Introduction

The Jostedalsbreen and Jotunheimen regions of southern Norway have been foci of research on Holocene glacier variations for many years. As a result, a detailed chronology of glacier and climatic variations has revealed both similarities and differences between these two regions, which are some 50 km apart (e.g. Matthews *et al.*, 2000; Nesje *et al.*, 2000, 2001). Little is known, however, about the glaciers and their fluctuations in the relatively remote mountain area of Breheimen, east of Jostedalsbreen and northwest of Jotunheimen (Fig. 1). This study represents the first part of an investigation of the Holocene glacier and climatic history of this area, which occupies a transitional location on a steep climatic gradient between the relatively maritime and continental climates respectively of Jostedalsbreen and Jotunheimen. The project as a whole is using a range of methods, including the use of moraine mapping and surface dating, and glaciofluvial and glaciolacustrine stratigraphy, which may be characterised as a 'multiproxy' approach.

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The Neoglacial maximum extent of glaciers in southern Norway is widely accepted to have occurred in the Little Ice Age (Matthews, 1991; Winkler, 1996a; Dahl *et al.*, 2002). Within the Little Ice Age, most glaciers in the Jostedalsbreen region (Østrem *et al.*, 1976; Grove, 1985, 1988; Erikstad and Sollid, 1986; Bogen *et al.*, 1989; Bickerton and Matthews, 1993) and in Jotunheimen (Matthews, 1974, 1977; Matthews and Shakesby, 1984; Erikstad and Sollid, 1986) attained their maximum extents in the eighteenth century. In this paper, we focus on the moraine-ridge sequences in front of the 'low-altitude', warm-based (temperate) glaciers of the Breheimen region. Our investigations of the higher altitude

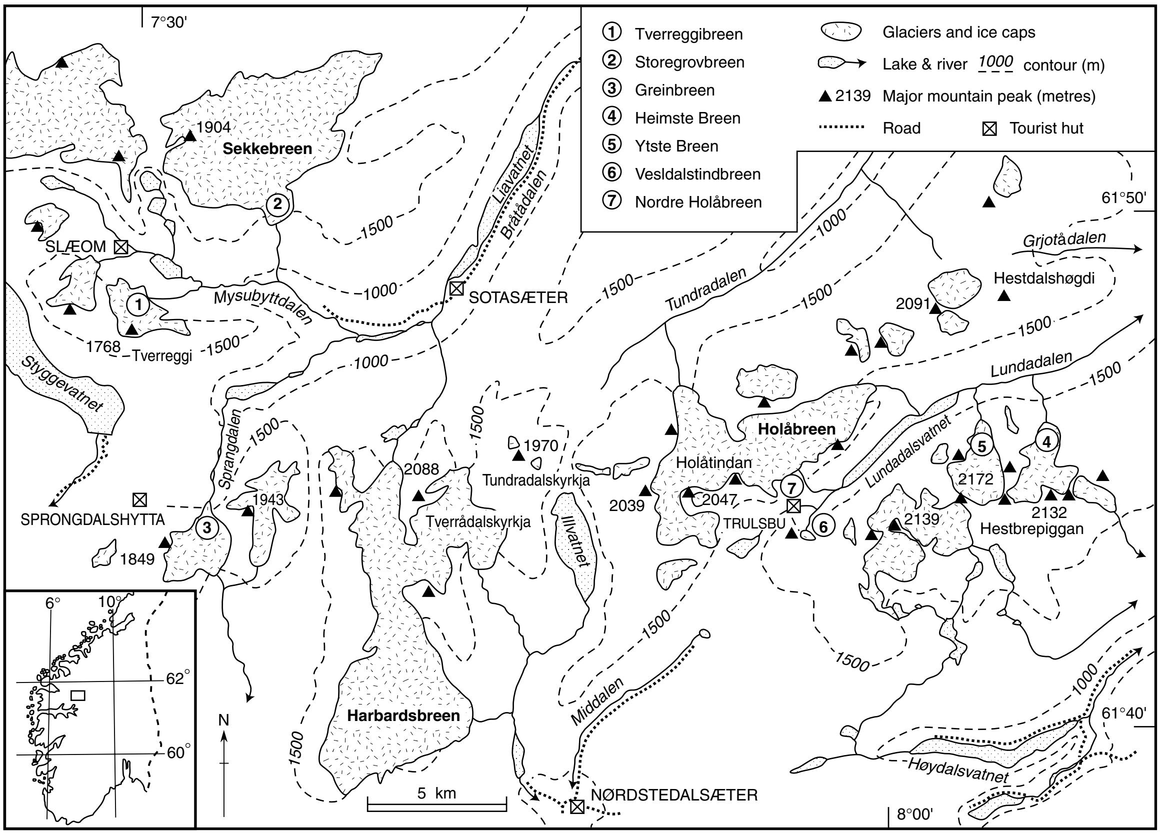

Figure 1 Location map of Breheimen and the 'low-altitude' glaciers investigated

glaciers, which are of the cold-based (polythermal or subpolar) type (Paterson, 1994; Benn and Evans, 1998), and of the distal glaciofluvial and glaciolacustrine sedimentary sequences, will be reported separately. This paper has five main aims:

1 to describe the moraine-ridge sequences of the low-altitude glaciers;
2 to identify the Little Ice Age moraines and differentiate them from any older Holocene moraines;
3 to date the moraines as accurately as possible using a combination of lichenometric dating, Schmidt hammer 'R-values' and radiocarbon dating;
4 to detect any synchroneity of glacier response to decadal-scale climatic fluctuations during the Little Ice Age interval;
5 to compare the pattern and timing of Little Ice Age glacier variations in Breheimen with those already established for Jostedalsbreen and Jotunheimen.

Study area

Breheimen refers to the region between Lustrafjord and the major valleys of Jostedalen, Ottadalen and Bøverdalen (Fig. 1). Although a number of mountain peaks rise to over 2000 m above sea-level, most of the region consists of high plateau areas around 1500–1800 m underlain by granitic and migmatic gneiss (Sigmond *et al.*, 1984; Lutro and Tveten, 1996) dissected by glaciated valleys such as Bråtådalen/Mysubyttdalen, Lundadalen and Fortunsdalen. The seven low-altitude glaciers under investigation here (Table 1 and Fig. 1; cf. Østrem *et al.*, 1988) were selected because they have the best developed moraine-ridge sequences. These glaciers are outlets from either small ice-caps or cirque glaciers, and five of them descended during the Little Ice Age on to valley floors between 1000–1350 m a.s.l. As the forelands of these glaciers lie above the regional tree line in the alpine zone, they are closer in size and character to those of Jotunheimen than to the larger outlet glaciers of Jostedalsbreen.

Although no meteorological data are available from the core of Breheimen, data from the nearest meteorological stations are summarised in Table 2 (Aune, 1993; Førland, 1993). Gjeilo i Skjåk and Bråtå, to the northeast and north, respectively, being located in one of the driest regions of southern Norway, are unlikely to be representative of the climate of Breheimen. Stations to the west and southwest (Bjørkehaug i Jostedalen and Fortun), being exposed to a more maritime climate, appear to be similarly unrepresentative but are indicative of the precipitation gradient. Short-term glaciometeorological measurements carried out at Harbardsbreen in central Breheimen in the late 1990s (Kjøllmoen, 2000) suggest fairly

Table 1 Characteristics of the seven 'low-altitude' glaciers investigated in Breheimen (modified from Østrem *et al.*, 1988)

Glacier	Area (km^2)	Glacier snout altitude (m)	Glacier foreland altitude[a] (m)	Aspect	Number of moraines
Tverreggibreen	1.77	1400	1050	Northeast	8
Storegrovbreen	9.13	1380	1300	South	13
Greinbreen	1.22	1180	1240	North	8
Heimste Breen	3.55	1580	1200	North	8
Ytste Breen	3.00	1560	1200	North	7
Vesldalstindbreen	0.13	1440	1320	Notheast	2
Nordre Holåbreen	9.87	1600	1320	Southeast	6

[a] Lowest altitude of outermost moraine.

Table 2 Climatic data from meteorological stations close to Breheimen (from Aune, 1993; Førland, 1993)

Station	Altitude (m)	Mean air temperature (°C)			Mean annual precipitation (mm)
		January	July	Year	
Bjørkhaug	324	−4.9	13.4	3.7	1380
Fortun	27	−5.1	14.2	4.4	739
Sognefjell	1413	−10.7	5.7	−3.1	860
Bråtå	712	−8.6	11.5	1.3	548
Gjeilo	378	−9.4	13.9	2.8	295

close correspondence with the data from Sognefjell to the south, which has a mean annual precipitation of 860 mm and a mean annual temperature of −3.1 °C at an altitude of 1413 m (Aune, 1993; Førland, 1993). The short-term glaciological studies at Harbardsbreen also confirm the character of the glaciers in Breheimen with a lower glacier mass turnover than in western Norway, but no significant net balance loss as in Jotunheimen. During fieldwork, no signs of recent glacier advances were indicated in the morphology of several glacier snouts visited in Breheimen.

Methods

The glacier forelands and individual moraine ridges were identified and mapped on vertical aerial photographs (e.g. Fig. 2) and checked in the field. Three geochronological methods were applied to the moraine ridges: lichenometric dating, relative-age dating based on the degree of surface weathering of boulders as indicated by Schmidt-hammer readings, and radiocarbon dating of buried soils and associated organic material.

Lichenometry

The moraines were dated in detail by lichenometry (cf. Innes, 1985a; Worsley, 1990; Matthews, 1994) with the aim of detecting synchronous moraine formation and hence possible Little Ice Age climatic fluctuations. The longest axes of specimens of the yellow-green crustose lichens of *Rhizocarpon* subgenus (Innes, 1985b; Poelt, 1988) were measured to the nearest millimetre from 25-m lengths of moraine proximal to the crest. Formerly known as *Rhizocarpon geographicum* agg., the lichens measured include specimens of both section *Rhizocarpon* and section *Alpicola*. The taxonomic group and procedures used ensured comparability with previous work in southern Norway (Matthews, 1974, 1994; Erikstad and Sollid, 1986; Bickerton and Matthews, 1992, 1993).

Application of lichenometry in Breheimen posed two main problems. First, there is no documentary evidence for the control points required for constructing local or regional lichenometric dating curves. Curves constructed for Jostedalsbreen and Jotunheimen (Matthews, 1974; Erikstad and Sollid, 1986; Bickerton and Matthews, 1992) therefore had to be used. Second, as the moraines were commonly short, fragmented and/or located in suboptimal positions for lichen growth (e.g. on unstable slopes or where disturbance by avalanches and fluvial activity had occurred), 25-m lengths of undisturbed moraine surfaces were difficult to find. Consequently, it was not possible to utilise the most extensively used approach based on five 25-m long sites (search areas) per moraine, which is generally considered to provide the most reliable lichenometric dates (e.g. Matthews, 1974, 1975).

