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Schmidt-hammer R-values from glacially-scoured bedrock surfaces across glacier-foreland boundaries: insights into Holocene weathering rates with implications for exposure-age dating

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ABSTRACT

Schmidt-hammer R-values were measured on glacially-scoured bedrock outcrops located inside and outside of 11 'Little Ice Age' glacier-foreland boundaries in the Jotunheimen and Jostedalsbreen regions of southern Norway. Analysing paired samples differing in exposure age by ~10,000 years constitutes a field experiment on chemical weathering rates within and between regions. Mean R-values (± 95% confidence intervals) from inside sites were 65.9 ± 0.6 and 66.9 ± 0.6 for rock surfaces composed of pyroxene-granulite gneiss in Jotunheimen at altitudes of 990–1360 m above sea level and granite and granitic gneiss in the Jostedalsbreen region at 270–620 m a.s.l. The corresponding values from outside sites of 39.9 ± 0.9 and 39.0 ± 0.9 were significantly lower, indicating a higher degree of chemical weathering. In contrast, regional differences in mean R-values were insignificant. A similar pattern is reflected in indices of rock weathering (39.0% for Jotunheimen and 41.6% for Jostedalsbreen), and weathering rate (2.8 R-value units and 3.0 units per 1000 years, respectively). These results imply an estimated minimum age resolution of Schmidt-

hammer exposure-age dating of ~350–625 years and a maximum age range of ~20,000 years. They suggest potential application of the Schmidt hammer to both studies of weathering rates and exposure-age dating at the regional scale, despite lithological variation associated with different rock types and climatic variation associated with altitudinal differences of up to 1000 m between the sites.

Key words: Schmidt hammer, R-values, rock-surface weathering, chemical weathering, exposure-age dating, glacier forelands, field experiment, South Norway

1. Introduction

R-values (rebound values or rebound numbers) obtained by Schmidt hammer measurement indicate the compressive strength of rock surfaces (Aydin, 2009). They are used in geomorphology and Quaternary geology to assess the degree of weathering (Goudie, 2013; Matthews et al., 2016), and the exposure age of bedrock outcrops and boulder landforms (Matthews and Winkler, 2022). Following the case study by Owen et al. (2007), we measure differences in R-values inside and outside of 'Little Ice Age' glacier-foreland boundaries in southern Norway. A geographical, comparative approach, in effect a field-experiment, is employed to analyse the variability in R-values across glacier-foreland boundaries. Our purpose is to investigate the rock-surface weathering rates that characterise gneissic and granitic rock surfaces in alpine to boreal environments.

Glacier forelands are defined here as the landscapes exposed after glaciers attained their maximum Little Ice Age extent. According to historical evidence and lichenometric dating, this occurred in the mid-eighteenth century in southern Norway (e.g. Østrem et al., 1977; Matthews, 2005; Grove, 1988a, 1988b; Bickerton and Matthews, 1992, 1993; Gjerde et al., 2023). In contrast, according to radiocarbon dating and cosmogenic exposure-age dating, the landscapes beyond the glacier-foreland boundaries were deglacierized in the Early Holocene (see Nesje and Matthews, 2024 and references therein). The age difference between the recently deglacierized terrain inside the glacier-foreland boundary and the terrain outside the glacier foreland is therefore known to be about 10,000 years. Our approach attempts to examine the effects of one variable (in this study, terrain age or time) while holding environmental variables (such as lithology, topography, climate and vegetation) as constant as possible. The crux of the field experiment is strategic sampling based on location.

On account of exposed, convex, glacially-scoured bedrock surfaces shedding water and therefore being relatively well drained, R-value differences across the glacier-foreland boundaries are attributed primarily to chemical weathering, rather than the physical or biological weathering processes that can be effective in the presence of greater moisture (cf. Colman and Dethier, 1986; Thorn et al., 2011; Matthews and Owen, 2011; Goodfellow et al., 2016; Matthews and Nesje, 2022). The microrelief of the rock outcrops and the general lack of fragmentation and loose particles support the absence of appreciable physical weathering, including frost weathering, which can be effective deep below the rock surface. However, a contribution from biological weathering by crustose lichens cannot be ruled out (cf.

McCarroll and Viles,1995; Chen et al., 2000; Etienne, 2002; Matthews and Owen, 2008; Wild et al., 2022). Over time, chemical weathering decreases the strength of the rock surface leading to lower R-values. Thus, the differences in R-values measured in this study across glacier-foreland boundaries provide insights into not only rates of chemical weathering but also the numerical relationship between R-value and rock-surface exposure age, which is the basis of Schmidt-hammer exposure-age dating.

