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'Little Ice Age' glacier variations in Jotunheimen, southern Norway: a study in regionally controlled lichenometric dating of recessional moraines with implications for climate and lichen growth rates

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Abstract: A new approach to regional lichenometric dating is developed and applied to 'Little Ice Age' moraine-ridge sequences on 16 glacier forelands in Jotunheimen, southern Norway. Lichenometric-dating curves, based on the *Rhizocarpon* subgenus, are constructed independently for west, central and east Jotunheimen. Although there are differences between the subregions, a composite regional moraine chronology for Jotunheimen identifies 12 episodes of moraine formation in AD 1743–1750 (the regional 'Little Ice Age' glacier maximum), 1762–1771, 1782–1790, 1796–1802, 1811–1818, 1833–1838, 1845–1854, 1860–1868, 1871–1879, 1886–1898, 1915–1922 and 1927–1934. Spatial and temporal patterns in glacier behaviour between the subregions and between Jotunheimen and the neighbouring Jostedalsbreen are explained in terms of the interaction of annual to decadal variations in summer temperature and winter precipitation: glacier advances and moraine-formation events driven primarily by winter-precipitation variations exhibit subregional patterns while summer-temperature forcing affects more synchronous glacier behaviour across the region. Regionally controlled lichenometric dating improves the accuracy of dating by up to about ±20 years on relatively old moraines and is dependent on regional patterns in the rate of lichen growth. On relatively young surfaces, mean cumulative growth rate declines from about 0.75 mm yr^{-1} in maritime west Jotunheimen to about 0.55 mm yr^{-1} in continental east Jotunheimen (though the differential in growth rate is less on older surfaces).

Key words: Lichenometry, *Rhizocarpon*, lichenometric-dating curve, lichen growth rates, regional control, glacier variations, 'Little Ice Age', moraine chronology, climatic variations, decadal scale, Jotunheimen, Norway.

Introduction

Lichenometric dating has been applied successfully to 'Little Ice Age' glacier variations ever since 'lichenometry' was invented around 50 years ago (Beschel, 1961). Applications have been based primarily on the so-called 'indirect approach', whereby a numerical relationship (lichenometric dating curve) is established between lichen size and surface age based on the size of lichens growing on surfaces of known historical age (control points). Thus, provided glacier history is sufficiently well known to establish *a priori* the age of enough surfaces for use as control points, lichenometric dating curves can be constructed and used to date surfaces of unknown age (Locke *et al.*, 1979; Worsley, 1990; Matthews, 1994).

The accuracy of the method is clearly dependent on the quality and quantity of control points. This leads to many studies having to employ control points derived from the wider region for the construction of lichenometric dating curves. Such regional lichenometric dating curves have the potential to date glacier variations over a wide area, to investigate regional glacier behaviour patterns and hence to detect climatic variations. They are based, however, on the assumption of regional environmental homogeneity (Matthews, 1994): to produce accurate dates, the environmental conditions that affect lichen growth must be the same both at the sites of the control points and on the surfaces to be dated. Yet it is known

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that a wide variety of environmental factors, especially moisture conditions, affect lichen growth (Jochimsen, 1973; Haines-Young, 1983; Innes, 1985a; 1985b), and environmental differences between localities are likely to increase as the scale of the area from which the control points are obtained increases. By sampling only the largest lichens, effects of environmental heterogeneity are reduced because the measured lichens tend to be growing in the optimum available environment on each surface. The assumption of regional homogeneity in the optimum conditions for lichen growth remains, however (Matthews, 1994).

Although it has long been recognized that different lichenometric dating curves are necessary to reflect varying lichen growth rates at the global to continental scale (Webber and Andrews, 1973), there have been relatively few attempts to take account of variations in the environmental conditions affecting lichen growth at regional to subregional scales. The most detailed research on this theme is that of Evans *et al.* (1999), who demonstrated regional differences in the growth rate of the *Rhizocarpon* subgenus between sites in the relatively arid north of Iceland compared with the relatively moist south, and concluded that a 350 mm rise in annual precipitation corresponded with an increase of about 0.1 mm yr^{-1} in the growth rate. Similarly, in southern Norway, differences in lichenometric dating curves between the 'mountain' and 'western' regions (Erikstad and Sollid, 1986) and between the Jotunheimen and Jostedalsbreen regions (Matthews, 1974; Bickerton and Matthews, 1992) may be attributed to climatic differences.

The main aim of this paper is to develop and apply a methodology for taking account of regional variation in lichenometric dating within Jotunheimen. There are five specific objectives: (1) to construct separate regionally controlled lichenometric dating curves for three subregions of Jotunheimen based on 'Little Ice Age' recessional moraines of known historical age; (2) to date 16 moraine sequences, 10 for the first time; (3) to construct composite moraine chronologies for each subregion and also for the Jotunheimen region as a whole; (4) to measure the potential improvements in the accuracy of dating brought about by the use of regionally controlled lichenometric dating; (5) to assess the implications of the results for understanding differences in glacier (and hence climatic) variations within Jotunheimen and between the Jotunheimen and Jostedalsbreen regions.

Study area

Jotunheimen, the highest mountain range in northern Europe (Figure 1), contains around 300 cirque and valley glaciers and small ice caps (Hoel and Werenskiold, 1962; Østrem *et al.*, 1988). Most of the region lies within the alpine zone, above the birch (*Betula pubescens*) altitudinal treeline at around 1000 m. Many mountain peaks rise to over 2000 m in altitude and the valley bottoms descend to below 1000 m at the margins of the region. Located over 150 km from the west coast, astride the main continental divide in southern Norway, the climate of Jotunheimen is transitional between maritime western Norway and the more continental eastern plateaux and valleys. The only meteorological station within the region, Sognefjell in western Jotunheimen, indicates a mean annual air temperature of −3.1°C (July mean + 5.7°C; January mean −10.7°C) and a mean annual precipitation of 860 mm at an altitude of 1413 m (Aune, 1993; Førland, 1993), although precipitation is likely to increase steeply with altitude and attain > 1000 mm over much of the high mountains (Erikstad and Sollid, 1986; Laumann and Reeh, 1993). The lower altitudinal limit of permafrost is at about 1460 m in eastern Jotunheimen, rising westwards (Isaksen *et al.*, 2002). Geologically, Jotunheimen is predominantly pyroxene granulite gneiss with areas of mylonite and

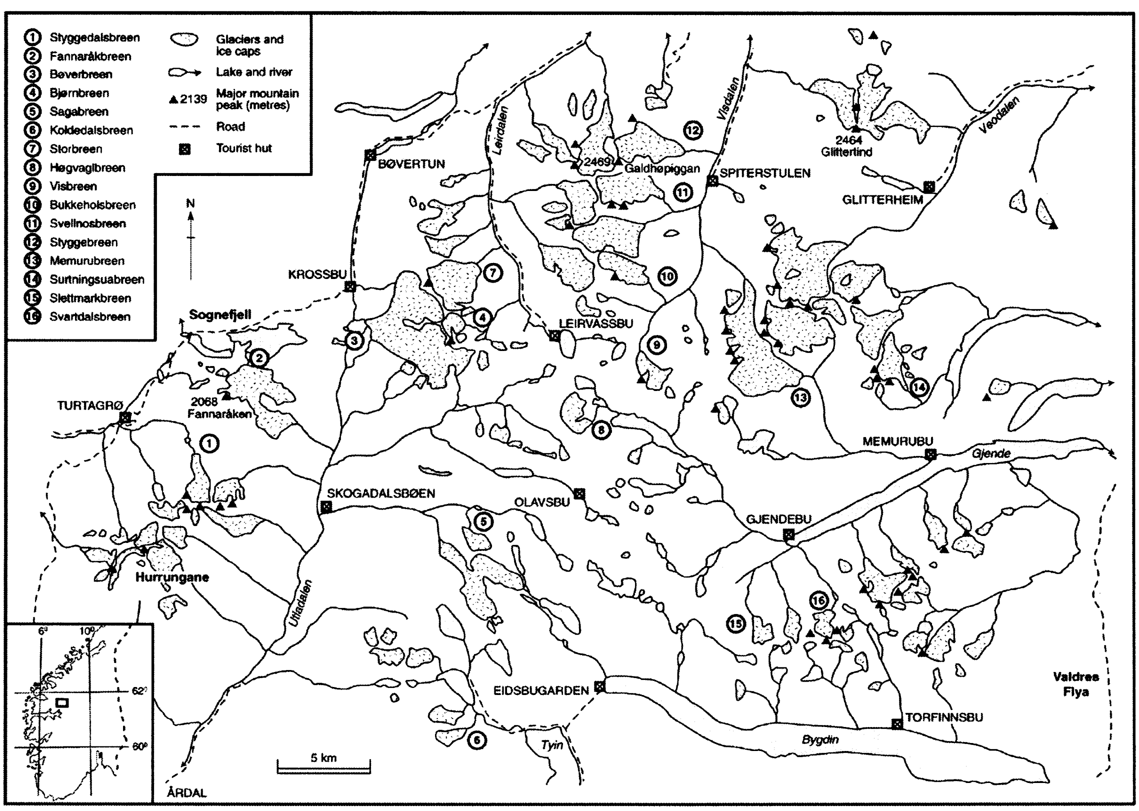

Figure 1 Location of the 16 glaciers and moraine sequences investigated in Jotunheimen, southern Norway.

minor peridotite intrusions (Battey and McRitchie, 1975; Lutro and Tveten, 1996).

Geographical and glaciological research in Jotunheimen has a relatively long history. Pioneering descriptions of the glaciers and measurements of glacier variations were carried out by Øyen (1893; 1908). Other important early investigations were made in western Jotunheimen on glacier mass balance (Ahlmann, 1922; 1940) and, in eastern Jotunheimen, on glacial geomorphological processes (Lewis, 1960) and on the nature and age of ice-cored moraines (Østrem, 1964; 1965). The theme of measuring and mapping contemporary glacier variations was taken up by Hoel, Werenskiold and Liestøl (Hoel and Werenskiold, 1962), and annual snout fluctuations and mass-balance data have continued to be published annually by the Hydrological Division of Norges Vassdrags- og Elektrisitetsvesen (e.g., Kjøllmoen, 2000). The glacier mass-balance record for Storbreen in central Jotunheimen, which began in 1947, is now the second longest in the world (Liestøl, 1967; Andreassen and Østrem, 1999).

Such research provides the background and, in some cases, a basis for establishing control points for lichenometric dating. The first studies of lichenometric dating in Jotunheimen were carried out at Storbreen (Figure 1). In a series of papers, Matthews (1974; 1975; 1977) used the Storbreen glacier foreland to contribute to the development of the statistical basis of lichenometric dating. Further systematic studies of lichenometric techniques were undertaken in Jotunheimen in the 1980s and 1990s by Innes (e.g., 1985a; 1985b), Haines-Young (1983) and McCarroll (1994). The first explicitly regional approach to lichenometry in Jotunheimen was developed by Erikstad and Sollid (1986) who produced lichenometric dating curves for the 'mountain regions' of southern Norway, which was based largely on control points from five glacier forelands in Jotunheimen. Lichenometric dating curves both for Storbreen and the mountain regions have since been widely applied throughout the region (see, for example, Matthews, 1994; Winkler *et al.*, 2003).

Table 1 Characteristics of the 16 glaciers (data from Østrem *et al.*, 1988)

Glacier name	Area (km^2)	Minimum altitude (m)	Maximum altitude (m)	Aspect
West Jotunheimen				
Styggedalsbreen	1.81	1270	2240	N
Fannaråkbreen	3.69	1430	1990	NE
Bøverbreen[a]	4.87	1420	2040	W/NW
Bjørnbreen	1.16	1540	2040	E
Sagabreen	1.13	1540	1940	N
Koldedalsbreen	0.90	1370	1790	E
Central Jotunheimen				
Storbreen	5.16	1380	1870	NE
Høgvaglbreen	0.65	1620	2060	NE
Visbreen	1.25	1500	2060	N
Bukkeholsbreen	3.05	1600	2130	SE
Svellnosbreen[b]	5.23	1600	2290	E/SE
East Jotunheimen				
Styggebreen	5.10	1660	2290	E
Vestre Memurubreen[c]	8.81	1590	2200	E
Surtningssuabreen	2.41	1600	2290	SE
Slettmarkbreen	1.19	1470	1990	N
Svartdalsbreen	1.26	1510	2140	N/NE

[a]Part of the area forms a different glacier foreland.
[b]Formerly confluent with Tverråbreen.
[c] Formerly confluent with Austre Memurubreen.

