Northwest Svalbard during the last glaciation: Ice-free areas existed

Jon Y. Landvik* Agricultural University of Norway, Department of Soil and Water Sciences, N-1432 Ås, Norway
Edward J. Brook Washington State University, Department of Geology and Program in Environmental Science, Vancouver, Washington 98686, USA
Lyn Gualtieri Quaternary Research Center, University of Washington, Seattle, Washington 98195-1360, USA
Grant Raisbeck Centre de Spectrométrie Nucléaire et de Spectrométrie de Masse, F-91405 Campus Orsay, France
Otto Salvigsen University of Oslo, Department of Geography, N-0316 Oslo, Norway
Françoise Yiou Centre de Spectrométrie Nucléaire et de Spectrométrie de Masse, F-91405 Campus Orsay, France

ABSTRACT

The possibility that ice-free areas existed during the late Weichselian glaciation of the Svalbard archipelago has been debated for several decades. This study reveals the first geologic evidence that nunataks existed on the islands of northwest Svalbard. Several ^{10}Be exposure ages were obtained from bedrock and glacial erratics on Danskøya and Amsterdamøya Islands. Exposure ages for glacial erratics laid down in block-field–covered plateaus >300 m above sea level show that the last ice sheet that completely covered the islands deglaciated >80 k.y. ago. Dating of marine sediments close to sea level reveals that full ice-free conditions were achieved by ca. 50 ka. During the late Weichselian, the coastal lowlands were glaciated, and the major fjords and troughs controlled glacier flow. The existence of nunataks at this time opens the possibility for glacial survival of plant species.

Keywords: Svalbard, Weichselian, Last Glacial Maximum, exposure age, nunataks.

