattern, showing no east–west tilt across Novaya Zemlya, and offshore moraines suggest a separate ice-dispersal center over Novaya Zemlya for the later stages of the Late Weichselian glacial cycle and possibly earlier.

Key Words: **glacio-isostasy; raised beaches; Novaya Zemlya; deglaciation; Barents Sea ice sheet.**

INTRODUCTION

The ice sheet that developed in the European Arctic during the Late Weichselian (30,000–15,000 cal yr B.P.; marine oxygen isotope stage 2) grounded over much of the continental shelf (Solheim *et al.*, 1990; Elverhøi *et al.*, 1995; Gataullin *et al.*, 1993; Polyak *et al.*, 1995, 1997). Postglacial isostatic uplift ensued with crust and mantle relaxation upon deglaciation, resulting in formation of raised shorelines around the Barents Sea. The pattern of postglacial emergence on Svalbard and Franz Josef Land (Fig. 1) indicates maximum ice-sheet loading over eastern Svalbard and the central Barents Sea (Bondevik *et al.*, 1995; Forman *et al.*, 1995, 1997; Landvik *et al.*, 1998). The isostatic rebound enables reconstruction by earth rheology models of a 2+ km-thick ice sheet over the Barents Sea, assuming ice-sheet limits and a parabolic ice-sheet profile (Lambeck, 1995; Peltier, 1996).

Recently produced ice-sheet models for the Late Weichselian depict a single large ice dome in the Barents Sea with ice flow extending over Novaya Zemlya into the Kara Sea (Lambeck, 1995, 1996; Peltier, 1996; Siegert *et al.*, 1999). The northern and northwestern extent of this ice sheet is fairly well known, with its margin on the outer continental shelf or slope (Mangerud *et al.*, 1992; Lubinski *et al.*, 1996; Polyak *et al.*, 1997; Landvik *et al.*, 1998, Forman and Ingolfsson, 2000). The southern margin of the ice probably terminated in the Pechora Sea (Fig. 1; e.g., Polyak *et al.*, 2000). The eastern continuation of the ice sheet remains unresolved, reflecting a paucity of glacial geological and relative sea-level measurements (Forman *et al.*, 1999a; Svendsen *et al.*, 1999). Apparent sea levels have been traced on central Novaya Zemlya at 54 to 56 and 120 to 150 m asl (Grønlie, 1924; Nordenskjöld and Mecking, 1928; Lavrova, 1932). Deposits with marine molluscs (*Astarte borealis*, *Mya truncata*, and *Saxicava arctica*) were encountered at elevations between 20 and 25 m asl in Krestov Bay on the Barents Sea coast and on Goltzovy Peninsula on the opposite coast (Lavrova, 1932). These elevations, and interpretation of the Markhida Moraine as the Holocene ice-margin of the Barents Sea ice-sheet, lead to a reconstructed ice loading of 3+ km (Grosswald, 1980; Lambeck, 1993, 1995, 1996; Peltier, 1996). Recent chronostratigraphic studies indicate that the Markhida Moraine is probably Middle or Early Weichselian in age and that the Late Weichselian ice limit lies offshore in the Barents Sea (Mangerud *et al.*, 1999; Polyak *et al.*, 2000). Dating of raised beaches on northwestern Novaya

0033-5894/01 $35.00

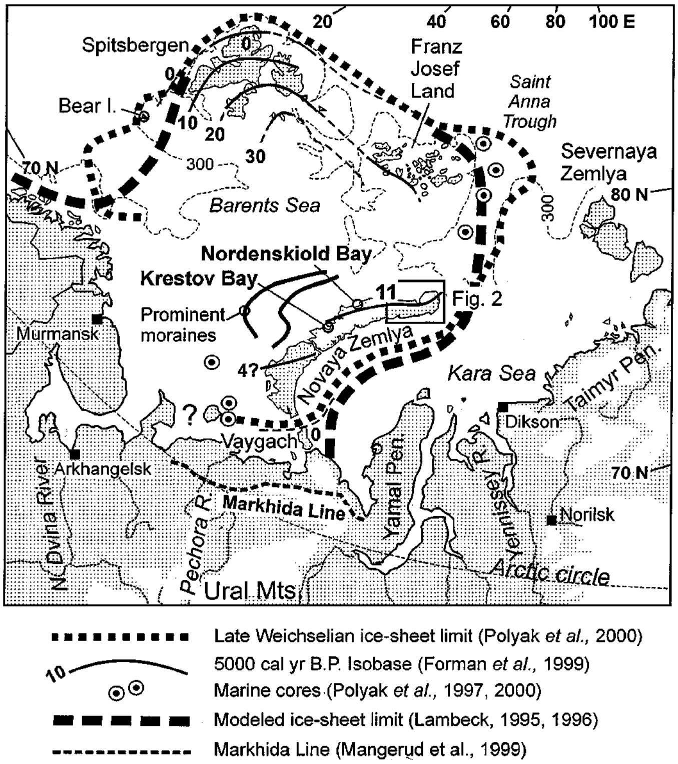

FIG. 1. Reconstructed Late Weichselian ice-sheet limits for the Barents and Kara seas based on field data (Polyak *et al.*, 2000) and models (Lambeck, 1995, 1996). The Markhida Line (Mangerud *et al.*, 1999; Forman *et al.*, 1999b) indicates the limit of the last (early or middle Weichselain) ice advance from the Barents and Kara seas. Uplift isobases (in meters above present sea level) for 5000 cal yr B.P. and a set of prominent arcuate moraines are illustrated for the northern (Forman *et al.*, 1995, 1997) and eastern (Gataullin and Polyak, 1997) Barents Sea, respectively. The 4-m isobase (southern Novaya Zemlya) and the southern extent of the 11-m isobase are inferred from Gronlie (1924). A minimum limiting age for deglaciation of ∼13,000 cal yr B. P. was obtained from marine cores from the St. Anna Trough (Polyak *et al.*, 1997). The thin dotted line traces the 300-m bathymetric contour.

Zemlya in the 1990s demonstrates that the Holocene marine limit lies a magnitude lower at 10 to 11 m above high tide (aht) (Forman *et al.*, 1995, 1999a). The age of this marine limit is constrained by radiocarbon ages on *in situ* driftage, with the oldest sample yielding an age range of 4570 to 4300 cal yr B.P. (GX-18291G) for a gravel beach at 8 m aht in Vilkitsky Bay. Extrapolation upward from the dated level suggests that the marine limit formed ∼6000 yr ago. This low and young marine limit indicates that Novaya Zemlya was at the thinning edge of the ice sheet (ice thickness <1000 m). This conclusion is inconsistent with the maximum models of Lambeck (1995, 1996) and Peltier (1995, 1996), which depict a thick combined Barents–Kara Sea ice sheet.

To refine our understanding of the Late Weichselian ice-sheet geometry in the Barents and Kara seas, postglacial emergence was assessed at five locations on the eastern and western coasts of northern Novaya Zemlya. Testing for potential east–west tilt is complicated by the relatively low marine limits and variable storm run-up indicated by the previous study, stressing the need for detailed emergence sequences from both coasts (Forman *et al.*, 1999a). Collection of emergence data in August and September 1998 was designed to maximize the distribution of sampling stations in an area spanning ∼150 km east to west and ∼125 km north to south (Figs. 1 and 2). Our data, combined with previous results from Novaya Zemlya, provide new insight on the pattern of postglacial isostatic adjustment and Late Weichselian ice-sheet geometry.

METHODS

Postglacial emergence is the earth-rheological response to ice-sheet loading and unloading of the crust (Lambeck, 1993, 1995). Maximum total emergence is the highest recognized raised shoreline (marine limit). Radiocarbon dating of driftage from raised beaches and measurement of corresponding elevations constrain an emergence history for studied forelands on northern Novaya Zemlya. Elevations are established in reference to the high-tide swash line and measured by a *Leitz* digital barometric altimeter with analytical precision of ± 0.1 m. Multiple measurements with two altimeters were averaged to account for atmospheric pressure variations, including those associated with wind gusts. Measurements achieved a reproducibility of ±0.5 m. Reported elevations are therefore rounded to the nearest 0.5 m (Tables 1–3). Relief on the raised strandlines often varies by ∼0.5 m, and the maximum inferred uncertainty of landform elevations may range up to ±1 m.