The approach is applied in this paper to 11 glacier forelands in the Jotunheimen and Jostedalsbreen regions of southern Norway (Fig. 1). Our main objectives may be summarised as follows:

(1) to establish the variability in R-values on bedrock surfaces inside and outside of each glacier-foreland boundary;

(2) to compare results between glacier forelands at different altitudes on two different lithologies (pyroxene-granulite gneiss in Jotunheimen and granitic rocks near Jostedalsbreen);

(3) to evaluate the use of R-values as an indicator of chemical weathering rates during the Holocene; and

(4) to assess the implications of the results for Schmidt-hammer exposure-age dating.

2. Study areas

2.1. Jotunheimen

The six glacier forelands in the Jotunheimen mountains of southern Norway (Bøverbrean, Hurrbrean, Koldedalsbreen, Sandelvbrean, Storbrean and Styggedalsbreen) are located above the tree line in the alpine zone, at altitudes of 990–1360 m above sea level (Table 1). The study sites lie below the lower altitudinal limit of mountain permafrost, which occurs at ~1450 m a.s.l. (Ødgård et al., 1992; Isaksen et al., 2002; Lilleøren et al., 2012) and are therefore subject to a severe seasonal periglacial climate. Based on climatic normals (AD 1961-1990) for the Sognefjell weather station (1413 m a.s.l.), adjusted for the difference in site altitudes, mean July air temperatures of 6.1 to 8.7 º C and mean January air temperatures of –7.7 to –10.3 º C characterise these sites where mean annual air temperature is –0.1 to –2.7º C (Aune, 1993; see also www.met.no). Mean annual precipitation is around 860 mm (Førland, 1993) with snow depths of the order of 2 m (http:www.senorge.no/), although snow accumulates less on upstanding rock outcrops.

Pyroxene-granulite gneiss, the dominant lithology of the rock outcrops throughout Jotunheimen (Battey and McRitchie, 1971; Lutro and Tveten, 1996), was the sampled bedrock type. Occasional intrusions of peridotite and quartzitic veins were easily recognised and avoided during R-value measurement. As exposed rock outcrops are generally not overtopped by the low-alpine dwarf shrubs and tall herbs that dominate the vegetation at these sites, they are fully exposed to the atmosphere. The rock surfaces are, however, often heavily encrusted with epilithic lichens, which were avoided as much as possible as points of impact of the Schmidt hammer.

Holocene glacier variations in Jotunheimen have been reconstructed from moraines dated by historical evidence, radiocarbon, lichenometry and cosmogenic exposure-age dating (e.g. Matthews, 1977, 1991, 2005; Matthews and Winkler, 2011; Matthews et al., 2014, 2023; Shakesby et al., 2020) and glacigenic sediments in distal lakes and stream-bank mires (Matthews et al., 2000, 2005; Matthews and Dresser, 2008). Based on the chronology of these reconstructions, the exposure ages of the rock outcrops inside the glacier-foreland boundaries are essentially modern, whereas outside sites have exposure ages close to 10,000 years.

2.2. Jostedalsbreen

The five glacier forelands associated with outlet glaciers from the Jostedalsbreen ice cap (Austerdalsbreen, Bødalsbreen, Fåbergstølsbreen, Nigardsbreen,and Tuftebreen) are located below the tree line in the boreal forest zone. The altitudinal range of the sites is 270–620 m a.s.l. (Table 1). Based on climatic normals (AD 1961–1990) for the Bjørkhaug weather station (324 m a.s.l.) mean annual air temperature at our sites is 1.4 to 4.1º C with mean July and mean January air temperatures of 11.1 to 13.8º C and –4.5 to –7.2º C, respectively. Mean annual precipitation is around 1380 mm, and snow depths are up to ~4 m. This seasonal periglacial climate is less severe than in Jotunheimen, despite some topoclimatic effects due to proximity to the ice cap.

Lithologically, the rock outcrops in the Jostedalsbreen region are dominated by granite and granitic gneiss (Lutro and Tveten, 1996). At some sites outside the glacier forelands, trees (mainly mountain birch, *Betula pubescens*) overtop the rock surfaces but the cover is usually light and unlikely to influence the microclimate enough to affect R-values. However, shading by trees, together with the higher precipitation in the region can result in moss carpets on the surface of rock outcrops, These might produce biochemical weathering effects where they are well developed.