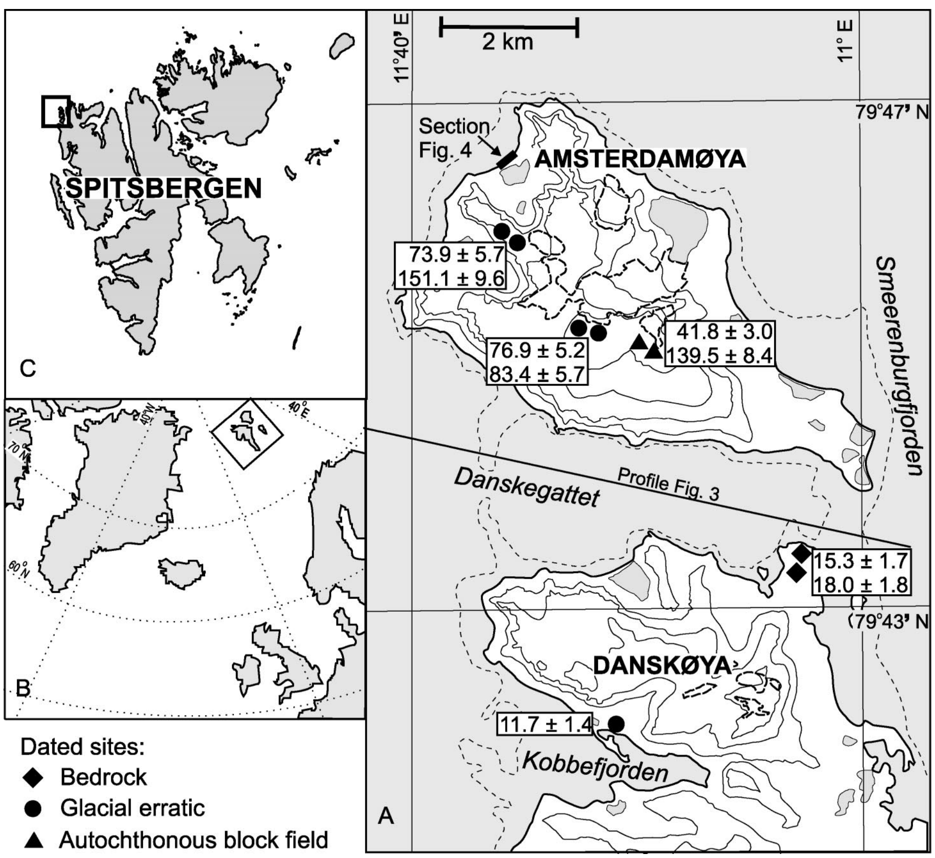

Figure 1. A: Amsterdamøya and Danskøya Islands with location of samples and obtained exposure ages (in ka) (see Table 1). Contour interval is 100 m, and −10 m contour is dashed. Glaciers and lakes are shaded. B and C: Location in oceanic context and on Spitsbergen, respectively.

INTRODUCTION

The reconstructions of the late Weichselian ice extent over Svalbard and the adjacent Barents Sea have ranged from almost no ice (Troitsky et al., 1979; Boulton et al., 1982) to thick ice extending to the western shelf edge of the Barents Sea as well as north of Svalbard (Schytt et al., 1968; Mangerud et al., 1992; Landvik et al., 1998). On the basis of their isolated occurrence on Svalbard, it has commonly been suggested by biologists that several plant and animal species survived the last glaciation in ice-free refugia (e.g., Rønning, 1963). Recent molecular studies indicate that plants immigrated to the archipelago after the last glaciation (e.g., Abbott and Brochmann, 2003; Brochmann et al., 2003). However, these results do not exclude the possibility that some populations may have survived in glacial refugia.

Setting limits on the vertical extent of the last ice sheet is possible by investigating the glacial landforms and deposits of the mountain range on the west coast of Spitsbergen and the adjacent islands. We used ^{10}Be cosmogenic isotope exposure dating to constrain the exposure history of bedrock and erratics on Danskøya and Amsterdamøya Islands (Fig. 1). This study provides the first documented constraints on geometry, extent, and chronology of the northwestern sector of the late Weichselian Svalbard–Barents Sea ice sheet, important for reconstruction and modeling of the ice sheet. The results set boundary conditions on the possibility for glacial survival, immigration, and development of the modern biota on the isolated Svalbard archipelago.

RESEARCH AREA

Western Svalbard is characterized by a coastal mountain range with summits reaching 1000 m above sea level (masl). A well-developed strandflat separates the mountains from the 30–60-km-wide continental shelf. In extreme northwest Svalbard, there is no strandflat, and the distance from the outermost island to the shelf break is only 8 km. Most

*E-mail: jon.landvik@nlh.no.

