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ABSTRACT

Reconstructions of late Weichselian glacier coverage on the continental shelves of the Russian Arctic range from a large ice sheet terminating in northern Siberia to isolated ice caps restricted to Arctic archipelagos. This disparity in glacier reconstructions reflects the lack of chronological control on glacial and deglacial landforms. We present new Holocene relative sea-level data from Franz Josef Land and northern Novaya Zemlya, Russia, that place the thickest glacier loads in the northern Barents Sea and not over Novaya Zemlya. Radiocarbon ages from shelf and terrestrial areas at the former ice-sheet margin support deglaciation of the northern Barents Sea between 13.0 and 10.3 ka, considerably later than inferred from isotopic records for the Arctic Ocean. This analysis indicates that the Barents Sea ice sheet was a dominant sea-level reservoir in northern Eurasia, and that glacier loading of Novaya Zemlya was comparatively limited during the last glaciation.

INTRODUCTION

One of the largest uncertainties in ice-volume estimates for the late Quaternary is the areal and vertical extent of ice sheets over the Barents and Kara seas and other shallow shelves bordering northern Eurasia. Glacial-maximum ice-sheet reconstructions range from nearly complete glacier coverage of northern Eurasia by a contiguous marine-based ice sheet (e.g., Grosswald, 1988) to individual ice sheets and ice caps centered on the Arctic archipelagos and advancing onto the adjacent shelf (e.g., Velichko et al., 1984). The discrepancy between reconstructions is equivalent to a global sea-level contribution of 5 to 10 m.

The discovery of a glacial diamicton in the Barents Sea and moraine banks on the Svalbard continental slope leaves little doubt that the Barents Sea was covered by an ice sheet during the late Weichselian (Solheim et al., 1990; Gataullin et al., 1993). This ice sheet supported outlet glaciers that filled fjords and sounds on Spitsbergen and terminated at the shelf edge (Lehman and Forman, 1992; Mangerud et al., 1992). The timing of deglaciation and glacial-isostatic compensation is well documented for Svalbard, the western sector of the Barents Sea ice sheet (Forman, 1990; Lehman and Forman, 1992; Mangerud et al., 1992). However, there is little chronological control on marine and terrestrial glacial and deglacial features in the eastern Barents Sea, Kara Sea, and other areas of the Russian Arctic, confounding reconstructions of late Quaternary ice sheets in northern Eurasia. We present new postglacial relative sea-level records from Franz Josef Land and northern Novaya Zemlya (Fig. 1) that provide constraints on deglaciation, areas of maximum glacier loading, and potential global sea-level contribution from former ice sheets on continental shelves in the Russian Arctic.

RAISED BEACHES

Raised beaches are ubiquitous on forelands that border the Barents Sea and provide a high-fidelity record of the response of the lithosphere to glacial loading and unloading. The altitude of raised beaches was measured by a Leitz digital altimeter (precision of 1 m) with mean high tide as the datum (tidal range is <0.6 m). The rate and course of relative sea-level change is determined by the radiocarbon dating of shell, driftwood, or marine-mammal bones from