Reconstructions of glacier variations in the Jostedalsbreen region (e.g. Nesje et al., 1991, 2000, 2001; Nesje, 2009) demonstrate a similar pattern and timing to those in Jotunheimen. Prominent Little Ice Age moraine ridges that delimit glacier foreland boundaries have been precisely dated to the mid-eighteenth century by historical evidence (e.g. Østrem et al., 1977; Grove, 1988a, Gjerde et al., 2023) supported by lichenometry (Bickerton and Matthews, 1992, 1993). Early Holocene moraines located up to about 1 km outside several of the glacier forelands have been dated by radiocarbon and *in situ* ^{10}Be to 10,200–9,700 years BP (the Erdalen Event; Dahl et al., 2002; Matthews et al., 2008). Thus, for present purposes, the exposure ages of glacially-scoured rock surfaces located inside the glacier-foreland boundaries are again modern and surfaces outside the boundary have exposure ages of ~10,000 years.

3. Methods

The glacier-foreland boundaries in this study were clearly defined by prominent lateral and/or terminal moraines and had glacier-scoured bedrock outcrops present on both sides of the boundary. The sampling strategy involved paired sites where, ideally, the same rock outcrop was traceable across the boundary. A conceptual model of our approach (Fig. 2) focuses on site selection and highlights outcrops that were regarded as acceptable or unacceptable for sampling. Acceptable inside sites were located >100 m from the boundary in order to avoid the marginal zone susceptible to the survival of pre-weathered surfaces. A pre-weathered surface is defined as a deglacierized bedrock surface exhibiting inherited traces of weathering that survived the earlier glacierization. Here, such inside surfaces may have survived glacial erosion during the Little Ice Age (cf. Owen et al., 2007). Pre-weathered surfaces were recognisable by their abnormal roughness compared to the surfaces recently abraded by glaciers. In practice, inside sites were located at distances of 100–200 m (with the exception of Storbrean South at 300 m and Nigardsbreen at 400 m) from the boundary; whereas outside sites were located 30–500 m from the boundary (exceptionally 600 m at Hurrbrean and 1000 m at Bødalsbreen) (Table 1). Examples are shown in Fig. 3. At both Fåbergstølsbreen and Storbrean, two sets of inside and outside sites were sampled. In total, 13 paired sites were sampled across 11 Little Ice Age glacier-foreland boundaries (i.e. a total of 26 sites).

At each inside and outside site, 300 R-values were measured using a mechanical N-type Schmidt hammer (Proceq 2017). Impacts were spread widely across the rock surfaces, avoiding as much as possible, sloping surfaces, irregular microtopography, cracks, edges, lichen and moss cover, and wet surfaces, all of which produce anomalously low R-values (cf. Shakesby et al., 2006; Matthews and Owen, 2010; Matthews and Winkler, 2022). The measurement strategy ensured that inside and outside rock surfaces were as comparable as possible in all respects apart from the lapse of time since deglacierization (i.e. terrain age). However, initial measurements made at 100–300 m inside the southern boundary at Nigardsbreen were later rejected in favour of those made at 500 m by Matthews and Owen (2010) on the grounds of anomalously low R-values attributed to pre-weathering (discussed further below). R-values measured by Owen et al. (2007) at Fåbergstølsbreen North were also incorporated into our data set.

Indices of rock weathering (IRW) and rock weathering rate (WR) were calculated from the difference in mean R-value between inside and outside sites, and their exposure ages (Matthews and Owen, 2011):

$$IRW = 100 - (100R_1 / R_2) \qquad (\textit{Equation 1})$$

$$WR = (R_2 - R_1)\ (A_1 - A_2) \qquad (\textit{Equation 2})$$

Where R_1 is the mean R-value of the outside (well weathered) rock surface, R_2 is the mean R-value of the inside (minimally weathered) rock surface, A_1 is the age of the outside site, and A_2 is the age of the inside site.

Our analysis includes calculation and visual representation of the statistical significance of differences between mean R-values for sites and regions with reference to 95% confidence intervals (cf. Matthews, 1981). The probability of the true mean lying beyond a 95% confidence interval is <5%. If two 95% confidence intervals overlap, then the null hypothesis of 'no difference' between mean values cannot be rejected, whereas non-overlapping confidence intervals indicate a statistically significant difference ($p < 0.05$).

In our discussion of the implications for Schmidt-hammer exposure-age dating, we use previously published age-calibration equations from Jotunheimen and

Jostedalsbreen regions (Matthews and Owen, 2010). Their R-value measurements for the control surfaces were collected from inside and outside sites that are fully comparable to those in the present study.