Age control for raised shorelines is derived from radiocarbon dating of driftwood logs, whalebones, and marine shells. We preferably collected samples that were embedded in beach gravel, but when these were unavailable we used material found loose on the surface. Travel time of driftwood from Siberian source areas is <5 yr (Johansen, 1998). This period is well within the error of the dating method, which may range up to ±100 cal yr. Whalebone is well preserved in arctic conditions and yields radiocarbon ages in agreement with those of driftwood collected from the same landform (Forman, 1990; Bondevik *et al.*, 1995; Forman *et al.*, 1997, 1999a). The collagen-dominated gelatin fraction of the dense inner bone sections is dated after the contaminated outer surfaces of the whalebones are removed by saw. Four bone and two wood samples (Table 2) yield ages inconsistent with results from other samples at the same elevation and the trend of the emergence curves (Fig. 2). These six samples were apparently displaced from their original elevations, by polar bear, storm surge, or human activity, and therefore are omitted from the emergence curves. Accelerator mass spectrometry (AMS) dating of marine shells from glacial diamicton provides ages that constrain timing of deglaciation. To compensate for the marine reservoir effect, 440 radiocarbon yr are subtracted from laboratory-reported radiocarbon ages on shell and whalebone (e.g,. Olsson, 1980; Stuiver and Braziunas, 1993; Forman and Polyak, 1997). To facilitate plotting on a linear time scale, radiocarbon ages are subsequently changed to calibrated (cal) ages with the CALIB 4.1 program (Stuiver *et al.*,

TABLE 1
Radiocarbon Ages on Driftwood and Whalebone from Holocene Raised Marine Landforms on North Novaya Zemlya and Vaygach Island

Sample	Shoreline altitude (m aht)	Reported age (^{14}C yr B.P.)	Reservoir-corrected (^{14}C yr B.P.)	$\delta^{13}C$
Cape Bismarck, marine limit ∼13m				
NZ-56 Partially buried 1.5-m log	12.5 (10)[a]	5365 ± 60 (GX25466)	6280–6060 (6170)	−24.7
NZ-57 Whale vertebra	10	3710 ± 75 (GX25467G)	3630–3380 (3500)	−16.8
NZ-55 2.5-m driftwood log	10	3485 ± 85 (GX24850)	3870–3590 (3730)	−25.1
NZ-58 Decayed 2-m log	7.2	2985 ± 50 (GX24851)	3240–3000 (3120)	−24.2
NZ-53 Root section	6.7	1365 ± 40 (GX25465)	1300–1260 (1280)	−25.5
NZ-59 Decayed 7-m log	5.1	1350 ± 50 (GX24852)	1300–1190 (1240)	−25.6
NZ-60 Partially buried 8-m log	4.7	1875 ± 50 (GX24853)	1870–1720 (1800)	−26.2
Cape Spory Navolok, marine limit <13m				
Log partially buried[b]	12 (18)[a]	4860 ± 140 (GX-18532)	5740–5340 (5540)	−26.4
Partially buried 3-m log	4.5	2955 ± 80 (GX-23233)	3240–2960 (3100)	−25.4
Willem Barents' ship timber	2	360	Gawronski & Zeeberg 1997	
Cape Zhelaniya, marine limit >10.5 m				
NZ-6 1.5-m root section[b]	7.1	4380 ± 60 (GX25459)	5050–4850 (4950)	−25.8
NZ-16 Log 5 m from snowbank[b]	6.5	4000 ± 85 (GX24835)	4570–4300 (4430)	−24.6
NZ-21 Log 2 m from solifluction	6.1	3710 ± 80 (GX24837)	4150–3900 (4020)	−26.3
NZ-22 Partially buried >1-m log	4.2	3200 ± 80 (GX24838)	3470–3280 (3370)	−23.8
NZ-23 Partially buried 5-m log	3.8	3205 ± 55 (GX24839)	3460–3360 (3410)	−24.7
NZ-10 Partially buried[b] >1-m log	3.7	1930 ± 45 (GX25460)	1920–1820 (1870)	−25.1
NZ-24 Partially buried 2.5-m log	3.5	1570 ± 70 (GX24840)	1530–1350 (1440)	−26.8
NZ-25 Partially buried 5-m log	1.9	795 ± 65 (GX24841)	740–670 (700)	−23.9
NZ-26 Partially buried 5-m log	1.4	770 ± 65 (GX24842)	740–660 (700)	−25.7
Ivanov Bay, marine limit 13.5 m				
NZ-30 Whale bone	13.5 (12)[a]	6885 ± 105 (GX24843G)	7390–7220 (7300)	−17.2
NZ-32 Whale bone	13.5 (12)[a]	7080 ± 105 (GX24844G)	7550–7390 (7470)	−17.1
NZ-48 Partially buried 3-m log	8.8	3760 ± 45 (GX25464)	4220–4000 (4110)	−23.8
NZ-33 Partially buried 3-m log	7.8	3530 ± 50 (GX24845)	3860–3700 (3780)	−24.5
NZ-34 Partially buried 2-m log	6.8	2805 ± 50 (GX24846)	2950–2850 (2900)	−25.3
NZ-35 Partially buried 4-m log	5	805 ± 55 (GX24847)	740–670 (700)	−26.6
NZ-38 Partially buried 2.5-m log	4.3	575 ± 40 (GX25462)	630–540 (580)	−23.0
NZ-37 Partially buried >5-m log	4.2	1830 ± 50 (GX24848)	1820–1700 (1760)	−26.4
Cape Medvezhy, marine limit ∼12 m				
NZ-99 3-m log solifluction lobe[b]	10.5 (10)[a]	4070 ± 55 (GX24864)	4800–4440 (4620)	−26.1
NZ-97 Log <2.5 m from snowbank[b]	9	3635 ± 50 (GX24863)	3990–3870 (3930)	−25.9
NZ-88 Partially buried >3-m log	6.9	3070 ± 50 (GX24860)	3350–3210 (3280)	−25.8
NZ-91 Decayed, partially buried 7-m log	6.2	2125 ± 75 (GX24861)	2290–1990 (2140)	−26.1
NZ-92 Partially buried 2.5-m log	5.6	1665 ± 50 (GX24862)	1610–1520 (1560)	−24.8
NZ-85 Decayed partially buried 4-m log	4.4	945 ± 55 (GX24859)	930–780 (850)	−26.6
NZ-84 Decayed partially buried 2.2-m log	3.8	295 ± 50 (GX24858)	430–290 (360)	−27.3
Russkaya Gavan', marine limit ∼12 m				
NZ-68 Partially buried ∼2 m log	6.5	4145 ± 50 (GX24857)	4820–4530 (4680)	−25.3
NZ-66 Buried ∼3-m log	3.6	2890 ± 50 (GX25469)	3160–2890 (3020)	−24.3
NZ-67 3-m log	3.6	3105 ± 75 (GX24856)	3380–3210 (3300)	−23.6
NZ-64 Partially buried ∼3-m log	2.9	1535 ± 50 (GX24855)	1520–1350 (1430)	−25.2
NZ-62 Root of 4-m log	2.1	600 ± 45 (GX25468)	650–540 (600)	−24.4
NZ-63 Decayed 7-m log	1.9	175 ± 75 (GX24854)	295–0	−25.7
Vaygach Island; Cape Bolvansky, marine limit ∼2 m				
VA2K-2 Partially buried 2.5-m log	1.6	540 ± 50 (GX27227)	620–510	−25.6
VA2K-8 Partially buried ∼2-m log	1	470 ± 40 (GX27229)	530–500	−25.5
VA2K-3 Partially buried root	<1	270 ± 40 (GX27228)	310–0	−24.9

Note. All elevations ±1 m. Calibrated ages are ranges at 1 sigma (Stuiver *et al.*, 1998). G after lab number indicates that the gelatine bone fraction was dated.
[a] Assigned elevation of associated landform; elevation of sample is between brackets (see text).
[b] Different beach in same area.

TABLE 2
Samples Inconsistent with Age Models

Sample	Shoreline altitude (m aht)	Reservoir-corrected age (^{14}C yr B.P.)	Comment
Cape Carlsen			
NZ-3 Bone	10.6	2115 ± 75 (GX25458)	Probably displaced
Cape Zhelaniya			
NZ-15 Bone	11.7	1140 ± 70 (GX24834)	Probably displaced
NZ-17 Trunk with roots	8.7	455 ± 65 (GX24836)	Has nail, displaced by humans
NZ-19 Bone	>7.3	1910 ± 75 (GX25461)	Probably displaced
Ivanov Bay (Cape Varnek)			
NZ-41 Bone	>9	1510 ± 70 (GX25463)	Probably displaced
Cape Bismark			
NZ-54 Wood, 4-m slice	8.3	1650 ± 55 (GX24849)	Probably displaced

