Schmidt hammer age evaluation of the moraine sequence in front of Bøyabreen, western Norway

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The entire moraine sequence in front of Bøyabreen, a southern outlet of Jostedalsbreen in southern Norway, has until now been regarded as being made up of 'Little Ice Age' (LIA) moraines. As the historical evidence does not support a LIA date for the outermost moraine, a Schmidt hammer was used to measure the degree of surface weathering from boulders on the three outermost moraine ridges. The R-values suggest that the boulders on the moraine (M1) below Bøyafjellstølen are much more weathered and consequently much older than those on the second (M2) and third (M3) moraines 500 m up-valley. The lichen sizes suggest a pre-LIA date. According to the glacial history of the Jostedalsbreen region, the M1 probably date to the Early Holocene.

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Introduction

Bøyabreen, located 8 km north of Fjærlandsfjorden in southern Norway, is a southerly 900 m-high outlet from the Jostedalsbreen ice cap (Fig. 1). In total, ca. 16 moraine ridges occur along the 2 km-long part of the valley bottom between the present glacier front and the M1 moraine 50 m to the south of Bøyafjellstølen (Figs. 2 and 3). This moraine ridge has been interpreted to represent the southernmost position of Bøyabreen during the 'Little Ice Age' (Rekstad 1900, 1901, 1910; Grove 1988; Mjanger & Hofsøy 1989; Aa & Sønstegaard 1995). According to Rekstad (1900), Bøyabreen was at its outermost LIA position in AD 1743, some years prior to Nigardsbreen (AD 1748). Fægri (1934) made a sketch of the moraine ridges, but the main river has in the meantime changed its course, making it hard to locate the single moraine ridges. According to distances referred to in the text, it is obvious that Fægri also used the M1 as the maximum LIA moraine. However, according to T. Mundal (pers. comm. 1998) the Bøyafjellstølen could not have been overridden by the glacier at that time. He referred to a 'Merkesbrev' dated 11 September AD 1748 from the Bøyafjell-støls area. We know of no other historical documents concerning the glacier margin during the period AD 1743–1867. For the period after 1868, several photos and frontal measurements may be used to reconstruct the ice margin fairly well (Sexe 1869; de Seue 1870; Rekstad 1900, 1901, 1904; Fægri 1934, 1950).

Because of the uncertainty as to whether the M1 moraine dates to the LIA, we undertook to estimate its relative age compared to moraines M2 and M3 by Schmidt hammer tests. We also compared the relative sizes of lichens on the actual moraines.

Methods

To date the moraines of Bøyadalen, lichens were measured and compared with the Nigardsbre curve (Mjanger & Hofsøy 1989), proposed by Erikstad & Sollid (1986). Fægri (1934) suggested that the lichen method could not be used in Bøyadalen where there was too much moss and various kinds of lichens. Lichens approaching ca. 250 mm are usually difficult to recognize (Matthews et al. 1996). However, we were able to recognize well-developed lichens ranging from 7–30 cm on the actual moraine ridges. The largest sample of single lichen on each boulder was measured, according to the approach developed by McCarroll (1994a).

The Schmidt hammer is an instrument that records the distance of rebound of a spring loaded mass impacting a surface. The distance of rebound (R) is related to the elastic properties of the surface. In this study we used the Schmidt hammer to evaluate the degree of weathering as an indicator of surface age of moraine boulders (Matthews & Shakesby 1984; McCarroll 1989). Evaluation of age, based on Schmidt hammer rebound values, will always be a sort of *relative* dating based on some reference rebound values. This investigation employed the same types of methods as those recommended by McCarroll (1994b).

We used boulders of similar lithology, and band gneiss with anisotropic orientation of the mineral grains was preferred (McCarroll 1990). Augengneiss was omitted, as it seems to produce large deviations (McCarroll 1994b). Moss- and lichen-covered surfaces were also avoided. Where *Rhizicarpon geographicum* agg. lichens were found, they were measured and compared with the Schmidt hammer results.

