The vertical extent of ice sheets in Nordfjord, western Norway: measuring degree of rock surface weathering

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BOREAS

McCarroll, D. & Nesje, A. 1993 (September): The vertical extent of ice sheets in Nordfjord, western Norway: measuring degree of rock surface weathering. *Boreas*, Vol. 22, pp. 255–265. Oslo. ISSN 0300-9483.

Degree of rock surface weathering was measured on sites in Oldedalen and Brigsdalen, where dates of deglaciation have been estimated, and on an altitudinal transect on the slopes of Skåla, representing one of the highest supra-marine reliefs in western Norway. The Schmidt hammer is useful only for distinguishing sites deglaciated during the Little Ice Age from those deglaciated during the Lateglacial and early Holocene. Degree of roughness of granitic augen gneiss bedrock surfaces was quantified from profiles measured *in situ* using a micro-roughness-meter and profile gauge. There is a significant increase in surface roughness above a clear trimline at *c*. 1350 m a.s.l. but no significant increase above a higher trimline previously proposed as the vertical limit of the last ice sheet in this area (*c*. 1560 m a.s.l.). The roughness of boulder surfaces on the summit blockfield does not differ significantly from the roughness of bedrock surfaces downslope as far as the lower trimline. These unexpected results suggest that bedrock surfaces between the two trimlines were not glacially abraded during the Late Weichselian, so that the upper trimline is unlikely to represent the vertical limit of ice during either the Late Weichselian or a subsequent readvance. Preliminary results of ^{10}Be dating of surface quartz samples from above the lower trimline support the proposal that the site was not abraded during the last glaciation. The results can be interpreted in two ways: (1) The upper trimline represents the vertical limit of a pre-Late Weichselian advance. During the Late Weichselian the mountains were completely covered but surfaces down to the lower trimline were protected by cold-based ice. (2) The lower trimline marks the vertical limit of the Late Weichselian ice and the upper limit an older and more extensive glaciation.

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The Quaternary ice sheets that covered Scandinavia and much of northern Europe had a profound effect on ocean and atmospheric circulation patterns and world sea levels, and resulted in isostatic depression of the crust. To understand these effects it is essential to be able to reconstruct the extent and surface profile of past ice sheets. Lateral extent of the Scandinavian ice sheets can be reconstructed from morphological and sedimentary evidence (e.g. Sejrup *et al.* 1987), but the vertical extent, and therefore the surface profile, is more difficult to define (e.g. Nesje *et al.* 1988; Nesje & Sejrup 1988).

The vertical extent of the last (Last Weichselian) ice sheet in the mountainous areas of western Norway has long been the subject of debate (see Nesje *et al.* 1987 for a review). At the end of the last century discoveries of endemic plant species led botanists to postulate the existence of ice-free 'refugia' during the Late Weichselian maximum. Geological evidence used to support this argument included the occurrence of steep-sided 'alpine' peaks, interpreted as nunataks. The strongest evidence, however, was the widespread occurrence of summit blockfields (felsenmeere) produced by *in situ* rock weathering. These were considered to form over a longer timescale than the Holocene and thus to pre-date the Late Weichselian.

Mapping of the horizontal extent of the ice sheet, however, suggests that it extended to the edge of the continental shelf beyond the Møre area of western Norway and south as far as Jutland, Denmark (Nesje & Sejrup 1988). The extent of the ice to the south west is uncertain, with some authorities suggesting confluence with Scottish ice in the central North Sea (e.g. Boulton *et al.* 1977, 1985; Andersen 1981) and others proposing less extensive ice cover with dry land and an embayment between southern Norway and Scotland (Sejrup *et al.* 1987).

If the surface profiles of modern ice sheets, such as that in west Greenland, are used as a basis for extrapolating back from the horizonal limits of the Scandinavian ice sheet, then the vertical extent is predicted to exceed by far the altitude of the highest mountains. For example, Vorren (1977) constructed a parabolic profile from the southern boundary of the ice sheet and suggested an ice thickness of *c*. 3000 m in the Hardangervidda area. The ice sheet reconstructions of Andersen (1981) and Boulton *et al.* (1985) suggest complete ice cover over all southern Norwegian mountains during the Late Weichselian maximum. Both models assume greatest ice thickness over the Gulf of Bothnia. If such models are accepted, the preservation of alpine terrain and autochthonous blockfields can be explained by spatial variations in the basal thermal regime of the ice sheet. Where the ice is thick, basal ice is likely to reach pressure melting point, leading to basal sliding and thus erosion. On summits, where the ice is thinnest, basal pressures are lower so that the ice can freeze to the substrate, protecting rather than eroding the pre-glacial topography.

Despite the theoretical predictions of complete ice cover, interest in the geological evidence of ice-free areas has continued, and a detailed survey of the altitude of ice scoured and blockfield covered surfaces in the Nordfjord to Møre area of western Norway has proved particularly interesting (Dahl 1961; Sollid & Sørbel 1979; Sollid & Reite 1983; Rye *et al.* 1987; Nesje *et al.* 1987, 1988; Nesje & Sejrup 1988). The lower boundary of the blockfields displays marked lateral continuity, declines in altitude towards the coast and displays local variations that respond to local topography. This is precisely the pattern that would be expected if the lower limit of the blockfields represented the vertical limit of an ice sheet. Nesje *et al.* (1988) and Nesje & Sejrup (1988) have presented models of the Late Weichselian Scandinavian ice sheet assuming that the autochthonous blockfields protruded as nunataks. They propose a low gradient poly-centred ice sheet with the ice divide located close to the present main watershed. The low surface profile reflects very low basal shear stress beneath marginal parts of the ice sheet which rested on unconsolidated, deformable sediments.