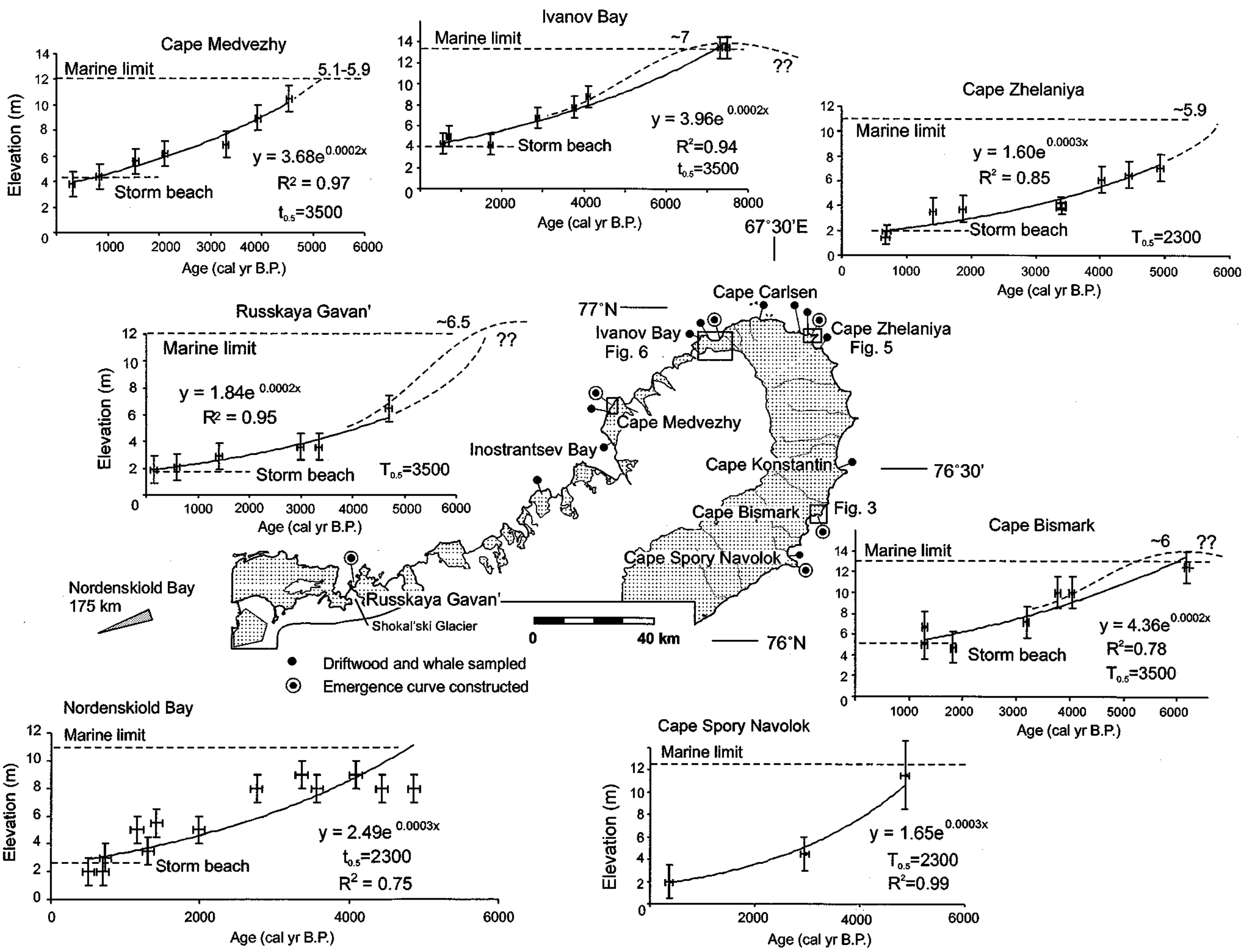

FIG. 2. Emergence curves for northern Novaya Zemlya and Nordenskiold Bay (Forman *et al.*, 1999), west-central Novaya Zemlya (see Fig. 1). Boxes show the locations of Figs. 3, 5, 6, and 7.

1998). The emergence curves were plotted with the midpoints of the calibrated age ranges (1 sigma; Table 1). These midpoint values (cal yr B.P.) are used throughout the text.

MARINE LIMIT AND RELATIVE SEA-LEVEL RECORD

Kara Sea Coast

Cape Bismark and Cape Spory Navolok. The marine limit is marked in a bay south of Cape Bismark (northeastern Novaya Zemlya; Figs. 2 and 3) by a well-developed raised beach berm that varies in elevation between 12.5 and 13.5 m aht. The western end of the berm consists of rounded beach pebbles and terminates against frost-shattered, lichen-covered bedrock (Fig. 4a). Driftwood collected immediately behind the berm and dated to 6170 cal yr B.P. (GX-25466; Table 1) provides a close limiting age on initial emergence (Fig. 5). Two other samples collected behind the berm (NZ-55 and 57) yielded ages of 3500 cal yr B.P. (GX-25467) and 3730 cal yr B.P. (GX-24850) and probably were carried over the berm crest during more recent storm surges. The modern storm beach limit at Cape Bismark is 6.4 m aht, reflecting exposure of the bay to a predominately southeastern fetch.

The marine limit at Cape Spory Navolok, a headland projecting ~4 km into the Kara Sea 15 km south of Cape Bismark, is a distinct wave-abraded escarpment at 7 to 11 m aht (Zeeberg, 1997; Forman *et al.*, 1999a). A diamicton above this escarpment at 12 ± 1 m aht is unwashed. Previously, a driftwood log (5540 cal yr B.P.) was retrieved at Cape Spory Navolok by M. G. Grosswald (Forman *et al.*, 1995). The emergence curve and marine limit ≤13 m asl for nearby Cape Bismark indicate that the elevation of 18 ± 2 m aht estimated for this log is too high. Consequently, this sample has been assigned an elevation of 12 m.

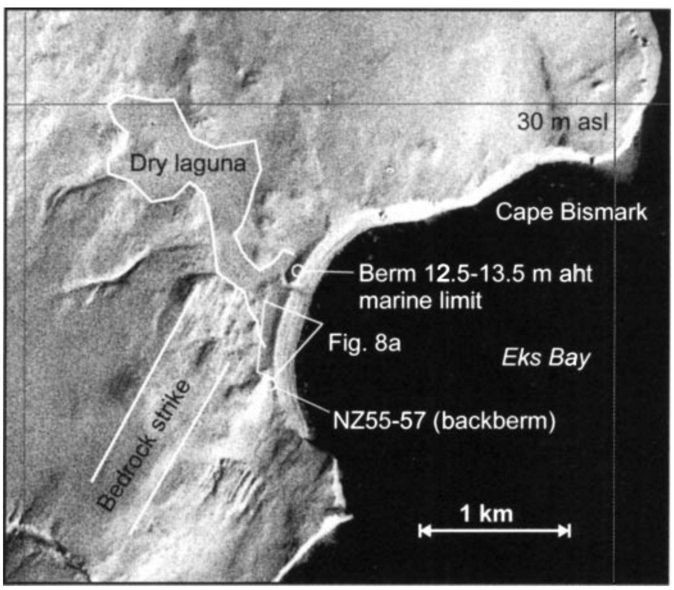

FIG. 3. Sampling locations and geology at Cape Bismark (Eks Bay).

Cape Zhelaniya. The marine limit in the Cape Zhelaniya area lies between a 10.5-m-high berm crest southwest of Cape Mavriki (Fig. 6) and an unwashed diamicton at 13 m aht. The storm beach limit at Cape Zhelaniya is ~1.5 m, indicating low wave run-up. Cape Zhelaniya is a ~500-to-200-m-wide promontory protruding ~1.5 km into the Kara Sea. The pattern of postglacial emergence for the Cape Zhelaniya area is constrained by samples from Cape Mavriki (NZ-6 and NZ-16), Cape Serebryannikov (NZ-10), and a sequence in the ~600-m-wide bay east of Cape Mavriki (Fig. 6). A heavy driftwood root section provides the oldest (4950 cal yr B.P.; GX-25459) and highest (7.1 m aht) sample (NZ-6; Table 1). The wood was collected from rounded cobbles on a bedrock notch, indicating a washing limit at 9.5 m aht at the base of a soliflucting escarpment.

There is a possible washing level above the Holocene marine limit (≤13 m) between 20 and 30 m aht. These older marine shoreline features include notches eroded into bedrock at Cape Mavriki and prominent horizontal, beachlike platforms at ~24 m asl at Cape Zhelaniya. Similar platforms were observed at the Orange Islands, ~25 km to the northwest of Cape Zhelaniya.

Barents Sea Coast

Ivanov Bay. The marine limit at Ivanov Bay is marked by a prominent raised berm that infills a 2-km-wide valley of up to 13.5 m aht (Figs. 7 and 4b). Skeletal remains of a beached whale scattered over this berm at 11.5 and 12 m aht yielded ages of 7300 cal yr B.P. (GX-24843) and 7470 cal yr B.P. (GX-24844), providing the oldest age constraint for the marine limit on northern Novaya Zemlya (Table 1). The highest raised beach at the foot of the berm at 8.8 m aht is dated to 4110 cal yr B.P. (GX-25464). Modern wood was encountered up to 4.3 m aht in Ivanov Bay and on Cape Varnek. Driftage at both locations included German sea mines from September 1942 (Woodman, 1994) at 2 m aht, indicating low storm surge activity in the past ~60 yr.

Cape Medvezhy. A detailed record of emergence was established on a 4-km-long stretch immediately southwest of Cape Medvezhy (Fig. 2). This area is exposed to Barents Sea storm surges, resulting in maximum storm run-up of 6 m aht in stream valleys. Driftwood associated with the modern 4-m-high storm ridge encroaches onto the slightly lower fossil beach (Fig. 5). Subfossil driftwood partly buried in this surface at 3.8 m aht yielded an age of 360 cal yr B.P. (GX-24858; Table 1), indicating little to no effective emergence in the past ~400 yr. The raised beach sequence terminates against a ~5-m-high escarpment, and the highest discernable raised beach was found at 10.5 m aht (Figs. 5 and 8). A driftwood log at 10.3 m aht behind this ridge yielded an age of 4620 cal yr B.P. (GX-24864). Two kilometers to the south of this location a regressional littoral fill was found deposited against the escarpment. The fill extends to 12 m aht, and marks the marine limit for this area.