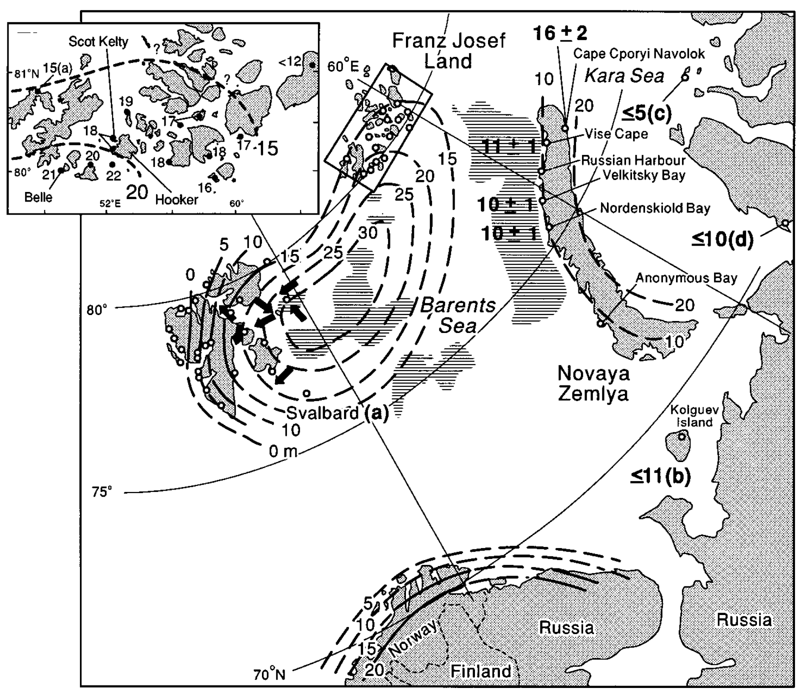

Figure 1. Inferred isobases of emergence since 5 ka for Barents and Kara seas. Isobase pattern for northern Fennoscandinavia from Møller (1987) and J. Snyder (1993, personal commun.). Data for Svalbard (a) from Forman (1990) and Møller et al. (1992). Altitude of Holocene marine limit on Kolguev Island (b; Komissarova, 1972), Izvestia Islands (c; Aller and Uhl, 1936), and Yamal Peninsula (d; Gataullin, 1988). Horizontal ruled pattern shows areas below 200 m water depth in northern Barents Sea. Inset shows inferred isobases of emergence since 5 ka for Franz Josef Land, Russia. Numbers indicate elevation of 5 ka shoreline on islands of archipelago. These observations are basis for constructing isobases.

TABLE 1. RADIOCARBON AGES ON ORGANIC MATIERAL FROM LATE WEICHSELIAN AND HOLOCENE RAISED MARINE DEPOSITS ON FRANZ JOSEF LAND AND NOVAYA ZEMLYA, RUSSIA

Sample and deposit	Shoreline altitude (m asl)	Laboratory and reservoir corrected ^{14}C Age* (yr B.P.)	$\delta^{13}C$	Laboratory number
Hooker(H) and Scot Kelty (S) Islands: marine limit 36 ±2 m asl				
Driftwood, raised beach (H)	1	775 ± 65	-24.7	GX-17200
Paired M. truncata shells from glacial-marine silts (H)	1	8325 ± 100	1.8	GX-17265
Driftwood, raised beach (S)	2	1100 ± 80	-23.8	GX-17199
Driftwood, raised beach (S)	5	2215 ± 125	-24.6	GX-17187
Driftwood, raised beach (S)	8	2970 ± 145	-23.0	GX-17188
Driftwood, raised beach (S)	12	4485 ± 75		GX-17191
Driftwood, raised beach (S)	16	4640 ± 75	-21.5	GX-17189
Driftwood, raised beach (S)	26	6590 ± 85	-24.4	GX-17190
Whalebone, raised beach (H)	26	6555 ± 95	-17.4	GX-17558G
Driftwood, raised beach (H)	29	7245 ± 100	-25.6	GX-17556
Driftwood, raised beach (H)	30	8715 ± 100	-25.0	GX-17198
Whalebone, raised beach (H)	32	7560 ± 295	-19.3	GX-17557G
Whalebone, raised beach (H)	33	9415 ± 125	-17.8	GX-17197G
Paired valves of M. truncata from sublittoral sediment (H)	36	10290 ± 115	-0.3	GX-17266
Paired valves of M. truncata from sublittoral sediment (H)	36	9995 ± 85		AA-8566
Paired valves of M. truncata from sublittoral sediment (H)	34	9645 ± 80		AA-8567
Nordenskiold Bay, Northern Novaya Zemlya: marine limit 11 ± 1 m asl				
Driftwood, raised beach	2	445 ± 60	-24.8	GX-17899
Driftwood, raised beach	3.5	1380 ± 65	-25.6	GX-18318
Whalebone, raised beach	5	1725 ± 120	-23.5	GX-18317G
Driftwood, raised beach	5.5	1510 ± 65	-23.5	GX-17898
Walrus bone, raised beach	8	3775 ± 75	-14.6	GX-18320G
Whalebone, raised beach	9	3625 ± 75	-17.0	GX-18319G
Cape Cporyi Navoluk, Northern Novaya Zemlya, marine limit 18 ± 2 m asl†				
Driftwood, raised beach	16 ± 2	4860 ± 140	-26.4	GX-18532

*The North Atlantic reservoir correction of 440 yr was subtracted from radiocarbon ages on marine materials (Olsson, 1980).

†Sample and marine limit elevations provided by M. G. Grosswald.