Research design and methods

Glacier forelands, moraines and aggregate species

Sixteen glacier forelands were selected from throughout Jotunheimen for this investigation (Figure 1 and Table 1). Forelands were chosen on the basis of the extent and development of their marginal moraine sequences. This was determined from aerial photographs and also by ground visits to assess conditions for lichen growth (see below). Many glacier forelands were rejected due to poorly developed moraine sequences while some, mainly at relatively high altitude, were rejected because of the 'snow-kill' effects of semi-permanent snowbeds (e.g., Urdadalsbreen) or disturbance from the thawing of ice-cored moraines (e.g., Gråsubreen; cf. Østrem, 1964; Shakesby *et al.*, 2004). A small number of glacier forelands at relatively low altitude were rejected due to poor lichen growth: examples include Storjuvbreen (where rain shadow and/or wind effects appear to have reduced moisture availability) and Maradalsbreen (where air pollution from the Årdal aluminium smelter may have had an effect). This study is nevertheless believed to be representative of the variations of the relatively low-altitude temperate glaciers with glacier forelands in the low- and mid-alpine belts over the approximate altitudinal range of 1100–1500 m.

Individual moraines were mapped onto enlarged aerial photographs in the field. Lichenometric measurements were generally made on the proximal slopes of the moraines. Occasionally former snout positions not defined by moraines were also used (see below). In all cases, the entire length of the moraine or snout position was searched as described in Matthews (1975). For measurement purposes, the search areas were subdivided into sites 25 m long (aligned along the moraine crest) and 8 m wide. The long axis of the five largest specimens of the yellow-green *Rhizocarpon* subgenus were measured to the nearest millimetre and permanently recorded for each site. This taxon includes both section *Rhizocarpon* and section *Alpicola* (Innes, 1985c; Poelt, 1988). Previous work has shown that section *Rhizocarpon* is the predominant species group but that, due to the faster rate of growth of later-colonizing individuals and possibly superior competitive ability, section *Alpicola* is likely to be important in the data set where the largest thalli exceed about 100 mm (Innes, 1982; 1983; Bickerton and Matthews, 1992; see also Winchester and Sjöberg, 2003).

Control points

Control points used to construct lichenometric dating curves are summarized in Table 2. These are of three types: first, moraines or glacier snout positions considered to have been accurately dated to within ±1 year at specific glaciers based on historical measurements, photographs (Figure 2) or maps (Type I control points dating from AD 1893–1951); secondly, relatively young moraines assumed to date from AD 1930 (Type II); and, thirdly, moraines originating from the 'Little Ice Age' glacier maximum, which is assumed to date from about AD 1750 (Type III).

Type I control points from around 1930 refer to dates between 1928 (Storbreen) and 1933 (Memurubreen) for comparable ridges: after this time, there was protracted glacier retreat until the 1980s. Type II control points are considered to be dated with an accuracy of ±5 years based on the knowledge that they represent the youngest moraine ridges of the 'Little Ice Age' sequence. Using the 'Little Ice Age' maximum moraines as Type III control points is more problematic as no 'Little Ice Age' glacier maximum in Jotunheimen has been

Table 2 Regionally controlled lichenometric dates for the moraine sequences at 16 glacier forelands in Jotunheimen

Moraine no.	No. of sites	Lichen size (mm)		Predicted date (AD)	Historical date (Type)[a]
		Single largest (1.1)	Five largest (5.1)		
Styggedalsbreen (measured 1978)					
M1	47	117	114.0	1767	1750 (III)
M2	18	92	84.2	1841[b]	–
M3	10	92	86.8	1835	–
M4	24	86	73.2	1864	–
M5	8	75	64.2	1882	–
M6	2[c]	59	55.0	1899[c]	1906 (I)
M7	18	40	38.2	1927	1931 (I)
Fannaråkbreen (measured 1992)					
M1	3[c]	118	111.0	1790[c]	–
M2	5	112	97.0	1826	–
M3	5	95	89.8	1843	–
M4	6	93	88.2	1846	–
M5	5	94	81.8	1860	–
M6	6	86	81.0	1862	–
M7	8	78	71.0	1883	–
M8	6	48	43.0	1933	1930 (II)
Bøverbreen (measured 1990)					
M1	18	118	115.0	1777	1750 (III)
M2	12	122	113.2	1782	–
M3	14	107	99.4	1818	–
M4	10	99	92.4	1835	–
M5	13	99	90.8	1838	–
M6	9	85	78.0	1867	–
M7	14	63	58.4	1905	–
M8	11	46	44.2	1929	1930 (II)
Bjørnbreen (measured 1992)					
M1	15	137	127.2	1743[b]	1750 (III)
M2	6	136	127.2	1743[b]	–
M3	7	158	132.4	1727	–
M4	5	143	111.4	1789	–
M5	5	93	87.4	1848	–
M6	5	85	81.4	1861	–
M7	7	76	68.6	1888	–
M8	5	46	42.4	1934	1930 (II)
Sagabreen (measured 1977)					
M1	16	144	130.0	1719	1750 (III)
M2	12	103	102.0	1798	–
M3	8	88	78.4	1853	–
M4	8	72	66.8	1876	–
Koldedalsbreen (measured 1978)					
M1	22	129	120.0	1750	1750 (III)
M2	9	109	106.4	1788	–
M3	12	103	99.4	1806	–
M4	10	90	82.4	1845	–
Storbreen (measured 1971 and 1974[d])					
M1	15	114	107.5	1764	1750 (III)
M2	11	91	88.0	1813	–
M3	7	88	78.4	1835	–
M4	10	80	72.1	1849	–
M5	8	70	64.5	1864	–
M6	5	52	46.7	1897	1900 (I)
M7	6	43	35.8	1915	1917 (I)
M8	7	30	28.3	1927	1928 (II)
M9[e]	29	31	29.2	1928	1936 (I)
M10[e]	17	14	12.2	1950	1951 (I)
Høgvaglbreen (measured 1979)					
M1	18	120	111.0	1764	1750 (III)
M2	8	125	103.0	1785	–
M3	8	103	90.4	1817	–
M4	8	83	80.4	1840	–
M5	8	57	53.6	1893	1893 (I)
M6	8	45	41.6	1914	–
M7	8	42	36.8	1922	–
M8	6	26	21.6	1922	1933 (I)
Visbreen (measured 1979)					
M1	11	124	117.1	1746	1750 (III)
M2	12	113	105.7	1778	–
M3	8	111	100.0	1793	–
M4	9	88	83.6	1833	–
M5	8	86	81.4	1838	–
M6	8	74	67.0	1868	–
M7	8	62	54.4	1892	–
M8	8	42	38.2	1919	–
M9	8	38	30.2	1932	1930 (II)
Bukkeholsbreen (measured 1992)					
M1	13	133	124.6	1737	1750 (III)
M2	8	126	118.8	1754	–
M3	6	115	99.6	1807	–
M4	6	84	80.4	1853	–
M5	6	73	67.8	1879	–
M6	7	59	56.4	1901	–
M7	6	53	46.6	1919	–
M8	9	47	43.8	1923	1930 (II)
Svellnosbreen/ Tverråbreen (measured 1990)					
M1	24	134	121.0	1746	1750 (III)
M2	16	115	101.6	1800[b]	–
M3	19	113	106.4	1787	–
M4	22	92	90.4	1828[b]	–
M5	24	111	101.4	1800	–
M6	19	87	80.8	1850	–
M7	15	74	69.6	1874	–
M8	17	66	63.6	1886	–
M9	14	63	55.0	1902	–
M10	16	50	45.6	1918	–
M11	14	42	38.4	1930	1930 (I)
Styggebreen (measured 1992)					
M1	12	132	116.0	1743	1750 (III)
M2	12	105	99.6	1793	–
M3	7	106	98.0	1797	–
M4	6	99	93.0	1811	–
M5	11	98	91.4	1815[b]	–
M6	12	99	91.8	1814	–
Memurubreen (measured 1977, 1979 and 1987[f])					
M1	44	132	124.4	1699	1750 (III)

Table 2 (*Continued*)

Moraine no.	No. of sites	Lichen size (mm)		Predicted date (AD)	Historical date (Type)[a]
		Single largest (1.1)	Five largest (5.1)		
M2	8	100	96.4	1789[b]	–
M3	20	125	114.4	1735	–
M4	16	125	103.8	1767	–
M5	16	96	91.4	1802	–
M6	16	85	81.2	1828	–
M7	10	86	78.8	1842	–
M8	8	77	66.4	1862	–
M9	16	66	61.6	1872	–
M10	7	54	52.8	1898	–
M11	7	43	41.6	1919	1910 (I)
M12	24	30	28.2	1933	1933 (I)
Surtningssuabreen (measured 1992)					
M1	9	123	110.0	1762	1750 (III)
M2	7	106	101.4	1787[b]	–
M3	6	119	103.4	1782	–
M4	13	82	75.8	1854	–
M5	9	69	61.4	1886	–
M6	4[c]	52	83.4	1909[c]	–
M7	4[c]	41	39.0	1928[c]	1930 (II)
Slettmarkbreen (measured 1978 and 1992[g])					
M1	16	109	102.2	1771	1750 (III)
M2	8	96	93.4	1796	
M3	7	84	78.7	1833	
M4	8	81	72.8	1847	
M5	8	58	53.0	1889	
M6	8	32	30.6	1928	1930 (II)
M7[e]	8	42	37.2	1931	1940 (I)
M8[e]	8	34	32.4	1939	1947 (I)
Svartdalsbreen (measured 1978 and 1992[h])					
M1	18	102	95.6	1790	1750 (III)
M2	12	96	86.8	1813	–
M3	12	89	82.8	1823	–
M4	12	63	59.8	1875	–
M5	12	55	50.8	1893	1900 (I)
M6	6	45	44.0	1915	1910 (I)
M7	12	31	27.2	1934	1930 (II)
M8[e]	5	37	29.8	1944	1947 (I)

[a]Type of control point in brackets.
[b]Site age out of chronological order (should be older than next youngest site; unreliable date).
[c]Mean of the largest n lichens, where n = no. of sites = <5; possible unreliable date.
[d]Storbreen: M1–M8 measured 1971; M9 and M10 measured 1974.
[e]Mapped snout position, not a moraine (Storbreen M9 and M10, Slettmarkbreen M7 and M8, Svartdalsbreen M8).
[f]Memurubreen: M1 measured 1977; M2–M6, M8–M9 and M12 measured in 1979; M7, M10 and M11 measured 1987.
[g]Slettmarbeen: M1–M6 measured 1978; M7 and M8 measured 1992.
[h]Svartdalsbreen: M1–M7 measured 1978; M8 measured 1992.

accurately dated to Type I standards. However, three lines of evidence support the assumption of an AD 1750 date for the outer moraines throughout Jotunheimen. First, in a number of papers, the earliest dating from 1893, Øyen wrote that Amund Elvesæter (born 1848; died 1904) had reported that Storbreen formed an ice bridge across the Leira river 'about 100 years ago' (Øyen, 1893: 27). That places the age of the outermost 'Little Ice Age' moraine at Storbreen in the eighteenth century, which is not inconsistent with a mid-eighteenth century date (see also Matthews, 1974; Erikstad and Sollid, 1986). Secondly, in the neighbouring Jostedalsbreen region, the advance of several outlet glaciers of the Jostedalsbreen ice cap to their 'Little Ice Age' maximum about AD 1750 is firmly dated based on historical sources. At Nigardsbreen in particular the outermost moraine appears to date to shortly after AD 1748 when, according to the account of M. Foss, the parson of Jostedal, a slow retreat of the glacier began (Grove, 1988; see also Bickerton and Matthews, 1992; Matthews, 1997). The analogy is strengthened by the good agreement between the timing of glacier fluctuations in the Jotunheimen and Jostedalsbreen regions in the twentieth century (Liestøl, 1967). Thirdly, independent lichenometric tests of the '1750 moraine hypothesis' were carried out at Storbreen based on the extrapolation of lichenometric dating curves based only on control points from the twentieth century (Matthews, 1977). It was concluded that the hypothesis could not be rejected and that the 'Little Ice Age' maximum probably occurred early in the second half of the eighteenth century.