Russkaya Gavan'. Russkaya Gavan' (*Russian Harbor*) is a 10-km-long by 5-km-wide fjord that has a north–south orientation (Fig. 2). The emergence sequence was established

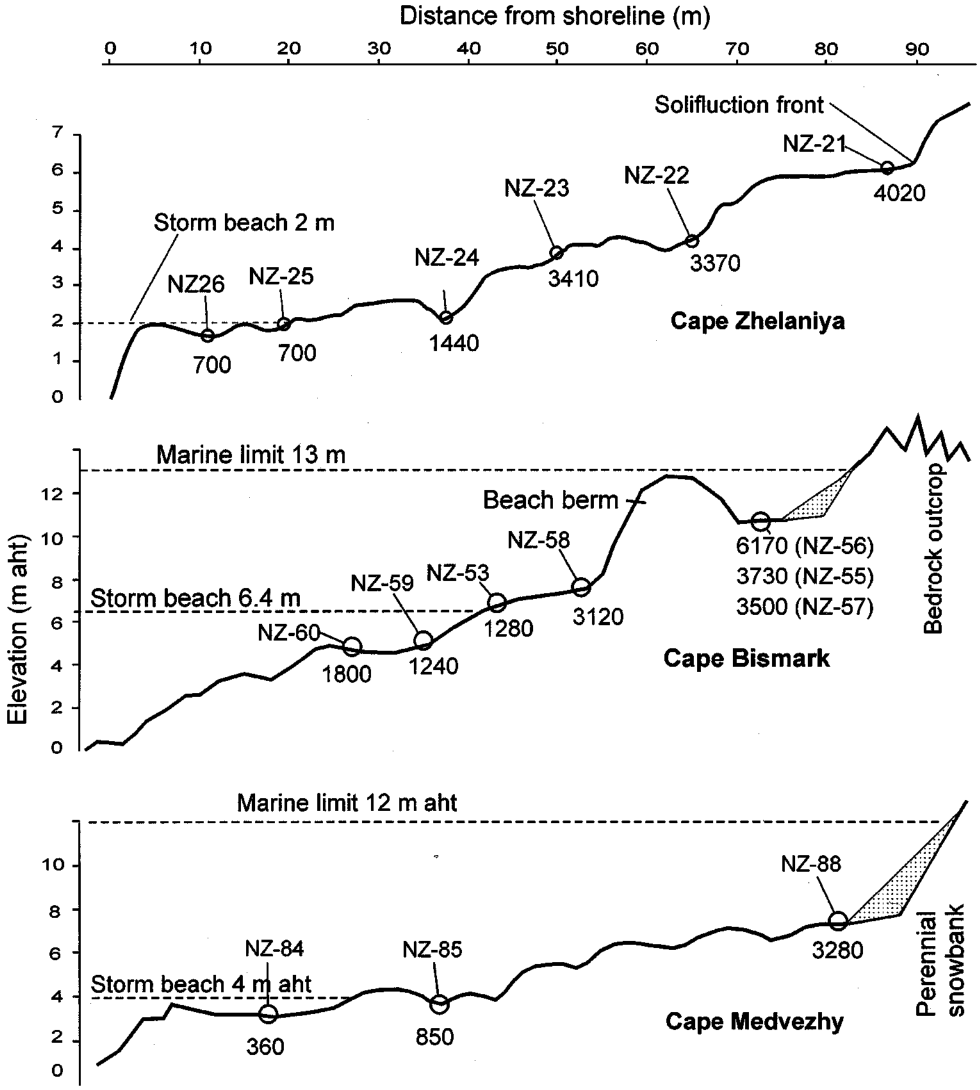

FIG. 4. Selected topographical profiles of beach sequences on northern Novaya Zemlya, showing variations in beach gradient and storm beach elevation. See Figs. 6 and 8 for locations of the profiles. Beaches at relatively high elevations near the marine limit are often obscured by solifluction lobes or snowbanks or terminate against abraded escarpments. Marine limits are expressed as either the highest raised beach berms, as in the Cape Bismark section, or as the highest elevation of the washed contact between diamicton and beach sediments. The location of the sampling sites and their associated midpoint age (cal yr B.P.) are shown with open circles (see also Table 1).

on a ~400-m-long beach in a 2-km-wide bay that is separated from the main fjord by a promontory (Fig. 2). The storm beach is <2 m high. A series of raised beaches descends from a well-defined raised berm at 11.5 to 12.5 m aht, which is cut by a meltwater stream draining a valley that parallels the Shokal'ski Glacier. The marine limit is indicated by a clear contact between rounded pebbles and bedrock covered by a thin (<0.5 m) diamicton, containing angular, poorly sorted clasts. Subfossil driftwood is found between 2 and 4 m aht but is rarer at higher elevations. The highest retrieved driftage is a 2-m-long log at 6.5 m aht, which yielded an age of 4680 cal yr B.P. (GX-24857; Table 1, Fig. 2). The general scarcity of driftwood and a low-elevation storm beach probably reflect the bay's sheltered topography and position to Barents Sea storm run-up.

A pronounced bedrock notch at ~23 m on the promontory north of the polar station at Russkaya Gavan' possibly indicates a pre-Holocene washing limit. This level appears to be similar to the pre-Holocene levels found at Cape Mavriiki, Cape Zhelaniya, and the Orange Islands.

Vaygach Island. The Vaygach marine limit was studied in summer, 2000, around Cape Bolvansky and Cape Diakanova, the northern and southernmost capes respectively of this 100-km-long island. The marine limit coincides with the modern storm beach at ~2 m asl. Radiocarbon ages on weathered, probably *in situ* driftwood collected among modern, sawn logs on Cape Bolvansky indicate little (<2 m) relative sea-level change in the past ~six centuries (Table 1).

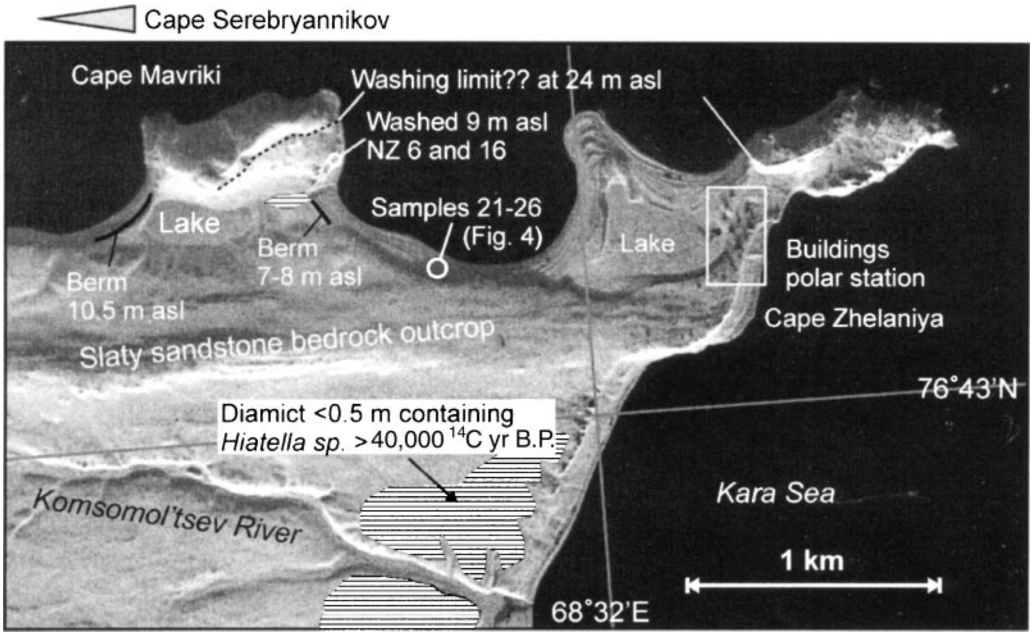

FIG. 5. Sampling locations and geology near Cape Zhelaniya.

DISCUSSION

Evidence for Late Weichselian Ice Cover and Incursion of the Sea

On north Novaya Zemlya, little geological evidence exists for the presence of an ice sheet during the Late Weichselian and subsequent deglacial period. The bedrock of the investigated areas consists of low-grade metamorphosed, mostly fine-grained, Permian sandstone (Badyukov, 1997). Its intense foliation and vertical tilt make a brittle surface that does not preserve striation. Coastal areas were inspected to about 1 km inland and are irregularly covered by a veneer of drift <0.5 m thick. The drift contains striated clasts, indicating a glacial origin. Two *Hiatella arctica* fragments from a diamicton blanketing coastal areas near Cape Zhelaniya yielded ages of >40,000 and >43,000 ^{14}C yr B.P. (Fig. 6, Table 3). The drift is thus constrained between ~7000 cal yr (marine limit) and >40,000 cal yr (shells in diamicton), and it may be Late Weichselian in age, as inferred for a similar diamicton in Nordenskiold Bay (Forman *et al.*, 1999).

Retreat of outlet glaciers from the outer coast of northwestern Novaya Zemlya was complete by the earliest Holocene. *Hiatella arctica* fragments (PL-9900871A, AA-36289; Table 3) collected from the lateral moraine of the Shokal'ski Glacier indicate that prior to ~9500 cal yr B.P. the glacier terminus was >1 km behind the present margin, allowing incursion of the sea. Subsequently, the glacier advanced and incorporated shells into its lateral moraine. Similarly, a minimum limiting age of ~10,200 cal yr B.P. for deglaciation of coastal areas is implied from foraminifer abundance levels in a marine core from the mouth of Nordenskiold Bay, 100 km south of Russkaya Gavan' (A-102; Forman *et al.*, 1999a).