To obtain an old reference site (R1), 150 blows were

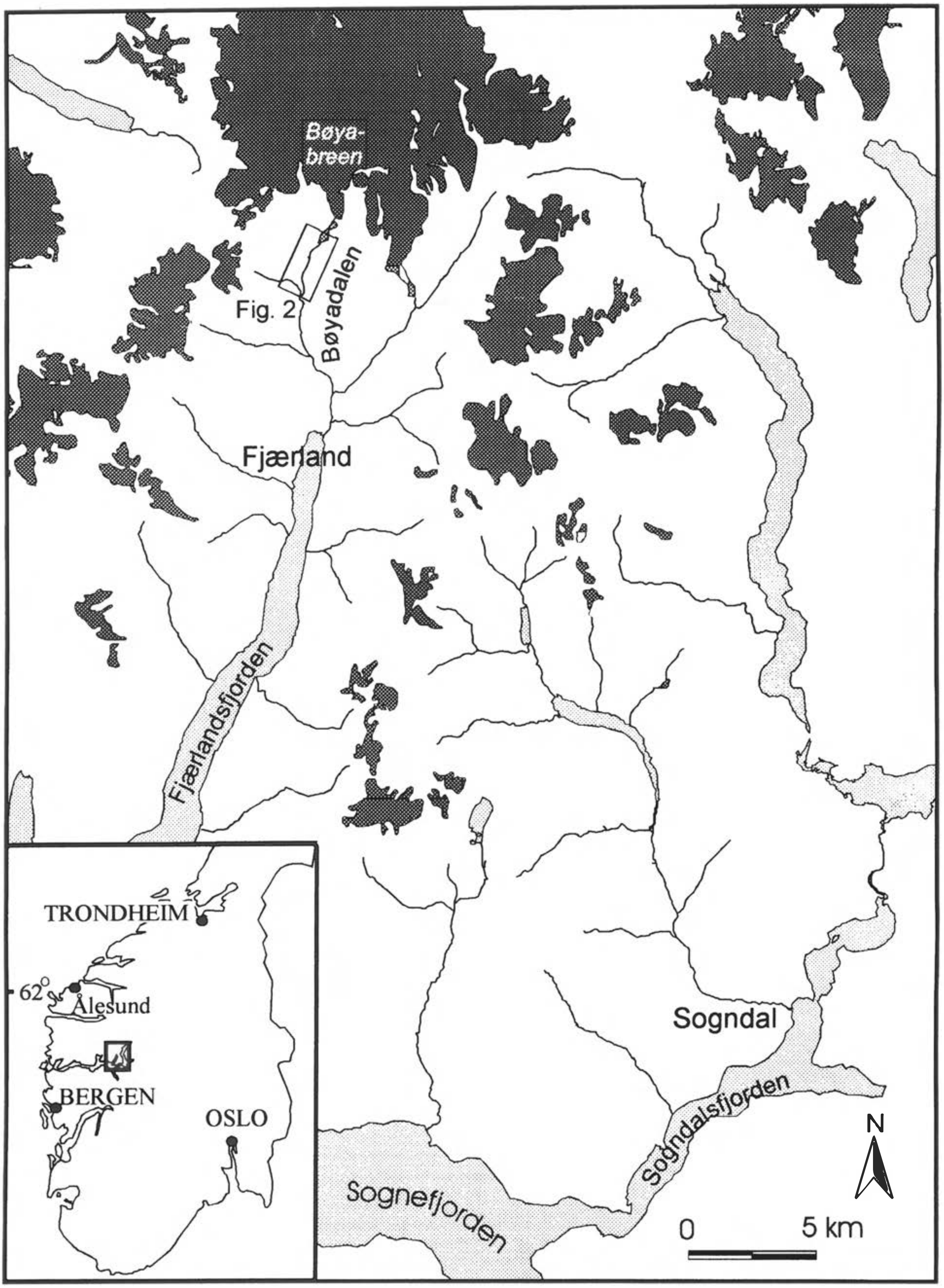

Fig. 1. Location map.