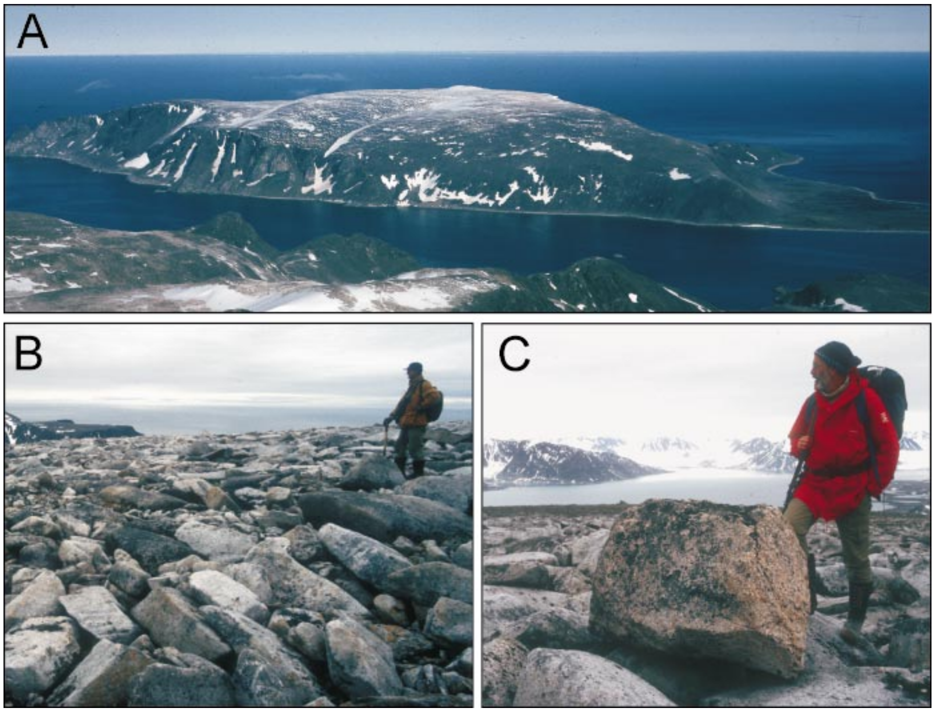

Figure 2. A: Photograph looking north at Amsterdamøya. B: Autochthonous block field at 400 m above sea level (asl). C: Red granitic erratic in block field (400 masl).

of the coastal range is composed of metamorphic and metasedimentary rocks, whereas gneisses and migmatites dominate the islands in this study (Hjelle and Ohta, 1974).

Fjords, sounds, and cross-shelf troughs, clearly showing a history of long-term glacial activity, characterize the large-scale geomorphology of northwest Spitsbergen. The glacially scoured lower ground (<200 masl) of Danskøya and parts of Amsterdamøya is marked by numerous glacially formed basins, roches moutonnées, and erratics, and large submarine moraine lobes are found off the mouth of Smeerenburgfjorden and in the sound between Danskøya and Amsterdamøya Islands (Liestøl, 1972; Salvigsen, 1977). There has been no net postglacial uplift (Forman, 1990; Landvik et al., 1998), and all surfaces above present sea level have been subaerially exposed since the last deglaciation.

In contrast to the alpine topography of the coastal mountains, the islands exhibit gently sloping plateaus >300 masl surrounded by steep cliffs (Figs. 1 and 2). The plateaus on Amsterdamøya are covered with a 5–10-m-thick autochthonous block field (Fig. 2B). Erratic boulders, some perched on subrounded cobbles, are superimposed on the blocks of the block field (Fig. 2C). Numerous erratics are identified as derived from the red Hornemantoppen granite, which crops out at the head of Smeerenburgfjorden, 30–40 km to the southeast.

EXPOSURE AGE DATING

We sampled glacially scoured bedrock and erratics from the lower ground and erratics from the block fields (Fig. 1). Samples were collected in late winter from sites with limited snow cover, and most samples were obtained by using a rock drill from the top surface of the boulders. Two independent samples were collected at each site when feasible.

Samples (Table 1) were crushed in a jaw crusher and disk mill and then sieved. Quartz was purified from the samples with a combination of magnetic separation and sequential leaching in a weak HF solution in a 70 °C ultrasonic bath. Quartz samples of ~30–40 g were dissolved in HF with 0.5 mg ^{9}Be carrier. The Be was purified with anion and cation exchange and converted to BeO in a quartz crucible by using a Bunsen burner flame. For details of analytical procedures, see Licciardi (2000). The concentration of ^{10}Be was measured at the Tandetron Accelerator Mass Spectrometry Facility in Gif-sur-Yvette, France (Raisbeck et al., 1994), relative to the U.S. National Institute of Standards and Technology standard (SRM 4325). Concentrations were corrected for a procedural blank of $1.56 \pm 0.96 \times 10^5$ atoms ^{10}Be. Uncertainties (1σ) in ^{10}Be concentrations are based on counting statistics, a conservative 5% instrumental uncertainty, and the blank uncertainty. We calculated exposure ages by using the production-rate estimates and scaling factors similar to those described by Stone (2000), and the standard relationship between atmospheric pressure and altitude adopted by Lal (1991). Stone (2000) suggested that under Holocene climate conditions, production rates at ~60°N might be underestimated by ~4% when using the standard atmosphere. We recognize that uncertainties in production rate calibration and scaling may be ~10%; however, these uncertainties do not affect the main conclusions of our study.