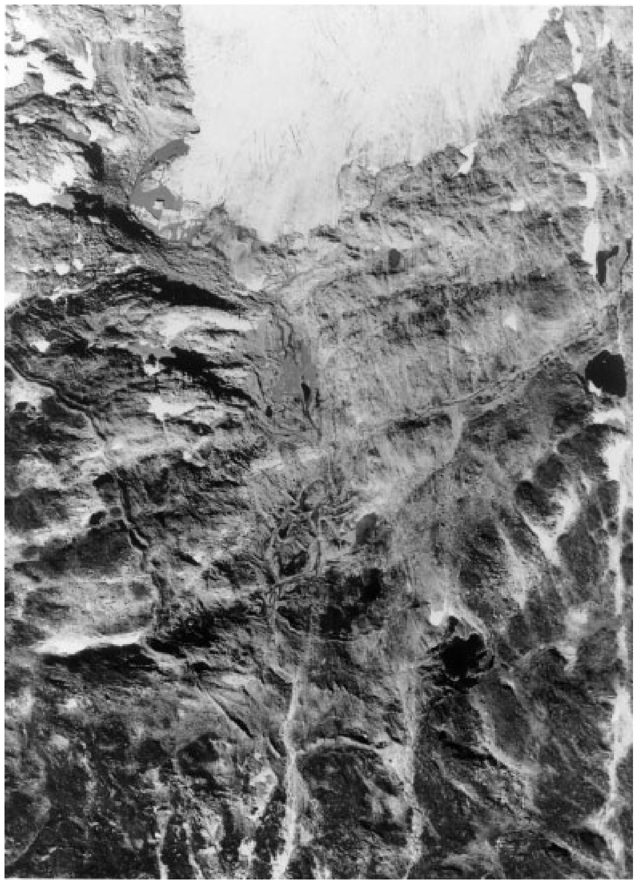

Figure 2 Vertical aerial photograph of the glacier foreland of Storegrovbreen (compare with the map in Figure 5)

Taking into account these problems, and the greater degree of accordance in general of Breheimen climatic conditions to those of Jotunheimen, most reliance has been placed on the lichenometric dating curve (1.5 using the notation of Matthews, 1974) from Storbreen, Jotunheimen, based on the five largest lichens from the single site on each moraine with the largest lichens (equation 1):

$$\log(y + 60) = 1.8601 + 0.0054x \qquad (1)$$

where x is lichen size in millimetres and y is moraine age in years. This avoids potential problems of unrepresentative single lichens and is available for all the moraines and moraine fragments under investigation. We have, however, dated all the moraines using a range of other curves, especially those defined by equations (2)–(4):

$$\log(y + 30) = 1.6597 + 0.0065x \qquad (2)$$

$$\ln(y + 150) = 5.0299 + 0.0071x \qquad (3)$$

$$\log(y + 123) = 2.080 + 0.0039x \qquad (4)$$

Equation (2) is based on the single largest lichen per moraine, from Storbreen, Jotunheimen (1.1 from Matthews, 1974). Equation (3) is based on single largest lichens from moraines and other control points of known age in the Jostedalsbreen region (one of the ‘western curves’ of Erikstad and Sollid, 1986). Equation (4) is based on the five largest lichens from the optimum single site per moraine at Nigardsbreen, a major outlet glacier of the Jostedalsbreen ice-cap for which historical evidence of moraine age has been firmly established (1.5 from Bickerton and Matthews, 1992).

Schmidt hammer 'R-values'

The Schmidt hammer is used here to identify possible pre-Little Ice Age moraines, an approach that was pioneered in Jotunheimen (Matthews and Shakesby, 1984; McCarroll, 1989a, 1991, 1994). Measurements were carried out on samples of 50 boulders (one impact per boulder) on outermost moraine ridges, and on additional sites both outside the glacier foreland (normally comprising boulder surfaces but sometimes bedrock outcrops) and on selected inner moraines. Unstable boulders were avoided and near-horizontal, lichen-free boulder surfaces were selected where possible. The gneissic rock types dominating Breheimen provided, except for the Hestbrepiggane granitic area, widely jointed blocky boulders favourable for Schmidt hammer use (cf. Winkler and Shakesby, 1995; Winkler, 2000).

If the outermost moraine on a glacier foreland dates from the Little Ice Age, the mean 'R-value' (rebound value) from the outermost moraine will be indistinguishable from unweathered boulders from inner moraines of relatively recent origin. If, on the other hand, the mean is similar to that obtained for a sample of boulders from outside the outermost moraine, the latter could date from much earlier in the Holocene, with the exception of any bulldozed boulders incorporated into the moraine (e.g. Matthews and Shakesby, 1984; McCarroll, 1989b). Statistical significance of differences between means was assessed using 95% confidence intervals (Matthews, 1981).

Radiocarbon dating

Excavations were made at seven sites in the distal slope of the outermost moraine at Tverreggibreen, Storegrovbreen and Greinbreen to search for datable buried organic material. No suitable sites were found at the other four glaciers. Buried arctic–alpine podsols, brown soils and humic regosols (Ellis, 1979, 1980) were radiocarbon dated to provide maximum estimates of moraine age (Matthews, 1985, 1993a). At both Tverreggibreen and Greinbreen, the stratigraphy of distal mires close to the outermost moraines revealed inwashed minerogenic layers associated with the timing of the Little Ice Age glacial maximum. For the former glacier, organic material buried beneath fluvioglacial sediments near the outermost terminal moraine provided additional evidence for the timing of glacier variations prior to the Little Ice Age maximum.

Radiocarbon dating was carried out using conventional gas-proportional counting techniques and acid-washed, 1-cm-thick samples unless stated otherwise. Thin slices of organic material in soils and peats were used to investigate age–depth gradients near the buried surfaces in the manner described by Matthews (1980, 1993a). The dates were calibrated using the computer program of Stuiver and Reimer (1993) and the data set in Stuiver *et al.* (1998).

Results and interpretation

Results for each individual glacier foreland are considered as a prelude to construction of a composite Little Ice Age moraine chronology for all seven Breheimen low-altitude glaciers.

Tverreggibreen

Officially 'Øvre Otta No. 24' (Østrem *et al.*, 1988), this glacier is the northeastern outlet of a rapidly thinning, small ice-cap on Tverreggi (1768 m; Fig. 1). The present glacier snout descends to ca. 1400 m but the outermost moraine of the glacier foreland reaches the valley bottom of Mysubyttdalen at about 1050 m. A sequence of eight arcuate recessional moraines, some fragmented and partially buried by glaciofluvial and colluvial activity, occurs on the glacier foreland (Fig. 3).

Lichen sizes and predicted moraine ages are summarised in Table 3. Lichen sizes on the outermost moraine ridge (M1) suggest a date of AD 1734 according to the Storbreen lichenometric dating curve (1.5; equation 1) but the lichens on the second moraine (M2) are some 10 mm larger yielding a date earlier in the late-seventeenth century. The difference in predicted ages of M1 and M2 is clearly indicative of the potential scale of the dating errors resulting from local differences in microclimate and other factors affecting lichen growth. Even larger differences in predicted age result from use of the lichenometric dating curves from the Jostedalsbreen region (equations 3 and 4), which that suggest local and regional differences in lichen growth also occur within Breheimen.

There is nevertheless a consistent pattern of lichen sizes and predicted dates across the remaining moraines in the sequence. Only short fragments of M3 and M4 are undisturbed, however, which casts doubt on the accuracy of the dates estimated. Steep bedrock cliffs behind moraine M9 (predicted date AD 1908) would have prevented the deposition of any younger moraines after this date. The location of this relatively low-altitude glacier, with a northeastern aspect near the western margin of Breheimen, may mean that the local conditions on the foreland of Tverreggibreen are relatively favourable for lichen growth and hence may exaggerate moraine age when estimates are based on lichenometric dating curves from Jotunheimen.

Comparison of Schmidt hammer readings from M1 and M2 and on a bedrock outcrop outside the glacier foreland do not suggest any pre-Little Ice Age moraine formation (Table 4). There is no statistically significant difference ($p > 0.05$) between the mean R-values for sites on M1 and M2, both of which are significantly higher than the mean for the well-weathered bedrock site by at least 10 R-value points but similar to those obtained from unweathered, recently exposed rock surfaces. Thus, according to the Schmidt hammer results, all moraines were apparently deposited during the Little Ice Age.

Radiocarbon dates from four sites are summarised in Table 5 and Figs 3 and 4. At site 1 (Fig. 4a), the outermost moraine is located at the edge of a small, shallow mire, and seven radiocarbon dates here relate to samples from five sedimentary units recognised within the mire. At the base, unit 1 is a buried humus-iron podsol consisting of a thin (1 cm thick), dark brown, surface A_o horizon underlain by a 5-cm-thick pinkish-grey, leached A_2 horizon, below which are well-developed illuvial B_h (black) and B_s (orange-brown) illuvial horizons. Alternating minerogenic and organic units 2–5 lie

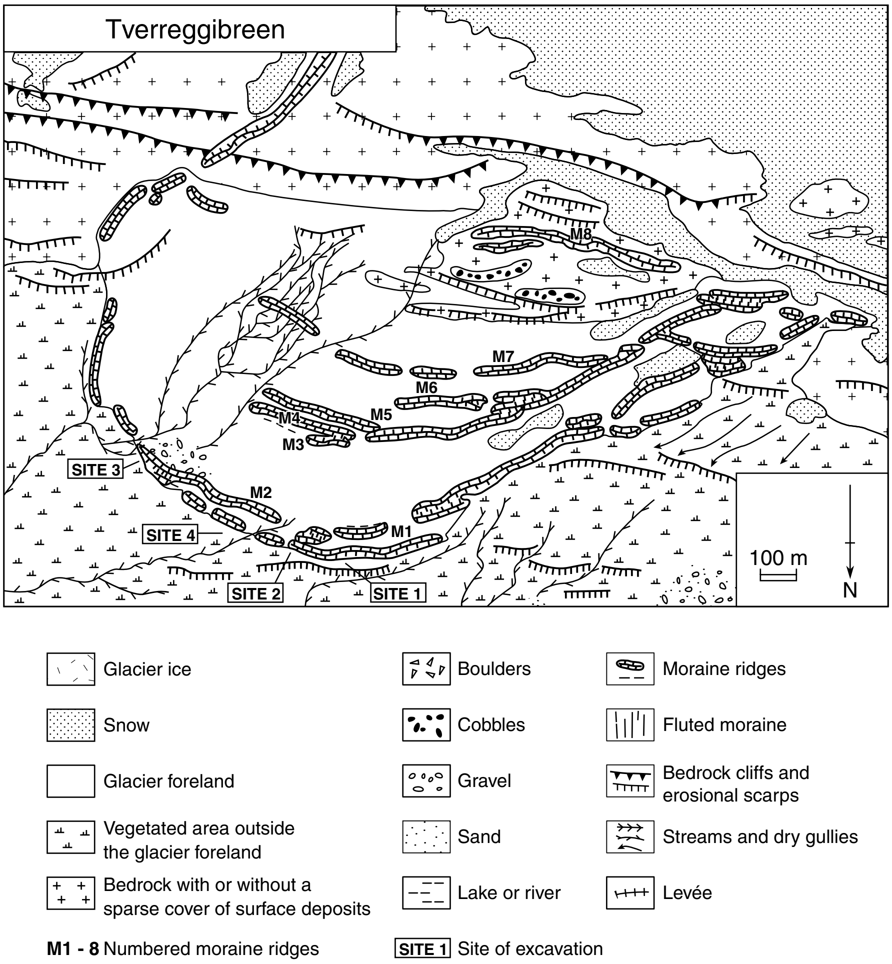

Figure 3 The glacier foreland and moraine sequence of Tverreggibreen

Table 3 Lichen sizes and lichenometric dating results from seven low-altitude glaciers in Breheimen: note that predicted dates using equation (1) have been used in Fig. 11