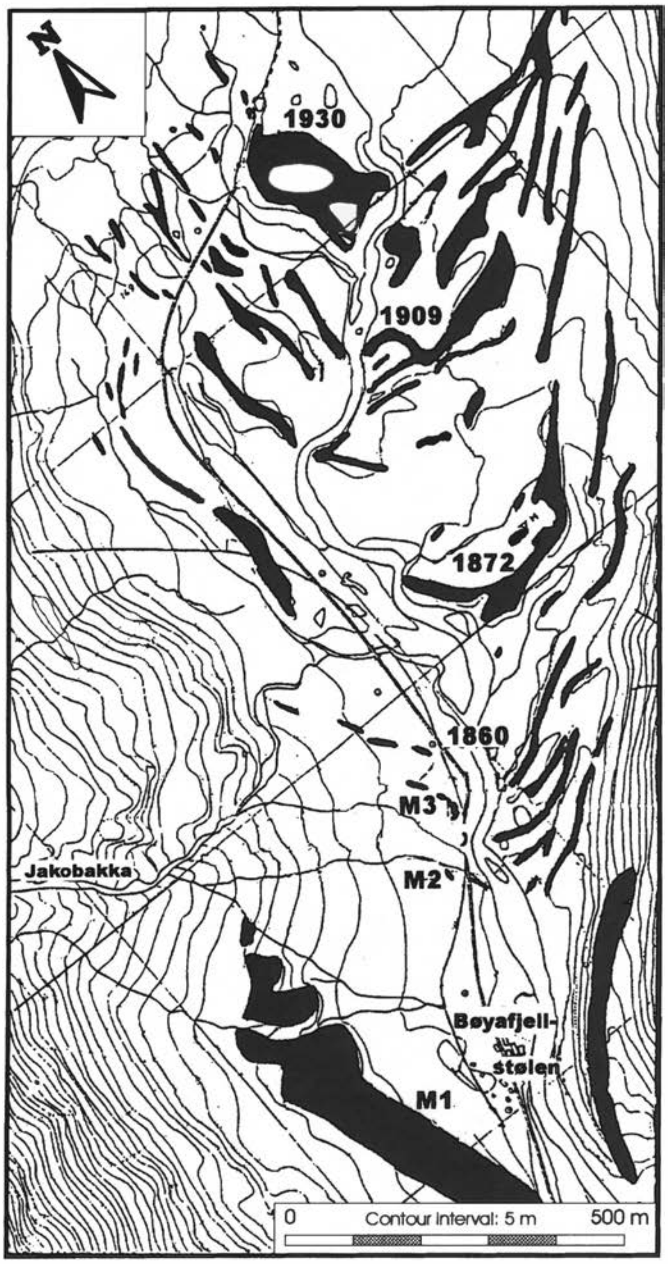

Fig. 2. The moraine sequence in front of Bøyabreen, modified from Mjanger & Hofsøy (1989).

made 125 m a.s.l. at the head of Fjærlandsfjorden. The time of deglaciation has not been exactly dated, but we suppose ca. 9800 ^{14}C yr BP deduced from the general deglaciation history of the Sognefjord area. A shell date from the mouth of Sogndalsfjorden (Fig. 1) gave 9740 ± 120 ^{14}C yr BP (Aa 1982), which represents a minimum age for the deglaciation in that part of the main fjord. Fjærlandsfjord was probably also ice free at that time. In addition, a relatively high marine limit of 110 m a.s.l. accounts for early deglaciation in Fjærland.

To obtain a young reference site (R2), 175 blows were made on an excavated rock surface at the entrance to the Fjærland-Skei tunnel in Bøyadalen and on fresh boulders of the new road cut at Fjærlandsfjorden, giving a mean R-value of 62.4. Here, an exposure age of 10 years is used.

Fig. 3. Aerial photo of Bøyadalen from moraine M1 at Bøyafjellstølen (B) to Brevatnet (Norfly A/S).

Histograms of the Schmidt hammer measurements on the reference sites are shown in Fig. 4A, B. In total, 160 blows were made on the M1 moraine ridge, including 5 shots on each boulder. On moraines M2 and M3, 70 blows were made. Histograms of the Schmidt hammer measurements on the moraines are shown in Fig. 4C–E.

The average error limits are given as ±2 standard deviations (95% confidence interval) of the arithmetic mean of the R-values obtained from the individual boulders.