Bedrock and Glacial Erratics

Two samples from quartz veins in the glacially sculptured landscape below 100 masl on northeast Danskøya yielded ages of 15.3 ± 1.7 and 18.0 ± 1.8 ka. A boulder anchored in the top of a prominent moraine at Kobbefjorden, western Danskøya, yielded ages of 11.7 ± 1.4 ka. The area is characterized by numerous glacially polished and striated surfaces, and the ages have thus not been corrected for postglacial erosion. A hypothetical maximum correction is obtained by using the data from samples 99-23 and 99-24 (see subsequent discussion) and assuming that they are at steady state with respect to erosion and were exposed continuously. We calculated a maximum erosion rate of ~0.9 cm/k.y., which corresponds to a real age of ca. 22 ka for a sample with an apparent age of 18 ka.

On the plateaus (Figs. 1 and 3), a pair of erratics close to the top of Amsterdamøya yielded comparable ages of 76.9 ± 5.2 and 83.4 ± 5.7 ka. Because reduction of exposure ages by erosion is more significant with older ages, the pre–Last Glacial Maximum ages should strictly be considered minimum ages. These results suggest that the summit emerged from the ice prior to ca. 80 ka. Two other erratics are perched on large angular blocks of the block field, demonstrating that little or no movement has taken place in the block field after the erratics were laid down. They have exposure ages of 73.9 ± 5.7 and 151.1 ± 9.7 ka. One explanation for the higher age is that this boulder was exposed at an earlier time, prior to deposition. We consider this the most likely explanation given the consistency of the rest of the data set, but can not constrain the exposure history of this sample further with the existing data.

Autochthonous Block Field

Two angular to subangular blocks of granite from the autochthonous block field yielded ages of 41.8 ± 3.0 and 139.5 ± 8.4 ka. The higher age suggests relatively long exposure histories of some of the block surfaces, and parts of the isotope production probably predate the last glaciation.

TABLE 1. ^{10}Be DATA AND EXPOSURE AGES FOR THE AMSTERDAMØYA AND DANSKØYA SAMPLES

Sample number	Sample description	Longest boulder axis (cm)	Coordinates		Elev. (m)	Sample mass (g)	^{10}Be (10^4 atom g^{-1})	1σ (10^4 atom g^{-1})	$^{10}Be_{sn}$* (10^4 atom g^{-1})	Production rate† (atom g^{-1} yr^{-1})	Age§# (ka)
			Lat (°N)	Long (°E)							
99-1	Quartz vein	N.A.	79°43.4′	10°57.0′	77	34.643	6.95	0.771	7.26	5.45	15.3 ± 1.7
99-5	Quartz vein	N.A.	79°43.3′	10°56.9′	74	41.478	8.14	0.795	8.51	5.43	18.0 ± 1.8
99-8	Gneiss boulder in moraine	130	79°42.0′	10°48.9′	50	40.949	5.05	0.593	5.41	5.30	11.7 ± 1.4
99-14	Perched granite boulder	60	79°46.0′	10°43.8′	293	33.559	41.20	3.160	43.00	6.77	73.9 ± 5.7
99-15	Perched granite boulder	60	79°45.9′	10°44.2′	292	33.844	83.00	5.240	86.80	6.76	151.9 ± 9.7
99-17	Gray granite in block field	70	79°45.0′	10°47.7′	469	41.556	27.70	2.010	29.00	7.99	41.8 ± 3.0
99-18	Gray granite in block field	300	79°45.1′	10°49.9′	469	30.386	90.30	5.420	94.50	7.99	139.5 ± 8.4
99-23	Gneiss boulder	150	79°45.1′	10°48.1′	462	34.396	54.40	3.730	56.80	7.94	83.4 ± 5.7
99-24	Pink granite boulder	150	79°45.1′	10°48.1′	462	31.412	50.20	3.420	52.50	7.94	76.9 ± 5.2

*^{10}Be normalized for sample interval and topographic shielding assuming attenuation factor of 150 g/cm^2 (Brown et al., 1992) and topography correction from Dunne et al. (1999). All samples were 5 cm thick. Topography corrections for 99-8 and 99-17 and 18 were 1.024 and 1.001, respectively; no topography corrections for the other samples.

