Schmidt hammer relative-age evaluation of a possible pre-'Little Ice Age' Neoglacial moraine, Leirbreen, southern Norway*

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Leirbreen is one of very few glaciers in southern Norway at which a moraine ridge has been identified which may record a pre-'Little Ice Age' Neoglacial advance. Previous attempts to date this ridge using ^{14}C dating of buried palaeosols, lichenometry and the Schmidt hammer have produced equivocal results. This detailed Schmidt hammer study suggests that anomalously low rebound values obtained on the possibly older ridge reflect spatial variations in lithology. Comparison of R-values from boulders of carefully specified lithologies reveals that boulders on the ridge are no more weathered than those elsewhere on the foreland and considerably less weathered than those beyond the moraine limits. Results are consistent with formation during the 'Little Ice Age', when other southern Norwegian glaciers reached their maximum extent.

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In northern Scandinavia, the Alps and elsewhere, moraine ridges in front of cirque and small valley glaciers have been attributed to glacial advances throughout the Holocene (Denton & Karlén 1973; Röthlisberger 1976; Grove 1979, 1988). In southern Norway, by contrast, Leirbreen is one of very few glaciers at which a moraine has been identified which may record a Holocene advance pre-dating the 'Little Ice Age' of the mid-eighteenth century. Attempts have been made to date this ridge using ^{14}C and lichenometry (Griffey & Matthews 1978; Griffey & Ellis 1979; Matthews & Shakesby 1984), but results have proved equivocal. Here, Schmidt hammer rebound (R-) values are used, together with careful analysis of lithological variability, to determine whether the boulders on this moraine ridge are significantly more weathered than those deposited closer to the glacier during the 'Little Ice Age'.

Site description

Leirbreen lies on the western flank of Smørstabbtindane, 2 km east of Krossbu in Breiseterdalen, western Jotunheimen (Fig. 1). The present snout, at 1500 m a.s.l., is more than 1 km broad and the glacier rises gently to an altitude of about 2000 m. During the 'Little Ice Age', about 250 years ago, the glacier extended a maximum of 500 m to the west. Intermittent retreat has exposed a poorly vegetated foreland marked by a sequence of moraine ridges. At the western terminus of the foreland, just north of the main meltwater stream, the outer moraine bifurcates. At first the ridges are similar, both consisting largely of boulders with little soil or vegetation cover, but farther northeast the outer ridge becomes increasingly subdued, is less bouldery and supports a more substantial vegetation cover. Five hundred metres northeast of the meltwater stream the outer ridge becomes so subdued that it can no longer be followed.

Griffey & Matthews (1978) obtained ^{14}C dates from the upper 2.5 cm of well-developed palaeosols buried beneath the outer ridge. Various soil organic fractions were dated and they concluded that the ridge was deposited about 1300 BP. Similar ages have been attributed to Neoglacial (i.e. Post Altithermal and pre-Little Ice 'Age') glacial advances in north Norway (Griffey & Worsley 1978; Worsley 1974; Worsley & Alexander 1976a,

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1976b), northern Sweden (Karlén 1973; Karlén & Denton 1976) and in other parts of the world (Mayr 1964; Patzelt 1973; Denton & Karlén 1977). However, subsequent research on age-depth relationships within buried palaeosols in Jotunheimen and Jostedalsbreen (Matthews 1980, 1981, 1982, 1985; Matthews & Dresser 1983; Matthews & Caseldine 1987) has led to a reappraisal of the dates obtained from Leirbreen and elsewhere, to the extent that Matthews (1980 and pers. comm.) considers them consistent with burial during the 'Little Ice Age'.

The possibility that there may have been a relatively extensive pre-'Little Ice Age' Neoglacial advance at Leirbreen has been reappraised by Harris et al. (1987). They obtained samples from a thin Arctic Brown Soil, close to the northern margin of Leirbreen, which was buried by pro-glacial lake sediments following retreat of the ice from its maximum 'Little Ice Age' limit. Chemical, palynological and ^{14}C analyses suggest that the soil was relatively immature at the time of burial. Harris et al. (1987) suggest that the soil is much younger than the Preboreal palaeosols investigated by Griffey & Matthews (1978), pedogenesis being initiated sometime after 1400 calendar years BP. An erosional event must have removed the Preboreal soil prior to renewed pedogenesis and they suggest that 'in view of the close proximity to the glacier, a pre-'Little Ice Age' Neoglacial advance extending beyond, but not far beyond, the '1750' [AD] limit on the northern margin of Leirbreen would appear a likely cause' (Harris et al. 1987, p. 88). They tentatively suggest that, in the western sector of the foreland, the outer ridge of the double moraine (since it is better vegetated and 'older looking'), may provide morphological evidence of a pre-'Little Ice Age' advance.