Resistance to the concept of ice-free areas has continued, however. Follestad (1990), for example, stresses the consistent pattern of striations in the Nordmøre and Romsdal areas of western Norway, suggesting ice movement largely independent of the local terrain and inferring an ice surface well above the mountain plateaux. He also notes the presence of erratic blocks and tills in some blockfields reaching a level of at least 600–700 m above sea level. This provides clear evidence that blockfields can be overrun by ice without being eroded. Similar evidence of Late Weichselian ice failing to erode large areas of terrain fashioned by periglacial processes and earlier glaciations has been reported from several areas of Scandinavia, including Norway (Roaldset *et al.* 1982; Follestad 1990), Sweden (Lagerbäck, 1988a, b; Rodhe 1988; Kleman 1990, 1992; Kleman & Bergström 1990; Kleman *et al.* 1992) and Finland (Kaitanen 1969; Kujansuu 1975). Follestad (1990) accedes that the continuity of the blockfield boundary in western Norway suggests that it is a glacial trimline, but suggests the most likely explanation is that it was formed by a readvance at some stage after the Late Weichselian maximum.

The origin of the distinct trimline between autochthonous blockfields and ice-moulded terrain in western Norway thus remains contentious. Evidence for the preservation of 'old' landscapes beneath cold-based ice is widespread, yet the lateral continuity of the boundary strongly suggests glacial trimming. Nesje *et al.* (1988) have assumed that the trimline represents the vertical limit of the Late Weichselian ice sheet, whereas Follestad (1990) proposes preservation beneath a thick cold-based ice sheet followed by trimming during a re-advance. The situation is further complicated, since detailed field mapping has revealed that on some mountains in western Norway there appears to be a second trimline well below the summit blockfield yet well above the position of the ice sheet during the Younger Dryas cold period (11,000 to 10,000 BP).

Mountains with two trimlines provide an opportunity to test some of the theories discussed above. The presence of a trimline suggests a difference in the amount of time that the rocks have been exposed to weathering processes. The degree of weathering of the rocks above and below the trimline should, therefore, be age-related. Since rates of weathering tend to decay over time (Colman 1981), a significant difference in degree of weathering suggests a substantial difference in surface age.

One of the clearest examples in western Norway of a mountain with a blockfield and lower trimline is Skåla, close to Loen in inner Nordfjord (Figs. 1, 2). The lower boundary of the blockfield forms a clear trimline at *c.* 1560 m. Further down the slope at *c.* 1350 m another trimline is apparent, marked by a slight change in rock colour and by a discontinuous line of boulders, particularly on the steep south west slopes. Farther down slope at *c.* 1100 m a clear ridge marks the lateral boundary of Younger Dryas ice which extended from the south into Fosdalen (Nesje & Dahl 1992a).

The aim of this study was to measure degree of rock surface weathering on sites in Oldedalen and Brigsdalen, where dates of deglaciation have been estimated, and on an altitudinal transect on the southern slopes of Skåla, which represents one of the highest supra-marine reliefs in western Norway. In particular, we aimed to determine whether the rocks on the summit blockfield are significantly more weathered than those downslope and to investigate any differences in degree of rock surface weathering above and below the lower trimline at *c.* 1350 m. Degree of rock surface weathering was quantified using the Schmidt hammer and measures of rock surface roughness.

Study area

The high relief, uniform lithology and westerly location of the inner Nordfjord area (Fig. 1) provide an ideal location in which to investigate the vertical extent of the ice sheets. In this study, degree of bedrock weathering was measured on approximately horizontal outcrops of granitic augen gneiss of the Fjordane Complex (Oftedahl 1980). On the summit of Skåla, bedrock sites were unavailable and large blocks of augen gneiss were used.

Four sites were located in Oldedalen (Fig. 1), on surfaces where time of exposure is relatively well known from radiocarbon dating (Rye *et al.* 1987); two on the foreland of Brigsdalsbreen, which reached its Little Ice

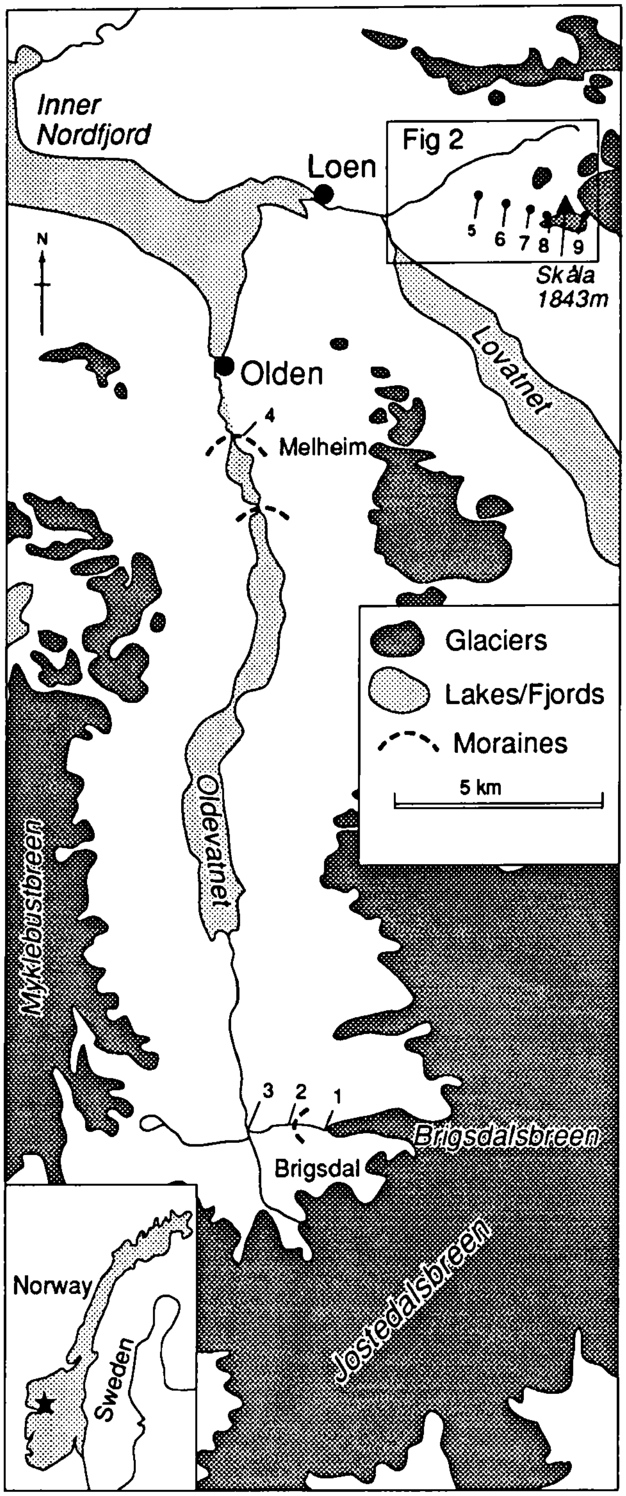

Fig. 1. Location of study sites (numbered) in the Nordfjord area of western Norway.