†Production rates after Stone (2000).

§Production rates decreased by a factor of 0.875 in age calculations to account for differences between NIST ^{10}Be standard used at Gif-sur-Yvette and standards used to calibrate production rates (Middleton et al., 1993).

#Error estimates include analytical uncertainties only.

STRATIGRAPHIC CONSTRAINTS ON THE LAST GLACIATION

On northwestern Amsterdamøya, two glacially shaped valleys are cut into the block-field–covered plateaus (Fig. 1A). A sediment section in the valley fill (Fig. 4) gives important constraints on the age of the latest glaciation. The surface is capped by a matrix-supported bouldery diamicton interpreted as a till (unit 1, Fig. 4). It contains large angular boulders of local origin and red granites from Spitsbergen. The till is underlain by glaciolacustrine sediments (unit 2), and a succession of marine and glacial proximal sediments (units 3 and 4) contains paired mollusks of *Mya truncata*, radiocarbon dated to 43,110 ± 960 (Tua-2897) and 44,655 +1230/−1065 (Tua-2896) ^{14}C yr B.P. (Fig. 4). Low amino acid ratios on the same shells (Fig. 4) overlap with ratios on shells from the termination of the late Weichselian (Mangerud et al., 1992). The optically stimulated luminescence ages ages cluster at 50 ka (Fig. 4), which we conclude is a reasonable age estimate for the subtill succession. This age is consistent with the middle Weichselian Kapp Ekholm interstadial, dated to 60–50 ka by Mangerud et al. (1998).

DISCUSSION AND CONCLUSIONS

Ice Extent and Deglaciation

The ages obtained from glacial erratics in the block fields indicate an exposure history >80 k.y. The undisturbed autochthonous block fields suggest that the depositing glacier was cold based or had limited basal transport at this elevation. Thus, the erratics must have been transported englacially from their source area in the mountains east of Smeerenburgfjorden (Fig. 1).There is no positive evidence to support later cover by cold-based glaciers, although it is not possible to unequivocally rule out this possibility. However, the delicate arrangement of perched boulders would be very sensitive to any later inundation by glacial ice. Furthermore, none of the erratic boulders yield young exposure ages, which would be expected if a younger ice sheet had overrun the surface.

From the present evidence we propose that the plateaus have been ice free for >80 k.y.; consequently, the late Weichselian glaciers were confined to the fjords, sounds, and coastal areas of northwest Svalbard. The exposure ages suggest that the lower ground of Danskøya and Amsterdamøya was deglaciated by 18–15 ka (Fig. 3). These are the first age estimates for the last deglaciation in the area.

Style of Glaciations

We have found evidence for two glacial phases with different local ice thicknesses. During the older glaciation, the ice flow crossed the >200-m-deep Smeerenburgfjorden basin, as well as the summit of Amsterdamøya. If it is assumed to have reached the shelf break to the west, the surface gradient must have been >60 m/km (adjusted for eustatic sea level 60 m lower than present, negligible isostasy). This suggests considerable buildup of ice over northwest Spitsbergen at the time, including ice cover for the highest mountains. Even if 80 ka should be regarded as a minimum age, the style of glaciation complies with the extensive early Weichselian glaciation suggested by several studies (see review in Mangerud et al., 1998), thus supporting the radiocarbon ages being finite. The high relative sea level found at 50 ka suggests that extensive glacial loading prevailed into the middle Weichselian.