Glacier and moraine	Largest lichen (mm)	Mean of the five largest lichens (mm)	Predicted dates (AD) from numbered equations[a]				Number of sites per moraine
			1	2	3	4	
Tverreggibreen							
M1	138	120.6	1734	1668	1742	1767	6
M2	149	133.8	1677	1604	1709	1722	6
M3	112	97.0	1817	1785	1810	1835	1
M4	105	89.4	1839	1809	1825	1854	1
M5	101	93.2	1828	1822	1836	1844	3
M6	100	93.6	1827	1825	1838	1843	4
M7	91	80.8	1861	1851	1857	1874	8
M8	65	58.8	1908	1908	1906	1918	9
Storegrovbreen							
M1	118	98.4	1813	1762	1796	1831	2
M2	117	97.8	1815	1766	1798	1833	2
M3	110	87.2	1845	1792	1815	1859	2
M4	83	77.2	1870	1871	1873	1882	1
M5	80	75.2	1874	1878	1879	1886	3
M6	82	70.8	1884	1873	1875	1895	6
M7	77	70.6	1885	1884	1885	1895	2
M8	66	64.0	1898	1906	1905	1908	2
M9	64	59.0	1908	1910	1908	1918	6
M10	48	42.8	1936	1935	1934	1945	2
M11	53	46.0	1931	1928	1926	1940	7
M12	32	30.8	1953	1955	1957	1963	1
M13	29	27.6	1957	1958	1961	1968	1

(*continued overleaf*)

Table 3 (*Continued*)

Glacier and moraine	Largest lichen (mm)	Mean of the five largest lichens (mm)	Predicted dates (AD) from numbered equations[a]				Number of sites per moraine
			1	2	3	4	
Greinbreen							
M1	111	104.6	1793	1798	1813	1814	4
M2	89	70.6	1885	1856	1861	1895	2
M3	81	69.0	1888	1875	1877	1899	1
M4	77	67.8	1891	1984	1885	1901	1
M5	60	56.0	1914	1917	1915	1923	2
M6	73	64.6	1897	1893	1892	1907	2
M7	43	42.0	1937	1942	1941	1947	1
M8	42	36.4	1945	1943	1943	1955	1
Heimste Breen (Hestbrepiggane)							
M1	124	107.2	1784	1737	1780	1807	7
M2	100	93.6	1817	1825	1838	1843	1
M3	112	100.4	1807	1785	1810	1826	3
M4	80	73.4	1879	1878	1879	1890	2
M5	64	60.2	1906	1910	1908	1916	3
M6	68	60.2	1906	1903	1901	1916	2
M7	52	44.4	1933	1930	1928	1943	4
M8	42	39.8	1940	1943	1943	1950	2
Ytste Breen (Hestbrepiggane)							
M1	131	124.8	1717	1705	1761	1753	2
M2	128	115.4	1755	1719	1770	1783	2
M3	107	102.6	1799	1802	1822	1820	2
M4	94	85.2	1850	1842	1851	1864	3
M5	70	67.2	1892	1899	1898	1902	1
M6	84	75.8	1873	1868	1871	1885	1
M7	87	81.2	1860	1861	1865	1873	1
LM1[b]	53	52.0	—	—	—	—	2
LM2	135	126.0	1712	1684	1750	1749	2
LM3	28	25.0	—	—	—	—	2
Vesldalstindbreen							
M1	112	100.2	1807	1785	1810	1826	7
M2	93	81.8	1859	1845	1853	1871	5
Nordre Holåbreen							
M1	125	112.2	1767	1732	1776	1793	7
M2	110	103.2	1798	1792	1815	1818	5
M3	115	101.4	1808	1774	1803	1823	6
M4	101	99.2	1810	1822	1836	1829	5
M5	98	84.6	1852	1831	1842	1865	6
M6	82	80.6	1862	1873	1875	1874	6

[a] Equations (1)–(4) are given in the text.
[b] Lateral moraine ridges high on plateau (see Fig. 9).

above the buried soil. Units 4 (light brownish-grey, organic-stained medium sand) and 2 (light-grey, fine sandy silt) are separated by a 2-cm-thick brown peat (unit 3). The 11-cm-thick surface organic layer of the mire (unit 1) is largely unhumified orange-brown peat.

The radiocarbon dates from site 1 are consistent with mire development on the podsolic soil when Little Ice Age moraine deposition caused ponding of water against a bedrock knoll. Prior to moraine formation, the presence of a well developed podsolic soil at the site would have required prolonged, undisturbed soil formation. It is probable that the formation of this mature humo-ferric podsol would have required several thousand years to form in this arctic–alpine environment (cf. Ellis and Matthews, 1984). Colluvial deposition of sandy minerogenic sediments from the distal slope of the moraine certainly began some time after 1720 ± 50 ^{14}C yr BP (SWAN-436). This date is unlikely to represent a close estimate of the time elapsed since moraine formation because even thin surface organic horizons of well-developed arctic–alpine podsols can contain carbon with a considerable apparent mean residence time (Matthews and Dresser, 1983; Matthews, 1993a,b). This interpretation is borne out by the dates of 200 ± 50 and 330 ± 50 ^{14}C yr BP (SWAN-435 and SWAN-438, respectively) obtained from the base of unit 3, which represent close maximum estimates for a short-term cessation of colluvial deposition. As the difference between these two estimates does not differ statistically, they can be combined to produce a mean date of 265 ± 35 ^{14}C yr BP, which, when calibrated, yields an intercept age of 303 cal. yr BP or AD 1647 (upper and lower 2σ age limits are 430 and 153 cal. yr BP, respectively, or AD 1520 and 1797).

Following the short interval of stabilisation represented by unit 3, renewed minerogenic deposition (unit 2) occurred: as the sediments are not stained with organic matter and are relatively fine grained and well sorted, they probably represent a low-energy glaciofluvial deposit rather than colluvium. This deposition event had ceased by 165 ± 35 ^{14}C yr BP (a mean of SWAN-433 and SWAN-437, derived from the base of unit

Table 4 Schmidt hammer results for outermost moraines, inner moraines and sites outside the glacier forelands: values are mean 'R-values' and 95% confidence intervals ($n = 50$) for sites at seven low-altitude glaciers in Breheimen

Glacier	Outside site[a]	Outermost moraine	Inner moraines[b]
Tverreggibreen	47.06 ± 2.19[c]	57.58 ± 2.06	59.76 ± 1.86 (M2)
	47.66 ± 2.28[c]		
Storegrovbreen	43.92 ± 2.91	50.44 ± 3.05 (M1)	63.16 ± 1.80 (M10)
		57.26 ± 2.74 (M1)	63.16 ± 1.60 (M11)
		53.54 ± 2.94 (M2)	
		54.62 ± 3.01 (M2)	
		63.50 ± 1.67 (M2)	
Greinbreen	38.22 ± 2.73	50.30 ± 2.73	52.52 ± 2.45 (M2)
		51.22 ± 2.39	53.40 ± 2.99 (M2)
		51.54 ± 2.64	50.62 ± 2.28 (M3)
		51.56 ± 2.18	55.12 ± 2.46 (M4)
			54.14 ± 2.58 (M5)
Heimste Breen	49.64 ± 3.50	60.86 ± 2.24	No inner site recorded[d]
	50.62 ± 3.08		
	52.96 ± 2.92		
Ytste Breen	46.48 ± 3.49	60.86 ± 2.18	57.64 ± 2.40 (LM2)
	49.72 ± 3.00	57.62 ± 3.77	57.94 ± 2.10 (LM2)
		57.62 ± 1.76 (LM1)	58.50 ± 2.17 (LM3)
		59.56 ± 1.82 (LM1)	59.26 ± 2.27 (LM3)
			60.48 ± 1.73[e]
			60.86 ± 2.31[e]
Vesldalstindbreen	47.37 ± 2.44	53.52 ± 1.99	55.52 ± 1.82 (M2)
		55.98 ± 1.87	
Nordre Holåbreen	48.54 ± 3.47	58.24 ± 1.63	57.17 ± 1.43 (M6)
		59.26 ± 1.59	

[a] Sites outside the glacier foreland.
[b] Recessional moraines on the glacier foreland (excluding the outermost moraine, M1).
[c] Bedrock surfaces outside the glacier foreland (not boulders).
[d] Inner sites from Ytste Breen considered sufficient.
[e] Boulders inside the glacier foreland (but not on a particular moraine ridge).

Table 5 Radiocarbon dating results from Tverreggibreen, Storegrovbreen and Greinbreen

Glacier and site	Laboratory number	^{14}C age (yr BP)	Material	Depth (cm)	$\delta^{13}C$ (%)	Calibrated age[a] (cal. yr BP)
Tverreggibreen						
Site 1	SWAN-432	170 ± 50	Peat	9.0–10.0	−28.0	305 (274, 186, 180, 175, 148, 11, 4) 0[b]
	SWAN-433	100 ± 50	Peat	10.0–11.0	−28.0	282 (240, 232, 126, 125, 65, 38, 0) 0[b]
	SWAN-437	230 ± 50	Peat	10.0–11.0	−27.4	428 (291) 2
	SWAN-434	150 ± 40	Peat	20.0–21.0	−26.7	291 (268, 216, 144, 19, 3) 0[b]
	SWAN-435	200 ± 50	Peat	21.0–22.0	−27.0	313 (282, 168, 155) 0
	SWAN-438	330 ± 50	Peat	21.0–22.0	−27.3	506 (428, 377, 323) 291
	SWAN-436	1720 ± 50	Podsol A_o	28.0–29.0	−25.4	1732 (1687, 1675, 1612) 1524
Site 2	SWAN-439	20 ± 50	Podsol A_o	20.0–21.0	−26.2	257 (0[b]) 0[b]
	SWAN-440	1100 ± 50	Podsol A_o	21.0–22.0	−25.8	1168 (1046, 1040, 974) 928
Site 3	SWAN-431	290 ± 40	Podsol A_o	6.0–7.0	−24.6	467 (310) 160
Site 4	SWAN-427	200 ± 40	Immature soil	11.0–11.5	−25.5	308 (282, 168, 155) 1
	SWAN-428	660 ± 50	Immature soil	21.0–22.0	−25.4	675 (651, 575, 575) 546
	SWAN-429	680 ± 60	Immature soil	22.0–23.0	−25.2	707 (654) 546
	SWAN-430	1250 ± 70	Immature soil	26.0–27.0	−24.2	1295 (1175) 987
Storegrovbreen						
Site 1	SWAN-422	680 ± 50	Brown soil	15.0–16.0	−24.9	688 (654) 551
	SWAN-424	800 ± 50	Brown soil	16.0–17.0	−24.7	791 (694) 659
	SWAN-425	2050 ± 50	Brown soil	20.0–22.0	−23.3	2146 (1995) 1885
Site 2	SWAN-426	460 ± 50	Brown soil	26.0–27.0	−24.1	548 (511) 341
Greinbreen						
Site 1	CAR-1398	860 ± 60	*Eriophorum* sp.	25.0–28.0	−25.9	926 (758, 751, 742) 669
	CAR-1399	680 ± 50	Peat	12.0–15.0	−25.4	688 (654) 551
	CAR-1400	960 ± 60	Peat	15.0–15.5	−26.6	969 (916) 733
	CAR-1401	680 ± 60	Peat	15.5–16.0	−26.5	707 (654) 546
Site 2	SWAN-366	750 ± 50	Humic regosol	27.0–28.0	−26.2	756 (672) 571

[a] Calibrated ages include intercept ages in brackets and 2σ range.
[b] Possible influence of 'bomb' carbon.