Age maximum position during the mid-eighteenth century (Pedersen 1976), one just beyond the Little Ice Age glacier foreland in Brigsdalen (site 3) deglaciated at around 9,000 BP. Five sites were located on an altitudinal transect on the slopes of Skåla from the Younger Dryas lateral moraines at *c.* 1100 m, past the lower trimline at *c.* 1350 m to the summit blockfield at 1843 m (Fig. 2).

Methodology

The Schmidt hammer is a light, portable instrument that records the distance of rebound of a spring-loaded mass impacting a surface. The distance of rebound is related to the elastic properties of the surface and therefore its compressive strength. It has been used to compare the surface hardness of different rock types (Barton & Choubey 1977; Day & Goudie 1977), and as a measure of degree of rock surface weathering (Day 1980; Whitlow & Shakesby 1988; Ballantyne *et al.* 1989; McCarroll 1990; Sjöberg 1990, 1991; Sjöberg & Broadbent 1991). It has also been used for recording degree of weathering as an indicator of surface age (Ballantyne 1986; Dawson *et al.* 1986; Matthews & Shakesby 1984; McCarroll 1989a, b, 1991a; Cook-Talbot 1991).

In this study 50 rebound (R-) values were recorded on horizontal bedrock surfaces at nine sites. For comparison with previous work, all of the values have been calibrated following the procedure described by McCarroll (1987 and in press).

Although rock surface roughness has long been recognized as an indicator of degree of rock surface weathering, and thus terrain age, it is a difficult property to quantify and is usually estimated subjectively as part of a multi-parameter approach (McCarroll 1991b). A few roughness-related parameters have been measured, including depth of weathering pits (Boyer & Pheasant 1974; Mahaney *et al.* 1984), differential relief of adjacent mineral grains (McCarroll 1990) and relief of mineral veins (Birman 1964; Birkeland 1982), but these methods depend upon suitable lithologies and are not widely applicable. However, a new instrument and techniques have recently been described that allow rock surface roughness to be quantified (McCarroll 1992). The micro-roughness meter (MRM) is a simple portable instrument that is used to record relative heights (increments of 0.01 mm) of evenly-spaced points on a transect. Varying the measurement interval and transect length allows different scales of roughness to be investigated. Surface roughness is summarized using the difference in relative height between adjacent points on the transect ('slope' values). The index used here is the standard deviation of the 'slope' values.

In this study, the MRM was used to record the relative height of points at 1 cm intervals on 10 cm transects. However, the MRM was originally designed for measuring surface details at a much smaller scale, so profiles were also recorded using the less accurate but very convenient profile gauge. This instrument