4. Results

Site mean R-values are consistent for outside sites where the range between glacier forelands is 38.3–41.5 for Jotunheimen and 37.9–40.0 for the Jostedalsbreen region (Table 2 and Fig. 4). Mean R-values at inside sites, which range from 61.1–67.4 for Jotunheimen forelands and 60.5–67.9 for Jostedalsbreen forelands, are more variable. The 95% confidence intervals associated with each site mean show, however, that statistically significant differences exist for a few of the site means within each region, particularly in relation to the inside sites.

Statistically significant variation between inside sites is demonstrated by the non-overlap of ten of the site-mean confidence intervals with those of the relevant regional mean R-value (Table 2 and Fig. 4). In contrast, none of the site-mean R-values for outside sites from either Jotunheimen or the Jostedalsbreen region differs significantly from their respective regional-mean R-values. This is demonstrated by overlap between the individual 95% confidence intervals associated with each site mean and the collective 95% confidence intervals of the regional-mean R-values (shown as broad bands in Fig. 4). Non-overlapping confidence intervals for the site-mean R-values from northern and southern lateral moraine sites at both Storbrean and Fåbergstølsbreen further demonstrate local differences within glacier forelands that are statistically significant and comparable in scale to the differences between the single sites investigated at the other glacier forelands.

Overlapping 95% confidence intervals between the regional-mean R-values demonstrate that between-region differences are not significant, neither for inside nor outside sites (Table 2 and Fig. 4). Indeed, the (uncorrected) regional-mean R-values for inside sites of 64.8 ± 0.6 for Jotunheimen and 65.2 ± 0.8 for Jostedalsbreen are almost identical. For outside sites, the regional means of 39.9 ±0.9 for Jotunheimen and 39.0 ± 0.9 for Jostedalsbreen are also remarkably similar. In contrast, the differences between site-mean R-values from the inside and outside sites of particular glacier forelands, which range from 21.3 (Tuftebreen) to 29.6 (Fåbergstølsbreen North), are all highly statistically significant (Table 2 and Fig. 4). Thus, between-site variation in R-values is clearly much greater than the between-region variation.

The confidence intervals associated with mean R-values for the inside sites at Bøverbreen, Storbreen North, Austerdalsbreen and Tuftebreen do not overlap with the estimates for their respective regional-mean R-values (Fig. 4). A strong case can therefore be made for regarding these four inside sites with anomalously low mean R-values as statistical outliers, particularly as they can be explained in terms of pre-weathering (see below). Removal of these outliers, yields corrected regional-mean R-values for inside sites of 65.9 ± 0.6 for Jotunheimen and 66.9 ± 0.6 for the Jostedalsbreen region, and corrected regional average R-value differences (Δ Mean values in Table 2) across glacier-foreland boundaries of 26.0 for Jotunheimen and 27.9 for Jostedalsbreen (Table 2).

The corrected average R-value differences across glacier foreland boundaries in Jotunheimen and Jostedalsbreen translate into indices of rock weathering (IRW) for weathered outside surfaces of 39.0% and 41.6%, respectively (Table 2). The values of IRW at particular glacier forelands range from 35.2% at Tuftebreen to 43.9% at Fåbergstølsbreen North. Regional rates of rock weathering (WR), which reflect the decline in rock-surface strength (rock weakening) over the last 10,000 years of the Holocene, are 2.8 and 3.0 R-value units per 1000 years for Jotunheimen and Jostedalsbreen, respectively.

5. Discussion

Wide and consistent differences in site-mean R-values of ~20–30 across each glacier-foreland boundary (Fig. 4) are essentially controlled by the large (~10,000 year) exposure-age difference between the rock surfaces at inside and outside sites rather than differences in environmental factors. There is no major lithological or other environmental difference at each glacier-foreland boundary that could account for the large difference in mean R-value between the inside and outside sites. Furthermore, there is little evidence to suggest that lithology or altitude has an appreciable effect on the difference in mean R-values or weathering rates between the Jotunheimen and Jostedalsbreen regions. The results therefore provide *prima facie* evidence of relevance to understanding rock-surface weathering rates and have clear implications for Schmidt-hammer exposure-age dating.