Regionally controlled lichenometric dating curves

The potential for lichenometric dating curves that take account of regional differences in lichen growth rate is illustrated in Figure 3, which shows the available control points from Jotunheimen in relation to selected lichenometric dating curves from Jotunheimen and neighbouring regions. The control points are shown scattered around five lichenometric dating curves. First, the curve from Storbreen, in west-central Jotunheimen (Matthews, 1974) fits the younger control points quite well but overestimates the age of most of the older control points. Secondly, the 'adjusted mountain curve' (Erikstad and Sollid, 1986), which was derived from a much broader area from Nordvestlandet to eastern and central Jotunheimen (including Storbreen), tends to overestimate the age of almost all of the control points. Thirdly, the 'western curve' (Erikstad and Sollid, 1986), which covers the Hurrungane massif in western Jotunheimen together with the Jostedalsbreen region farther to the west, tends to underestimate the age of the control points, especially the older ones. The fourth curve, that derived from Nigardsbreen and applied by Bickerton and Matthews (1992; 1993) to glacier forelands of the outlet glaciers of the Jostedalsbreen ice cap, also underestimates the age of most of the control points, especially the younger ones. Fifthly, the previously unpublished 'Jotunheimen' curve is the best-fit line to the control points using the methods outlined below.

The goodness-of-fit of the five curves to the Jotunheimen control points and the systematic bias inherent in the first four curves are summarized in Table 3. This shows that the scatter in predicting the ages of these moraines using the published curves is ±16.9 to ±24.0 years (based on one standard devation) or ±33.8 to ±48.0 years (based on the more realistic two standard deviations) with a systematic bias ranging from an overestimate of +13.3 years to an underestimate of −13.1 years. These data therefore indicate that overall errors of up to ±62 years are likely in particular cases. Although there is no systematic bias present in the Jotunheimen curve, the error term is still ±33 years for individual moraines. It would be expected, however, that the scatter would be reduced, and hence more accurate predicted ages could be obtained, by constructing separate curves, each based on control points from different subregions of Jotunheimen. Thus, west, central and east Jotunheimen were defined so that

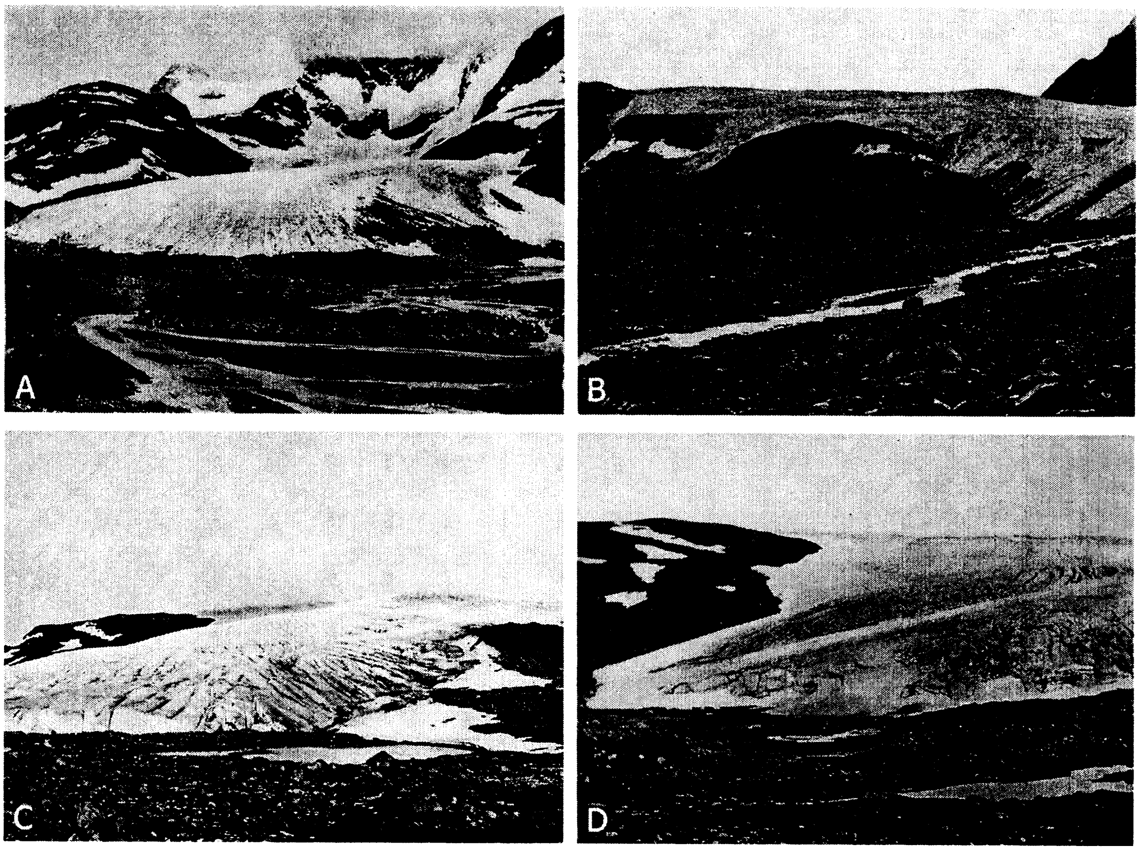

Figure 2 Selected historical photographs of Jotunheimen glaciers taken by P.A. Øyen. (A) Styggedalsbreen in 1904 (Øyen, 1909a). (B) Vestre Memurubreen in 1903 (Øyen, 1909a). (C) Bøverbreen, upper moraine series, in 1903 (Øyen, 1913). (D) Bøverbreen, lower moraine series, in 1903 (Øyen, 1909a).

each sub region included five or six glaciers and 10–15 control points (Figure 1 and Table 3). The western and eastern longitudinal boundaries of the central Jotunheimen subregion lie at approximately 8°11′ and 8°23′ E, respectively. This sub division is consistent with the likely moisture availability for lichen growth from the relatively maritime west of the region to the relatively continental east.

Lichenometric dating curves of the form $\log(y+c) = a+bx$ were constructed, where y is moraine age in years, x is mean size of the five largest lichens each from a separate site (coded 5.1 in Table 2) in millimetres, and a, b and c are constants (Matthews, 1974). Use of a mean lichen size calculated in this manner has been shown to produce more reliable lichenometric dates than either the single largest lichen (1.1 in Table

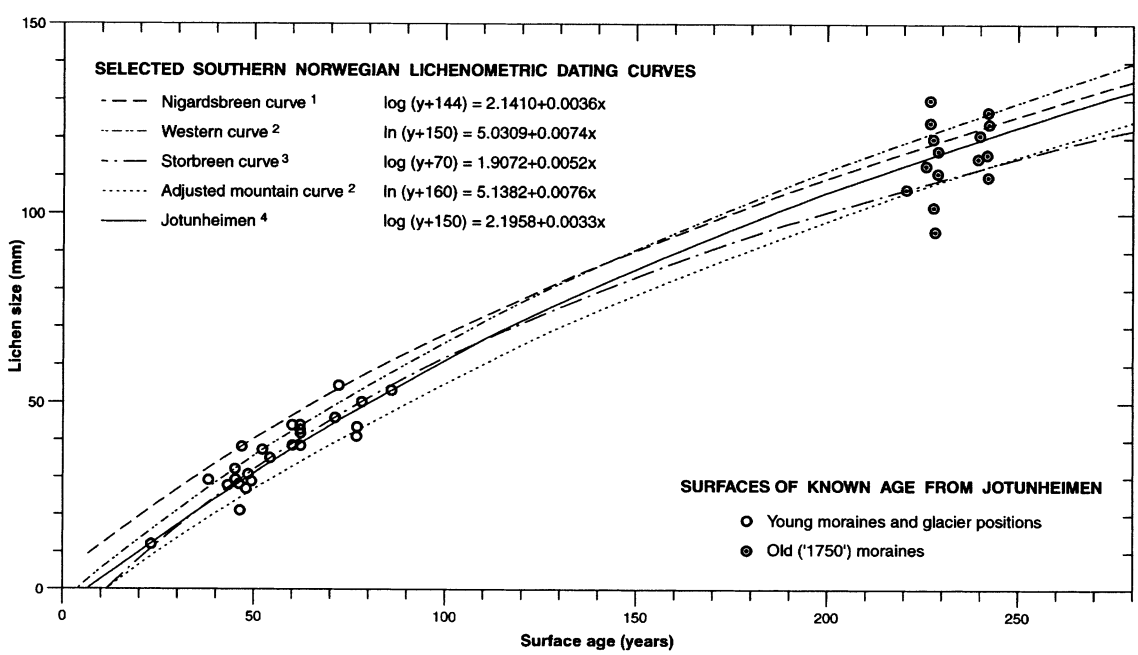

Figure 3 Selected published lichenometric dating curves from southern Norway in relation to the lichen sizes on surfaces of known age in Jotunheimen used as control points in this study. (1) Bickerton and Matthews, 1992; (2) Erikstad and Sollid, 1986; (3) Matthews, 1994; (4) this study.

Table 3 Mean and standard deviation ($\pm 1\sigma$) of age differences (in years) between Jotunheimen control-point age (n = 40) and lichenometric predicted ages for five lichenometric-dating curves. (Further explanation in the text)

Storbreen curve	Adjusted mountain curve	Western curve	Nigardsbreen curve	Jotunheimen curve
$+7.9 \pm 24.0$	$+13.3 \pm 18.3$	-11.4 ± 17.1	-13.1 ± 16.9	-0.5 ± 16.5

2) or a mean based on a greater number of largest lichens (Matthews, 1974; 1975; 1977) and also ensures maximum comparability with the previous studies mentioned above. Maximum goodness-of-fit for the three subregional curves considered together was achieved when constant *c* was set at 150. This produced correlation coefficients of $r = +0.991$ (n = 10), +0.996 (n = 15) and +0.985 (n = 15) for west, central and east Jotunheimen, respectively. Only negligible improvement (no improvement to three decimal places) of the correlation coefficients could be achieved by maximizing the goodness-of-fit of each subregional curve separately.

Predicted ages for moraines of unknown historical age were calculated using the appropriate regionally controlled lichenometric dating curve. Regionally controlled dates were then combined to produce composite moraine chronologies for Jotunheimen as a whole and for each subregion using graphical techniques described by Bickerton and Matthews (1993). Improvements in the accuracy of lichenometric dating as a result of using the regionally controlled approach were assessed by measuring differences between predicted lichenometric ages and true, historical, control-point ages.

Dating the moraine sequences

Regionally controlled lichenometric dating curves for west, central and east Jotunheimen are shown in Figure 4. The three curves suggest a systematic increase in growth rate across Jotunheimen from east to west. Resulting differences in predicted ages between curves increases from around 15 years on 50-year-old surfaces to around 40 years for a 250-year-old moraine. The 16 moraine sequences are summarized in Figures 5–7 and the dates of the moraines predicted from the regionally controlled curves are detailed in Table 2 and Figure 8 A.

Styggedalsbreen (Figure 5A)

Dating of seven arcuate lateral and frontal moraine ridges at an altitude of 1260–1280 m was attempted at Styggedalsbreen of which three (M1, M6 and M7) are control points that were also used by Erikstad and Sollid (1986). Two of the control points are of Type I quality. First, formation of the M7 moraine was observed for many years by H.W. Ahlmann: retreat began in AD 1930, and the glacier had retreated 25 m behind the 1925 snout position by 1933 (Ahlmann, 1935; Hoel and Werenskiold, 1962). Secondly, a photograph taken by P.A. Øyen in 1904 (Figure 2A), combined with annual snout measurements showing a 4 m advance in 1904–1905 followed by a 12 m retreat in 1905–1906, establishes deglacierization of M6 by 1906 (Øyen, 1909a). The lichenometric dates predicted for moraines M6 and M7 indicate apparent overestimates of age of seven and four years, respectively, despite there being only two sites available for lichenometric measurements on M6.

The apparent underestimate of age for the outermost 'Little Ice Age' moraine (M1) of 18 years may be real as this is a Type III control point without local independent evidence, and the extensive area that was searched for lichenometry (47 sites) ensures reliable lichen-size data. An attempt was made by Griffey and Matthews (1978) to date M1 using radiocarbon dating and it was initially concluded that this moraine was much older than the 'Little Ice Age'. The discovery of steep age-depth relationships near the surface of buried soils elsewhere in southern Norway led, however, to the rejection of this interpretation (Matthews, 1980; 1991).