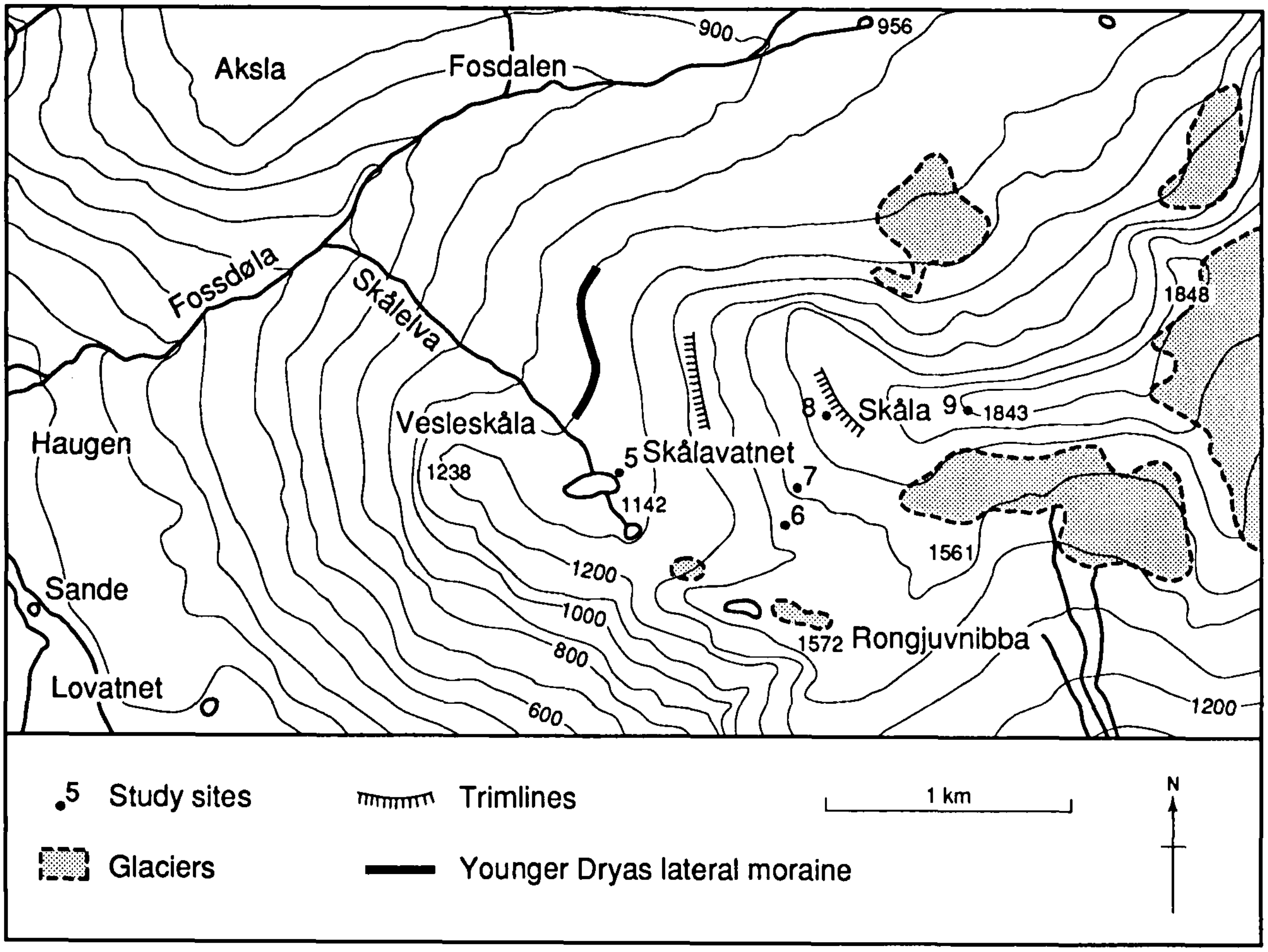

Fig. 2. Location of study sites, trimlines and Younger Dryas moraines on Skåla.

comprises a line of 209 freely moving pins which is pushed against the surface to record the profile. Typical measured profiles are displayed in Fig. 3. Similar instruments have been used previously to record rock surface profiles (Barton 1973; Barton & Choubey 1977; Bandis *et al.* 1981) but no attempt was made to quantify the roughness of the surfaces. Here we use a suite of indices, based on the index described above but varying the measurement interval and transect length.

The MRM was used to record 75 profiles on approximately horizontal rock surfaces at 7 sites. On a later visit the gauge was used to record 10 profiles at each of 9 sites, including those where the MRM had been used. The gauge profiles were transferred straight to 1 mm graph paper in the field, facilitating simple calculation of depths of points below an arbitrary datum (Fig. 4). Depths were measured at 5 mm intervals (increments of 0.5 mm) and the following combinations were used to derive roughness indices:

1. All 38 values, at 5 mm intervals, on the 19 cm transects (index rf-1).
2. Using values at 1 cm intervals over the 19 cm transects provides two related indices, based on alternate 5 mm measurements (rf-2 and rf-3).
3. For comparison with the MRM measurements it was desirable to derive indices based on 1 cm intervals on 10 cm transects. For this purpose this first and last 22 values were used, providing four related indices (rf-4 to rf-7).

These measures provide three pairs of indices that are particulary useful:

1. rf-1 represents roughness at a scale of 5 mm measured over the whole 19 cm transect.
2. rf-8 is the mean of indices 4–7 and represents roughness at a scale of 1 cm over 10 cm transects, and so is comparable directly with the MRM results.
3. rf-9 is the mean of rf-2 and rf-3, and so represents roughness at a scale of 1 cm measured over the whole 19 cm transect.

A fourth, independent, roughness index (rf-10) was calculated using quite a different approach. The maxi-

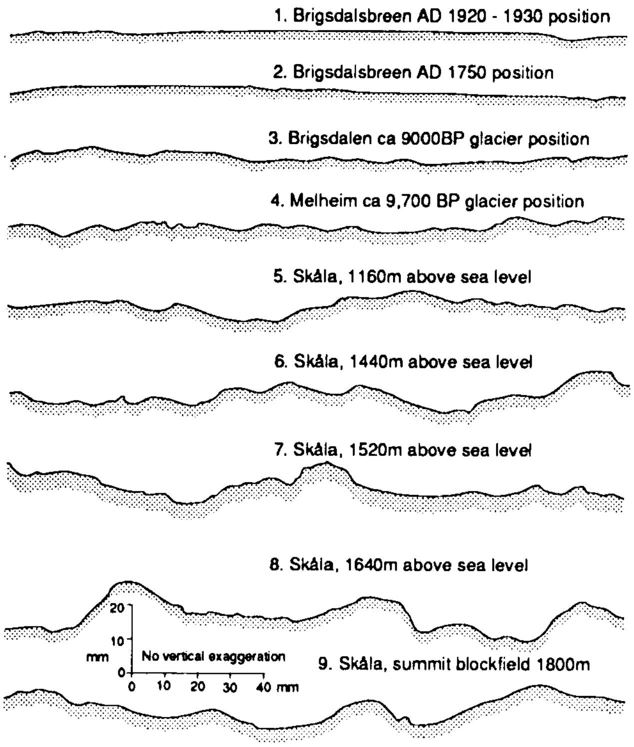

Fig. 3. Typical surface profiles of granitic augen gneiss bedrock recorded using the profile gauge.

mum relief was measured within each 5 mm section and averaged over the length of the profile.

Results

Schmidt hammer

The Schmidt hammer results (Fig. 5) distinguish clearly two groups of sites. Sites 1 and 2 yield high values, with mean values from samples of 50 blows ranging from 62.7 to 65.7. All of the other sites yield lower values with means in the range 28.8 to 39.3 (Table 1). The results from site 2 are particularly interesting because this site lies on a rock bar a few metres downvalley from the large outer moraine at Kleivanetrinnet. Pedersen (1976) suggests, mainly on the basis of lichenometry, that this moraine was formed between AD 1740 and AD 1800, which corresponds to the maximum extent of many southern Norwegian glaciers during the Little Ice Age (Andersen & Sollid 1971; Erikstad & Sollid 1986; Grove 1988; Nesje *et al.* 1991; Brickerton & Matthews 1993; Matthews in press). The Schmidt hammer results suggest that the glacier advanced as far as the edge of the rock bar, where it would have avalanched into the valley below. A search of the rock bar revealed no lichens of section *Rhizocarpon* larger than 140 mm, which would support a Little Ice Age date for exposure of this surface. Similar bedrock surfaces downvalley support section *Rhizocarpon* thalli in excess of 300 mm. Pedersen (1976) mapped a small moraine on top of the rock threshold and this may also date from the Little Ice Age. These results demonstrate that the Schmidt hammer is useful for distinguishing relatively fresh surfaces that were glaciated during the Little Ice Age from sites deglaciated during the Lateglacial and early Holocene. It is particularly useful where evidence of glacial limits is erosional rather than depositional.