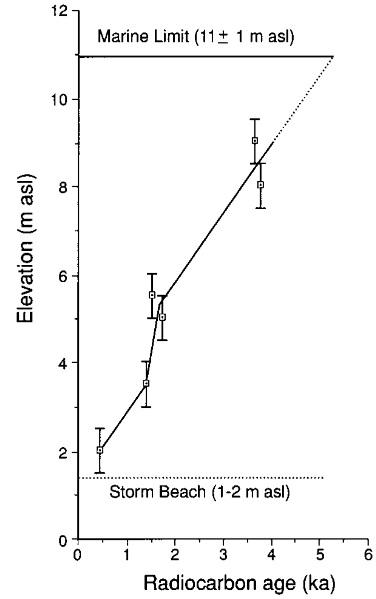

Figure 2. Height-age relation (m asl = metres above sea level) for raised beaches in Nordenskiold Bay, northern Novaya Zemlya, Russia.

raised beaches with known elevations (Table 1).

Previous reconstructions of a large ice sheet over the Kara Sea are based partly on the identification on Novaya Zemlya of raised beaches to heights of 100 to 150 m above sea level (m asl) (Grønlie, 1924; Zagorskaya, 1959; Kovaleva, 1974; Grosswald, 1988). In contrast, we found a uniformly low postglacial marine limit of 11 ± 1 m asl on northwestern Novaya Zemlya, between Nordenskiold and Foreigner bays (Fig. 1). The marine limit is isochronous on the northeast coast of Novaya Zemlya and rises to ~18 ± 2 m asl (Fig. 1), indicating a thickening ice sheet toward the Kara Sea. Similar low Holocene marine limits have been identified on Kolguev Island, southern Barents Sea (11 m asl; Komissarova, 1972) and on the northeastern (4 to 5 m asl; Aller and Uhl, 1936) and the southeastern (10 m asl; Gataullin, 1988) Kara Sea coasts (Fig. 1). Marine records from the mouth of Nordenskiold Bay indicate deglaciation of coastal areas prior to 10 ka (L. Polyak and S. Forman, unpublished data). However, radiocarbon ages of driftwood and marine-mammal bones found near the marine limit indicate a later transgression of the sea sometime between 5 and 6 ka (Fig. 2), reflecting the dominance of isostatic recovery and stabilization of global sea level (Fairbanks, 1989). A 35 yr tide gauge record from Russian Harbor on the northwest coast of Novaya Zemlya (Fig. 1) indicates that land is currently emerging at ~2 mm/yr (Emery and Aubrey, 1991, p. 114), similar to rates inferred from postglacial uplift.

We have identified higher raised beaches on Novaya Zemlya up to ~100 m altitude, but they are covered by a discontinuous and thin glacial drift. Mollusks from raised-marine deposits beneath this drift and above the Holocene marine limit yield radiocarbon ages of >28 ka (Table 2), indicating that the higher beaches on Novaya Zemlya reflect substantial glacier loading from a pre-late Weichselian event(s).

Field studies on Franz Josef Land concentrated on the raised-beach forelands on Hooker and Scot Kelty islands adjacent to the 500-m-deep British Channel. These forelands are covered by a regressional raised-beach sequence, emplaced into an inferred late Weichselian drift. One of the oldest ages for deglaciation in the northern Barents Sea of 10.3 ka was obtained on in situ shells near the marine limit on Hooker Island in western Franz Josef Land (Table 1). Similar deglacial ages have been determined for Edgeøya, eastern Svalbard (Landvik et al., 1992). The elevation of the marine limit and the isobases of emergence increase toward the southwest; the highest marine limit is 49 ± 2 m asl on Belle Island. A southwest tilt of strandlines on Franz Josef Land and an eastern strandline tilt on Svalbard (Forman, 1990) indicate a thickening ice sheet into the northern Barents Sea.

Hooker and Scot Kelty islands are covered by an extensive raised-beach sequence, which provides a detailed record of relative sea-level changes after deglaciation (Fig. 3). Initial emergence on Hooker Island from ~10.3 to 8.0 ka was apparently modest (<8 m), reflecting a rate of uplift that just outpaced the rate of eustatic sea-level rise. A radiocarbon age of 8340 ± 100 yr B. P. on in situ paired valves of the mollusk *Mya truncata* from a nearby raised glacial-marine sediment indicates that outlet glaciers were at or behind their present margins by the early Holocene, evidence against remnant glacier loading dampening emergence. A radiocarbon age of 775 ± 65 yr B. P. on driftwood from a raised beach at 1 m asl in a protected bay on Hooker Island indicates that emergence is not complete; the inferred present emergence rate is 1 to 2 mm/yr.