Undated moraine ridges within the 'Little Ice Age' sequence are fragmented and/or characterized by poor lichen growth conditions. These include a distinct single ridge between M4 and M5 (moraine 'f' of Erikstad and Sollid, 1986) and several ridges within the complex of at least eight moraine ridges

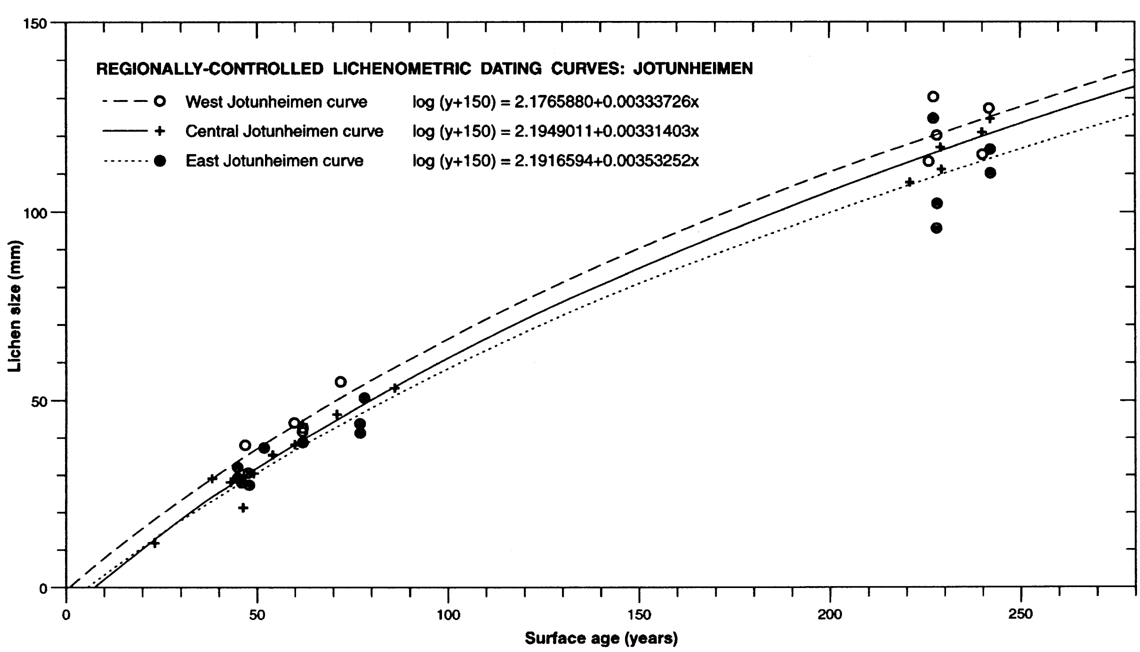

Figure 4 Regionally controlled lichenometric dating curves for west, central and east Jotunheimen derived from the control points identified by characteristic symbols.

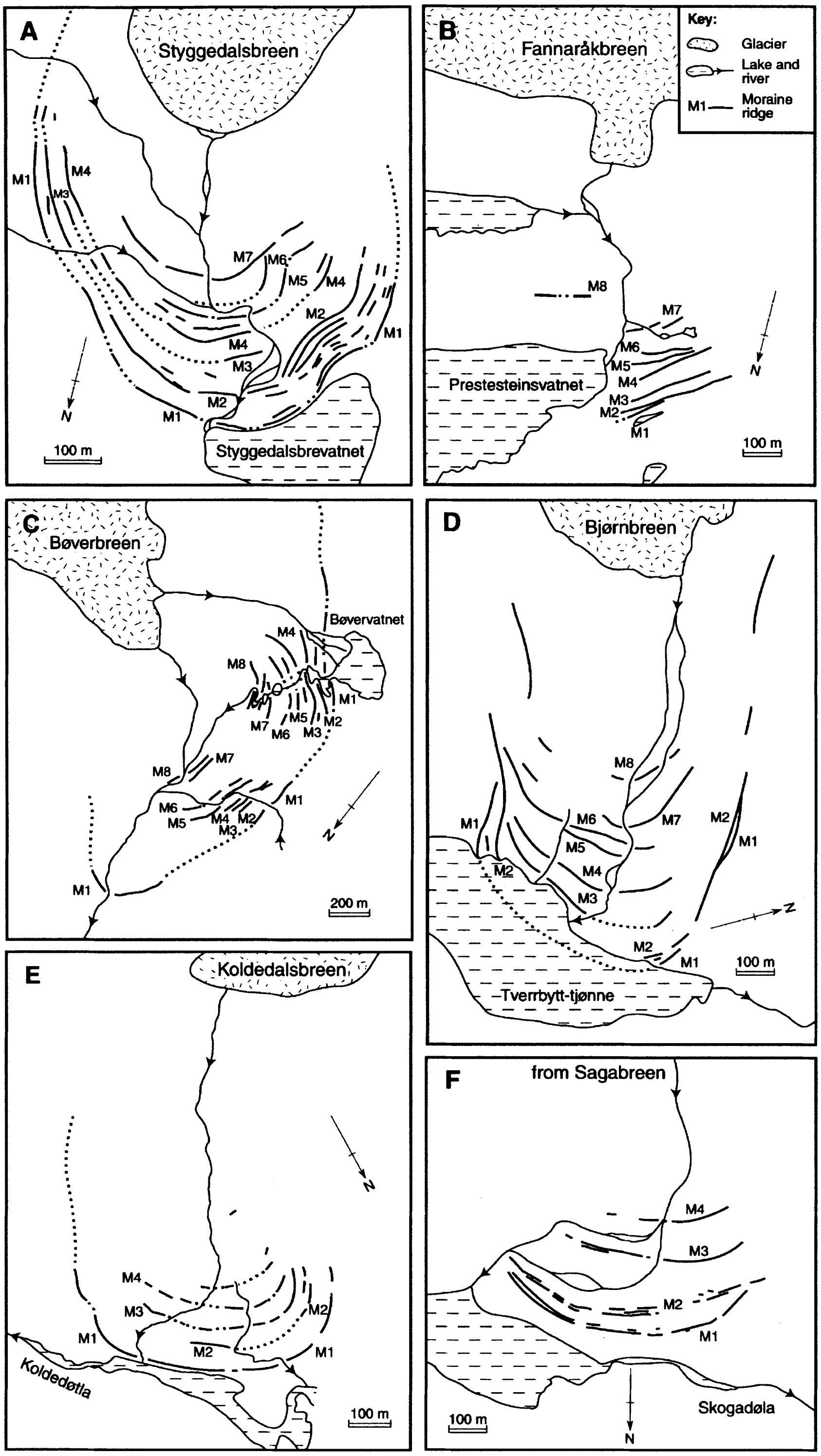

Figure 5 Moraine sequences in west Jotunheimen. (A) Styggedalsbreen; (B) Fannaråkbreen; (C) Bøverbreen; (D) Bjørnbreen; (E) Koldedalsbreen; (F) Sagabreen.

between M1 and M3 on the western side of the meltwater stream, which have been destroyed and/or buried by lake-dredging operations since lichen-size measurements were made. Only the outer (M1) and the inner (M3) ridge of the latter complex (which corresponds with moraines 'a–d' of Erikstad and Sollid, 1986) had lichens sufficiently large to be useful for dating purposes. Dating of M2 was attempted but, as lichen sizes suggest a younger age than M3, the predicted age is not reliable. All the other moraine dates have been predicted in correct chronological order.

Beyond the 'Little Ice Age' moraine sequence, several well-developed older moraine ridges are present, which have been assigned a Preboreal age by Vorren (1973). A pre-'Little Ice Age' date for these ridges is indicated by three lines of evidence in addition to the morphostratigraphic correlation approach of Vorren: (1) very large lichens growing on and between the moraines (single largest over a wide search area 330 mm; mean of the five largest 300 mm) indicate a pre-'Little Ice Age' date; (2) the development of thick Arctic Brown Soils on the ridge tops indicates an age of at least several thousands

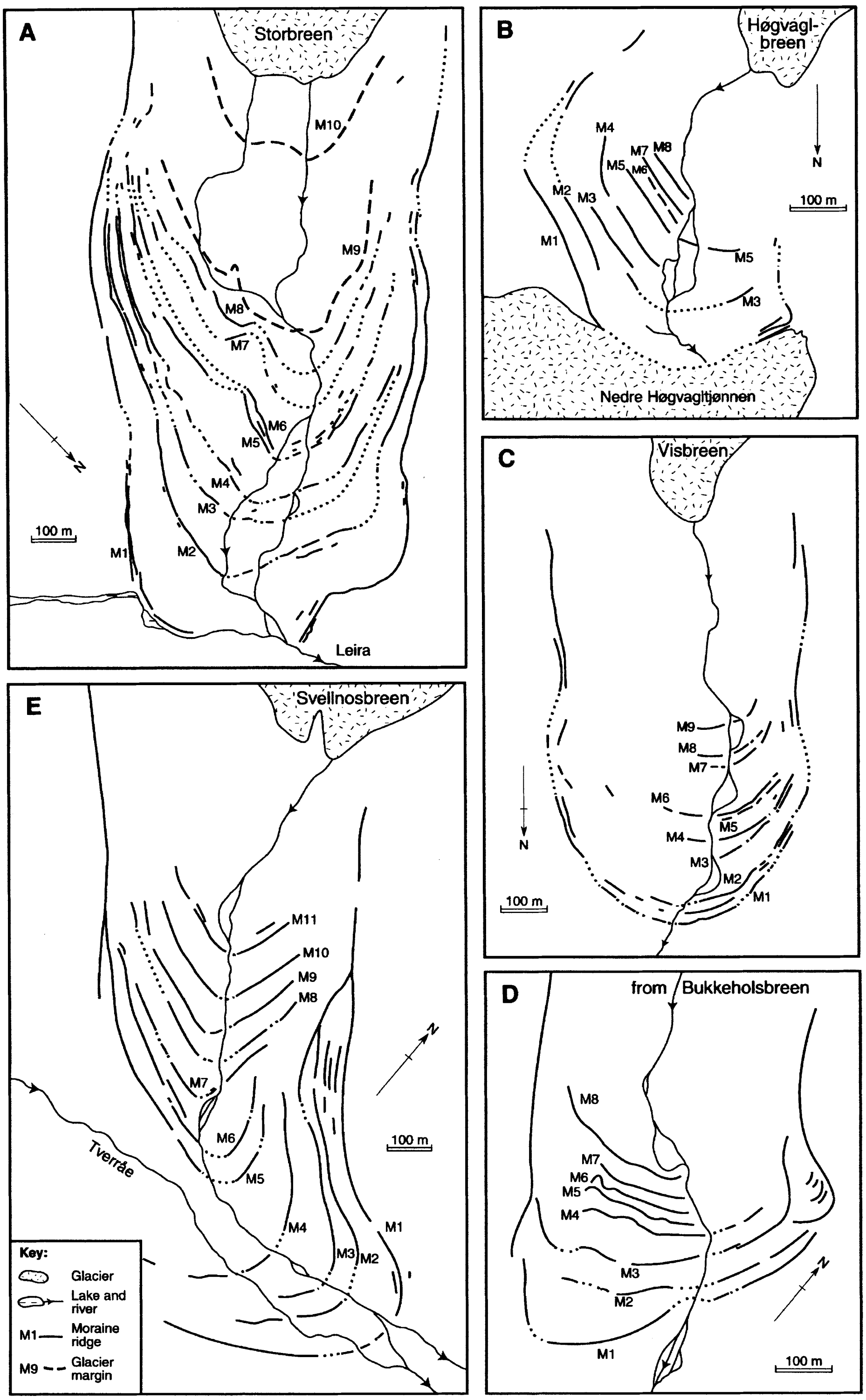

Figure 6 Moraine sequences in central Jotunheimen. (A) Storbreen; (B) Høgvaglbreen; (C) Visbren; (D) Bukkeholsbreen; (E) Svellnosbreen/ Tverråbreen.

of years (cf. Matthews and Caseldine, 1987; McCarroll and Ware, 1989); and (3) the occurrence of large-scale periglacial sorted patterned ground on the flat terrain between the ridges (Griffey and Matthews, 1978) requires a more severe periglacial climate than that experienced since the Preboreal.