The age of the outermost moraine at Leirbreen has also been investigated by Matthews & Shakesby (1984). They used lichenometric measurements, together with Schmidt hammer rebound (R-) values (which provide an index of boulder-surface hardness and thus degree of weathering) to assess the relative age of the outer moraines at 33 Jotunheimen glaciers. Leirbreen was one of only seven glaciers at which the outer moraine yielded anomalously low R-values. At two high-altitude glaciers the lichenometric measurements confirm that the outer ridges probably pre-date the 'Little Ice Age' by a considerable margin. At the five lower altitude glaciers (including Leirbreen) the lichenometric and Schmidt hammer results disagree, and Matthews & Shakesby (1984) suggest that the low R-values may reflect the incorporation of older, weathered boulders by 'a simple push mechanism'. The typically platykurtic, bimodal frequency distributions of R-values is considered to support this interpretation.

At Leirbreen, however, because of the close proximity of the two outer ridges, it is possible that the absence of large lichens reflects lichen-kill caused by a persistent snow-cover when, during the 'Little Ice Age', the glacier approached an earlier, Neoglacial, limit. If this is the case, then the low R-values on the outer ridge may represent the weathering of boulders *in situ* rather than incorporation of older material by pushing. To investigate this possibility, a detailed Schmidt hammer study was undertaken.

The Schmidt hammer

The Schmidt hammer was designed for measuring the surface hardness of concrete. It records the rebound of a spring-loaded mass, which depends upon the elastic recovery of the surface and thus its hardness and compressive strength. It has been used in geomorphology as a measure of rock hardness and degree of weathering (see McCarroll [1987] for a review). Since, in arctic–alpine areas the degree of boulder-surface weathering provides a useful index of time since deposition (Birkeland et al. 1979; Brookes 1982; McCarroll 1985), Schmidt hammer rebound (R-) values have been used as indices of relative-age (Matthews & Shakesby 1984; Ballantyne 1986; Dawson et al. 1986; Matthews et al. 1986; Shakesby et al. 1987; Sjøberg 1987a, 1987b, 1987c; McCarroll 1986). Hard, fresh rock surfaces yield higher R-values than weathered (older) rock surfaces.

R-values are, however, influenced by factors other than degree of boulder-surface weathering. Instrument errors (McCarroll 1987), inappropriate sampling design, lithological variability and differences in boulder-surface texture can all lead to misinterpretation of results (McCarroll 1986 and in press). The influence of these factors was carefully considered in interpreting the R-values obtained in this study.

Relative-age evaluation

R-values were recorded from 16 sites on Leirbreen foreland and three sites beyond the moraine

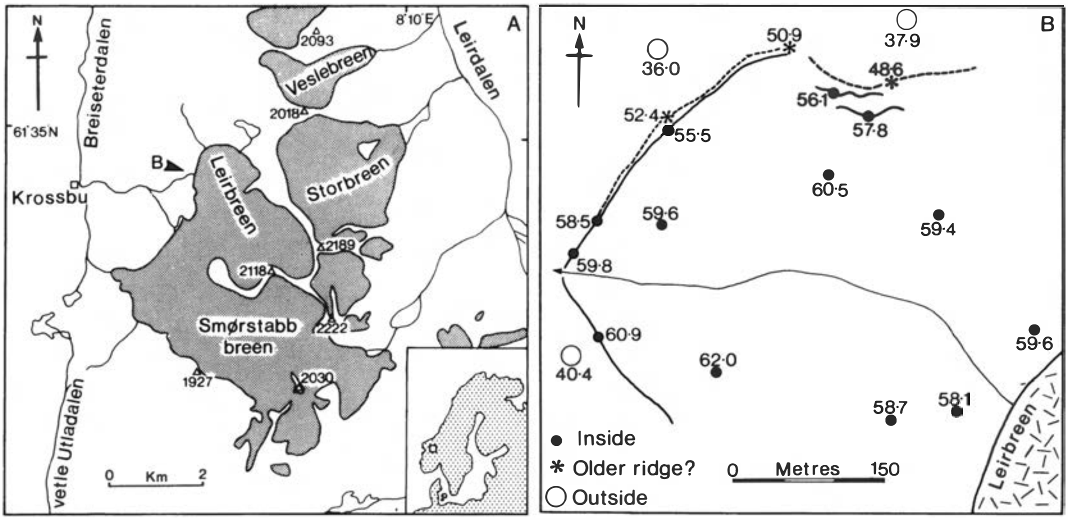

Fig. 1. Maps showing (A) location of Leirbreen and (B) sites at which Schmidt hammer R-values were recorded.