Postglacial Emergence and Uplift

The marine limit formed on northern Novaya Zemlya between 7500 and 6000 cal yr B.P. (Fig. 2, Table 1), when global

TABLE 3
Shells from Diamict around Cape Zhelaniya and Russkaya Gavan'

Sample	Elevation (m aht)	Reservoir-corrected age (^{14}C yr B.P.) and lab number	$\delta^{13}C$	Age (cal yr B.P.)
Cape Zhelaniya (Cape Mavrikya)				
NZ-28 *Hiatella arctica* fragment	13	39500 ± 1200 (AA31369)	3.017	
Cape Zhelaniya (Komsomoltsev River)				
NZ-20 *Hiatella arctica* fragment	6.5	42800 ± 1800 (AA31371)	1.783	
Russkaya Gavan; lateral moraine Shokal'ski Glacier				
NZ-71 *Hiatella arctica* fragment	60	8380 ± 100 (PL9900871A)	1.6	9450–9250
NZ-71 *Hiatella arctica* fragment	60	8715 ± 70 (AA36289)	3.5	9850–9530

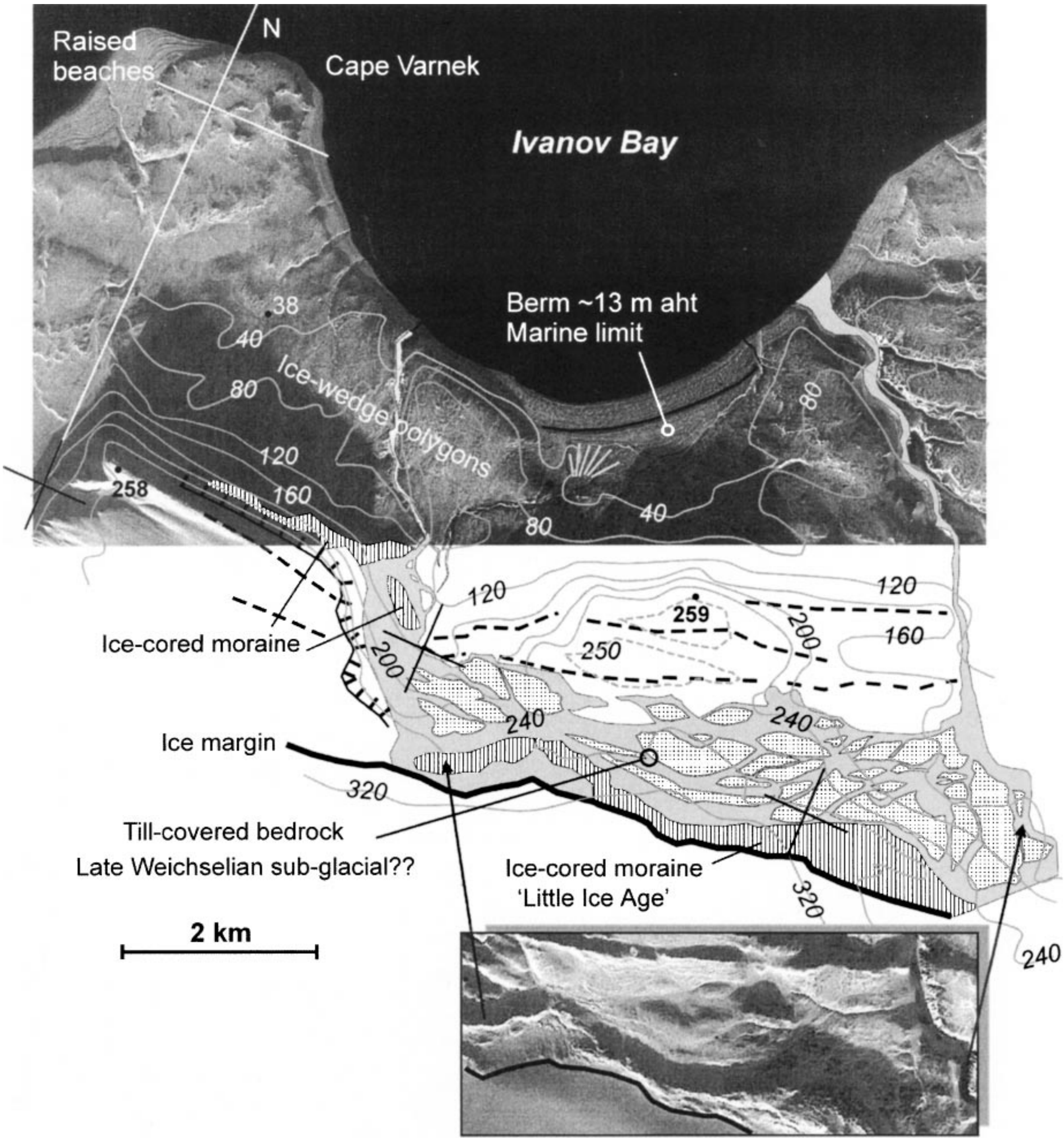

FIG. 6. Topography and Quaternary geology near Ivanov Bay. The figure shows a *Corona* satellite-image (6 October, 1964) and the interpretation of channels outside 'Little Ice Age' moraines (Zeeberg and Forman, 2001). These channels are partly covered by a diamiction with striated clasts, which likely was deposited as lodgement or melt-out till, and are associated with Late Weichselian proglacial or subglacial drainage. Striped pattern indicates an ice-cored moraine.

sea level was stabilizing (Kidson, 1982; Fairbanks, 1989; Bard *et al.*, 1996). All sites show little apparent emergence, with raised landforms at identical heights to storm beaches during the past 2000 yr (Fig. 5). The course of this modest uplift can be mathematically represented by a negative exponential function, reflecting earth's viscous response to unloading (after initial elastic relaxation of the crust) with backflow of displaced mantle material (Andrews, 1968; Cathles, 1975). First-order estimates of isostatic uplift on Novaya Zemlya are calculated directly from our age–height diagrams, because the relative sea-level records began only after the stabilization of global sea level and show continual emergence [Uplift = Remnant Uplift (e^{kt})] (Andrews, 1968; Forman *et al.*, 1997).

The emergence curves for northern Novaya Zemlya (Fig. 2) indicate an average upliftrate of ~0.5 mm/yr at present and ~2.5 mm/yr between 6000 and 5000 cal yr B.P. However, a 35-yr-long tide gauge record from polar station Russkaya Gavan' yields modern uplift rates of 2 mm/year for northern

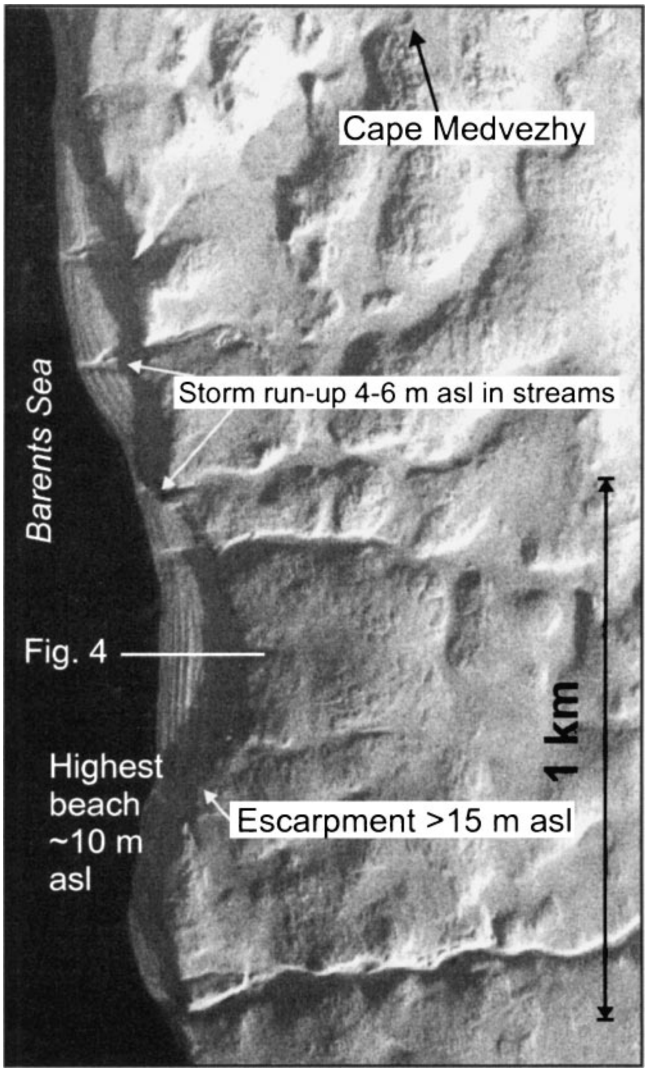

FIG. 7. Sampling locations and geology near Cape Medvezhy.

Novaya Zemlya (Emery and Aubrey, 1991). The lower value indicated by the emergence curves probably reflects the influence of wave run-up, which tends to redeposit driftage near the storm beach limit. The emergence record was thus "leveled" during the past ∼4000 yr, when the uplift rates were low (<2.5 mm/yr). Therefore, the uplift rates of 0.5 mm/yr and half-lives of 3500 yr for the past ∼4000 yr are artifacts of the fitted exponential curve. Actual half-lives are probably shorter, falling between 2300 and 3500 yr (Fig. 2).

The current uplift rates of <1 to 2 mm/yr for Novaya Zemlya resemble calculated uplift rates of <0.7 to 2 mm/yr for portions of southwestern Svalbard, Franz Josef Land, and southwest Norway (Svendsen and Mangerud, 1987; Mangerud *et al.*, 1992; Forman *et al.*, 1997). Uplift half-lives [$t_{1/2} = \ln 2\ (k^{-1})$] for these regions and northern Canada are approximately 2200 yr (Andrews, 1968; Bakkelid, 1986; Dyke *et al.*, 1991; Forman *et al.*, 1997). At northern Novaya Zemlya, three or four half-lives of 2300 to 3500 yr have passed since deglaciation of the coast at ∼10,000 cal yr B.P. This suggests that northern Novaya Zemlya is at or close to isostatic equilibrium, consistent with the low modern uplift rates indicated by the emergence curves.