Fannaråkbreen (Figure 5B)

At the northern outlet of Fannaråken ice cap on the Sognfjell plateau, at an altitude of 1360–1400 m, eight laterofrontal moraine ridges were dated, one of which was used as a control point (M8; Type II). The predicted age for M8 suggests a possible underestimate of age by three years. The outermost moraine (M1) was not considered a control point as it is partly overidden by M2 and consisted of only three sites: its predicted date of AD 1790 may therefore underestimate the true age, and is considered unreliable. There is little reason to doubt the lichenometric dates for the remaining moraines (M2–M7) because a minimum of five sites were available for each moraine ridge and the predictions are in correct chronological order. Only one useful historical photograph of Fannaråkbreen has been located, which was taken in AD 1916 (Nordenskiold,

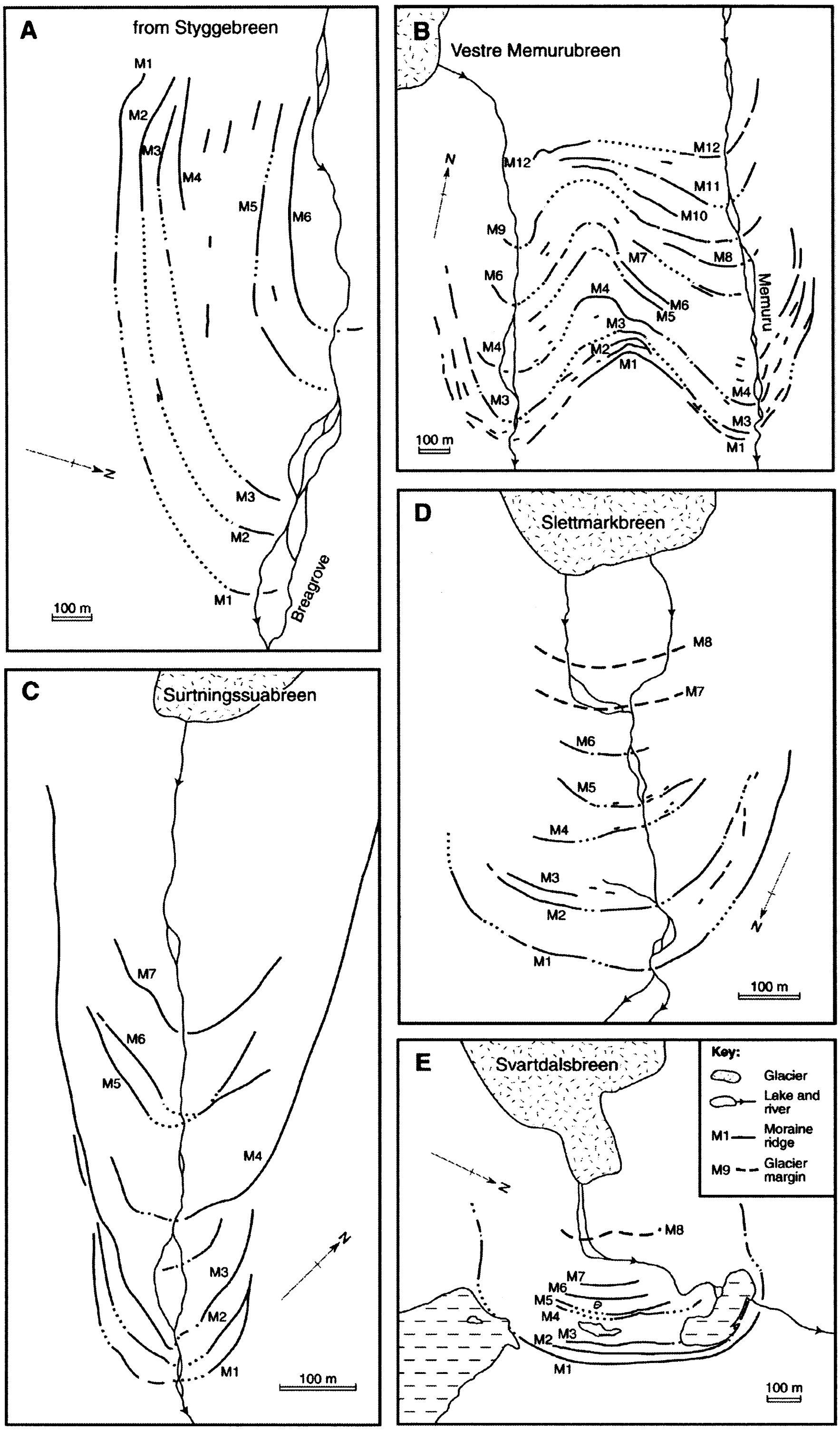

Figure 7 Moraine sequences in east Jotunheimen. (A) Styggebreen; (B) Memurubreen; (C) Surtningsuabreen; (D) Slettmarkbreen; (E) Svartdalsbreen.

1917): although this shows a distant view, it appears to be consistent with the lichenometric results.

Bøverbreen (Figure 5C)

Bøverbreen is the northwestern outlet of the Smørstabbreen ice cap and has an extensive glacier foreland. Lichens were measured at two series of sites: data from eight of the lateral moraines described in Matthews *et al.* (1986) at an altitude around 1370–1380 m close to the shore of Falkebergtjønne (also known as Bøvervatnet) were combined with a second series of eight laterofrontal and frontal moraines to the north at an altitude of 1280–1340 m. As the combined data set was a large one involving a minimum of nine and up to 18 sites per moraine, and as all the predicted ages are in correct chronological order, the lichenometric dates are likely to be reliable.

M8 and M1 were used as Type II and Type III control points, respectively. The AD 1930 date for M8 is corroborated by the predicted lichenometric date of 1929, an apparent overprediction of age by only one year. Although the lichenometric date for M1 appears to be an underprediction of age by 27 years, the possibility that this Type III control point dates from close to AD 1777, rather than around 1750, cannot be

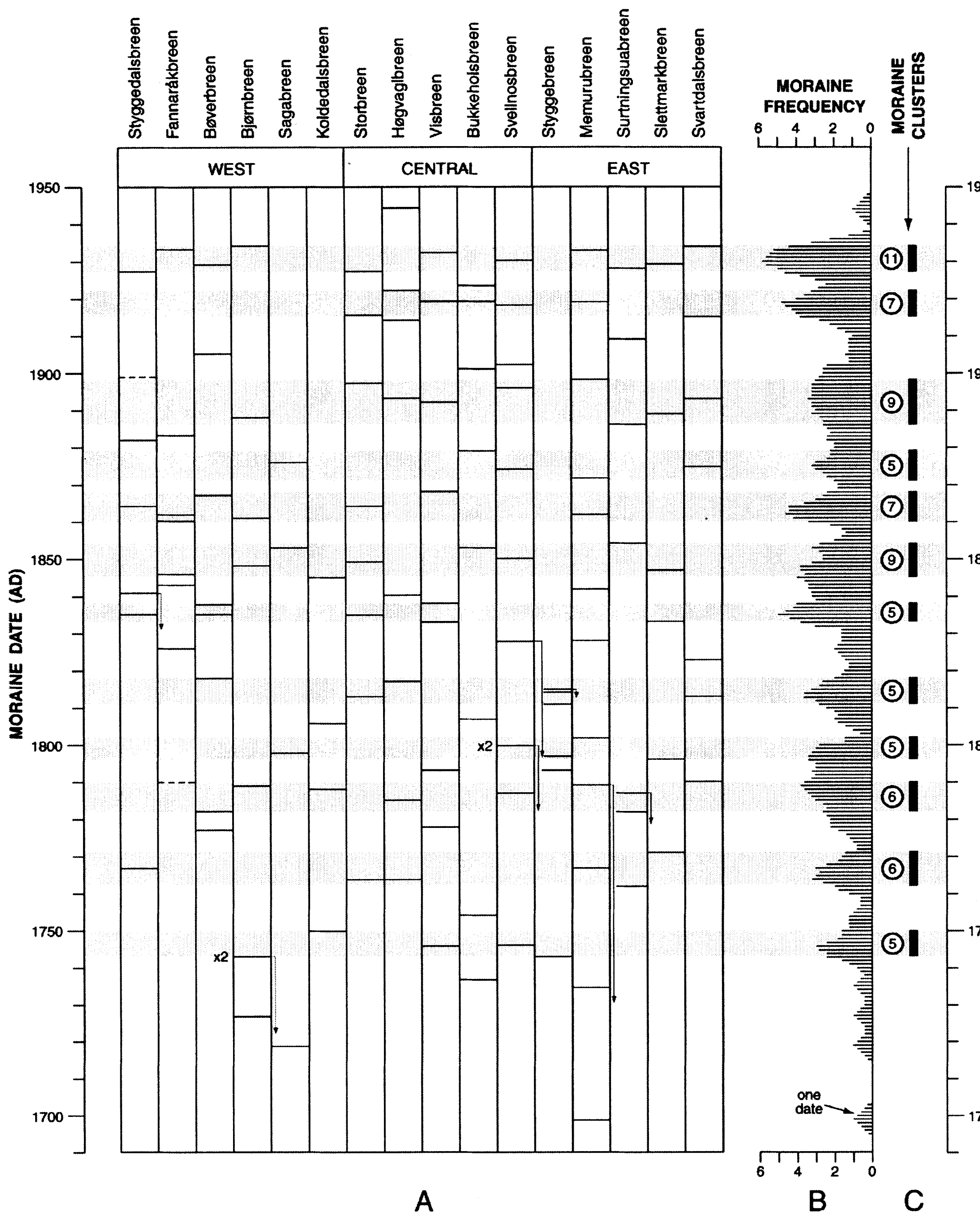

Figure 8 Lichenometric dates and the composite 'Little Ice Age' moraine chronology for 16 Jotunheimen glaciers. (A) Dated moraine sequences at each glacier foreland. (B) Histogram of weighted moraine frequency in which individual dates are plotted over a 10-year time interval. (C) Moraine clusters when moraine formation occurred at several glaciers (number of glaciers in each cluster is circled). Grey bands across the figure indicate the timespans of the moraine clusters. Further explanation in the text.

ruled out. Based on bracketing ages for ice-dammed lake sediments (Matthews *et al.*, 1986; Matthews, 1991), the 'Little Ice Age' glacier maximum has been dated by radiocarbon but the calibrated results are not sufficiently precise to resolve the problem.

A photograph taken by P.A. Øyen in 1903 at the upper moraine series (Figure 2C; Øyen, 1913) shows the glacier and some of the moraines. Unfortunately moraine ridge M7, which has been dated by lichenometry to AD 1905, is not clear on the photograph. Although this moraine ridge has not therefore been used as a control point, it nevertheless appears to date from around this time when the glacier was more or less stationary (Hoel and Werenskiold, 1962). A second photograph (Figure 2D; Øyen, 1909a) at the lower moraine series shows a steep glacier front that is also consistent with a glacier that was advancing or stationary at this time, but the terrain close to the glacier is mostly obscured by snowbeds banked against the snout.

Bjørnbreen (Figure 5D)

No previous investigations are known to the writer relating to this glacier or its 'Little Ice Age' moraine sequence, which consists of eight well-developed, arcuate lateral and frontal moraine ridges, several of which descend from around 1450 m to enter the lake Tverrbytt-tjønne at 1350 m. An additional moraine ridge occurs on both sides of the glacier foreland between M7 and M8 but this was too fragmented to be dated. Two of the moraines were used as Type II and Type III control points (M8 and M1, respectively). The predicted lichenometric dates for these control points are in good agreement, with an apparent underprediction of age by four years for M8 and an apparent overprediction of only seven years for M1.

Predicted dates for moraines M8–M4 are in chronological order and based on between five and seven sites per moraine. Moraine M2 is characterized, however, by lichens that are of equal size to those on M1 and, moreover, M3 has the largest lichens recorded on any 'Little Ice Age' moraine in Jotunheimen (five largest 132 mm; single largest 158 mm), which must cast doubt on the veracity of the predicted age of M1. The likely explanation for the relatively large lichens and hence the relatively old predicted dates at Bjørnbreen is the location of the glacier foreland close under the eastern flank of Storbjørn (2222 m), the highest mountain in the Smørstabbtinden massif. Although similarly high mountains occur close to the headwall of many of the other glaciers investigated in west Jotunheimen (most notably the Skagastølstinden in the Hurrungane massif, which rise to >2400 m), all the other glaciers are larger and their moraines consequently lie much farther from the high peaks. It is probable, therefore, that precipitation and hence moisture supply to the lichens is significantly greater on the Bjørnbreen glacier foreland. Although no meteorological data are available from the Smørstabbtinden massif to support this assertion, the annual precipitation at the former meteorological station on Fannaråken (2062 m) (Norske Meteorologiske Institutt, 1949) was considerably higher than the 860 mm currently recorded at Sognfjell (1413 m).

Koldedalsbreen (Figure 5E) and Sagabreen (Figure 5F)

Both glaciers have retreated up steep bedrock slopes: consequently, relatively young moraines are difficult, if not impossible, to identify. However, four well-developed arcuate moraines characterize the flat, lower parts of both glacier forelands, at altitudes of about 1200 and 1300 m, respectively. At Koldedalsbreen, fragments of at least two younger moraine ridges are present inside M4 and, at Sagabreen, the three outer moraines each comprise two or three distinct ridges. It was not possible to date these additional ridges due to disturbance and/or insufficient area available for lichen growth.