Study sites

The Bøyafjellstøls moraine (M1)

This is an 8–10 m-high ridge (Fig. 2) 2 km below the present glacier margin. To the east of the main river the moraine is well defined. To the west of the river, however, there is a broad marginal zone disturbed by avalanches from the western mountainside. Along the tributary river of Jakobakka (Fig. 2) large snow avalanches occur annually, and only sporadic remnants of the marginal moraine can be seen.

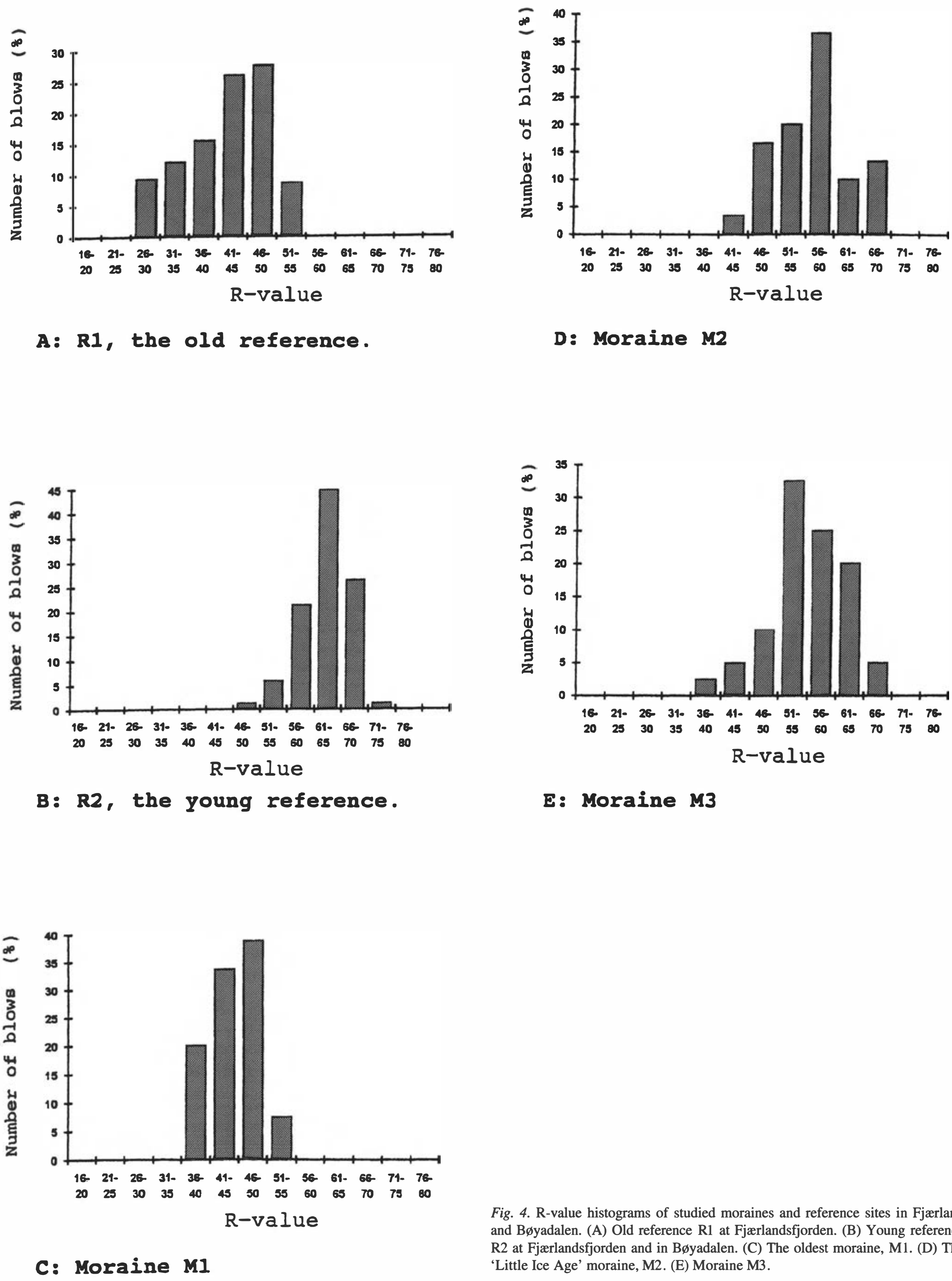

Fig. 4. R-value histograms of studied moraines and reference sites in Fjærland and Bøyadalen. (A) Old reference R1 at Fjærlandsfjorden. (B) Young reference R2 at Fjærlandsfjorden and in Bøyadalen. (C) The oldest moraine, M1. (D) The 'Little Ice Age' moraine, M2. (E) Moraine M3.