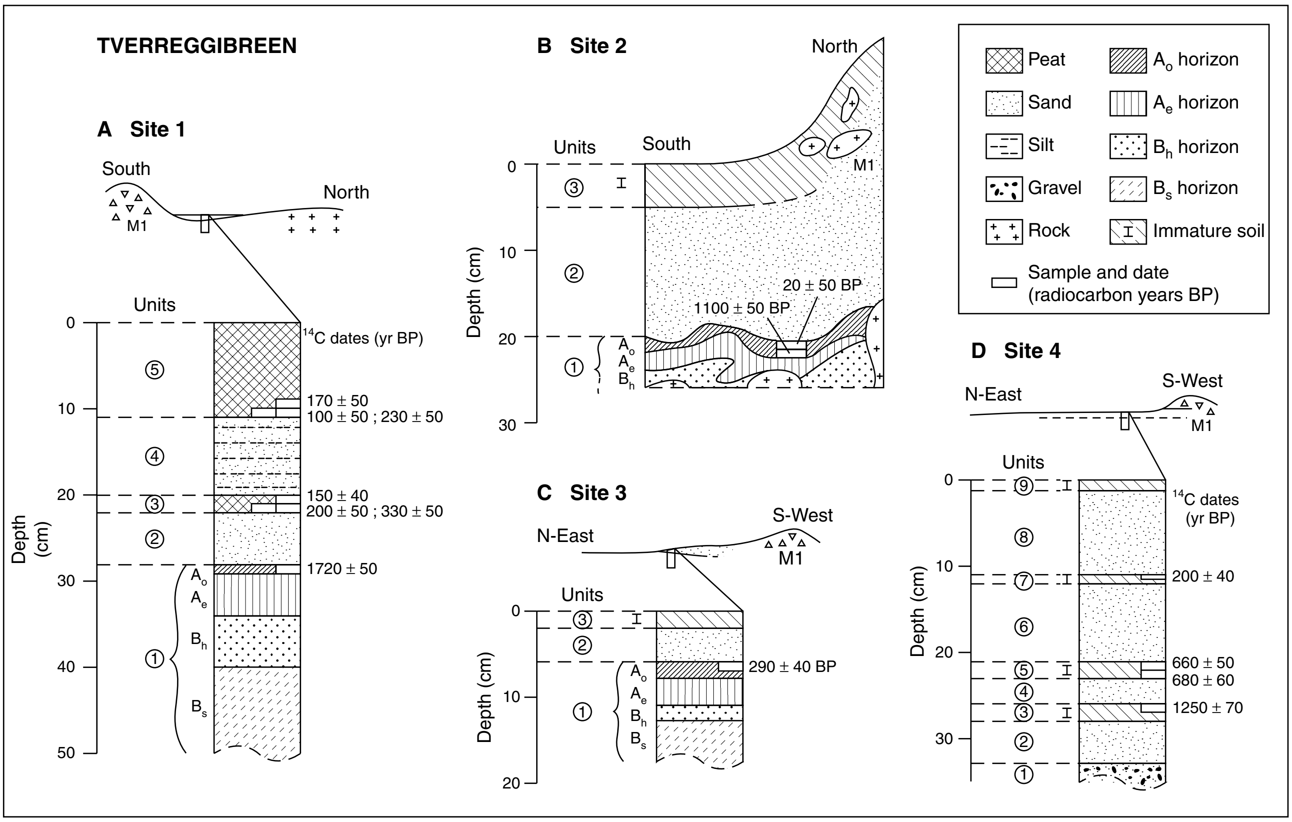

Figure 4 Excavations at Tverreggibreen showing the positions of the radiocarbon dates in relation to stratigraphical units (circled numbers) and schematic cross profiles: (A) mire stratigraphy and buried humus-iron podsol at site 1; (B) buried podsolic soil beneath the moraine at site 2; (C) fluvioglacial stratigraphy and buried podsolic soil at site 3; (D) fluvioglacial stratigraphy and buried immature soils at site 4. Radiocarbon dates are in uncalibrated radiocarbon years BP

5), which yields several intercept ages within an overall 2σ calibrated age range of 0–293 cal. yr BP, after which there was 10 cm of uninterrupted peat accumulation. This pattern of deposition is consistent with a fluctuating glacier close to its Little Ice Age maximum extent, final glacier retreat from the site being marked by the beginning of the accumulation of unit 5 no earlier than 293 cal. yr BP or AD 1657 (with 95% statistical certainty).

Site 2 at Tverreggibreen revealed a buried podsolic soil, which was only slightly disturbed by moraine deposition (Fig. 4b). The buried soil resembled that at site 1 and the 2-cm-thick organic surface horizon (A_o) appeared intact. This soil was overlain by a 20-cm-thick light yellow-brown sand, which also extends under the moraine. Radiocarbon dates from upper (SWAN-439) and lower (SWAN-440) 1-cm-thick slices of the A_o horizon potentially provide the basis for two approaches to estimating the *maximum* age of moraine deposition at the Little Ice Age glacier maximum, which appears to have been preceded by deposition of fluvioglacial sediments during the advance and immediately prior to moraine ridge deposition. As the youngest buried material yields the closest estimate of moraine age, the date of 20 ± 50 ^{14}C yr BP (SWAN-439) indicates that the moraine formed after 257 cal. yr BP (upper 2σ age limit), i.e. after AD 1693. However, as the intercept and lower age limit indicate zero age (Table 5), the possibility of this date being affected by young contaminants cannot be ruled out. Possible contamination would also affect any estimate based on the age–depth gradient approach (Matthews, 1991, 1993a), using the considerably older date of 1100 ± 50 yr BP for SWAN-440.

Site 3 lies a few metres distal to moraine M1, where an undisturbed podsolic soil is buried beneath a 4-cm-thick, grey silty sand layer of presumed fluvioglacial origin (Fig. 4c). The upper 1.0 cm of the buried surface A_o horizon is here dated to 290 ± 40 ^{14}C yr BP (SWAN-431). The upper 2σ calibrated age limit of 467 cal. yr BP (AD 1483) from this uncomplicated site is interpreted as providing another maximum age estimate of fluvioglacial deposition closely preceding the deposition of M1.

Site 4 records a more complex environmental history prior to and during the deposition of the outermost moraine (Fig. 4d). A predominantly mottled, brown-yellow sand (units 2, 4, 6 and 8) contains three immature black to grey-brown buried soils (units 3, 5 and 7). Each buried soil is 1–2 cm thick and comparable to the surface soil at the present day. A gravelly sand (unit 1) lies at the base of the sequence. Although the sand extends beneath the outermost moraine and the soils are laterally continuous for over 30 m in the distal direction, they do not extend beneath the moraine. The uppermost buried soil (unit 7), which yielded a date of 200 ± 40 ^{14}C yr BP (SWAN-427), is interpreted as having been buried by Little Ice Age glaciofluvial deposition after 313 cal. yr BP (AD 1637), most likely when the glacier was close to M1. The deeper soils are thought to represent phases of land surface stability interrupted by episodes of fluvioglacial sand deposition well before the glacier attained its Little Ice Age maximum. As the soils are immature, the radiocarbon dates cannot reflect high apparent mean residence times of soil carbon (Matthews, 1985, 1993b), as demonstrated by the closely similar dates of SWAN-428 and SWAN-429 and the absence of any detectable age–depth gradient. Instead, the dates from these buried soils are likely to represent close maximum estimates for burial events around 1250 ± 70 ^{14}C yr BP (SWAN-430) and 670 ± 39 ^{14}C yr BP (average of SWAN-428 and SWAN-429), respectively. Calibrated ages derived from these dates are 1175 cal. yr BP (2σ range 1295–987 cal. yr BP, or AD

963–655) and 653 cal. yr BP (673–554 cal. yr BP, or AD 1396–1277), which are tentatively interpreted as representing pre-Little Ice Age and early Little Ice Age phases of glacier growth, respectively.

Storegrovbreen

Storegrovbreen is a southern outlet of Sekkebreen, a relatively large ca. 24 km^2 ice-cap (Fig. 1). Although classified as 'low altitude' because its glacier foreland lies almost entirely within the altitudinal range 1300 to 1400 m, this glacier is unusual in that it failed to extend into Mysubyttdalen even at its Little Ice Age maximum (Figs 2 and 5). The glacier foreland is also distinguished by a relatively large number of moraine ridges comprising not only several major moraines a few metres high, but also many small (<1 m high) 'annual' moraines (cf. Andersen and Sollid, 1971), mostly on the inner part of the foreland. Thirteen recessional moraines (M1–M13 in Fig. 5) were recognised for dating purposes. The prominent outer moraine is for the most part M2, M1 being largely overridden except in the southwestern part of the foreland. Unbroken fluted-moraine surfaces proximal to M13 on the eastern side of the foreland suggest continuous glacier retreat since the deposition of the youngest recessional moraine.

Lichenometric dating showed a consistent pattern (Table 3) with only one moraine ridge (M11) out of sequence but the exposed location of the moraines on the plateau, indicated by extensive coverage of black foliose lichens on moraine boulders (Haines-Young, 1983, 1985) suggests that local conditions are relatively unfavourable for growth of the *Rhizocarpon* subgenus, leading to relatively few optimal microclimatic sites where lichen size is representative of moraine age, a problem unfortunately particularly acute on the older moraine ridges otherwise relatively unaffected by fluvioglacial disturbance and therefore relatively stable.