The Schmidt hammer results do not distinguish between the sites beyond the Little Ice Age limits of Brigsdalsbreen and show no clear trend with increasing altitude on the slopes of Skåla. It would seem that the surface properties that influence Schmidt hammer results, including surface hardness and micro-roughness (McCarroll in press), reach an approximate equilibrium between the age of the oldest Little Ice Age site (*c.* 250 years) and the youngest site beyond the Little Ice Age limits (*c.* 9000 years). The Schmidt hammer cannot be used, therefore, to investigate the vertical extent of ice sheets in the Nordfjord area.

Roughness

The micro-roughness meter has been used previously to measure the roughness of natural rock surfaces and to demonstrate how surface roughness is related to the transport history of boulders and also degree of rock surface weathering and thus terrain age (McCarrroll 1992). The profile gauge has been used to record rock surface profiles but not to quantify surface roughness. Since at seven sites both instruments were used, and both the MRM index and gauge index rf-8 are based on measurements at 1 cm intervals on 10 cm transects, the results can be compared directly (Fig. 6) and are very strongly correlated ($R = 0.9666$, $p > 0.001$). This suggests that surface roughness at the scales of interest in this study can be measured satisfactorily using the profile gauge, which is considerably more convenient than the MRM. Measuring roughness at much smaller scales (McCarroll 1992), or measuring the differential relief of adjacent mineral grains (McCarroll 1990), requires the greater accuracy of the MRM.

The four roughness indices derived from the gauge profiles can be used to examine changes in rock surface roughness on surfaces of increasing age in the range 67 to 9,700 years (Table 1). On surfaces above the Younger Dryas lateral moraines (*c.* 1100 m) the indices can be used to locate any abrupt change in degree of rock surface texture that might reflect a similar change in degree of rock surface weathering. Such an abrupt weathering boundary might represent the vertical limit of the last (Late Weichselian) ice sheet.

Plotting on opposing axes the roughness indices derived from each profile (Fig. 7) demonstrate that the data fall into three groups representing Little Ice Age sites, sites below the trimline at 1350 m and sites

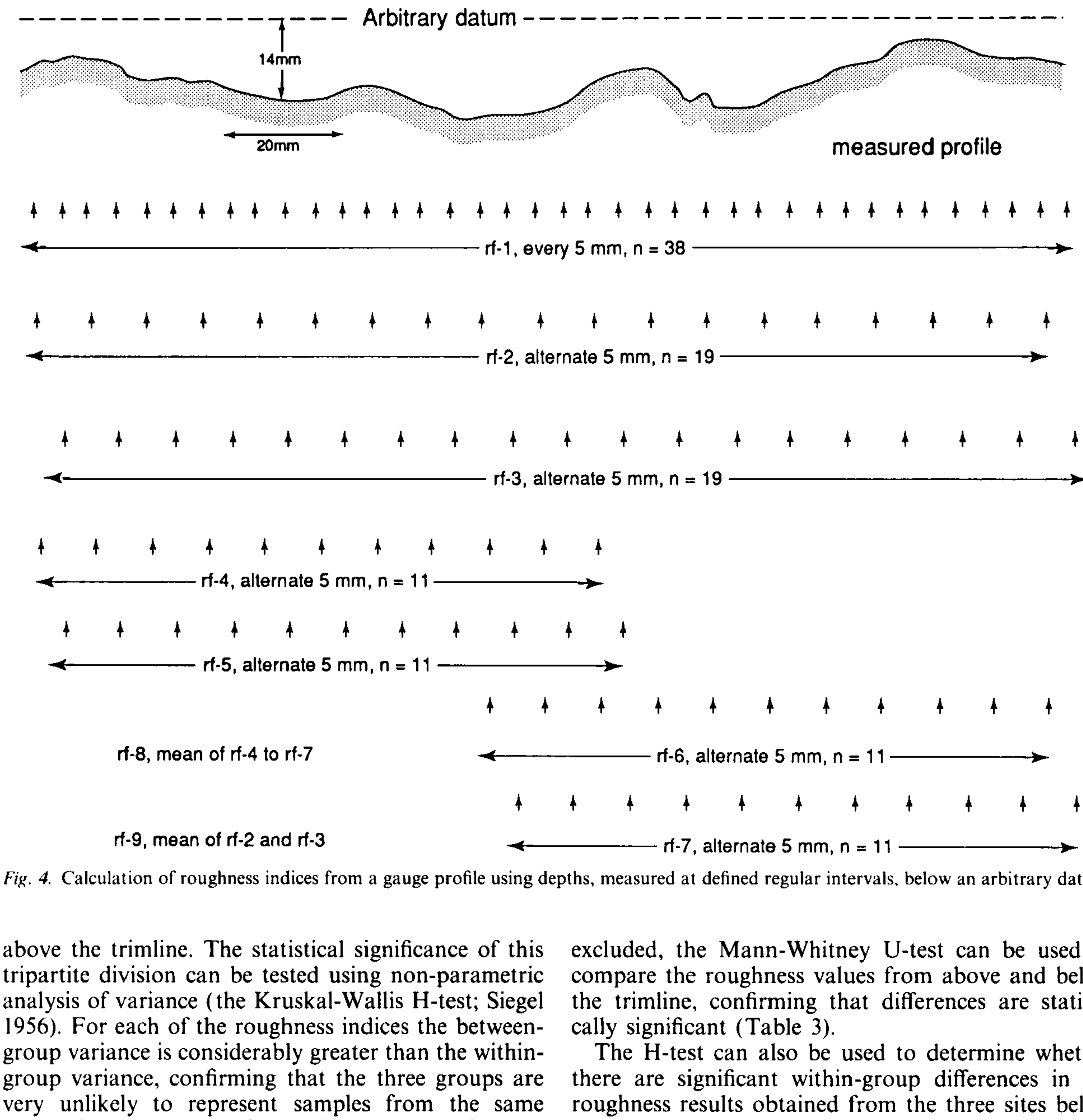

Fig. 4. Calculation of roughness indices from a gauge profile using depths, measured at defined regular intervals, below an arbitrary datum.

above the trimline. The statistical significance of this tripartite division can be tested using non-parametric analysis of variance (the Kruskal-Wallis H-test; Siegel 1956). For each of the roughness indices the between-group variance is considerably greater than the within-group variance, confirming that the three groups are very unlikely to represent samples from the same population (Table 2). If the Little Ice Age sites are excluded, the Mann-Whitney U-test can be used to compare the roughness values from above and below the trimline, confirming that differences are statistically significant (Table 3).