Table 1. Age estimates of moraines M1, M2 and M3 based on Schmidt hammer data and linear interpolation between reference ages. Concluded ages based on all available evidence are shown in the last column.

Locality	Age estimate	±2 standard deviations	Concluded ages (based on all evidence)
Old ref. (R1)	9740 yr BP		Early Preboreal age
Young ref. (R2)	10 yr		Recent age
Older moraine (M1)	8560 yr BP	342	Early Holocene age
M2	2890 yr BP	1127	Late Holocene age
M3	3317 yr BP	951	Late Holocene age

In total, 160 blows were made on M1 over the entire ridge to the west of the main river. On boulders with well-developed lichens we measured the largest; lichens with diameters of 16–22 cm were not unusual. A group of lichens with diameters of approx. 22 cm was separated. The mean R-value of 44.59 suggests that these lichens are older. A histogram of the Schmidt hammer measurements is shown in Fig. 4C.

The M2 moraine

From 500 m to the north of M1 towards the glacier there are several moraines. The southernmost of these, M2 (Fig. 2), is partly destroyed by snow avalanches from the western valley side along the tributary river Jakobakka. The remnants of the ridge are about 3 m high. To the east of the main river the ridge is larger and more continuous.

The largest lichens were 9.5–10 cm, except for a single one with a diameter of 13 cm. Mjanger & Hofsøy (1989) found an average of 9.2 cm for the three largest lichens. Thirty Schmidt hammer measurements at the road gave a mean R-value of 56.53. A histogram of the R-values is shown in Fig. 4D.

The M3 moraine

Although somewhat modified by snow avalanches, this ridge (Fig. 2), situated 50 m proximally to M2, is more continuous than M2. It is 2 m high close to the road, but only 1 m high further up on the Jakobakka avalanche fan, where it is probably partly buried by avalanche debris.

One lichen with a diameter of 12 cm was measured, but most of the lichens had diameters between 6 and 10 cm. Lichens on M3 were not measured by Mjanger & Hofsøy (1989), but on the neighbouring ridge to the north they determined 8.1 cm to be the average of the three largest lichens.

Table 2. Statistical parameters of the Schmidt hammer measurements.

Site	Mean	SD	Median	Modus	Skewness
R1	42.12	6.83	43	47	−0.48
R2	62.61	4.28	63	63	−0.69
M1	44.59	4.04	44	48	−0.07
M2	56.53	6.33	57.5	58	−0.09
M3	55.63	6.26	55	54	−0.36

Forty Schmidt hammer measurements were carried out on this ridge, giving a mean R-value of 55.63, which is not far from the mean R-value of M2. On the basis of morphostratigraphy and the lichen diameters, the M3 should be younger than M2. However, the degree of weathering is probably too small to be registered by the Schmidt hammer method. A histogram of the R-values is shown in Fig. 4E.

Discussion

The statistical parameters of the Schmidt hammer measurements are shown in Table 2. The number of blows may be too small for comprehensive analyses, but some conclusions can be drawn. The distribution of R-values shows some negative skewness for all sites, which is also indicated by the medians and moduses. This may point to a somewhat lower mean of the R-values than we observed. However, as long as negative skewness is present for all sites, it will not influence the relative chronology.

The mean R-value of the M1 ridge (Figs. 4 and 5) is significantly lower than those of the other two ridges, M2 and M3. When comparing with the reference values (R1 and R2), we can conclude that M1 was probably formed during the Early Holocene. Although there is some difference in the mean R-value between M2 and M3, the statistical material is too small to draw the conclusion that either of them is the oldest. In our opinion the rebound values indicate that M2 and M3 were formed during the LIA.