During the late Weichselian glaciation, ice in the coastal area was thinner and abundant

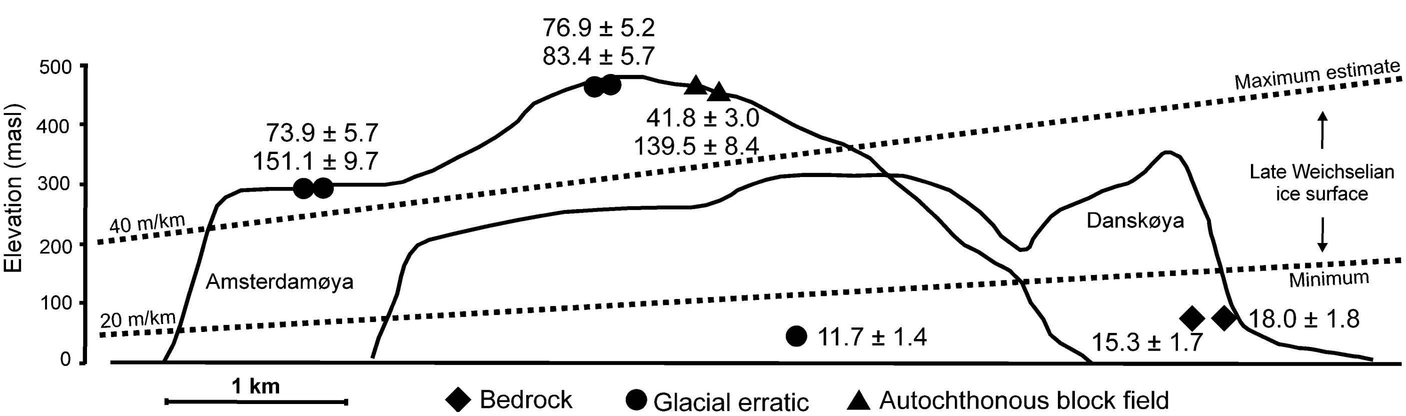

Figure 3. Topographic profiles of Amsterdamøya and Danskøya (see location in Fig. 1) with all dated samples (exposure ages shown are in ka; masl—meters above sea level). Minimum and maximum estimates of late Weichselian ice-sheet surface are shown.

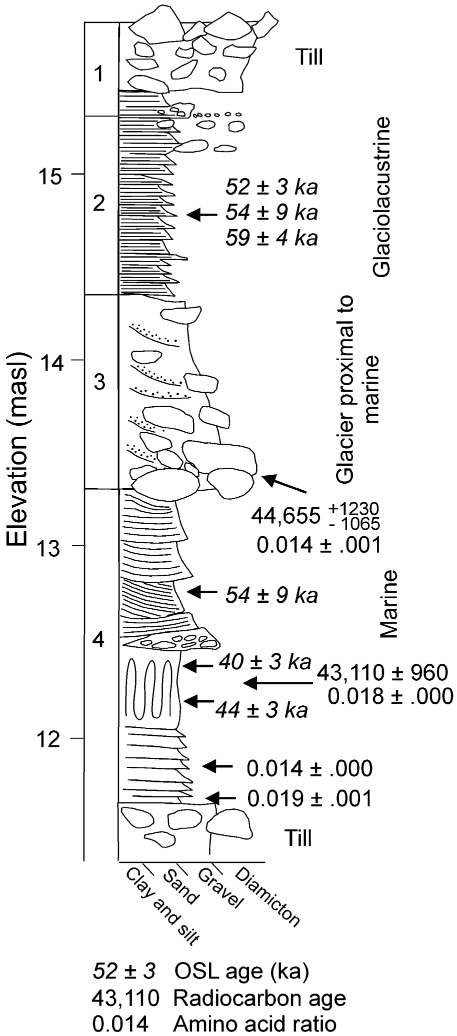

Figure 4. Simplified lithologic log of sediment section located in Figure 1. Optically stimulated luminescence (OSL) ages (Murray and Wintle, 2000) were obtained by Nordic Laboratory for Luminescence Dating, Risø, Denmark. Radiocarbon samples (^{14}C yr B.P., laboratory prefix Tua- in text) were prepared at Laboratory for Radiological Dating, Trondheim, and targets were run on accelerator mass spectrometer at Swedberg Laboratory, University of Uppsala. Amino acid ratios alle/Ile (total) (see Miller and Brigham-Grette, 1989) were analyzed at Amino Acid Laboratory, University of Bergen; masl—meters above sea level.