As a result of these problems, the suggested dates of AD 1813 and 1815 based on equation 1 for moraines M1 and M2, respectively, are thought to be underestimates of age, the respective single largest lichens of 118 and 117 mm predicting dates in the AD 1760s (equation 2) probably providing more accurate age estimates. The predicted dates for the other moraines investigated suggest multiple moraine formation towards the end of the nineteenth century and during the twentieth century, with annual-moraine deposition taking place during the early decades of the twentieth century. These results are likely to have been affected by the generally unfavourable conditions for lichen growth, a possibility supported by predicted dates in the AD 1950s for the two youngest moraines. In comparison, the youngest recessional moraines on glacier forelands throughout the Jostedalsbreen and Jotunheimen region consistently date from the AD 1930s and only occasionally from as late as 1941 (Hoel and Werenskiold, 1962; Bickerton and Matthews, 1993; Winkler, 1996b). It is likely that the well developed moraine M11 (predicted date AD 1931) has been dated accurately, but that

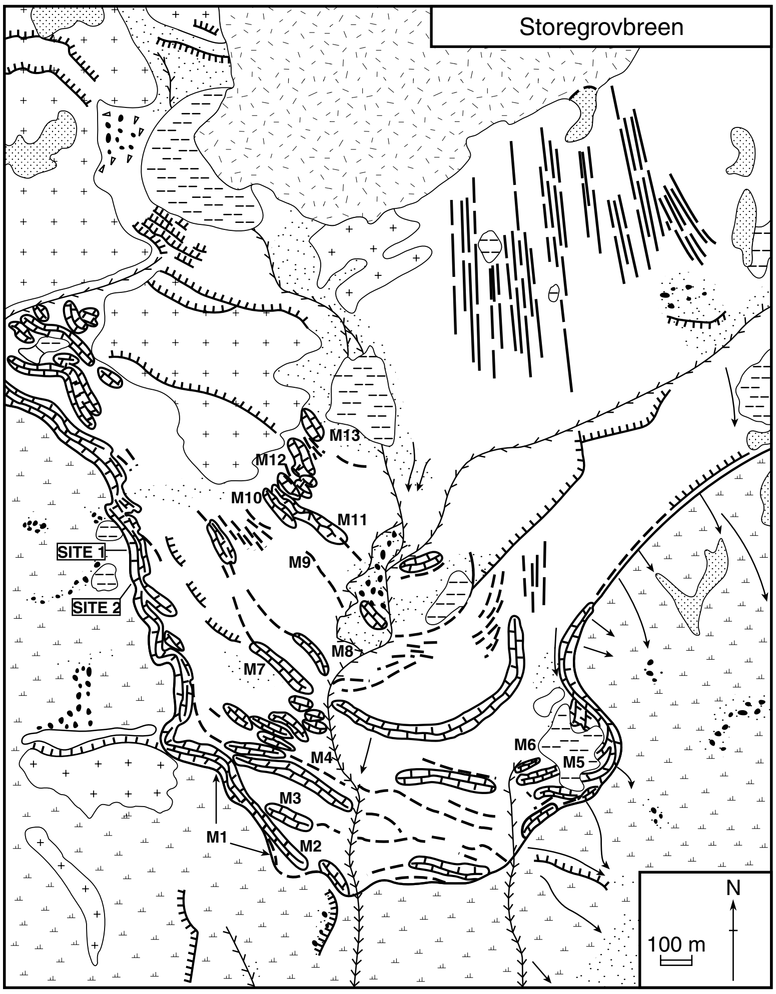

Figure 5 The glacier foreland and moraine sequence of Storegrovbreen (key as in Fig. 3)

the dates of M12 and M13 (based on only one site per moraine) are too young.

Schmidt hammer results for Storegrovbreen are inconclusive (Table 4). First, there are major differences in average R-values (of the order of 10 points) obtained from the inner moraines, which can be explained by the variable surface texture caused by the heterogeneous gneissic petrology. Two sites on M1 also differed significantly, possibly for the same reason, although both yielded significantly higher mean values than the single site from outside the glacier foreland.

Mature arctic–alpine brown soils, which are likely to require at least as long as mature, humo-ferric podsols to form (cf. Matthews and Caseldine, 1987), were dated from two sites (Figures 5 and 6). The dates from the uppermost 1 cm of the buried surface organic-rich horizon (680 ± 50 and 460 ± 50 ^{14}C yr BP; SWAN-422 and SWAN-426, from sites 1 and 2, respectively) provide maximum estimates for the age of the outermost lateral moraine. A third estimate can be based on the two dates from the uppermost 2 cm of the same horizon at site 1, which suggest an appreciable age–depth gradient in this soil, the maturity of which is confirmed by the date of 2050 ± 50 ^{14}C yr BP (SWAN-425) obtained from the 2-cm-thick sample at a depth of some 5 cm beneath the buried soil surface. This last date also provides a minimum estimate of the time elapsed since deglaciation of the site.

Using the upper 2σ calibrated age limits of the youngest samples from the two sites, outermost moraine formation must have occurred after 688 cal. yr BP (AD 1262) and 548 cal. yr BP (AD 1402), respectively. Using the intercept ages to define a calibrated age–depth gradient, the surface age of the buried soil at site 1 is predicted to be about 635 cal. yr BP (ca. AD 1315). These estimates are conclusive evidence for moraine M2 dating from the Little Ice Age but an older date for M1, and hence the existence of a pre-Little Ice Age Neoglacial highstand of approximately the same extent, cannot be ruled out (although this is considered unlikely).

Greinbreen

Greinbreen is the northern outlet of the small plateau ice cap, which extends down to *c.* 1,180 m into the valley head of Sprangdalen (Fig. 1). Owing to a combination of steep slopes and colluvial and glaciofluvial disturbances, the only well preserved moraine fragments are eight lateral moraines forming a sequence high on the western valley side at an altitude of ca. 1250–1300 m (Fig. 7A).

Lichenometric dating using equation (1) (Table 3) suggests that the outermost moraine dates from the late-eighteenth century and that the other seven moraine ridges are no older than the late-nineteenth century with the two youngest dating between AD 1937 and 1945. The predicted age (1897) of one moraine (M6) is out of sequence, indicating an error of at least 17 yr. The short lengths of most of these moraines, possible slope instability, and a likely reduced growing season caused by late-lying snow patches are all factors possibly leading to underestimates of moraine age.

The Schmidt hammer results (Table 4) consistently indicate that all seven moraines date from the Little Ice Age. Four sites on the outermost moraine ridge and five sites on four of the younger ridges (M2–M5) all have average R-values of 50.30 ± 2.73 to 55.12 ± 2.46, whereas the site outside the glacier foreland gave significantly lower values of 38.22 ± 2.73.

Four radiocarbon dates from a small mire partially buried by the outermost moraine (site 1; Fig. 7B) were obtained from thin samples of poorly humified peat and/or plant remains immediately beneath morainic boulders or colluvial minerogenic sediments apparently washed from the distal slope during moraine stabilisation. One sample (CAR-1398) consisted of well preserved, compressed stems of *Eriophorum* sp. immediately beneath a morainic boulder: the other samples were relatively unhumified orange-brown peat also suggesting rapid burial. The dates, all within the range 680 ± 50 ^{14}C yr BP (CAR-1399) to 960 ± 60 ^{14}C yr BP (CAR-1400), would

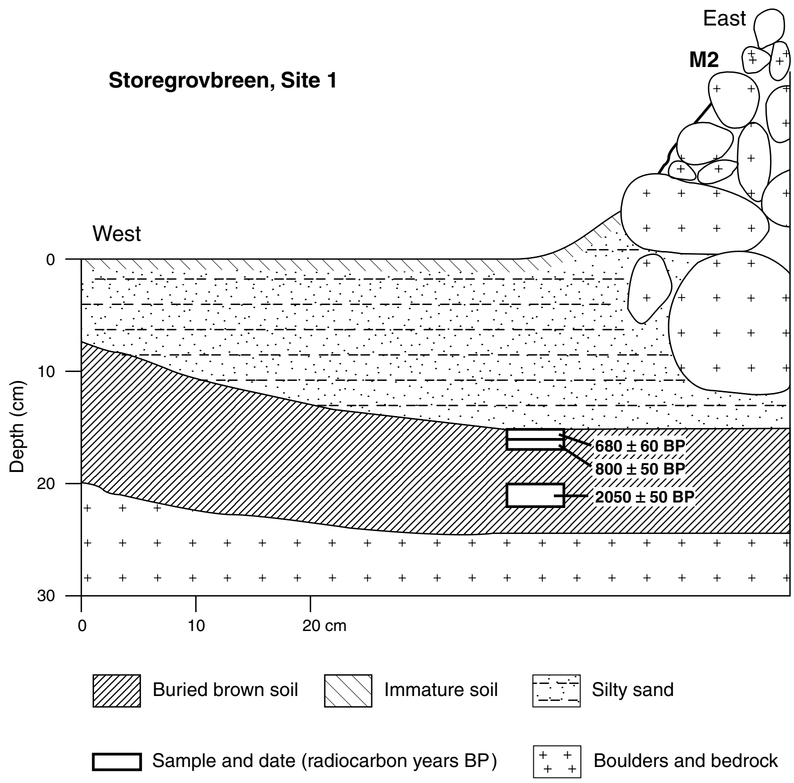

Figure 6 Excavation in the outermost moraine at Storegrovbreen, site 1, showing the stratigraphical position of the radiocarbon dated brown soil

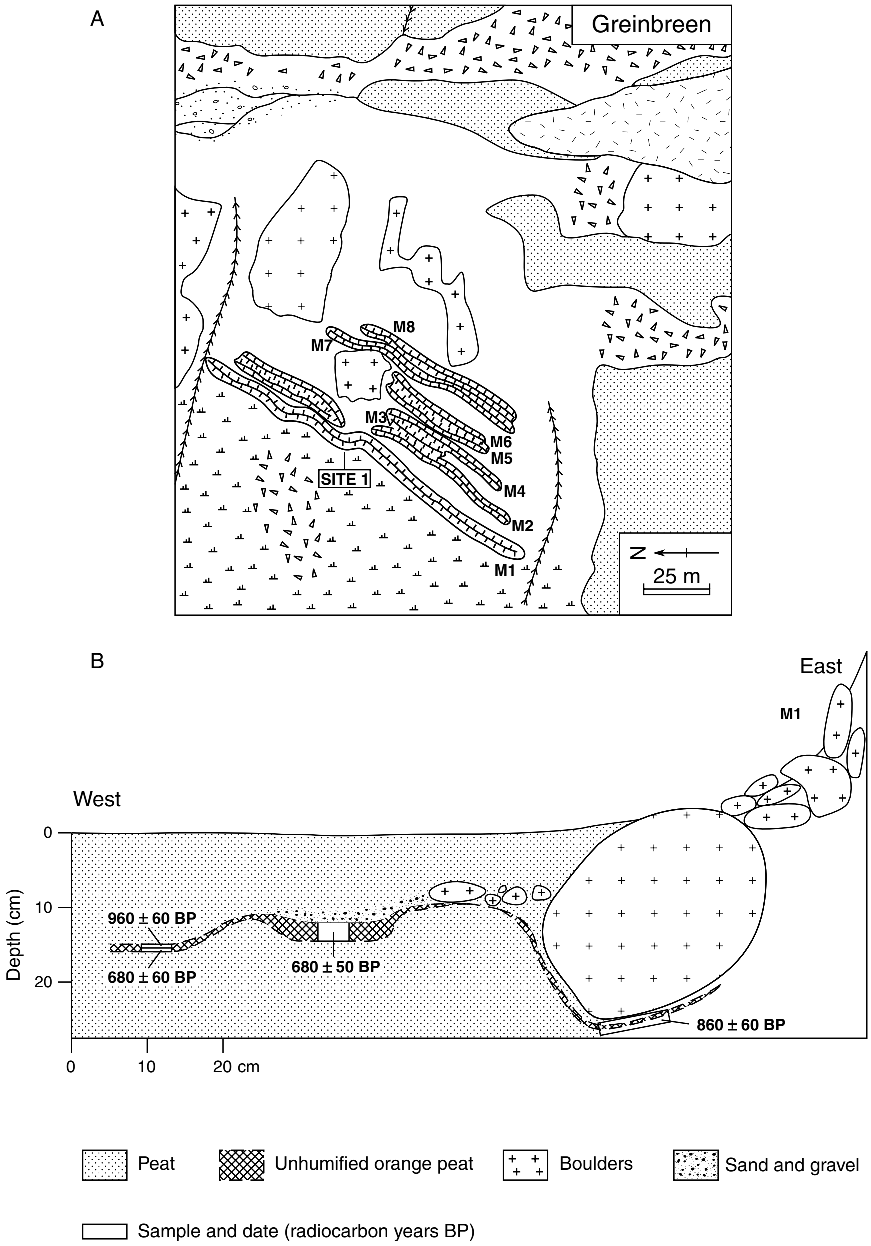

Figure 7 (A) The glacier foreland and moraine sequence of Greinbreen (key as in Fig. 3); (B) the excavation associated with the outermost lateral moraine at Greinbreen, site 1

be expected to represent close maximum age estimates for the timing of moraine formation. The calibrated age of the youngest sample is 654 cal. yr BP (AD 1294) with the extreme 2σ range for all three samples extending from 969 to 551 cal. yr BP (AD 981–1399). A similar date (750 ± 50 ^{14}C yr BP; SWAN-366) was obtained from the organic-rich buried surface horizon of a humic regosol (consisting of organic and mineral material characteristic of sites affected by late lying snow and solifluction; cf. Ellis, 1979, 1980) at the closely adjacent site 2.