DISCUSSION: IMPLICATIONS FOR GLACIATION OF THE BARENTS AND KARA SEAS

The maximum western expansion of the Barents Sea ice sheet probably occurred late in the glacial cycle sometime between 20 and 13 ka (Forman, 1990; Mangerud et al., 1992); it was simultaneous with high relative sea level (Forman, 1990) and early incursion of North Atlantic surface waters that may

TABLE 2. RADIOCARBON AGES ON SHELL FROM GLACIAL AND MARINE DEPOSITS ABOVE THE HOLOCENE MARINE LIMIT ON NOVAYA ZEMLYA, RUSSIA

Location	Sample altitude (m asl)	Sample and deposit	^{14}C age (yr B.P.)	Laboratory number
Nordenskiold Bay, Novaya Zemlya	25 ± 2	Valves of H. arctica from sublittoral sand	30,680 ± 440	AA-11742
Nordenskiold Bay, Novaya Zemlya	40 ± 4	Valves of H. arctica from sublittoral sand	28,230 ± 340	AA-11743
Anonymous Bay, Novaya Zemlya	8 ± 1	Valves of M. truncata from glacial diamicton	37,200 ± 970	AA-11739
Anonymous Bay, Novaya Zemlya	27 ± 1	Valves of M. truncata from glacial diamicton	36,525 ± 860	AA-11740
Anonymous Bay Novaya Zemlya	~120	Driftwood (Krasnozhen et al., 1982)	40,330 ± 940	LU-1209

have nourished glacier growth (Hebbeln et al., 1994). Marine and terrestrial records from the western margin of the Barents Sea ice sheet show initial retreat sometime between 12.5 and 13.5 ka with glaciers at or behind present margins before 9.5 ka (Hald and Vorren, 1987; Forman, 1990; Svendsen et al., 1992; Lehman and Forman, 1992). Radiocarbon ages from forelands on Franz Josef Land indicate full deglaciation of interisland channels by or before 10.3 ka. Terrestrial and shelf records from the Barents Sea area indicate a later deglaciation than inferred from a light $\delta^{18}O$ isotopic interval between 16.0 and 13.0 ka in Arctic Ocean marine cores (Jones and Keigwin, 1988; Stein et al., 1994). This light isotopic signal may not necessarily reflect ice-sheet collapse, but may signal drainage of ice-marginal lakes on Siberia or increased discharge of the Ob, Yenisey, and Lena rivers.

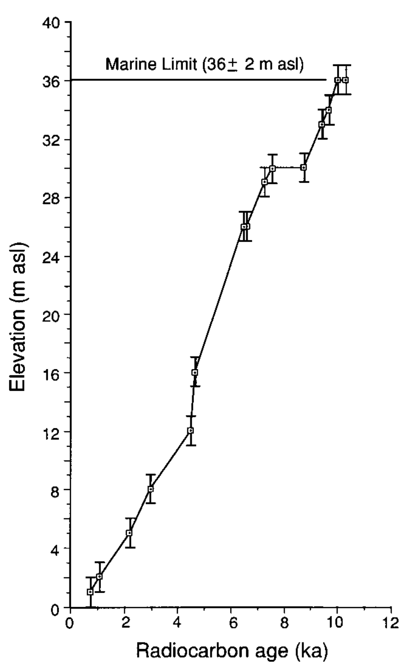

Figure 3. Height-age relation for raised beaches of Hooker Island and Scot Kelty Islands, Franz Josef Land, Russia.

The new relative sea-level data from Franz Josef Land and Novaya Zemlya show maximum emergence for the past 5 ka and earlier centered over the northern Barents Sea (Fig. 1). We infer from the regional isobase pattern that Franz Josef Land and Novaya Zemlya sustained a thinner glacier load than at the hypothesized center of the ice sheet over Kong Karls Land, Svalbard, where Holocene raised beaches have been identified to 110 m asl (Salvigsen, 1981). The pattern of postglacial emergence indicates that the Barents Sea ice sheet was the dominant load, and glacier coverage of Novaya Zemlya was comparatively limited. Varying directions of glacial striae on Svalbard (Ingolfsson et al., 1992) support the presence of an ice divide in the northern Barents Sea; ice was funneled through fjords and sounds on Svalbard.