The H-test can also be used to determine whether there are significant within-group differences in the roughness results obtained from the three sites below the trimline, which differ in age, and the three sites, of

Table 1. Mean roughness indices and Schmidt hammer R-values.

Site	UTM Grid reference	Altitude m.a.s.l	Surface age (years)	Mean rf-1	Mean rf-8	Mean rf-9	Mean rf-10	Mean MRM	Mean R-value
1	865390	360	67	0.40	0.52	0.49	0.30	0.89	64.27
2	855390	320	242	0.40	0.50	0.50	0.32	0.67	63.85
3	848388	180	9000	0.86	1.28	1.26	0.77	1.51	35.25
4	848558	40	9700	1.07	1.40	1.40	1.04	1.08	32.65
5	916610	1160	< 10000	1.32	1.96	1.91	1.28	1.37	31.20
6	922609	1440	?	1.80	2.75	2.74	1.61	N/A	35.55
7	922610	1520 .	?	1.89	2.94	2.97	1.64	N/A	33.28
8	924613	1640	?	2.00	3.15	3.34	1.77	3.01	29.25
9	929613	1800	?	1.71	2.69	2.74	1.44	2.21	32.00

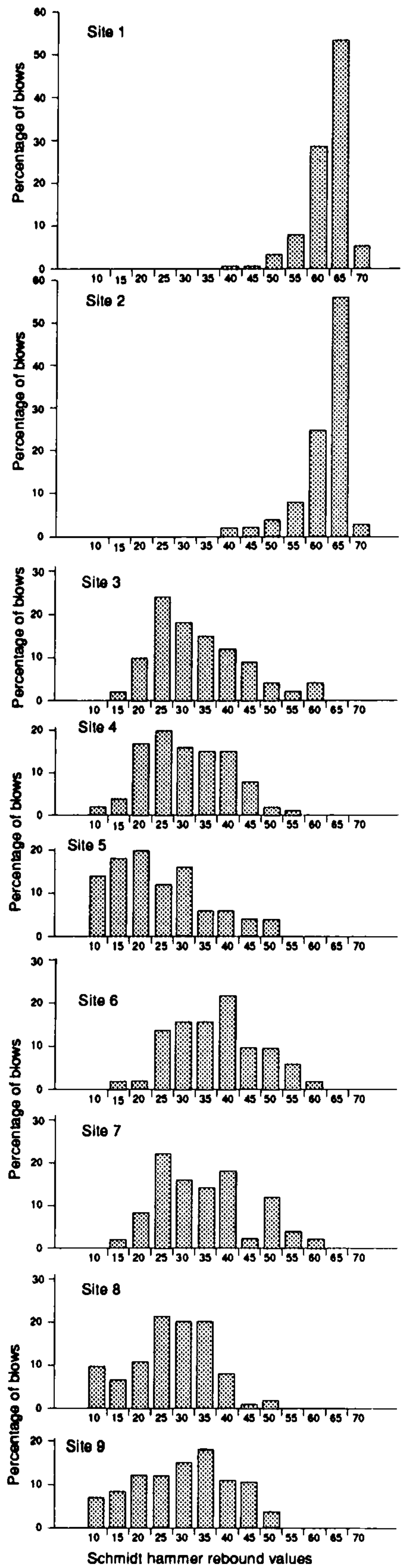

Fig. 5. Schmidt hammer rebound values. Higher values are obtained from hard, unweathered surfaces.

undetermined age, above the trimline (Table 4). Below the trimline the differences between the sites are significant ($p < 0.01$) and above the trimline the differences are not significant ($p > 0.05$).

The roughness results obtained from large blocks of augen gneiss on the summit blockfield of Skåla are compared, in Table 5, with the roughness results obtained from sites on bedrock between the trimline and the blockfield. Only index rf-10 displays a significant difference ($p < 0.05$), with the summit blockfield yielding lower values than the sites downslope.

Discussion

The results reported above demonstrate clearly that on outcrops of augen gneiss in the inner Nordfjord area surface roughness increases with increasing sur-

Table 2. Between-group non-parametric analysis of variance (H-test) of Little Ice Age sites, below the lower trimline and sites above the lower trimline.

Index	rf-1	rf-8	rf-9	rf-10
H =	72.58	74.31	75.50	70.99
p =	<0.01	<0.01	<0.01	<0.01

Table 3. U-test comparing post-Little Ice Age sites above and below the lower trimline.

Index	rf-1	rf-8	rf-9	rf-10
U =	44	26	14	60
z =	6.60	6-81	6.95	6.409
p =	<0.01	<0.01	<0.01	<0.01

Table 4. Within-group non-parametric analysis of variance of sites above and below the lower trimline.

Index	rf-1	rf-8	rf-9	rf-10
Below H =	14.55	16.26	17.22	17.66
Trimline p =	<0.01	<0.01	<0.01	<0.01
Above H =	1.37	0.56	2.58	2.51
Trimline p =	<0.05	<0.05	<0.05	<0.05

Table 5. U-test of difference between the summit blockfield and sites above the lower trimline.