These dates are not consistent with a conventional (eighteenth century) Little Ice Age maximum date for M1. They point to early- or pre-Little Ice Age moraine formation several hundred years prior to the conventional Little Ice Age maximum. The age reversal exhibited by CAR-1400 and CAR-1401 of almost 300 ^{14}C yr may be important, however, as it suggests age overestimation caused by an unidentified, relatively old contaminant at or close to the buried surface of the mire (although the *Eriophorum* remains comprising CAR-1398 would have been less susceptible to contamination than either the peat or the soil).

Heimste Breen and Ytste Breen (Hestbrepiggane)

These two glaciers flow northwards out of composite cirques cut into the Hestbrepiggane massif (Fig. 1). Today the glacier snouts terminate on the plateau at 1500–1700 m but at their Neoglacial maxima they extended down to about 1200 m in Lundadalen. Arcuate recessional moraine ridges draped across the valley side have been fragmented by glaciofluvial erosion in frontal areas and by instability on the upper valley sides (Figs 8 and 9). The lateral moraines are better preserved.

Despite similar locations and moraine patterns, lichenometric dating has yielded widely different moraine ages with the dates for Heimste Breen being younger than those for Ytste Breen (Table 3). This can be attributed to apparently poorer local conditions for lichen growth at Heimste Breen where only one predicted date (M2) is out of sequence: equation (1) suggests a late-eighteenth century date (AD 1784) for the outermost moraine, and the two youngest moraines are predicted to date from AD 1933 (M7) and 1940 (M8).

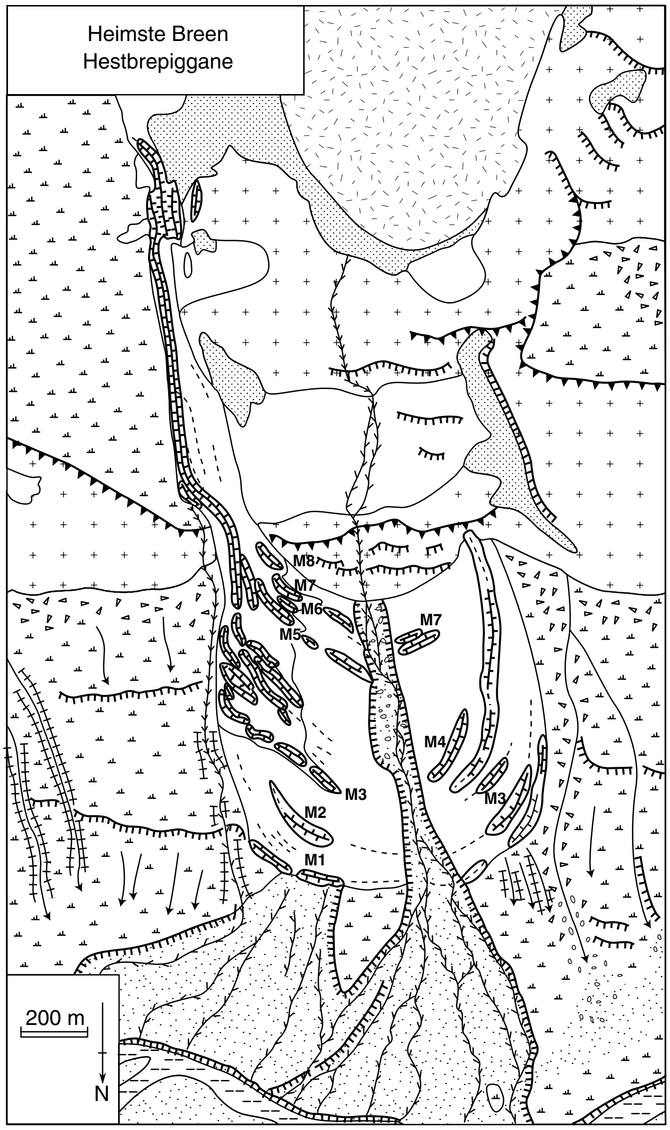

Figure 8 The glacier foreland and moraine sequence of Heimste Breen, Hestbrepiggane (key as in Fig. 3)

At Ytste Breen, all seven moraines are estimated to date from the nineteenth century or earlier. The absence of younger moraines is attributed to the steepness of the upper valley sides, which are too precipitous for moraine deposition and survival. Little confidence can be placed in the precision of the dates indicated for moraine ridges M5–M7 as each is based on only one site per moraine and predicted dates are out of sequence. The lichenometric dates of the two outermost moraine ridges at Ytste Breen are of particular interest as they suggest that M1 may date from the early eighteenth century (AD 1717 according to equation 1), with M2 dating from the mid-eighteenth century (AD 1755). The existence at this glacier of moraines pre-dating the conventional mid-eighteenth century Little Ice Age maximum is supported by the similar early eighteenth century date obtained for lateral moraine LM2 high on the plateau (Fig. 9). It should be noted, however, that equations (3) and (4) both predict a conventional mid-eighteenth century age for M1 and LM2.

There are no signs of pre-Little Ice Age moraine ridges at either Heimste Breen or Ytste Breen, a conclusion strongly supported by the Schmidt hammer results from both terminal- and lateral-moraine sites (Table 4). Mean R-values for outermost-moraine sites at both glaciers are in close agreement (ranging between 57.62 ± 3.77 and 60.86 ± 2.24), differ significantly from those of sites outside the glacier foreland (range 46.48 ± 3.49 to 52.96 ± 2.92), but do not differ significantly from those of inner moraines and other sites from inside the glacier foreland (range 57.64 ± 2.40 to 60.86 ± 2.31).

Vesldalstindbreen and Nordre Holåbreen

These morphologically very different glaciers are located at the head of Lundadalen (Fig. 1). The glacier foreland of Vesldalstindbreen, a very small cirque glacier on the east side of Vesldalstinden (1805 m) known officially as 'Øvre Otta Nr. 8' (Østrem *et al.*, 1988), is characterised by two arcuate moraine ridges that are well separated from both the glacier and each other (Fig. 10). Nordre Holåbreen is that part of Holåbreen to the west of Austre Holåtindan (2043 m) and six well developed moraine ridges were dated below the southwestern glacier tongue. The moraines are located on a south-facing, sloping shelf near the foot of the valley side close to Trulsbu but have not been mapped because they lie in deep shadow on the available aerial photographs.

The results of lichenometry (Table 3) demonstrate that none of these moraines dates from the late nineteenth or early twentieth centuries, an interpretation supported by predicted

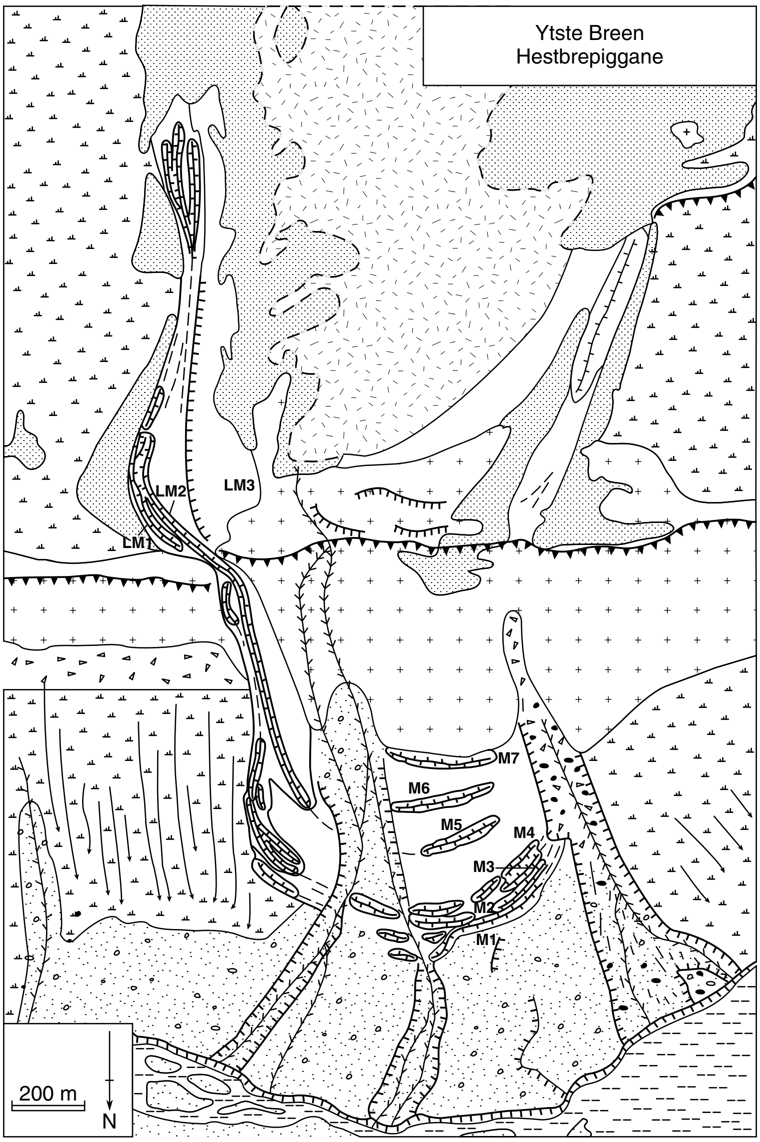

Figure 9 The glacier foreland and moraine sequence of Ytste Breen, Hestbrepiggane (key as in Fig. 3)

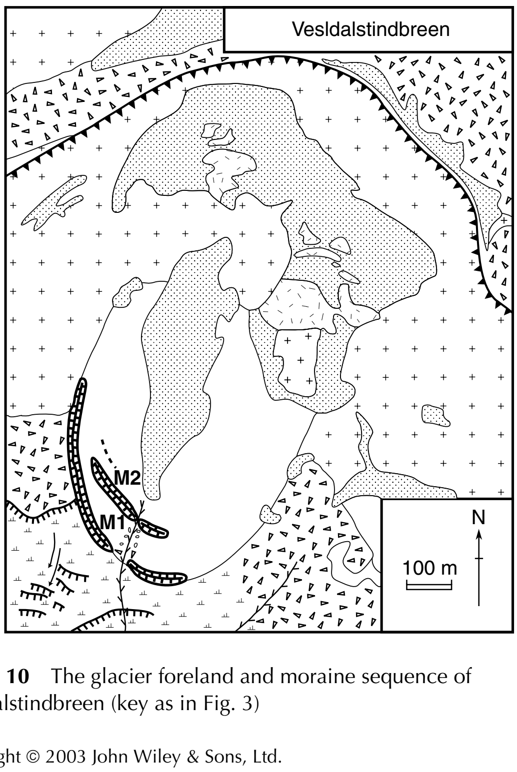

Figure 10 The glacier foreland and moraine sequence of Vesldalstindbreen (key as in Fig. 3)

dates from all four equations (Table 3). At Nordre Holåbreen, the absence of younger moraines is attributed to the valley-side topography above the shelf, where slopes are too steep for moraine-ridge deposition: at Vesldalstindbreen, the absence of younger moraines suggests that this glacier was in a shrunken state, close to the cirque headwall, by the end of the nineteenth century.