The disintegration of the marine-based Barents Sea ice sheet may be coincident with the rapid initial rise in global sea level between 13.0 and 11.5 ka (Fairbanks, 1989) and not a response to maximum isostatic depression (Jones and Keigwin, 1988). The rise in global sea level may have destabilized the ice sheet, particularly in the deepest part of the Barents Sea, the troughs bordering the Barents Sea, and the interisland channels on Franz Josef Land. The recent identification of iceberg scour traces at 300 to 600 m water depths on the Yermak Plateau (Vogt et al., 1994) supports the presence of a thick (>1000 m) ice sheet in the northern Barents Sea during the late Weichselian. The iceberg scour traces imply an ice sheet decoupled from the sea bed as it entered water depths of >500 m in the troughs bordering the Arctic Ocean. Elevated summer insolation values (Berger and Loutre, 1991), particularly later in the deglaciation between 12.0 and 9.0 ka, probably accelerated the demise of land-based outlet glaciers of the Barents Sea ice sheet (Svendsen and Mangerud, 1992).

The current low rates of land emergence (1 to 2 mm/yr) and the relatively low marine limits (10 to 50 m asl) on Franz Josef Land and Novaya Zemlya are similar to the Austrheim area in southwestern Norway, within 150 km of the margin of the Fennoscandinavian ice sheet (Emery and Aubrey, 1991, p. 86–87; Hafsten, 1983). The similarity in the present and postglacial emergence rates between southwestern Norway and Franz Josef Land and Novaya Zemlya may reflect equivalent ice-sheet loads, assuming similar earth rheology and deglacial history. The reconstructed ice-sheet thickness during the late Weichselian over southwestern Norway is ~1500 m (Tushingham and Peltier, 1991; Elverhøi et al., 1993), which is our initial estimate of the thickness of the Barents Sea ice sheet over Franz Josef Land and northern Novaya Zemlya. The Barents Sea ice sheet—having an inferred maximum thickness of 2500 m over the northern Barents Sea and thinning to ~1500 m over Franz Josef Land and Novaya Zemlya—was a substantial sea-level reservoir during the last glaciation, accounting for ~6 m of global sea-level rise (cf. Nakada and Lambeck, 1988; Tushingham and Peltier, 1991).

The 1500 m estimated ice-sheet thickness over Novaya Zemlya is, however, at least 40% thinner than previous estimates of 2500 to 3000 m (Grosswald, 1988; Tushingham and Peltier, 1991; Elverhøi et al., 1993), implying a thinner Kara Sea ice sheet. A 40% thinner ice sheet over Novaya Zemlya would reduce the global sea-level contribution from the Kara Sea ice sheet to <4 m, less than previous estimates of ~7 m (Tushingham and Peltier, 1991; Nakada and Lambeck, 1988).

The pattern of postglacial emergence places the maximum ice-sheet load over the northern Barents Sea and thinning over Novaya Zemlya. Modest glacier thicknesses over northern Novaya Zemlya call into question the presence of a thick (>1500 m) ice sheet over the Kara Sea that terminated in northern Siberia (Grosswald, 1988; Tushingham and Peltier, 1991). We contend that much of Siberia was distal to moisture sources, like northern Alaska, and thus glacier extent possibly resembles limited valley-glacier and ice-cap expansion characteristic of the Brooks Range, Alaska (Hamilton, 1986). Many studies of the eastern Kara Sea (Astakhov, 1992), the Laptev Sea, and adjacent lowlands (Vigdorchik, 1980; Velichko et al., 1989) provide equivocal evidence for coverage by a large ice sheet, but support the presence of a refugium with large Pleistocene mammals and possibly humans surviving throughout the late Weichselian into the Holocene (Mochanov, 1978; Vereschagin and Baryshnikov, 1984; Velichko et al., 1989; Makeyev et al., 1993; Vartanyan et al., 1993).

This analysis of relative sea-level data from the northern Barents Sea potentially reduces the global sea-level contribution from ice sheets on Russian Arctic continental shelves to between 6 and 10 m, considerably less than previous estimates of 16 m (Nakada and Lambeck, 1988; Tushingham and Peltier, 1991). The lower estimate on sea-level contribution from former ice sheets in the Russian Arctic increases the apparent discrepancy between eustatic sea-level depression and grounded global ice volume to more than 30 m of global sea-level equivalent at the time of the last glacial maximum (cf. Andrews, 1992).

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