Deglaciation and Ice Load

Ice retreat from coastal areas of northwestern Novaya Zemlya is constrained by the 9300 and 9700 cal yr B.P. shell ages from Ruskaya Gavan' and a basal age of 10,200 cal yr B.P. on a marine core from Nordenskiold Bay (Table 3; Forman *et al.*, 1999a). Initial retreat of outlet glaciers on Novaya Zemlya prior to 10,200 cal yr B.P. is potentially coincident with cessation of glacial marine deposition in northern and eastern Barents Sea cores at ∼10,000 cal yr B.P. and the onset of postglacial emergence on Franz Josef Land and eastern Svalbard at ∼10,300 cal yr B.P. (e.g., Forman *et al.*, 1995, Bondevik *et al.*, 1995; Lubinski *et al.*, 1996; Landvik *et al.*, 1998; Polyak *et al.*, 1995, 2000). Older minimum limiting deglacial ages of ∼13,000 cal yr B.P. have been obtained on marine cores from the deep (water depths >450 m) troughs in the northern shelf margin of the Barents Sea, indicating initial decay of the Barents Sea ice sheet (Lubinski *et al.*, 1996; Polyak *et al.*, 1997; Hald *et al.*, 1999).

Early Holocene uplift, prior to formation of the marine limit (∼7000 cal yr B.P.), is extrapolated from the relative sea-level record. Calculated uplift rates of 5 to 6 mm/yr between 10,000 and 7000 cal yr B.P. indicate that during this period ∼15 to 20 m of uplift occurred, compared with ∼40 m of global sea-level rise (Kidson, 1982; Fairbanks, 1989; Bard *et al.*, 1996). Thus, it is inferred that sea-level rise outpaced uplift, implying a transgression until cessation of global sea-level rise ∼7000 to 6000 cal yr B.P. Isostatic rebound dominated postglacial eustatic sea-level rise after ∼7000 cal yr B.P., resulting in the formation of the marine limit and regression to the present shore. Novaya Zemlya's uniformly low (12 ± 1 m) marine limit is similar to those found in southwestern Scandinavia (Svendsen and Mangerud, 1987) and on northwestern and southern Svalbard at the thinning edge of the Barents Sea ice sheet (Forman, 1990; Ziaja and Salvigsen, 1995; Forman and Ingolfsson, 2000). Based on these studies and assuming a comparable rheological response to unloading, Novaya Zemlya's low Holocene marine-limit and current uplift rates of ∼1 to 2 mm/yr reflect a Late Weichselian ice load of <1000 m (Lambeck, 1995, 1996; Peltier, 1996).

Isobase Pattern

Since 5000 cal yr B.P., isostatic uplift of northern Novaya Zemlya is 11 ± 1 m on the eastern (capes Bismark and Spory Navolok) and the western coasts (Ivanov Bay and Cape Medvezhy). Lower uplift values of 7 ± 1 m over the same interval at Cape Zhelaniya and Russkaya Gavan' are probably due to low wave run-up in those areas that resulted in driftwood deposition at lower elevations (Fig. 2). In the Nordenskiold–Vilkitsky area, 300 km south of our northern study area, isostatic uplift since 5000 cal yr B.P. is 11 ± 1 m, suggesting that the isobase pattern runs parallel to the Novaya Zemlya coastline. Furthermore, the similarity of uplift on Cape Medvezhy and Cape Bismark, areas with comparable storm run-up on opposite sides of the island,

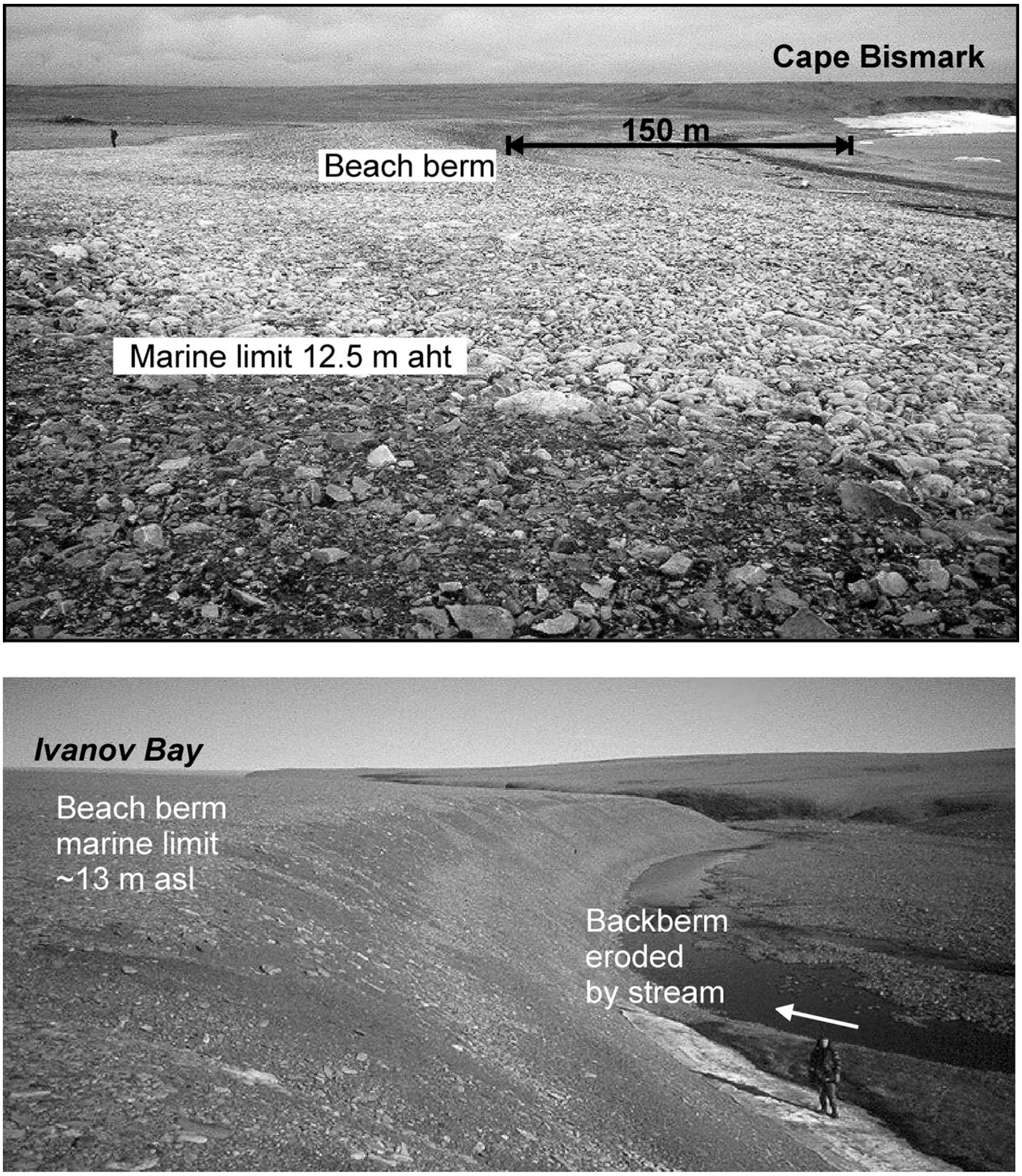

FIG. 8. Marine limits at Cape Bismark (top) and Ivanov Bay (bottom). The marine limit at Cape Bismark is the contact between unwashed, lichen-covered diamict (dark) and rounded beach pebbles (light). The marine limit at Ivanov Bay is a 12.5-to-13.5-m-high beach berm.

suggests little differential uplift across the ~80 km width of Novaya Zemlya (i.e., no east-west tilt). No Late Weichselian or Holocene raised marine sediments occur along the coastlines of northern Russia and southwestern Yamal (Mangerud, *et al.* 1999; Forman *et al.*, 1999a). This observation and the absence of Holocene raised beaches on northernmost Vaygach Island imply that the line of zero-emergence runs immediately south and east of Novaya Zemlya (Fig. 1).