The Holocene history of climate and glacier variations in the Jostedalsbre region (e.g. Nesje et al. 1991) reveals three actual events: the LIA and the Early Holocene Finse and Erdalen events. If the M2 and M3 date to the LIA, which is probable according to the reference values of the actual lichen diameters, it is obvious that the M1 dates to the Early Holocene. McCarroll & Nesje (1993) showed that Schmidt hammer measurements of 'Little Ice Age' moraines clearly differed from those obtained on Early Holocene localities.

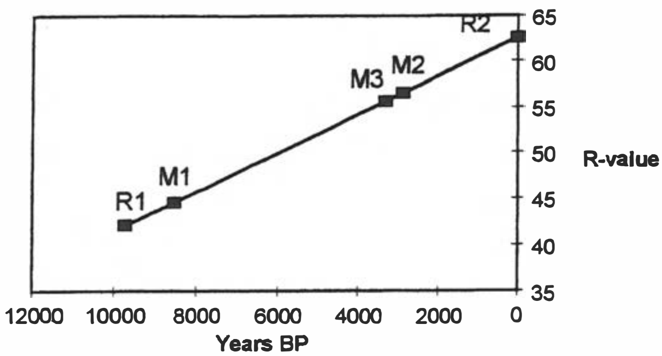

Fig. 5. Age estimates for moraines M1, M2 and M3 in Bøyadalen based on sites of 'known' age, Rl (the rock surface at Fjærlandsfjorden, deglaciated about 9740 BP), and R2 (fresh rock surface in Bøyadalen and fresh boulders at the Fjærland–Sogndal tunnel entrance).

In addition to the differences in surface weathering, the moraines also differ as to material content. M1, unlike M2 and M3, contains unsorted glacial till, which means that the glacier did not advance over glaciofluvial deposits, which, however, seems to be the case with M2 and M3, where retransported, rounded gravel and stones are observed. This supports the assumption that M1 dates from the Early Holocene with a halt or short re-advance of the glacier tongue. In general, 'Little Ice Age' moraines of the flat valley bottoms around Jostedalsbreen contain sorted sediments picked up from proglacial sandur outwash plains.

As regards the vegetation, there are generally large contrasts beyond and inside the LIA moraines. Such contrasts are absent in Bøyadalen, probably for two reasons. First, the valley bottom is only 150 m a.s.l., with a relatively short season of snow cover, and precipitation is high, leading to rapid growth of vegetation with small differences between the early deglaciated surfaces outside and freshly deglaciated terrain inside the 1750 moraine. Secondly, the large snow avalanche fan of Jakobakka covers a broad area of ca. 500 m on both sides of the M2 and M3 moraines, almost down to the M1 moraine. The vegetation is almost of the same age over the entire fan. The contrasts between vegetation outside and inside the M2 moraine seem more marked to the east of the main river, where avalanche activity is less, at least in the southernmost parts towards M1, the Bøyafjellstøls moraine.

Moraines from the Preboreal/Boreal transition are probably present in other parts of Fjærland as well. They are, however, not yet dated. In the eastern adjacent valley, Sogndalsdalen (Fig. 1), a large complex of terminal moraines is dated by proximal gyttja and lake sediments to 9100 ^{14}C yr BP (Eik & Kvalsvik 1997).

Conclusion

It seems obvious that the large difference in degree of surface weathering, according to the Schmidt hammer measurements, points to a much higher age of the M1 moraine than the M2 and M3 moraines. This assumption is also supported by lichenometry, the average diameters of *Rhizocarpon geographicum* being much larger on the M1 moraine than on M2 and M3. In addition to the differences in surface weathering and lichen diameters, the moraines also differ in material content, which indicates that M2 and M3 contain re-transported material. This seems not to be the case for the M1 moraine. We have made a proposal of the moraine ages based on the Schmidt hammer results, shown in Fig. 5 as the relation between rebound values and time (R/t). The straight line between R1 and R2 is based on an inferred linear weathering rate. Such a linearity is not proved, but chosen for clarity. It must be stressed that the age estimates are not absolute, but we have used these ages tentatively to interpret a relative chronology of the moraine sequences.

The age estimates and inferred ages are summarized in Table 1.

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