Index	rf-1	rf-8	rf-9	rf-10
U =	98	124	116	62
z =	1.624	0.812	1.062	2.749
p =	<0.05	<0.05	<0.05	<0.01

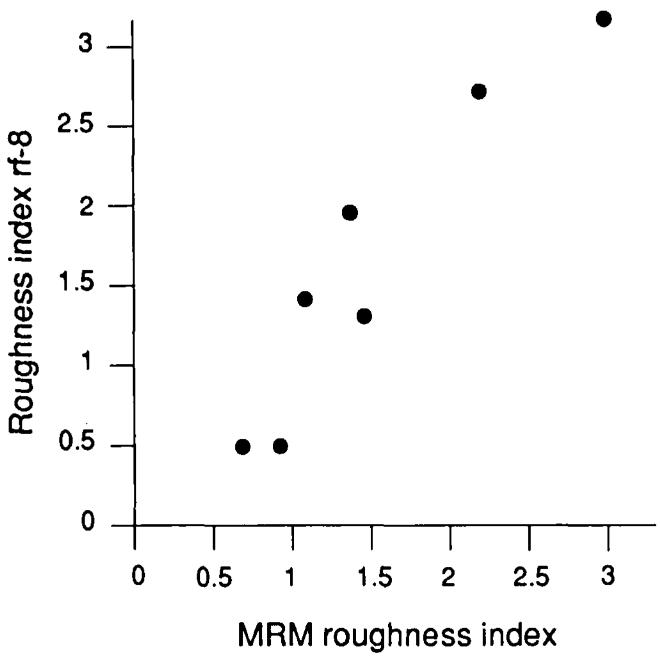

Fig. 6. Comparison of roughness values obtained from microroughness meter (MRM) measurements with equivalent values obtained using a profile gauge.

Table 6. U-test of difference between the highest site below the trimline and the lowest site above the trimline.

Index	rf-1	rf-8	rf-9	rf-10
U =	12	7	4	10
p =	<0.01	<0.01	<0.01	<0.01

face age in the range <240 to 9,700 years. On Skåla there is a significant difference between the roughness of sites above and below a clear trimline at *c.* 1350 m, which is well below the lower limit of summit blockfields which has been proposed as the vertical limit of the last ice sheet. There is no significant difference between the roughness of blocks on the summit blockfield and bedrock at sites between the lower trimline and the blockfield.

These unexpected results can be interpreted in several ways. One possibility is that the difference in roughness across the lower trimline is an artifact of the sampling framework; increasing rock surface roughness reflecting increased rock surface weathering with increasing altitude. This is difficult to test using this data set because below the trimline, altitude and surface age are not independent (Table 1). It is therefore difficult to determine whether the significant differences in roughness of sites below the trimline reflect differences in age or differences in altitude. Above the trimline, between-site differences in roughness are not statistically significant (Table 4), but it could be argued that the relationship between weathering rate and altitude is negatively exponential, so that it is indiscernible above a certain height.

One way to lend weight to either side of the argument is to compare the roughness values obtained from the highest site below the trimline and the lowest site above the trimline (Table 6). Using each of the four roughness indices the sites are significantly different ($p < 0.01$). Either the height at which increased weathering with altitude is no longer discernible lies (fortuitously) just above the trimline, or the difference in roughness reflects a real difference in degree of surface weathering and therefore surface age.

If the difference in degree of weathering and surface age is accepted, the lower limit of summit blockfields is very unlikely to represent a post-Late Weichselian readvance trimline, as suggested by Follestad (1990). If that was the case the weathering difference would occur across the *upper* trimline. There is very little time available between the postulated readvance and

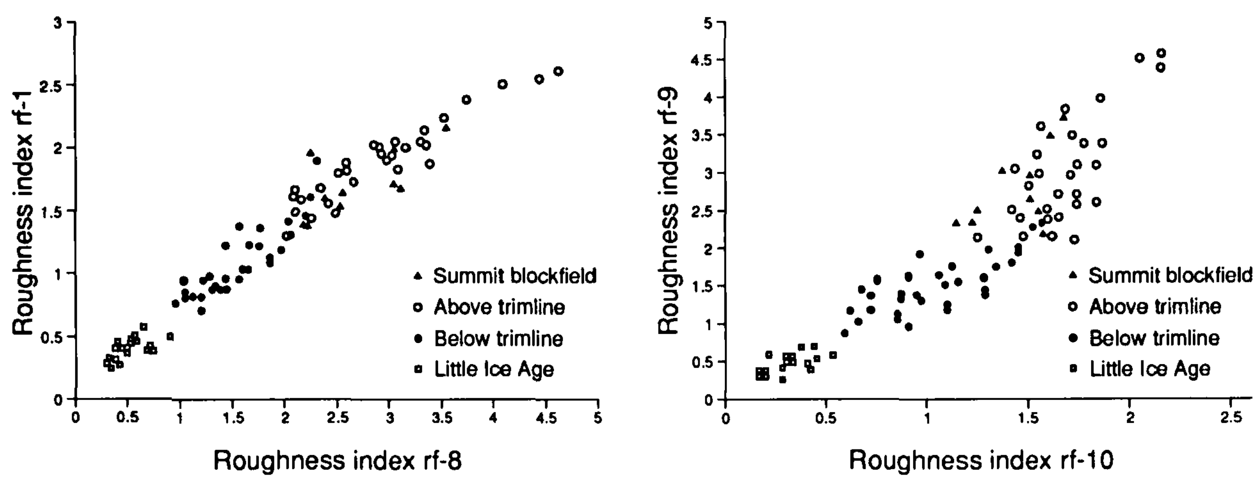

Fig. 7. Comparison of roughness values obtained from gauge profiles using four different indices. Note that the results fall into three clear groups.

the Younger Dryas, so there is no clear mechanism available to create the lower trimline and no reason for any difference in degree of weathering across it.

A similar problem arises if, as suggested previously by Nesje *et al.* (1988), the lower boundary of the blockfields is taken as the maximum vertical limit of the Late Weichselian ice sheet. Again the weathering difference should be across the upper trimline. Even if the lower trimline is attributed to a readvance, the time available between the Later Weichselian maximum and the Younger Dryas is insufficient to explain a marked difference in degree of rock surface weathering.

Independent support for the suggestion that bedrock surfaces between the upper and lower trimlines were not glacially abraded during the Late Weichselian comes from a recently developed dating technique based on the accumulation of cosmogenic nuclides. Several samples were submitted, including surface quartz samples from 1420 m. Preliminary ^{10}Be measurements performed at the Tandetron AMS facility at CNRS-CSNSM in Gir-sur-Yvette, France, suggest an age of about 18,000 years (Brook *et al.* unpubl.). This corresponds to the maximum extent of the last (Late Weichselian) North European ice sheets and would suggest that the site was not abraded during that event.