The prevalence of apparent washing levels at a number of sites at ~24 m asl on northern Novaya Zemlya suggests that pre-Late Weichselian ice-sheet loading occurred in this region. These northern levels are probably related to raised beach deposits between 20 m and at least 36 m asl in Nordenskiold Bay, ~175 km to the southwest, which have been interpreted to reflect ice loading by an Early or Middle Weichselian ice sheet (Forman *et al.*, 1999a). Evidence for earlier glacial events is better delineated on the Eurasian mainland. Marginal formations in northern Russia (Markhida Line) and western Siberia indicate ice-sheet advance from the Barents and Kara seas onto the mainland during the Early or Middle Weichselian (Astakhov, 1998; Mangerud *et al.*, 1999; Svendsen *et al.*, 1999). A diamicton formed during the last glacial advance from the southern Kara Sea onto the Yamal Peninsula is constrained by ^{14}C and optically stimulated luminescence (OSL) ages of >26,000 cal yr B.P. and >55,000 cal

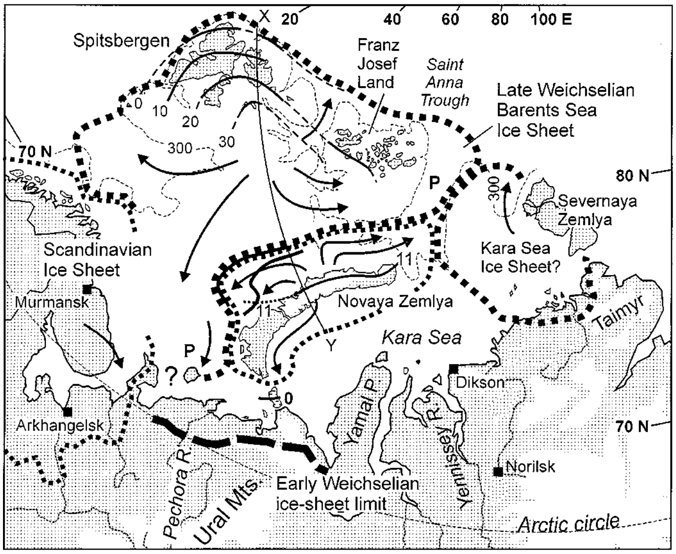

FIG. 9. Schematic reconstruction of the ice-sheet geometry for the Barents and Kara seas for the later stages of the Late Weichselian glacial cycle and possibly earlier. This reconstruction is based on the untilted isobase pattern for Novaya Zemlya (uplift isobases since 5000 cal yr B.P.) and offshore marine studies (P = Polyak *et al.*, 1997, 2000; compare with Fig. 1). The Scandinavian ice-sheet limit is taken from Svendsen *et al.* (1999). The Middle- or Early Weichselian terminus is from Mangerud *et al.* (1999). Arrows indicate inferred directions of ice flow. Line X-Y refers to the ice-sheet profile in Fig. 10. The 0 and 11 lines are isobases.

yr B.P. and considered Early Weichselian (60,000–80,000 cal yr B.P.) in age (Forman *et al.*, 1999b).

A Satellitic Ice Dome?

The untilted, 5000 cal yr B.P. isobase of Novaya Zemlya runs parallel to the northern island, implying uniform loading across its ~1000-m-high mountains. This plateau may have supported an independent ice-dispersal center during the decay phase of the Barents Sea ice dome. Radial flow from Novaya Zemlya is indicated by parallel recessional moraines in the northern and eastern Barents Sea seen in seismic sections and sidescan-sonar images (Gataullin and Polyak, 1997; Polyak *et al.*, 1997). These moraines, although undated, are fresh looking and probably indicate the ice configuration of a separate Novaya Zemlya ice cap near the end of the Late Weichselian glacial cycle and possibly earlier.

The first-order dimensions of the Late Weichselian Barents Sea ice sheet are indicated by the maximum uplift pattern in the northwestern Barents Sea, and the position of moraines on the shelf edge north of Spitsbergen and around Bear Island (Elverhøi *et al.*, 1995; Forman and Ingolfsson, 2000; Salvigsen and Slettemark, 1995). These constraints imply an ice dome with a radius of ~500 km (Figs. 9 and 10). We believe that its eastern limit probably terminated in the eastern Barents Sea. Eastward ice flow likely followed the topography, with major ice streams descending into the St. Anna Trough and spreading into the southern Barents Sea (Polyak *et al.*, 1997, 2000; Siegert *et al.*, 1999). The ice dome drained to the southwest with an ice stream into the Bear Island Trough. Eastward ice flow from the Barents Sea dome toward Novaya Zemlya would have to overcome accelerated flow into the St. Anna Trough and then overtop Novaya Zemlya's steep and high (1000-m) topography. Mountains and plateaus of Novaya Zemlya, therefore, may have sustained a satellitic ice dome during the last glacial maximum. Thus, future ice-sheet modeling for the Barents and Kara Sea region should incorporate ice streams and separate ice-dispersal centers to enhance understanding of atmosphere–ocean–ice sheet interactions in the Eurasian north (c.f. Lambeck, 1995; Forman and Ingolfsson, 2000).

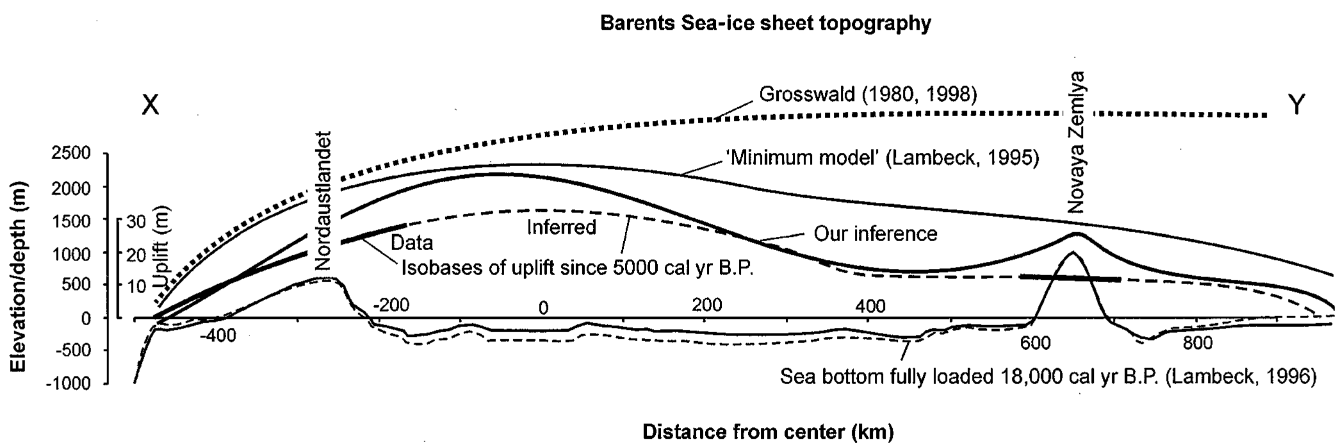

FIG. 10. Northwest to southeast section (Fig. 9) through the Barents Sea and Novaya Zemlya ice sheets during the later stages of the Late Weichselian glacial cycle and possibly earlier. Ice thicknesses are based on the amount of uplift since 5000 cal yr B.P. (broken line) and analogies with the modeling exercises by Lambeck (1995, 1996), assuming deglaciation around 10,000 cal yr B.P. and a homogeneous rheological response to unloading throughout the Barents Sea region. The "maximum" configuration postulated by Grosswald (1980, 1998) and the "minimum" configuration of Lambeck (1995) are also shown.

CONCLUSIONS

1. The Holocene marine limit follows the western and eastern coasts of northern Novaya Zemlya between 10.5 and 13.5 m aht. It occurs either as an escarpment in metamorphosed fine-grained Permian sandstone or as a constructional gravel berm in bay settings.

2. *Hiatella arctica* fragments from the lateral moraine of the Shokal'ski Glacier, Russkaya Gavan', yielded ages of 9400 and 9700 cal yr B.P. The shells indicate incursion of the sea and glacier retreat of >1 km behind the present margin by the earliest Holocene. These dates are minimum ages for the deglaciation of the coast of Novaya Zemlya and are consistent with findings in a marine core in the mouth of Nordenskiold Bay, 175 km to the south.

3. Radiocarbon-dated emergence curves demonstrate the formation of a low (<13.5 m aht) marine limit on northern Novaya Zemlya between 7500 and 6000 cal yr B.P. Late Weichselian ice thickness was probably <1000 m at the present shoreline based on (a) earth rheological modeling of nearby regions with comparable low rates of emergence (<2 mm/yr) for the past 2000 yr; (b) a low and young marine limit; and (c) deglaciation prior to 10,000–9000 cal yr B.P. (Lambeck, 1995, 1996).

4. The 5000 cal yr B.P. uplift isobase runs parallel to the ∼1000-m-high mountain range in northern Novaya Zemlya. The isobase shows no preferential east–west tilt across the island. This uniform pattern and the geometry of recessional moraines off of Novaya Zemlya and in the St. Anna Trough (Polyak *et al.*, 1997) suggest that Novaya Zemlya supported a satellitic ice cap separate from the Barents Sea ice dome during the later phases of the Late Weichselian glaciation, if not earlier.

5. There is a paucity of glacial geologic evidence for ice-sheet cover on northern Novaya Zemlya during the Late Weichselian and subsequent deglaciation. A Late Weichselian origin is inferred for a diamicton blanketing coastal areas near Cape Zhelaniya. *Hiatella arctica* fragments taken from this diamicton yielded minimum limiting ages of >40,000 yr ^{14}C B.P.

6. An earlier and larger glacial event is implied by faint but ubiquitous washing levels between 20 and 30 m asl in northern Novaya Zemlya and raised marine sediments at similar elevations in Nordenskiold (Forman *et al.*, 1999) and Krestov bays (Lavrova 1932).

ACKNOWLEDGMENTS

This research was supported by National Science Foundation award OPP-9796024 and was undertaken in cooperation with Leonid Polyak (Ohio State University). We express our gratitude to Pyotr Boyarsky and the Heritage Institute (Moscow) for providing access to Novaya Zemlya (1995, 1998) and Vaygach Island (2000). Dmitri Badyukov supported us in the field. Thanks are also due to George Maat and Henk van Veen (Stichting Willem Barents, The Netherlands) for help with logistical arrangements and the Corps Marines of the Royal Dutch Navy for provision of gear. Transport in 1998 was aboard R.V. *Ivan Petrov* (Archangelsk).