glacial striae show warm-based basal conditions. By extending the calculated surface gradients of 20–40 m/km (Fig. 3) eastward, nunataks probably also existed along the mountains of northwest Spitsbergen at this time.

Significance of the Ice-Free Areas

More extensive ice-free areas along the west coast of Svalbard during the last glaciation have been postulated by a series of studies where radiocarbon ages on mollusk shells and whalebone, as well as amino acid racemization and soil development, suggest that the sediments at the present surface are of pre–late Weichselian age (Forman and Miller, 1984; Miller et al., 1989; Andersson et al., 1999; Houmark-Nielsen and Funder, 1999). Our study confirms that ice-free areas existed as nunataks in northwest Svalbard during the last glaciation. Such nunataks may have influenced immigration and development of biota on the archipelago. The proposed scenario opens the possibility for plant or plant seed survival, but leaves no coastal lakes as refugia for freshwater fish (arctic char) or any of the present mammals.

ACKNOWLEDGMENTS

The field work was funded by the Research Council of Norway (the Norpast Program) and the University Centre on Svalbard. Tandetron operation was supported by the Centre National de la Recherche Scientifique, Institut National de Physique Nucléaire et de Physique des Particules, Institut National des Sciences de l'Univers, and Commissariat à l'Energie Atomique. Ottar Salvigsen and Jakob Fjellanger assisted in the field, and Heather Clark, Leah Bjerkelund, and Henriette Linge provided laboratory assistance.

REFERENCES CITED

Abbott, R.J., and Brochmann, C., 2003, History and evolution of the arctic flora: In the footsteps of Eric Hultén: Molecular Ecology, v. 12, p. 299–313.

Andersson, T., Forman, S.L., Ingólfsson, Ó., and Manley, W.F., 1999, Late Quaternary environmental history of central Prins Karls Forland, western Svalbard: Boreas, v. 28, p. 292–307.

Boulton, G.S., Baldwin, C.T., Peacock, J.D., McCabe, A.M., Miller, G., Jarvis, J., Horsefield, B., Worseley, P., Eyles, N., Chroston, P.N., Day, T.E., Gibbard, P., Hare, P.E., and von Brunn, V., 1982, A glacio-isostatic facies model and amino acid stratigraphy for late Quaternary events in Spitsbergen and the Arctic: Nature, v. 298, p. 437–441.

Brochmann, C., Gabrielsen, T.M., Nordal, I., Landvik, J.Y., and Elven, R., 2003, Glacial survival or *tabula rasa*? The history of North Atlantic biota revisited: Taxon (in press).

Brown, E.T., Brook, E.J., Raisbeck, G.M., Yiou, F., and Kurz, M.D., 1992, Effective attenuation lengths of cosmic-rays producing ^{10}Be and ^{26}Al in quartz—Implications for exposure age dating: Geophysical Research Letters, v. 19, p. 369–372.

Dunne, J., Elmore, D., and Muzikar, P., 1999, Scaling factors for the rates of production of cosmogenic nuclides for geometric shielding and attenuation at depth on sloped surfaces: Geomorphology, v. 27, p. 3–11.

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

Forman, S.L., and Miller, G.H., 1984, Time dependent soil morphologies and pedogenic processes on raised beaches, Bröggerhalvøya, Svalbard archipelago: Arctic and Alpine Research, v. 16, p. 381–394.

Hjelle, A., and Ohta, Y., 1974, Contribution to the geology of north western Spitsbergen: Norsk Polarinstitutt Skrifter, v. 158, p. 1–107.