Both outermost moraines (M1) were used as control points. The lichenometric dates of AD 1750 and 1719 predicted for these type III control points at Koldedalsbreen and Sagabreen, respectively, are based on a large number of sites in both cases. It is possible that moisture conditions for lichen growth are particularly favourable on the Sagabreen glacier foreland (based on similar reasoning to that given for Bjørnbreen), but there are no other reasons to doubt the reliability of the lichenometric dates from these forelands, all of which are in correct chronological order. Radiocarbon dates obtained on moss and soil samples from beneath M1 at Sagabreen, the youngest of which is 210 ± 65 ^{14}C years BP (Matthews, 1991), confirm the 'Little Ice Age' status of the outermost moraine but such dates provide a broad range of possible calendar ages when calibrated.

Storbreen (Figure 6A)

Eight arcuate lateral and frontal moraines (M1–M8) descend to the valley bottom from an altitude over 1350 m to about 1120 m on the eastern side of the Smørstabbtinden massif. Four of these moraines (M1 and M6–M8) and two more recent glacier snout positions (M9 and M10) were used as control points in this study and have been used in previous lichenometric dating by Matthews (1974; 1975; 1977) and Erikstad and Sollid (1986). The evidence for the control points, which is based on observations and measurements by P.A. Øyen and others, historical photographs, maps and aerial photographs, has been described in detail by Matthews (1974; 1975). Radiocarbon dates as young as 270 ± 60 ^{14}C years BP, obtained from moss and soil samples excavated from beneath M1 (Matthews, 1991), confirm that the outermost moraine (M1) dates from the 'Little Ice Age' but are insufficiently precise to provide a control point for lichenometric dating.

The age of M1 according to the central Jotunheimen lichenometric dating curve underestimates the apparent historical age by 15 years, and the age of M5 is overestimated by eight years, but the other four control points have lichenometric ages within $\pm$ 3 years of the known historical age. The lichenometric dates for M2–M5 given in Table 2 are in correct chronological order and are considered to be of comparable accuracy as they differ from the preferred dates in Matthews (1975) by 3–10 years. Additional moraine ridges between M5 and M6, and distal to both M2 and M1 have not been dated due to insufficient area for lichen growth, though dates have been suggested by comparison with regional tree-growth trends (Matthews, 1977). Other supposed moraine ridges located inside M8 by Erikstad and Sollid (1986) on their map are considered to be largely erosional features and therefore were not included in this study.

Høgvaglbreen (Figure 6B)

Eight frontal and laterofrontal moraine ridges were identified by Erikstad and Sollid (1986) at an altitude of 1400–1440 m on the relatively flat glacier foreland of Høgvaglbreen, which lies east of Austre Høgvagltind (1916 m) and south of Nedre Høgvagltjønnen. The same ridges and control points are recognized in this study: M5 was observed during formation in AD 1891 (Øyen, 1893) and the youngest moraine (M8) was dated with reference to a photograph in the possession of Norges Geografiske Oppmåling that was taken between 1932 and 1934 (Erikstad and Sollid, 1986). The lichenometric ages of the youngest (M8) and oldest (M1) control points are underpredictions by 11 and 14 years, respectively, but the date of AD 1893 for M5 is accurately predicted, and all the predicted dates are in chronological order.

Visbreen (Figure 6C) and Bukkeholsbreen (Figure 6D)

Nine frontal and laterofrontal moraine ridges have been dated at Visbreen (M1–M9) where the glacier foreland extends northwards at an altitude of 1430–1480 m into upper Visdalen. On the opposite side of upper Visdalen, eight arcuate frontal and lateral moraine ridges of Bukkeholsbreen (M1–M8) occur on the relatively steep, southeast-facing valley side at an altitude of 1400–1600 m. One additional ridge occurs on the Visbreen glacier foreland between M1 and M2 but this was not dated because it was partially overridden by M2 and had too few habitats conducive to lichen growth.

The M1 lateral moraines of Bukkeholsbreen are exceptionally large (exceeding 30 m in height on both sides of the glacier foreland) with the northern one having developed into a small rock glacier (Vere and Matthews, 1985). These lateral moraines dominate the landscape but have relatively small lichens due to exposure and/or slope instability. Lichen measurements were therefore confined to the smaller laterofrontal and frontal parts of the moraines.

The youngest and oldest moraine on both glacier forelands were used as Type II and Type III control points. Whereas the ages of both control points at Visbreen were predicted within $\pm$4 years by the central Jotunheimen lichenometric-dating curve, the ages of those at Bukkeholsbreen appear to have been overpredicted by 7 (M8) and 13 (M1) years, though all predicted dates at both Visbreen and Bukkeholsbreen are in correct chronological order.

Svellnosbreen/Tverråbreen (Figure 6E)

At their 'Little Ice Age' maximum extent, and during the deposition of at least M1–M4, Svellnosbreen and Tverråbreen were confluent. After the two glaciers separated, seven further moraine ridges (M5–M11) were deposited by Svellnosbreen while no clear moraines survive on the glacier foreland of Tverråbreen. The combined sequence of lateral and frontal moraines extends from an altitude of about 1200 m (at the foot of the bedrock cliff below the current Svellnosbreen snout) to about 1400 m (in the Tverråbreen valley bottom). The western lateral moraine of Svellnosbreen is exceptionally large and of comparable size to those of Bukkeholsbreen.

The youngest moraine ridge (M11) is a Type I control point based on several photographs of Svellnosbreen taken in AD 1927 and 1929 by A. Koller and others (e.g., Hesselberg and Birkeland, 1941), combined with the measured retreat of 9.5 m between AD 1927 and 1929 (Hoel and Werenskiold, 1962). Although it is possible that the M11 ridge is up to three years older, the AD 1930 date is supported by an identical predicted lichenometric date. A photograph by W. Solheim shows that the glacier had retreated rapidly up a steep bedrock cliff by AD 1941 (Werenskiold, 1948).

Two of the 11 moraine ridges (M2 and M4) are considered undated as the predicted dates are not in chronological order. There are also several additional lateral moraine-ridge fragments on the eastern side of the Svellnosbreen foreland between M1 and M2, and a well-vegetated, laterofrontal moraine ridge on the south side of the Tverråbreen valley, about 300 m in front of M1. Although lichenometric dating of this older ridge was not possible because of insufficient lichen cover, it may well date from before the 'Little Ice Age' (Schroeder-Lanz, 1983).

Styggebreen (Figure 7A)

Six arcuate, often fragmented, laterofrontal moraine ridges were identified on the east-facing lower slopes of Visdalen at an altitude of about 1120–1250 m. The outermost moraines (M1–M3) extend below the birch treeline but the best preserved ridges are on the southern side of the glacier foreland, above the treeline. Younger moraines are absent because of steep bedrock cliffs at higher elevations. Only the outermost moraine (M1) was used as a control point (Type III), the lichenometric age of which appears to be an overestimate of seven years. As the lichen sizes on the three oldest lateral moraines (M1–M3) are unaffected by tree growth, it is likely that these moraines have been successfully dated by the east Jotunheimen lichenometric dating curve. However, uncertainty remains about the age differences between the younger moraines (M4–M6), as their lichenometric dates lie within ± 5 years of each other with one (M5) out of chronological order. There are also three undated moraine-ridge fragments between M4 and M5.

Memurubreen (Figure 7B)

The 'Little Ice Age' moraine sequence at Memurubreen is extensive, occupying two parallel, south-trending valleys and the interfluve between, at altitudes of 1400 to 1550 m. These moraine ridges are particularly well developed near the crest of the interfluve, as shown on a detailed geomorphological map of the glacier foreland (Erikstad and Sollid, 1990). Two present-day glaciers – Austre and Vestre Memurubreen – were confluent when most of these moraines were deposited. Located about 0.5 km downstream from the 'Little Ice Age' moraines in the western valley, at an altitude of about 1390 m, is a distinct, older moraine ridge of presumed Preboreal age. A minimum age estimate of 4440 ± 70 ^{14}C years BP has been obtained for this older moraine based on samples from the arctic-alpine Brown Soil developed on the moraine crest (Matthews, 1993).

Lichenometric dating of 12 'Little Ice Age' moraine ridges (M1–M12) was attempted, 11 of which correspond to moraines 'a–k' of Erikstad and Sollid (1986). An additional, undated ridge occurs between M1 and M2 but there was insufficient surface area for dating due to partial burial by M2 on the interfluve and disturbance in the western valley. In addition to using M1 as a Type III control point, M11 and M12 were used as Type I control points. The historical photographic and measurement evidence for assigning dates of AD 1910 and 1933 to the two younger moraine ridges has been discussed by Erikstad and Sollid (1986). Annual retreat measurements made by P.A. Øyen clearly indicate deglacierization of M11 by AD 1910 but there are inconsistencies between some of the available photographs.

The age of M1 has also been investigated by radiocarbon dating of an arctic-alpine Brown Soil found buried beneath it. A date as young as 495 ± 55 ^{14}C years BP provides a maximum age estimate (Matthews and Caseldine, 1987). However, when calibrated, this date is again too imprecise to improve the reliability of the control point for lichenometric dating purposes. The predicted lichenometric date for M1 appears to overpredict the age of this control point by 51 years, which suggests either that the moraine is older than expected or that lichen growth rate has been enhanced relative to other sites in east Jotunheimen. Although the relatively high altitude of the site may be a factor, there is no evidence for relatively high lichen growth rates from the younger control points, the predicted age of M12 being identical to the historical age and that for M11 being an underprediction by nine years. It is possible, therefore, that the 'Little Ice Age' maximum may have been earlier than AD 1750 at Memurubreen. Only one lichenometric date from the Memurubreen moraine sequence (M2) is rejected for being out of chronological order.

Surtningssuabreen (Figure 7C)

This relatively small glacier foreland slopes steeply down into Øvre Russglopet on the eastern side of the Surtningssua massif from an altitude of nearly 1700 m to about 1400 m in the valley bottom. Lichen sizes were measured on eight moraine ridges below about 1520 m, but lichenometric dating was attempted at only seven of these (M1–M7) as there was very little lichen growth on the ridge indicated between M3 and M4. Lichen growth was also restricted on the large lateral moraines, which are comparable in size and type to those of Bukkeholsbreen. Six moraines are considered to have been dated successfully, M2 being out of chronological order, the age of the Type II control point (M7) being overpredicted by only two years and that of the older, Type III control point (M1) underpredicted by 12 years.

Slettmarkbreen (Figure 7D) and Svartdalsbreen (Figure 7E)

These small glaciers are located in the mountains between lakes Gjende and Bygdin, southeastern Jotunheimen. At Slettmarkbreen, lichen-size measurements were carried out on six frontal and laterofrontal moraine ridges (M1–M6), two of which (M1 and M6) were used as Type III and Type II control points, respectively. Two younger, glacier snout positions (M7 and M8), which have been mapped in detail by O. Liestøl (Hoel and Werenskiold, 1962: 171), provided additional control points. The glacier foreland has very little relief resulting in an altitudinal range of 1400–1450 m. Lichenometric dates of the three youngest control points are overpredictions of between one and eight years, whereas the outer moraine (M1) is underpredicted by 21 years.

Seven moraine ridges with an altitudinal range of only 1470 to 1490 m in the bottom of Svartdalen indicate that the former snout of Svartdalsbreen had a lobate form similar to a piedmont glacier. Four of these moraines (M1 and M5–M7) and one additional snout position (M8) sufficiently well dated to be used as control points are shown on a detailed map produced by O. Liestøl (Hoel and Werenskiold, 1962: 172). The ages of the four youngest control points were deduced by Erikstad and Sollid (1986) based on the annual measurements of P.A. Øyen. There is also a distant view of the glacier in a photograph taken in AD 1904 (Øyen, 1909b), which appears to be consistent with the ages of control points M5 and M6. Lichenometric ages of control points M5–M8 include overpredictions of age by up to seven years and underpredictions of up to five years, whereas M1 is underpredicted by 40 years. As the lichenometric dates for the outermost moraines at Slettmarkbreen and Svartdalsbreen are both substantial underpredictions, this suggests that the 'Little Ice Age' maximum of these two glaciers may indeed date from the late eighteenth century rather than the mid-eighteenth century.

Composite moraine chronologies

Composite moraine chronologies have been constructed for the Jotunheimen region as a whole and for the three subregions separately using the lichenometric dating results from the 16 glacier forelands summarized in Table 2. The approach is based on two principles (Bickerton and Matthews, 1993): first, that the effects of any errors in the dating of individual moraine sequences are reduced when the data from a number of glaciers are combined; and, secondly, that a large data set enables the regional glacier response, and hence the climatic effects, to be differentiated from local glacier behaviour.