limits (Fig. 1). Three of the foreland sites were located on the outer (possibly older) ridge. At each site, four R-values were obtained from the smoothest available lichen-free points on each of 30 boulders. In Jotunheimen, this is the optimum sampling scheme (McCarroll 1986). Schmidt hammers were regularly tested and R-values calibrated following the procedure outlined in McCarroll (1987). Mean R-values from the outer ridge (48.6 to 52.4) are intermediate between those obtained inside (55.5 to 62.0) and beyond this limit (36.0 to 40.4).

On the adjacent foreland of Storbreen, it has been demonstrated that mean R-values obtained from 'Little Ice Age' moraines are closely correlated with mean boulder roundness (which provides a surrogate measure of boulder-surface roughness, McCarroll in press), and that where there is a concentration of relatively angular (rough) boulders, low R-values result. For the 16 sites on Leirbreen foreland mean boulder roundness was calculated using the adaption of Powers' (1953) visual comparison technique proposed by Matthews & Petch (1982). Mean roundness and R-values are not correlated (Fig. 3) and the low R-values obtained on the outer ridge cannot, therefore, be explained by a concentration of relatively angular (rough) boulders.

Comparison of frequency distributions (Fig. 2A) reveals that a wider spread of R-values was obtained from the outer ridge than from the inside or outside sites. Such a distribution might be expected if the ridge comprised a mixture of fresh and incorporated older, weathered, boulders. However, the possibility that a surface of intermediate age might produce a platykurtic distribution of R-values cannot be discounted. The peaked distributions could represent equilibrium conditions for fresh and relatively weathered boulders, whilst a surface of intermediate age could comprise material weathering at different rates, yielding a wider spread of R-values.

Another factor which may influence the frequency distribution of R-values is lithological variation. To test this, the lithology of each boulder included at three 'Little Ice Age' sites was recorded. The pyroxene granulites of Jotunheimen are dominated by feldspar and pyroxene (Battey & McRitchie 1975), so a relatively simple classification is possible based on average crystal size and relative percentage of dark to light minerals. Three varieties were present (Table 1), but the R-values were not significantly distinguishable (Mann-Whitney U-test, $P > 0.05$). However, a quite distinct coarse-grained feldspathic crush-rock (Banham et al. 1979) was also present, which yielded significantly lower R-values (Table 1). Close examination revealed, moreover, that the feldspathic crush-rock is not evenly distributed over the study area. Although present over the entire foreland it is particularly common towards the western margin and forms the dominant lith-

Table 1. Mean R-values (±95% confidence intervals) obtained from boulders of different lithologies on 'Little Ice Age' sites.

Lithology	Number of boulders	Mean R-value
Fine-grained, leucocratic pyroxene-granulite	7	61.5 ± 3.1
Fine-grained, mesocratic pyroxene-granulite	46	59.6 ± 1.4
Medium-grained, mesocratic pyroxene-granulite	22	59.1 ± 3.0
Feldspathic crush-rock	12	53.6 ± 4.2

ology on the outer ridge. Immediately beyond the outer ridge it forms the local bedrock and almost all of the boulders.

To test whether the observed variations in lithology might explain the anomalous Schmidt hammer results, R-values were recorded from two samples of 50 pyroxene granulite boulders on the outer ridge. The mean values (62.97 ± 1.86; 63.56 ± 1.86) are higher than those obtained elsewhere on the foreland and the frequency distribution is similar to that obtained from the inside sites (Fig. 2). The mean R-value obtained from 50 boulders of feldspathic crush-rock on the outer ridge (51.06 ± 2.11) is significantly higher than that obtained from the outside sites (Fig. 2), suggesting that the boulders on the ridge are considerably less weathered.