REFERENCES

Andrews, J. T. (1968). Postglacial rebound in Arctic Canada: Similarity and prediction of uplift curves. *Canadian Journal of Earth Sciences* **5,** 39–47.

Astakhov, V. (1998). The last ice sheet of the Kara Sea: Terrestrial constraints on its age. *Quaternary International* **45/46,** 19–28.

Badyukov, D. D. (1997). Geology of Cape Spory Navolok and the archaeological site. *In* "Northbound with Barents" (J. H. Gawronski and P. V. Boyarsky, Eds.), pp. 58–62. Jan Mets, Amsterdam.

Bakkelid, S. (1986). The determination of rates of land uplift in Norway. *Tectonophysics* **130,** 307–326.

Bard, E., Hamelin, B., Arnold, M., Montaggioni, L., Cabioch, G., Faure, E., and Rougerie, F. (1996). Deglacial sea-level record from Tahiti corals and the timing of global meltwater discharge. Nature **382,** 241–244.

Bondevik, S., Mangerud, J., Ronnert, L., and Salvigsen, O. (1995). Postglacial sea-level history of Edgeøya and Barentsøya, eastern Svalbard. *Polar Research* **14,** 153–180.

Cathles, L. M. (1975). "The Viscosity of the Earth's Mantle." Princeton Univ. Press, Princeton, NJ.

Dyke, A. S., Morris, T. F., and Green, D. E. C. (1991). Postglacial tectonic and sea-level history of the central Canadian Arctic. *Geological Survey of Canada Bulletin* **397,** 1–56.

Elverhøi, A., Anders, E. S., Dokken, T., Hebblen, D., Spielhagen, R., Svendsen, J., Sørflaten, M., Rørnes, A., Hald, M., and Forsberg, C. S. (1995). The growth and decay of the Late Weichselian ice sheet in western Svalbard and adjacent areas based on provenance studies of marine sediments. *Quaternary Research* **44,** 303–316.

Emery, K. O., and Aubrey, D. G. (1991). "Sea Levels, Land Levels, and Tide Gauges." Springer-Verlag, New York.

Fairbanks, R. G. (1989). A 17,000 year glacio-eustatic sea level record: Influence of glacial melting rates on the Younger Dryas event and deep-ocean circulation. *Nature* **342,** 637–642.

Forman, S. L. (1990). Post-glacial relative sea-level history of northwestern Spitsbergen, Svalbard. *Geological Society of America Bulletin* **102,** 1580–1590.

Forman, S. L., and Polyak, L. (1997). Radiocarbon content of pre-bomb marine mollusks and variations in the ^{14}C reservoir age or coastal areas of the Barents and Kara seas, Russia. *Geophysical Research Letters* **24,** 885–888.

Forman, S. L., and Ingolfsson, O. (2000). Late Weichselian glacial history and postglacial emergence of Phippsøya, Sjuøyane, northern Svalbard: A comparison of modeled and empirical estimates of a glacial-rebound hinge line. *Boreas* **29,** 16–25.

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

Forman, S.L., Weihe, R., Lubinski, D., Tarasov, G., Korsun, S., and Matishov, G. (1997). Holocene relative sea-level history of Franz Josef Land, Russia. *Geological Society of America Bulletin* **109,** 1116–1133.

Forman, S. L., Lubinski, D. J., Zeeberg, J. J, and Polyak, L. (1999a). Postglacial emergence and Late Quaternary glaciation on northern Novaya Zemlya, Arctic Russia. *Boreas* **28,** 133–145.

Forman, S. L., Ingolfsson, O., Gataullin, V., Manley, W. F., and Lokrantz, H. (1999b). Late Quaternary stratigraphy of western Yamal Peninsula, Russia; new constraints on the configuration of the Eurasian ice sheet. *Geology* **27,** 807–810.

Gataullin, V. L., and Polyak, L. (1997). Morainic ridge complex, eastern Barents Sea. *In* "Acoustic Images of Glaciated Continental Margins" (T. A. Davies, Ed.), pp. 82–83, Chapman & Hall, London.

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

Gawronski, J. H., and Zeeberg, J. J. (1997). The wrecking of Barents' ship. *In* "Northbound with Barents" (P. V. Boyarsky and J. H. G. Gawronski, Eds.), pp. 89–92. Jan Mets, Amsterdam.

Grønlie, O. T. (1924). "Contributions to the Quaternary Geology of Novaya Zemlya. Report of the Scientific Results of the Norwegian expedition to Novaya Zemlya 1921, Vol. 21." A. W. Broggers Boktrykkeri, Oslo.

Grosswald, M. G. (1980). Late Weichselian ice sheets of northern Eurasia. *Quaternary Research* **13,** 1–32.

Hald, M., Kolstad, V., Polyak, L., Forman, S. L., Herlihy, F. A., Ivanov, G., and Nescheretov, A. (1999). Late-glacial and Holocene paleoceanography and sedimentary environments in the St. Anna Trough, Eurasian Arctic Ocean margin. *Palaeogeography, Palaeoclimatology, Palaeoecology* **146,** 229–249.

Johansen, S. (1998). The origin and age of driftwood on Jan Mayen. *Polar Research* **17,** 125–146.

Kidson, C. (1982). Sea level changes in the Holocene. *Quaternary Science Reviews* **1,** 121–151.

Lambeck, K. (1993). Glacial rebound and sea-level change: An example of a relationship between mantle and surface processes. *Tectonophysics* **223,** 15–37.

Lambeck, K. (1995). Constraints on the Late Weichselian ice sheet over the Barents Sea from observations of raised shorelines. *Quaternary Science Reviews* **14,** 1–16.

Lambeck, K. (1996). Limits on the areal extent of the Barents Sea ice sheet in Late Weichselian time. *Global and Planetary Change* **12,** 41–51.

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

Lavrova, M. (1932). Geomorphological outline of the Rusanov Valley in Novaya Zemlya. *Proceedings of the Geological Institute of the USSR.*, Trudy, 61–95.

Lubinski, D. J. Korsun, S., Polyak, L., Forman, S. L., Lehman, S., Herlihi, F. A., and Miller, G. H. (1996). The last deglaciation of the Franz Victoria Trough, northern Barents Sea. *Boreas* **25,** 89–100.

Mangerud, J., Bolstad, M., Elgersma, A., Helliksen, D., Landvik, J., Lønne, I., Lycke, A., Salvigsen, O., Sandahl, T., and Svendsen, J. I. (1992). The last glacial maximum on Spitsbergen, Svalbard. *Quaternary Research* **38,** 1–31.

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

Nordenskjöld, O. N., and Mecking, L. (1928). The geography of polar regions. *American Geographical Society, Special Publication* **8,** 154–163. Reprint.

Olsson, I. U. (1980). Content of ^{14}C in marine mammals from northern Europe. *Radiocarbon* **22,** 662–675.

Peltier, R. W. (1995). Paleotopography of glacial-age ice sheets. *Science* **267,** 536–538.

Peltier, R. W. (1996). Mantle viscosity and ice-age ice sheet topography. *Science* **273,** 1359–1364.

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

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

Polyak, L., Gataullin, V., Okuneva, O., and Stelle, V. (2000). New constraints on the limits of the Barents-Kara Ice Sheet during the last glacial maximum based on borehole stratigraphy from the Pechora Sea. *Geology* **28,** 611–614.

Salvigsen, O., and Slettemark, O. (1995). Past glaciation and sea levels on Bereneiland, Spitsbergen. *Polar Research* **14,** 245–251.

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

Solheim, A., Russwurm, L., Elverhoi, A., and Nyland-Berg, M. (1990). Glacial geomorphic features in the northern Barents Sea: Direct evidence for grounded ice and implications for the pattern of deglaciation and late glacial sedimentation. *In* "Glacimarine Environments: Processes and Sediments" (J. A. Dowdeswell and J. D. Scourse, Eds.), Geological Society of London, Special Publication 53, pp. 253–268. Geological Society of London, London.

Stuiver, M., and Braziunas, T. F. (1993). Modeling atmospheric ^{14}C influences and ^{14}C ages of marine samples to 10,000 BC. *Radiocarbon* **35,** 137–189.

Stuiver, M., Reimer, P. J., Bard, E., Beck, J. W., Burr, G. S., Hughen, K. A., Kromer, B., McCormac, F. G., v. d. Plicht, J., and Spurk, M. (1998). Intcal98 radiocarbon age calibration, 24,000-0 cal BP. *Radiocarbon* **40,** 1041–1083.

Svendsen, J. I., and Mangerud, J. (1987). Late Weichselian and Holocene sea-level history for a cross-section of western Norway. *Journal of Quaternary Science* **2,** 113–132.

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* **28,** 234–242.

Woodman, R. (1994). "The Arctic Convoys, 1941–1945." John Murray, London.

Zeeberg, J. J. (1997). New data concerning the glacial history of the Barents Sea. *In* "Northbound with Barents" (J. H. Gawronski and P. V. Boyarsky, Eds.), pp. 62–71. Jan Mets, Amsterdam.

Zeeberg, J. J., and Forman, S. L. (2001). Changes in glacier extent on north Novaya Zemlya in the twentieth century. *The Holocene* **11,** 161–175.

Ziaja, W., and Salvigsen, O. (1995). Holocene shoreline displacement in southernmost Spitsbergen. *Polar Research* **14,** 339–340.