Jotunheimen

The composite 'Jotunheimen' chronology shown in Figure 8 includes only lichenometric dates (even for the control points). Any date indicated by arrows as out of sequence in the chronology of an individual glacier (Figure 8 A) is omitted from the composite frequency histogram (Figure 8B) and the moraine clusters (Figure 8C). Questionable predicted dates at Styggedalsbreen and Fannaråkbreen derived from <4 sites per moraine ridge (indicated by dashed lines in Figure 8A) have also been omitted.

Twelve main clusters have been identified in Figure 8C. Each cluster contains moraines from at least five and up to 11 glaciers. The clusters contain 80 of the 112 moraines from which acceptable lichenometric dates have been obtained. Thus, a high proportion (71.4%) of the dated moraines fall into the 12 clusters, which occupy only 93 years (37.2%) of the 250-year record from AD 1700 to 1950.

The youngest cluster (AD 1927–1934), which includes moraines from 11 of the 14 glaciers where topography was conducive to moraine formation at the time, is in excellent agreement with the available historical evidence from Jotunheimen. The oldest cluster, which dates from AD 1743–1750 and is represented at five glaciers, is fully consistent with the conventional mid-eighteenth century 'Little Ice Age' maximum in southern Norway. Although early eighteenth-century maxima are suggested for four glaciers, the lack of any earlier clustering points to errors in dating and/or aberrant local glacier behaviour. Three further clusters occur in the late-eighteenth century at AD 1762–1771, 1782–1790 and 1796–1802), six in the nineteenth century (AD 1811–1818, 1833–1838, 1845–1854, 1860–1868, 1871–1879, 1886–1898) and one in the early twentieth century (AD 1915–1922).

Western, central and eastern subregions

Subregional chronologies (Figure 9A) allow the spatial pattern within Jotunheimen to be considered. Although the small number of glacier forelands in each subregion must be taken into account, important similarities and differences between subregions appear to be detectable in the three records:

- There is a prominent moraine cluster dating from around AD 1930 in all three subregions.
- Moraine clusters at AD 1915–1922 and 1886–1898 can be identified in east Jotunheimen and are particularly strongly represented in central Jotunheimen but are absent from west Jotunheimen.
- The moraine cluster identified at AD 1871–1879 in the composite Jotunheimen chronology is not strongly represented in any subregion.
- Three mid-eighteenth century moraine clusters at AD 1833–1838, 1845–1854, and 1860–1868 are prominent in west and central Jotunheimen but cannot be recognized in east Jotunheimen.
- Two prominent clusters at the end of the seventeenth and beginning of the eighteenth centuries (AD 1796–1802 and 1811–1818) in east Jotunheimen do not appear to be represented in west Jotunheimen and are difficult to recognize in central Jotunheimen.
- In relation to the older clusters at AD 1762–1771 and around 1750, small sample sizes make subregional patterns more difficult to discern.

Discussion

Before considering the implications of these results for understanding 'Little Ice Age' glacier and climatic variations, and for lichenometric dating in general, the accuracy of the predicted dates obtained in this study requires further discussion.

Accuracy of the regionally controlled approach

The values in Table 4 are differences between the true, historical age of the control points and the predicted age according to various lichenometric dating curves. These values therefore measure the errors in predicted dates. The first column refers to errors in the regionally controlled curves for west, central and east Jotunheimen; the second column refers to errors in the Jotunheimen curve (which uses all control points, taking no account of spatial variation in lichen growth rates across the region). Differences between the two columns therefore provide a measure of the improvements in accuracy brought about by using regionally controlled predicted dates. For each of the three subregions, the errors are shown separately for the younger control points (derived from surfaces 23–86 years old at the time of lichen measurement) and for the older control points (derived from the outermost 'Little Ice Age' moraines; 221–242 years old) as well as for all control points combined.

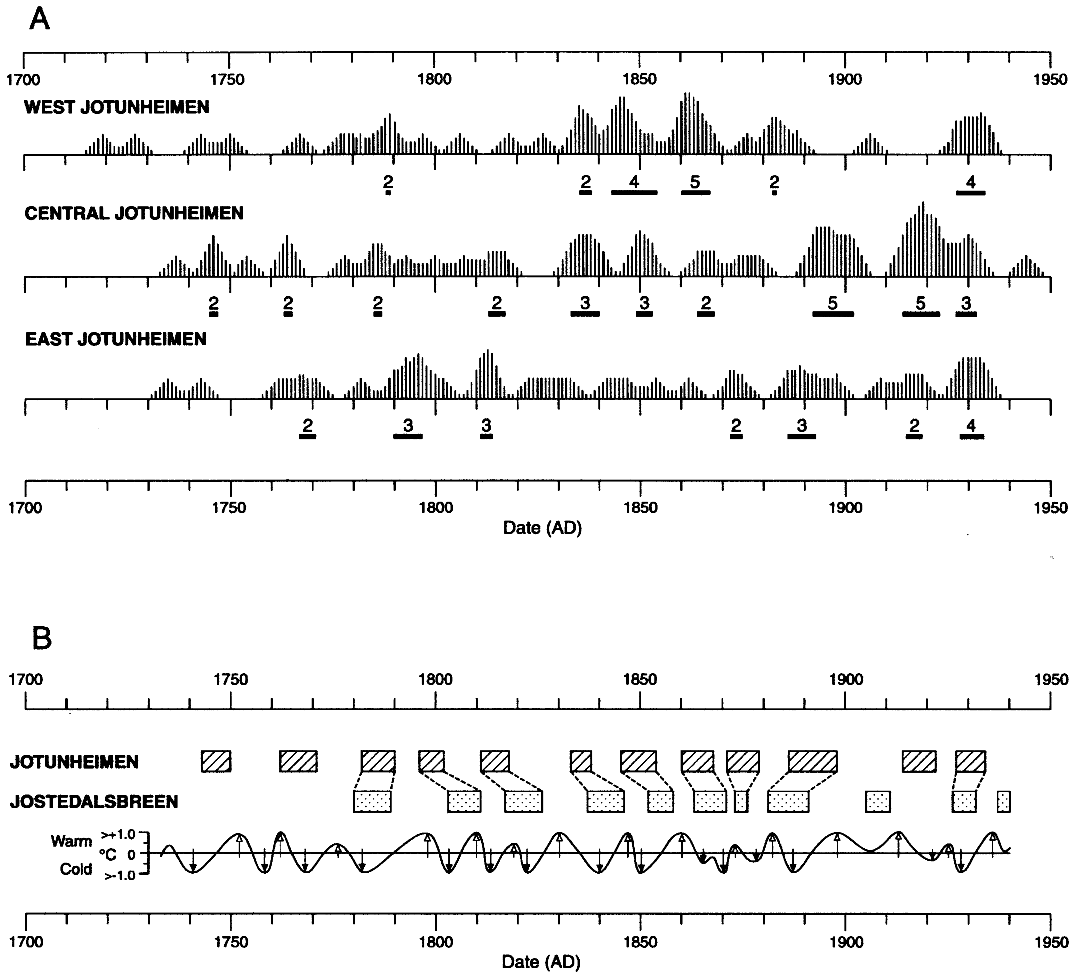

Figure 9 (A) Subregional 'Little Ice Age' moraine chronologies for west, central and east Jotunheimen (moraine frequency was weighted as in Figure 8 and numbers refer to the number of moraines in particular clusters). (B) Comparison of Jotunheimen and Jostedalsbreen moraine clusters with annual- to decadal-scale summer temperature oscillations derived from tree-ring data (possible age-equivalent moraine clusters are indicated by dashed lines). The curve in (B) is a summer temperature index (Bickerton and Matthews, 1993: 64) smoothed through major (>1°C) and minor (>0.5°C) maxima and minima (highlighted by arrows).

Considering first the results for all control points, the errors inherent in regionally controlled dating are shown to vary from $\pm$ 7.9 years for central Jotunheimen to $\pm$ 15.3 years for west Jotunheimen and $\pm$ 19.1 years for eastern Jotunheimen (based on $\pm 1\sigma$). As the average age of the control points is 123 years, these values represent errors of 6.5–15.5% (or 13–31% with 95% certainty). Nonregionally controlled dating (i.e., the Jotunheimen curve) adds, on average, an overestimate of age by 10 years for sites in west Jotunheimen, and an underestimate of age by eight years for sites in east Jotunheimen, whereas no effect is indicated in central Jotunheimen. Thus, when younger and older surfaces are not differentiated, the average improvement from use of regionally controlled lichenometry is about $\pm$ 10 years (or 8%).

Table 4 Mean and standard deviation ($\pm 1\sigma$) of age differences (in years) between Jotunheimen control-point age and lichenometric predicted ages from regionally controlled and nonregionally controlled lichenometric dating curves (further explanation in the text).

Control points	Regionally controlled lichenometric dating	Nonregionally controlled lichenometric dating
West Jotunheimen		
All surfaces	-0.1 ± 15.3	$+10.4 \pm 15.6$
Younger surfaces	$+1.1 \pm 4.8$	$+9.7 \pm 4.9$
Older moraines	-1.3 ± 22.4	$+11.1 \pm 22.9$
Central Jotunheimen		
All surfaces	-0.1 ± 7.9	-0.4 ± 7.9
Younger surfaces	$+0.6 \pm 5.2$	-0.7 ± 5.2
Older moraines	-1.5 ± 12.4	-2.7 ± 12.2
East Jotunheimen		
All surfaces	-0.3 ± 19.1	-8.0 ± 19.8
Younger surfaces	$+1.1 \pm 5.7$	-1.1 ± 5.8
Older moraines	-2.9 ± 34.5	-21.8 ± 30.6

The age of the younger control points are estimated to within $\pm$ 4.8–5.7 years ($\pm 1\sigma$) by the regionally controlled approach, whereas the predicted ages of the older surfaces contain errors of $\pm$ 12.4–34.5 years. Greatest improvements over the Jotunheimen curve are in evidence on the older surfaces in west and east Jotunheimen, where the data indicate an overestimate of 11 years and an underestimate of 29 years, respectively, have been avoided. As the older surfaces have an average age of about 233 years, these values represent improvements of 4.7 and 12.4%, respectively, the improvement in central Jotunheimen being negligible.

Among the younger moraines, there is relatively little improvement in accuracy, except for those in west Jotunheimen, where the improvement appears to be nearly 10 years (some 17%, given that the average age of the younger fixed points is 57 years). Thus, in west Jotunheimen, regionally controlled dating seems to have brought about a consistent improvement over the Jotunheimen curve of around 10 years, which applies to young and old surfaces alike, whereas in east Jotunheimen a greater improvement of over 20 years applies only to the older surfaces. The negligible improvement registered in central Jotunheimen can be explained by its intermediate location between sites in west Jotunheimen, the age of which are overestimated by the Jotunheimen curve, and sites in east Jotunheimen, the age of which are underestimated.

Implications for 'Little Ice Age' glacier and climatic variations

There are many implications of regionally controlled lichenometric dating for reconstructing glacier and climatic variations. First, the improved accuracy in dating, which is commonly ± 10 years and as much as ± 20 years for the older surfaces, is of considerable importance for the construction of composite regional moraine chronologies such as that for Jotunheimen (Figure 8) where both the duration of moraine-formation events and the time interval between the events is of a similar order. The average duration of the 12 moraine clusters defined in the Jotunheimen chronology is about eight years and the average interval between clusters (each defined by its midpoint in time) is 17 years.

The previously published regional moraine chronology for Jotunheimen of Erikstad and Sollid (1986: 98) was based on the 'adjusted mountain curve', which included control points from a much wider region than Jotunheimen. Eight moraine-building events were identified between about AD 1800 and 1930 using a nonregionally controlled approach. The greater accuracy of the dates from the regionally controlled approach, combined with the much larger number of moraine sequences investigated in Jotunheimen, must lead to the rejection of their major conclusion that the outermost 'Little Ice Age' moraines in Jotunheimen date from the period AD 1780–1820 (though this may be the case at Slettmarkbreen and Svartdalsbreen, two of the smallest glacier forelands where there also appear to be fewer relatively old moraines). Similarly, most if not all of their eighteenth-century moraines seem to be older than their results suggest. Their three youngest clusters around AD 1930–1935, 1915–1920 and 1895–1900 are, however, in good agreement with the three youngest clusters from this study, which is consistent with the regionally controlled approach producing greater improvements on the older surfaces. Even greater departures from true ages are likely where lichenometric dating is attempted using lichenometric dating curves from a *different* region: as used, for example, by Winkler *et al.* (2003) and Shakesby *et al.* (2004) who dated moraine sequences in Breheimen using curves from the neighbouring Jotunheimen and Jostedalsbreen regions.