Two possibilities remain, both of which are problematic:

1. The distinct, regionally mapped boundary between blockfields and ice-moulded summits may represent the vertical limit of a pre-Late Weichselian ice sheet. During the Late Weichselian maximum the ice sheet extended over all of the summits but cold-based ice protected surfaces as far down as the lower trimline.
2. The lower trimline could represent the maximum vertical limit of the Late Weichselian ice sheet, which would suggest that the higher limit (mapped by Nesje *et al.* 1987, 1988 and Rye *et al.* 1987) reflects an earlier, more extensive ice sheet (Saalian?).

The first hypothesis fits very well with recent work by Kleman (1992), who concludes that there is mounting evidence that Late Pleistocene glaciations in Fennoscandia have occurred in two distinct modes. Major glaciations (e.g. Saalian and Late Weichselian) resulted in large, thick ice domes centred over the Gulf of Bothnia, whereas less extreme events were characterized by smaller, elongate, west-centred (Scandinavian) ice sheets. On the basis of extensive geomorphological mapping (Kleman 1990, 1992; Kleman & Borgström 1990; Kleman *et al.* 1992) he suggests that the smaller Scandinavian ice sheets may have had a much greater effect on the landscape, and that the very large east-centred ice sheets had relatively little impact because over large areas they were cold-based.

This is a very tempting solution to a long-standing problem. It accepts the interpretation of the regionally mapped blockfield boundary as a glacial trimline rather than an englacial thermal boundary, yet allows for a very thick ice sheet during the Late Weichselian. The older trimline is preserved because the englacial thermal boundary lies farther downslope, at the lower trimline.

The argument that the major east-centred ice sheets have left little record in the landscape does, however, beg the question 'how much evidence is there that very large east-centred ice sheets existed at all during the Late Pleistocene?' The key piece of evidence used to support reconstructions of very thick ice over the Gulf of Bothnia is the present pattern of uplift in Scandinavia, which is centred on that region. However, it has been suggested that present uplift may be related to the thickness of the continental crust rather than to glacial unloading (Mörner 1980; Nesje & Dahl 1992b). Perhaps it is time to abandon the concept of a large and relatively simple ice dome, despite its convenience for computer modelling, and to concentrate instead on the complex field evidence of ice movement patterns, englacial thermal boundaries and vertical and horizontal ice limits.

A multi-centred but relatively thin ice sheet, with a major ice divide located along the mountains of southern Norway would seem to provide a reasonable starting point. Ehlers's (1990) model of the Scandinavian ice sheet, which accepts a western ice divide and relatively thin ice over western Norway, goes some way towards this. Going further, and removing the need for very thick ice over the Gulf of Bothnia, would help to explain the very rapid deglaciation of Finland and eastern Sweden (Boulton *et al.* 1985; Lundqvist 1986). The widespread occurrence of cold-based conditions (Kaitanen 1969; Kujansuu 1975; Lagerbäck 1988a, b; Rodhe 1988; Follestad 1990; Kleman 1990, 1992; Kleman & Borgström 1990; Kleman *et al.* 1992) also accords with a thinner ice sheet model, since thinner ice, with lower basal pressures, is more likely to freeze to the substrate.

Accepting the second hypothesis removes the need for a very thick Late Weichselian ice sheet but has the effect of depressing the upper limit of the ice sheet even farther than has been suggested previously. The lower trimline lies only 250 m above the lateral moraines formed during the Younger Dryas. However, during the Younger Dryas the ice front lay in the fjords, whereas during the Late Weichselian the margin probably extended to the edge of the continental shelf. This model would require extremely efficient removal of ice from the mountain area as the ice sheet developed. In effect, it requires that the vertical extent of the ice near to the ice divide varies over a range of only a few hundred metres between glaciations of very different magnitude.

Conclusion

The Schmidt hammer results clearly distinguish sites deglaciated during the Little Ice Age from sites deglaciated during the Lateglacial and early Holocene. The instrument is particularly useful where evidence of glacial limits is erosional rather than depositional. However, the rock surface properties that influence Schmidt hammer results reach an approximate equilibrium before the age of the youngest pre-Little Ice Age surface used in this study and the results could not, therefore, be used to investigate the vertical extent of ice sheets in the Nordfjord area.

The profile gauge provides a very convenient way to record rock surface profiles which can then be used to quantify rock surface roughness at a range of scales. Four indices used to quantify rock surface roughness separate the profiles into three clear groups: Little Ice Age, sites below the trimline at *c.* 1350 m and sites above the trimline. There is no significant difference between measured rock surface roughness on the summit blockfield of Skåla and at sites downslope as far as the lower trimline.

The unexpected results of this pilot study suggest that the lower limit of summit blockfields in the Nordfjord area is unlikely to represent a glacial trimline formed during either the Late Weichselian maximum or a subsequent readvance. If either was the case the weathering difference would be expected across the upper rather than the lower trimline. Independent evidence that rock surfaces above the lower trimline at *c.* 1350 m were not glacially abraded during the Late Weichselian is provided by a ^{10}Be date of 18,000 years obtained from surface quartz samples collected at 1420 m.

Two conflicting hypotheses could explain the observed pattern of weathering differences in relation to the two trimlines:

1. The upper trimline represents the vertical limit of a pre-Late Weichselian ice sheet. During the Late Weichselian the ice sheet covered all of the summits, but cold-based ice protected surfaces as far down as the lower trimline.
2. The lower trimline represents the maximum vertical extent of the Late Weichselian ice sheet. The upper trimline represents an earlier, vertically more extensive ice sheet (Saalian?).

These hypotheses could by tested by using the techniques presented in this pilot study on key sites elsewhere in southern Norway. If the weathering limit on Skåla represents the vertical limit of the Late Weichselian ice sheet then it should be possible to predict its position on other mountains, rising to the east and falling to the west in parallel with the higher and possibly older limit mapped using the distribution of autochthonous blockfields. Further advances in the dating of exposed rock surfaces using the accumulation of cosmogenic nuclides may provide some age control.

Acknowledgements. – This work was funded by a collaborative research grant from the British Council and the Research Council of Norway, Division NAVF.

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