Conclusions

Schmidt hammer R-values obtained from the outermost ridge in the western sector of Leirbreen foreland are intermediate between, and cover a wider range than those obtained on inside ('Little Ice Age') and outside (pre-Neoglacial) sites. The

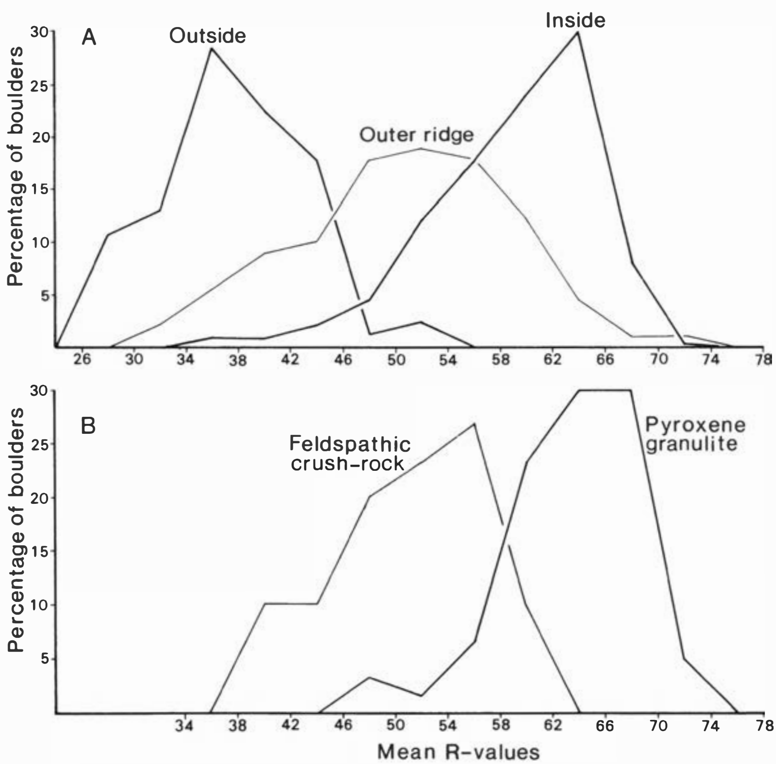

Fig. 2. Frequency distribution of mean R-values obtained from (A) boulders on the outer ridge compared with boulders inside and beyond the 'Little Ice Age' limits of Leirbreen and (B) from boulders of distinct lithologies on the outer ridge.

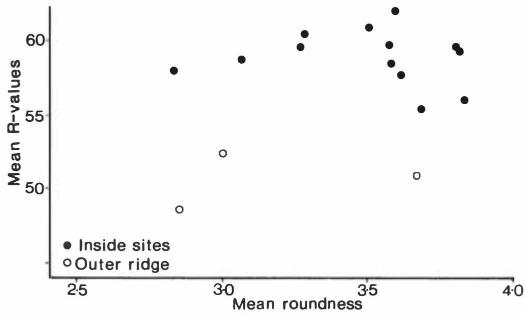

Fig. 3. Comparison of mean boulder roundness and mean R-values obtained from 'Little Ice Age' sites on Leirbreen foreland.

low values are not explained by a concentration of relatively angular (rough) boulders but reflect spatial variations in lithology. On 'Little Ice Age' sites, boulders of feldspathic crush-rock yield significantly lower R-values than those of pyroxene granulite. The former lithology is particularly common on the outer ridge and beyond the moraine limits. When only boulders of pyroxene granulite are included, the outer ridge does not yield low R-values. When only boulders of feldspathic crush-rock are included, R-values obtained from the ridge are significantly higher than those obtained outside.

The presence of fresh boulders of pyroxene granulite on the outer ridge suggests that it does not pre-date, by a considerable margin, the 'Little Ice Age'. Results are therefore consistent with formation of the outer ridge around 1750 AD, when other Jotunheimen and Jostedalsbreen glaciers reached their maximum extent. Although the ridge may contain some pre-Neoglacial material incorporated by a push mechanism, particularly towards the northern end, most boulders of feldspathic crush-rock are significantly less weathered than those outside, suggesting that they were deposited by the glacier.

This study demonstrates that the Schmidt hammer can prove valuable for relative-age dating of Holocene glacial deposits. However, R-values do not provide a direct measure of boulder-surface weathering and the influence of other factors must be assessed critically before results can be interpreted. In particular, care must be taken to minimise lithological variation between sites.

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