Although all the moraines are extensive and reach down to approximately the same altitude (ca. 1320 m), environmental conditions for lichen growth appear more favourable on the south-facing Nordre Holåbreen moraines than in the Vesldalstinden cirque where semi-permanent snow patches are extensive, leading to shorter growing seasons and possible snow-kill effects. Consequently, the predicted date of AD 1767 for the Little Ice Age maximum (M1; equation 1) at Nordre Holåbreen, and the other lichenometric dates at this glacier, may be close estimates, whereas the predicted dates of AD 1807 and 1859 are likely an underestimate of the age of the two moraines at Vesldalstindbreen.

Schmidt hammer R-values (Table 4) show no significant differences between the outermost and inner moraines, but large and significant differences between the outside sites and the moraines, consistent with these glaciers having attained their Neoglacial maxima in the Little Ice Age.

A composite moraine chronology for Breheimen based on lichenometry

The lichenometric moraine chronologies from the seven glaciers have been combined to produce a composite record for low-altitude Breheimen glaciers (Fig. 11). This follows the approach developed for the Jostedalsbreen outlet glaciers by Bickerton and Matthews (1993), based on two principles:

1 errors contained in the chronologies for individual glaciers are likely to be reduced in prominence when the results from a number of glaciers are combined;
2 the regional glacier response to climate is emphasised when differences in the responses of individual glaciers are minimised.

Any moraine date indicated as being out of sequence (too young) in the chronology for an individual glacier (arrows in Fig. 11A) is omitted from the regional histogram (weighted) of moraine frequency (Fig. 11B) and the Breheimen regional moraine clusters (Fig. 11C). Each date in the histogram is plotted over a 10-yr time span, the 'weight' decreasing linearly on either side of the predicted date in Fig. 11B. Because moraine dates based on single sites are more likely to be in error than those based on multiple sites, their effects on the histogram and the moraine clusters (in most cases minimal) are indicated by dashed lines.

Construction of the composite 'Breheimen' record differed from the 'Jostedalsbreen' record of Bickerton and Matthews (1993) in three main respects. First, owing to the less extensive nature of the Breheimen moraines, the predicted dates used are based on the five largest lichens from a single site (1.5

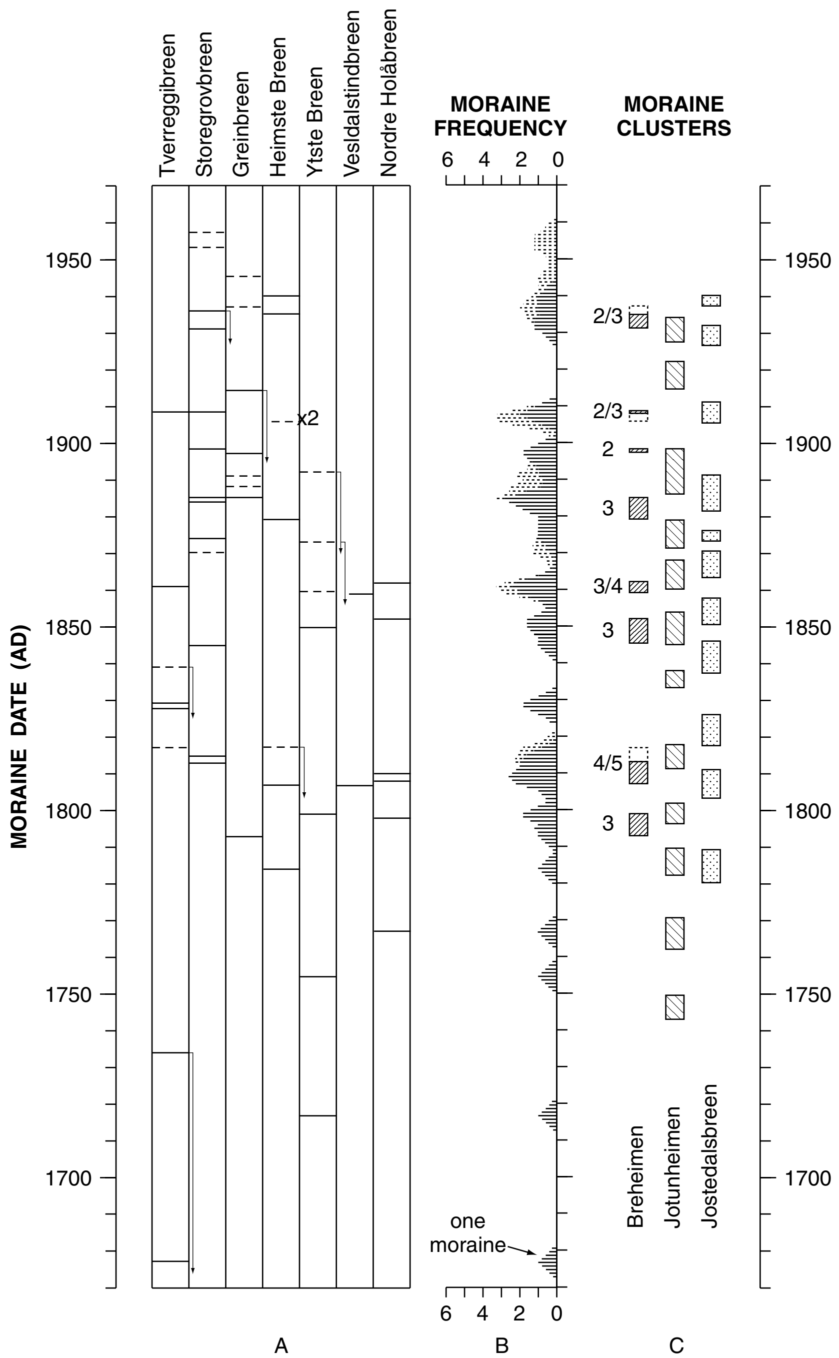

Figure 11 Lichenometric dates and the composite Little Ice Age moraine chronology for Breheimen: (A) dated moraine sequences at seven individual glaciers; (B) histogram of moraine frequency (weighted); (C) moraine clusters (further explanation in the text)

data). Second, owing to the lack of surfaces of known age from within Breheimen, the 1.5 lichenometric dating curve from Storbreen, Jotunheimen, was used (equation 1). Third, all dated moraines have been included in the histogram and moraine clusters, rather than only those with a minimum of four sites per moraine (although moraines with only one site per moraine are differentiated and treated with extreme caution).

This method has led to the identification of eight main clusters (shaded in Fig. 11C), which contain 20 of the 45 moraine ridges included in the study. Five of the eight clusters are each represented at three or four glaciers. Two more clusters include moraines from three glaciers if moraines consisting of only one site are included. One apparent cluster around AD 1830 of two moraines has been excluded as these moraines occur on the same glacier foreland.

The oldest cluster dates from AD 1793 to 1799. Although earlier moraines exist at three glaciers there is insufficient evidence to establish synchronous glacier behaviour. Moraines dating from the AD 1750s or 1760s occur, however, at two glaciers (Yste Breen and Nordre Holåbreen). In addition, older moraine ridges, possibly dating from the late seventeenth and early eighteenth centuries, occur at Tverreggibreen and Yste Breen, respectively.

Five clusters occur within the nineteenth century at AD 1807–1813, 1845–1852, 1859–1862, 1879–1885 and 1897–1898. Two clusters occur in the early twentieth century—AD 1906–1908 and 1931–1933—despite the steep slopes of the upper valley sides that were not conducive to moraine deposition at that time.

Discussion

The ages of the recessional moraines and their climatic implications

The composite Breheimen chronology appears to have successfully identified a regional glacier response. Broad synchroneity in glacier behaviour can be used in support of the general accuracy of the lichenometric dates. Two lines of independent evidence also support the accuracy of the composite chronology. First, the two youngest moraine clusters (AD 1906–1908 and 1931–1933) occur at the same time as known glacier advances of the Jostedalsbreen ice-cap, which have been documented historically and were closely associated with moraine-ridge deposition (Rekstad, 1902; Fægri, 1950; Bickerton and Matthews, 1993; Winkler, 1996b). Moraines dating from about AD 1930 are also well known in Jotunheimen (Hoel and Werenskiold, 1962; Erikstad and Sollid, 1986). Second, as there are commonly around eight moraine ridges on glacier forelands in Jotunheimen (Erikstad and Sollid, 1986; Matthews, unpublished), where glaciers are approximately the same size, recognition of eight moraine-date clusters in Breheimen is unlikely to be coincidental.

Comparison of the Breheimen moraine clusters (Fig. 11C) with those from Jostedalsbreen (Fig. 11E) and Jotunheimen (Fig. 11D) reveals some further similarities with the timing of particular moraine clusters but there is no general agreement with either chronology from these neighbouring regions. Breheimen moraines dated AD 1793–1799, 1807–1813, 1845–1852, 1859–1862 and 1897–1898, correspond most closely with moraines in Jotunheimen dated to AD 1796–1802, 1812–1818, 1845–1854, 1860–1868 and 1886–1898, respectively. Breheimen moraines dating to AD 1879–1886 and 1906–1908 correspond most closely with Jostedalsbreen moraines dated to AD 1882–1892 and 1906–1911, respectively. Only the clusters around AD 1930, and possibly those around 1810 and the 1850s appear to be in close agreement across all three regions.