Relatively accurate composite moraine chronologies also permit comparisons between regions and investigations of relationships to climate (Figure 9B). The regionally controlled moraine chronology for Jotunheimen shows greater similarities with the composite Jostedalsbreen moraine chronology of Bickerton and Matthews (1993) than a similar comparison of the two regions made by Erikstad and Sollid (1986: 98). According to Figure 9B, glaciers in both regions produced moraines around AD 1930 but the second youngest moraine cluster in Jotunheimen (AD 1915–1922) is not present at Jostedalsbreen and the youngest cluster at Jostedalsbreen (AD 1937–1940) is not represented in Jotunheimen (except possibly at Høgvaglbreen). The first decade of the twentieth century is notable in Jotunheimen by an absence of moraine formation, whereas a distinct moraine cluster dates from 1905–1911 at Jostedalsbreen. All these twentieth-century moraine-formation episodes are verified by historical evidence, which must strengthen confidence in the earlier moraine clusters predicted as a result of regionally controlled lichenometric dating in Jotunheimen.

Viewed as a whole, the composite moraine chronologies summarized in Figure 9B seem to suggest that intervals when the glaciers in the two regions have fluctuated in phase (around AD 1930, in the late 1800s, and in the 1780s) have alternated with intervals when they have fluctuated out of phase (notably in the first two decades of the twentieth century, and in the first half of the nineteenth century). A hypothesis explaining this complexity is proposed below, which involves the interaction of summer temperature fluctuations and winter precipitation.

Moraine formation during glacier retreat from the outermost moraine of each 'Little Ice Age' moraine sequence can be attributed to short-term episodes of glacier advance or still-stand. Bickerton and Matthews (1993) emphasized the near-instantaneous response of glacier tongues to runs of years with relatively low summer temperature: summer temperatures have traditionally been regarded as the dominant cause of such advances in the twentieth century in southern Norway (Fægri, 1950; Rogstad, 1951; Hoel and Werenskiold, 1962; Liestøl, 1967). The match between moraine clusters and episodes and intervals of reduced summer temperature (Figure 9B) is far from perfect. However, this is consistent with glacier variations being affected by both enhanced winter precipitation and lower summer temperatures. Indeed, there is increasing recognition that winter precipitation variations have been influential in late twentieth-century glacier advances (Nesje, 1989; Nesje *et al.*, 1995).

The fact that the net balance of the maritime glaciers of western Norway, such as the outlet glaciers of Jostedalsbreen, is more influenced by the winter balance than the summer balance, whereas the opposite is the case for the more continental glaciers of Jotunheimen (Nesje *et al.*, 1995; Nesje and Dahl, 2000: 85), helps account for some of the differences in glacier behaviour between the regions. Glacier advances caused, or predominantly caused, by low summer temperatures would, on the one hand, be expected to occur in both regions because temperature changes have high spatial coherence affecting relatively large areas in the same way. On the other hand, glacier advances caused by an increase in winter precipitation are more likely to be regional in character and, in the southern Norwegian case, be more effective in the maritime Jostedalsbreen region where the winter balance is dominant. It is proposed, therefore, that the out-of-phase glacier advances are forced by winter precipitation or, at least, that they are not simply the result of summer temperature variations.

Although other factors may also be influential, particularly in individual cases (such as dating errors or the differing response times of glaciers of different size) there is support for this hypothesis from the twentieth-century record of glacier and climatic variations around Jostedalsbreen (Nesje, 1989), which may be regarded as a modern analogue. The advances of the outlet glaciers in the 1900s and 1920s both correspond with intervals of below-average (AD 1901–1980) summer temperatures defined in terms of the summer tetratherm (mean June–September temperature). Crucially, however, the decadal mean summer temperature for AD 1901–1910 was not as low as for AD 1921–1930 (0.3°C and 0.5°C below the long-term average, respectively) and winter (October–April) precipitation was 24% above the long-term average during the 1901–1910 decade but did not differ from the average during the 1921–1930 decade (Nesje, 1989). Winter precipitation seems therefore to have played a much more important role in the earlier advance, which did not occur in Jotunheimen (Figures 8 and 9B).

There are similar implications in relation to the subregional moraine chronologies (Figure 9A) and to subregional differences in glacier behaviour, which are much more likely to be detected by an accurately dated regionally controlled approach. Several differences in the timing of moraine formation have been recognized in this study between west, central and east Jotunheimen. Many of these differences can also be explained by differences in the relative importance of the climate forcing factors affecting glacier variations along the regional climatic gradient from west to east Jotunheimen: the temperature-dependent AD 1930 glacier advances again being present across the whole region whereas winter precipitation-dependent advances are most prominent in west Jotunheimen.

Finally, there are implications relating to local variations of individual glaciers. Use of regionally controlled lichenometric dating provides more accurate moraine chronologies at the local scale. Ultimately, the most accurate approach to dating a particular moraine sequence is to construct a separate lichenometric dating curve for that moraine sequence using local control points only (Matthews, 1994), and this has been possible for a few glacier forelands in Jotunheimen (Matthews, 1974; Erikstad and Sollid, 1986). There are dangers, however, in anomalous control points having disproportionate effect where few control points are available at the local scale. Such dangers are to some extent reduced by employing subregional dating curves for local dating.

Implications for lichen growth rates

Different lichenometric dating curves for the different subregions (Figure 3) imply higher growth rates in the more maritime west Jotunheimen and lower growth rates in the more continental east Jotunheimen. The differences in growth rate are highlighted in Figure 10, which shows two west–east gradients in standardized growth rates: (1) that based on the size of lichens on the youngest moraine from each foreland (surface ages 43–62 years), which are characteristic of the first *c.* 50 years of lichen growth; and (2) that derived from the size of lichens on the outermost moraines (surface ages 221–242 years), which are characteristic of the next *c.* 200 years. These data sets are, however, subject to several qualifications. First, they are 'mean cumulative growth rates' rather than growth rates as such. Secondly, they incorporate any differences in the time taken for establishment or ecesis as well as growth rates (though Figure 3 suggests establishment times of <10 years in all subregions). Thirdly, differences in growth rates between the younger and older moraines may reflect different proportions of section *Alpicola* and section *Rhizocarpon* in the lichen populations (as well as declining growth rates over time).

The mean cumulative growth rate in the early stages reduces significantly from around 0.75 mm yr^{-1} in the west to around 0.55 mm yr^{-1} in the east. A less statistically significant decline in growth rate is apparent from the oldest moraine surfaces from slightly under 0.55 mm yr^{-1} in the west to about 0.45 mm yr^{-1} in the east. These mean growth rates are high by world standards (Webber and Andrews, 1973), comparable to those in Iceland (Evans *et al.*, 1999) and higher than in northern Sweden (Karlén and Black, 2002), indicating highly favourable conditions for the growth of the *Rhizocarpon* subgenus. The gradients of the linear regression lines are, respectively, 0.004 mm yr^{-1}km and 0.0014 mm yr^{-1}km, which can be attributed to the decrease in moisture available for lichen growth towards the east, though there are insufficient meteorological data available to relate the growth rates quantitatively to precipitation (cf. Evans *et al.*, 1999). Nevertheless, it may be concluded from these results that early differences in growth rate in response to moisture availability do not persist indefinitely. This in turn suggests that other environmental factors, such as competition, become more important controls on growth rates in the later stages of lichen growth on these surfaces.

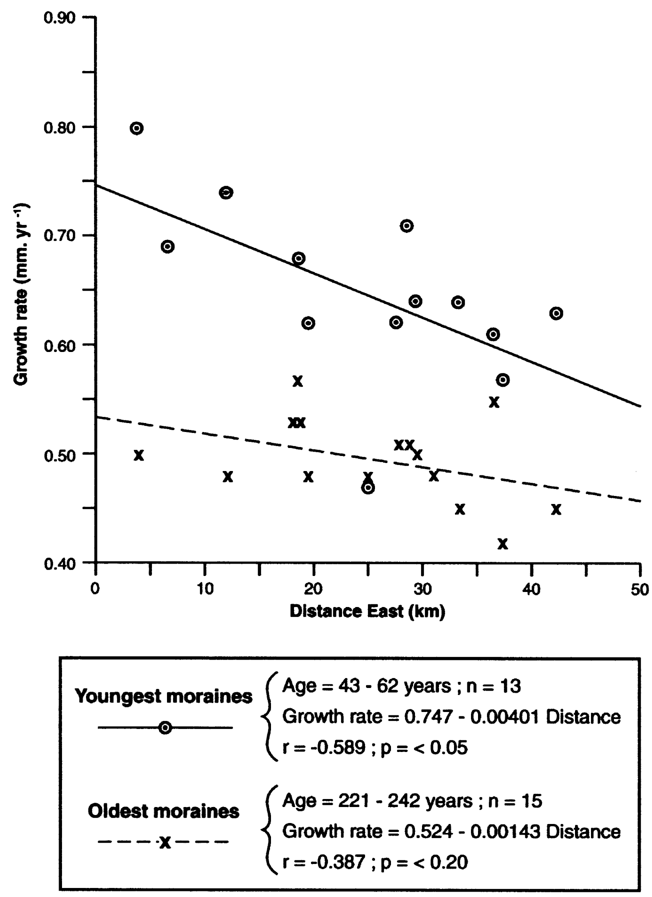

Figure 10 West–east gradient in lichen growth rates derived from lichen-size data on relatively young and relatively old 'Little Ice Age' moraines. Regression equations and other statistical data relating to the two relationships are shown in the box.

Summary and conclusions

(1) 'Little Ice Age' moraine ridge sequences on 16 glacier forelands in Jotunheimen, southern Norway, were mapped and dated by regionally controlled lichenometric dating (Figures 5–7; Table 2). Each moraine sequence comprises 4–13 frontal and lateral moraine ridges deposited since the beginning of the eighteenth century in the low- to mid-alpine zone (altitudinal range 1100–1500 m).

(2) Regionally controlled dating using the *Rhizocarpon* subgenus involved the construction of separate lichenometric dating curves for west, central and eastern Jotunheimen from surfaces of known historical age (control points) in the respective subregions (Figure 4). Accuracy of the curves was measured by comparing predicted lichenometric ages with control-point ages with the conclusion that surfaces that are about 50 years old can be dated with an accuracy of ± 6 years ($\pm 1\sigma$) while surfaces that are about 230 years old can be dated with an accuracy of ± 35 years. The regionally controlled approach improved dating accuracy by up to ± 20 years (about 12%) on relatively old moraine ridges in east Jotunheimen and up to ± 10 years (about 17%) on young and old moraine ridges in west Jotunheimen.

(3) A composite, regional moraine chronology for Jotunheimen (Figure 8) shows that over 70% of the dated moraines are grouped into 12 clusters (more or less synchronous, regional moraine-formation events) at AD 1743–1750, 1762–1771, 1782–1790, 1796–1802, 1811–1818, 1833–1838, 1845–1854, 1860–1868, 1871–1879, 1886–1898, 1915–1922 and 1927–1934 (with each moraine cluster represented at five or more glaciers). The earliest moraine cluster is consistent with a traditional mid-eighteenth-century date for the regional 'Little Ice Age' glacier maximum in Jotunheimen.

(4) The subregional moraine chronologies for west, central and eastern Jotunheimen (Figure 9 A) enable the identification of subregional differences in glacier behaviour. Similarities and differences between the subregional records and between the Jotunheimen record and that of Jostedalsbreen (Figure 9B) suggest that the climate forcing of glacier variations at the annual to decadal scale involves the complex interaction of summer temperature and winter precipitation. Glacier advances and moraine-formation events that are summer-temperature dependent occur synchronously throughout the regions, whereas spatially restricted events are more likely to be driven by winter precipitation variations, which are a more effective control on the glacier net balance in western Norway and west Jotunheimen.

(5) Differences between the regionally controlled lichenometric dating curves from west, central and eastern Jotunheimen reflect moisture availability: lichen growth rates are relatively high in the maritime west and decline towards the continental east (Figure 10). However, growth rates also decrease with moraine age, probably reflecting competitive effects between lichens on the rock surfaces. On the youngest moraines (indicative of the first 50 years of growth) the mean cumulative grow rates of about 0.75 mm yr^{-1} in west Jotunheimen fall to about 0.55 mm yr^{-1} in east Jotunheimen; on the oldest surfaces (moraine ages about 230 years) there is a less significant decline from a little less than 0.55 mm yr^{-1} in the west to about 0.45 mm yr^{-1} in the east.

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