Houmark-Nielsen, M., and Funder, S., 1999, Pleistocene stratigraphy of Kongsfjordhallet, Spitsbergen, Svalbard: Polar Research, v. 18, p. 39–49.

Lal, D., 1991, Cosmic-ray labeling of erosion surfaces—In situ nuclide production rates and erosion models: Earth and Planetary Science Letters, v. 104, p. 424–439.

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 the Barents Sea and Svalbard area: Ice sheet extent and configuration: Quaternary Science Reviews, v. 17, p. 43–75.

Licciardi, J., 2000, Alpine glacier and pluvial lake records of late-Pleistocene climate variability in the western United States [Ph.D. thesis]: Corvallis, Oregon State University, 15 p.

Liestøl, O., 1972, Submarine moraines off the west coast of Spitsbergen: Norsk Polarinstitutt Årbok, v. 1970, p. 165–168.

Mangerud, J., Bolstad, M., Elgersma, A., Helliksen, D., Landvik, J.Y., Lønne, I., Lycke, A.K., Salvigsen, O., Sandahl, T., and Svendsen, J.I., 1992, The Last Glacial Maximum on Spitsbergen, Svalbard: Quaternary Research, v. 38, p. 1–31.

Mangerud, J., Dokken, T.M., Hebbeln, D., Heggen, B., Ingólfsson, Ó., Landvik, J.Y., Mejdahl, V., Svendsen, J.I., and Vorren, T.O., 1998, Fluctuations of the Svalbard–Barents Sea Ice Sheet during the last 150,000 years: Quaternary Science Reviews, v. 17, p. 11–42.

Middleton, R., Brown, L., Dezfouly-Arjomandy, B., and Klein, J., 1993, On ^{10}Be standards and the half-life of ^{10}Be: Nuclear Instruments and Methods in Physics Research, v. 82, p. 399–403.

Miller, G.H., and Brigham-Grette, J., 1989, Amino acid geochronology: Resolution and precision in carbonate fossils: Quaternary International, v. 1, p. 111–128.

Miller, G.H., Sejrup, H.P., Lehman, S.J., and Forman, S.L., 1989, Glacial history and marine environmental change during the last interglacial-glacial cycle, western Spitsbergen, Svalbard: Boreas, v. 18, p. 273–296.

Murray, A.S., and Wintle, A.G., 2000, Luminescence dating of quartz using an improved single-aliquot regenerative-dose protocol: Radiation Measurements, v. 32, p. 57–73.

Raisbeck, G.M., Yiou, F., Bourles, D., Brown, E., Deboffle, D., Jouhanneau, P., Lestringuez, J., and Zhou, Z.Q., 1994, The AMS facility at Gif-Sur-Yvette: Progress, perturbations and projects: Nuclear Instruments and Methods in Physics Research, v. 92, p. 43–46.

Rønning, O.I., 1963, Phytogeographical problems in Svalbard: Oxford, Pergamon Press, p. 99–107.

Salvigsen, O., 1977, Radiocarbon datings and the extension of the Weichselian ice-sheet in Svalbard: Norsk Polarinstitutt Årbok, v. 1976, p. 209–224.

Schytt, V., Hoppe, G., Blake, W., Jr., and Grosswald, M.G., 1968, The extent of the Würm glaciation in the European Arctic: A preliminary report about the Stockholm University Svalbard Expedition 1966: International Association of Scientific Hydrology Publication 79, p. 207–216.

Stone, J.O., 2000, Air pressure and cosmogenic isotope production: Journal of Geophysical Research, v. 105, p. 23,753–23,759.

Troitsky, L., Punning, J.-M., Hütt, G., and Rajamäe, R., 1979, Pleistocene glaciation chronology of Spitsbergen: Boreas, v. 8, p. 401–407.

Manuscript received 2 April 2003
Revised manuscript received 12 June 2003
Manuscript accepted 23 June 2003

Printed in USA