The timing of recessional moraine formation in Breheimen is likely to represent a response to both summer temperature and winter precipitation. Bickerton and Matthews (1993) discussed the close association of formation of the Little Ice Age recessional moraines of Jostedalsbreen with runs of cool summers and summer temperature minima of some 1.0–1.5 °C below the average for the period AD 1700–1950. They concluded that the short-term glacier advances responsible for moraine-ridge formation represented a near-immediate response to climate of the glacier tongues, which was superimposed upon the longer term dynamic response of the ice-cap. The latter is clearly affected by the different reaction times of the longer and shorter tongues, which varies from 3 to 4 yr for the shorter tongues, such as Brigsdalsbreen, to 23–27 yr for the longer tongues, such as Nigardsbreen (Nesje, 1989; Winkler *et al.*, 1997), and a variable influence of winter accumulation. Bogen *et al.* (1989) suggested that the outlets of Jostedalsbreen responded synchronously during the first three decades of the twentieth century but reacted differently to extensive melting and local changes in winter precipitation in later decades. Especially since the 1980s, increased winter precipitation has led to a positive net mass balance of the ice-cap and the largest glacier advances of the twentieth century (Nesje *et al.*, 1995b; Winkler *et al.*, 1997). It also has been demonstrated that the net balance for the maritime glaciers of southern Norway is more influenced by the winter balance than the summer balance, whereas the opposite holds for the more continental glaciers, such as Jotunheimen (Nesje *et al.*, 1995b; Winkler *et al.*, 1997; Nesje and Dahl, 2000). It is probable, therefore, that regional differences between the glacier response of Breheimen and that of Jostedalsbreen on the one hand and Jotunheimen on the other, is affected by differences in the relative importance of temperature and precipitation operating on more than one timescale (cf. Winkler and Nesje, 2000).

Although these differences between regions may be partly attributed to inaccuracies in dating (see below), they must also be influenced by differences in response between glaciers *within* the Breheimen region. The latter include effects of the west–east climatic gradient across the region and local differences between glaciers, which include morphological, aspect and altitudinal differences. Seven glaciers are not sufficient to analyse this within-region variation in detail. However, the greatest differences within Breheimen are found between Storegrovbreen and Vesldalstindbreen—a western ice-cap that faces south and an eastern cirque glacier with a northerly aspect.

Dating the Little Ice Age maximum and implications for Holocene glacier variations

Lichenometric dating, radiocarbon dates and Schmidt hammer R-values together convincingly demonstrate that the low-altitude glaciers in Breheimen attained their Neoglacial maximum extent in the Little Ice Age. Differences between glaciers in the precise timing of the Little Ice Age maximum are suggested by the lichenometric dates. Although some differences reflect limitations of the method and are considered below, other differences are real and must reflect such factors as glacier size, morphology and dynamics. The conventional view of a mid-eighteenth century Little Ice Age maximum seems at first sight to apply only at Nordre Holåbreen. At three other glaciers (Storegrovbreen, Greinbreen and Heimste Breen) underestimation of moraine age owing to suboptimal lichen growth conditions is a possibility so that a mid-eighteenth century maximum cannot be ruled out. The smallest glacier (Vesldalstindbreen) seems to have attained its Little Ice Age maximum early in the nineteenth century, whereas Tverreggibreen and Ytste Breen may have attained their maxima in the late-seventeenth or early-eighteenth centuries. At Tverreggibreen, where the outermost moraine (M1) is extensive and a significantly older date is predicted, it is particularly difficult to argue for a mid-eighteenth century Little Ice Age maximum. Such methodological problems appear less important in relation to the younger recessional moraines.

During the Little Ice Age, the glaciers overrode mature arctic–alpine soils that require several millennia to develop and the *minimum* age of which is shown by the oldest radiocarbon dates, whereas thin slices from the surface of these buried soils provide *maximum* estimates for the burial event and hence moraine age (cf. Matthews, 1985, 1991, 1993a). Although these radiocarbon-dating techniques are unable to define the timing of the Little Ice Age maximum exactly, the youngest radiocarbon dates provide precise limiting dates and show that it normally occurred late in the Little Ice Age, which is compatible with the lichenometric dating of the outermost moraines.

In a few cases (SWAN-432, SWAN-433, SWAN-434, SWAN-439) the possibility of contamination of shallow-buried material by 'bomb effect' carbon cannot be ruled out (cf. Matthews, 1985; Dresser, 2001) but the likelihood of such young contaminants affecting these samples through root penetration or other methods is considered low in view of the number of consistent dates from a variety of materials from different sites and depths. Where the dates are older, there are three possible explanations: first, the apparent mean residence time may be greater at depth in mature soils (SWAN-436, SWAN-440, SWAN-425); second, the apparent mean residence time may be greater near the surface of mature, mid-alpine brown soils (SWAN 422 and SWAN 424); third, the dates actually relate to relatively early events (SWAN-428, SWAN-429, SWAN-430). The only radiocarbon-dating evidence pointing towards a pre-Little Ice Age, Neoglacial maximum is from Greinbreen, where the range of the calibrated dates for the outermost moraine is AD 981–1399. These dates are not fully explained, however, as they are contradicted by the lichenometric evidence and are difficult to explain in terms of contamination by relatively old material.

Although no pre-Little Ice Age Neoglacial maximum has been established in Breheimen, there is evidence, based on the buried immature soils at Tverreggibreen (site 4), for relatively early glacier advances about AD 655–963 and AD 1277–1396. These short-lived soils have yielded reasonably precise dates for glaciofluvial burial events, which occurred before the glacier attained its Little Ice Age maximum and may have been associated with glacier advances. This conclusion is supported by glaciolacustrine studies in central Jotunheimen, where the Bøvertun II Event indicates a glacier expansion episode about AD 550–1150, prior to glacier contraction in the Mediaeval Warm Period (Matthews *et al*., 2000). Evidence for early Little Ice Age advances of glaciers (after the Mediaeval Warm Period) has also been found in the Jostedalsbreen region (Nesje and Dahl, 1991a; Nesje and Rye, 1993) and elsewhere in southern Norway (Elven, 1978; Nesje *et al*., 1995a) but this invariably relates to glaciers that were smaller, usually considerably smaller, than at their Little Ice Age maxima.

Further methodological implications

In the application of lichenometric dating to dating moraines in the relatively remote region of Breheimen where conditions for the technique are not ideal, several problems have been highlighted.

First, the use of lichenometric dating curves from a neighbouring region inevitably has reduced the general level of accuracy of predicted dates. The importance of local dating control has been emphasised in previous applications of lichenometry (Innes, 1985a; Worsley, 1990; Matthews, 1994).

This study has demonstrated that well-dated lichenometric curves from neighbouring regions provide an alternative approach. Second, predicted dates are likely to be less accurate where searched sections of moraines are short (because optimal growth conditions may be rare). Third, individual moraines may be missing, either because they never existed on steep valley sides or have been destroyed, fragmented or disturbed owing to colluvial activity and glaciofluvial erosion. In the reconstruction of the composite moraine chronology, however, it has proved possible to extract a general, regional glacial response even where moraines are short, disturbed and, in some cases, missing. The regional response has been detected despite heterogeneous glacier morphology and the existence of local and regional climatic gradients. The fact that 25 individual dated moraines in Fig. 11A fall outside the moraine clusters identified in Fig. 11C can be attributed to these problems. The lichenometric techniques used in this study should prove useful in similar circumstances elsewhere.

A combination of radiocarbon dating and Schmidt hammer R-values provides a 'multi-proxy' approach that enables the conclusions of lichenometry to be tested and the glacial chronology to be extended. Thus, although radiocarbon dates are less accurate than lichenometric dates over the Little Ice Age timescale, they provide stratigraphical insights into early and pre-Little Ice Age events that are not possible with the surface dating techniques. Although the Schmidt hammer is much less accurate as a chronological tool, it has the potential to differentiate Little Ice Age from earlier Holocene moraines.

There is, however, no current evidence relating to mid- or early Holocene glacier expansion episodes in Breheimen. Such glacier advances have been widely reported elsewhere in southern Norway, mainly from distal glaciolacustrine or glaciofluvial depositional sequences (e.g. Nesje and Dahl, 1991b, 1994; Nesje and Kvamme, 1991; Nesje *et al*., 1991, 1994, 2000, 2001; Karlén and Matthews, 1992; Matthews and Karlén, 1992; Dahl and Nesje, 1994, 1996; Matthews *et al*., 2000) and, in some cases, the existence of early Holocene moraines have been located beyond Little Ice Age glacier limits (see especially Dahl *et al*., 2002). In the present study, the Schmidt hammer results would have been the most likely to identify such relatively old moraines but provide little or no evidence for them.

Conclusions

1 Seven low-altitude (temperate) glaciers in Breheimen are fronted by well developed Little Ice Age moraine sequences, each characterised by 2–13 but most commonly eight moraine ridges.
2 There is little or no evidence for pre-Little Ice Age moraines associated with these glacier forelands. Based on radiocarbon dating, Schmidt-hammer R-values and lichenometry, the Breheimen glaciers reached their Neoglacial maximum during the Little Ice Age.

3 Radiocarbon dating of thin (1 cm thick) samples of soils and peat, either buried beneath outermost moraine ridges or associated with adjacent mires and glaciofluvial sites affected by moraine formation, provide close *maximum* age estimates for the timing of the Neoglacial maximum. These estimates range from the fifteenth century to AD 1693 at Tverreggibreen and Storegrovbreen, but a pre-Little Ice Age maximum dating from AD 981 is 1399 is a possibility at Greinbreen.
4 Close estimates of the age of immature soils buried by glaciofluvial sediments suggest relatively minor glacier advances about AD 655–963 and AD 1277–1396, during the build-up of Tverreggibreen towards its Little Ice Age maximum. Several dates up to about 2000 cal. yr BP obtained from buried mature soils provide *minimum* estimates (but not close estimates) of the period of undisturbed soil development prior to burial.
5 Mean Schmidt hammer R-values from boulders on outermost moraine ridges are consistent with a late-Neoglacial glacier maximum and the absence of earlier Holocene moraines: some relatively low R-values causing greater variability being attributed to heterogeneous petrology and/or the incorporation of highly weathered boulders by glacier push mechanisms.
6 According to the lichenometric data, there are no pre-Little Ice Age moraines at these low-altitude glaciers, but the precise timing of the Little Ice Age maximum appears to have varied between glaciers, ranging from the late-seventeenth century to the early-nineteenth century. A conventional mid-eighteenth century date cannot be ruled out for at least three glaciers.
7 A lichenometry-based composite moraine chronology indicates broadly synchronous formation of recessional moraine ridges during the following time intervals: AD 1793–1799, 1807–1813, 1845–1852, 1859–1862, 1879–1885, 1897–1898, 1906–1908 and 1931–1933. These are attributed to short-term glacier advances during the long-term recession from the Little Ice Age glacier maximum.
8 The response of the temperate glaciers of Breheimen is indicative of their transitional position on the regional climatic gradient between Jostedalsbreen and Jotunheimen. Although the regional response is closer to that in Jotunheimen, complexity is introduced by local climatic gradients, aspect and morphological differences between glaciers. Regional differences in the timing of moraine formation are likely to reflect a response to differences in both summer temperature and winter precipitation.
9 Methodological implications of the study include: (i) the potential of a 'multi-proxy' approach in the context of Holocene moraine stratigraphy, where lichenometric dating, radiocarbon dating and Schmidt hammer R-values can each play a role; and (ii) the sensitivity of the composite moraine chronology to short-term regional glacier advances and hence climatic fluctuations based on Little Ice Age recessional moraines.

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