5.1. R-values and chemical weathering rates

As stated in the introduction, we attribute the difference in mean R-values between inside and outside sites to chemical weathering. Prolonged chemical weathering is interpreted as transforming initially smooth, hard and resistant glacially-abraded rock surfaces into weaker surfaces. We assume that chemical weathering proceeds from the surface downwards and is likely to be most effective along crystal boundaries (cf. Dixon et al., 2002; Dixon and Thorn, 2005; Nicholson, 2008). Although some mineral grains and rock flakes are likely to have been removed by micro-erosional processes, thin surficial weathering rinds that have developed at outside sites are consistent with this interpretation. Several hydration and oxidation processes may be involved. These include hydrobiotite and vermiculite formation from biotite and the removal of pyroxene, which has been shown to be effective in Jotunheimen (Mellor, 1985, 1986; Darmody et al., 1987, 2005) and Fe oxidation, which accompanies biotite formation (Goodfellow et al., 2016). Thus, although there is uncertainty about specific processes, chemical weathering likely accounts for the lower mean R-values that characterise our outside sites compared to inside sites.

The most important processes affecting mean R-value variability between inside sites appear to be unrelated to weathering. They relate to the effectiveness of Little Ice Age glacier erosion in (1) removing any pre-weathered remnants from the rock outcrops and (2) creating smooth, sometimes polished, abraded surfaces. Rejection of sites in the marginal zone within the glacier-foreland boundary was intended to eliminate any sites where glacier erosion of pre-weathering had been ineffective (cf. the previous study by Owen et al., 2007 at Fåbergstølsbreen).

However, the anomalous mean R-values obtained at the inside sites of Bøverbreen, Storbreen North., Austerdalsbreen and Tuftebreen, which are significantly lower than their regional-mean R-values (Table 2 and Fig. 4), can be attributed to the effects of inefficient glacial erosion in a wider marginal zone extending to distances of at least 200 m inside the glacier- foreland boundary (see Table 1).

Survival of pre-weathering can be attributed to relatively thin ice thickness, short duration of the ice cover, slow ice velocity and/or local interactions between ice flow, subglacial debris and subglacial topography in the ice-marginal zone when the glaciers were close to their Little Ice Age maximum extent. Wide dispersion, skewness, long tails and/or more than one mode are to be expected in the statistical distributions of R-values from anomalous inside sites affected by pre-weathering (cf. Matthews and Winkler, 2022). Such features are clearly illustrated by data from Nigardsbreen, where R-values obtained from an initial inside site were rejected in favour of a site at 400 m within the glacier foreland boundary (Fig. 5). The extremely narrow dispersion of the histogram representing the inside site (R-values of 60–75), where glacial erosion has been efficient, contrasts with the broad dispersion (R-values of 20–60) exhibited by the outside site, where weathering has occurred over a protracted period. The marginal zone exhibits a hybrid distribution with the widest dispersion (R-values of 30–72), the longest tail and evidence of at least two modes (which occur within the ranges of the other two distributions and represent a diachronous surface).

Our corrected weathering rate (WR) values are similar to previous estimates of 2.7 and 3.4 R-value units per 1000 years based on more restricted data from the

Jotunheimen and Jostedalsbreen regions, respectively (see Matthews and Owen, 2011). However, as noted in relation to Δ Mean values, local differences (within and between glacier forelands) in both IRW and WR exceed the between-region differences. Hence the chemical weathering environment can be regarded as more-or-less similar across the gneissic rocks of Jotunheimen and the granitic rocks of the Jostedalsbreen region, albeit with the possibility of a marginally higher average rate of weathering in the Jostedalsbreen region. This conclusion is supported by analysis of potential correlations between altitude and each of the following: mean R-value of inside sites, mean R-value of outside sites, mean difference between inside and outside sites (Δ mean), IRW and WR. However, even the highest correlation of $r = 0.65$ between altitude and Δ mean was not statistically significant, though marginally so ($p>0.05$, $n = 9$).

Data from more traditional methods that have been used in the investigation of chemical weathering can assist in the interpretation of Δ mean and the weathering indices based on Schmidt hammer R-values. Several studies have inferred rock surface lowering rates based on differential weathering — i.e. the height of quartzitic veins upstanding from the surrounding rock surface. Matthews and Owen (2011) reported a mean surface lowering rate of 4.8 ± 1.0 mm per thousand years for pyroxene-granulite rocks in the Smørstabbtindan massif, Jotunheimen, at altitudes of 1229-1540 m a.s.l. On granitic surfaces in the Jostedalsbreen region at altitudes of 250-520 m a.s.l. the mean surface lowering rate was only 1.6 ± 0.1 mm per thousand years. Studies in Scandinavia using the differential weathering approach on crystalline rock over a wide range of altitudes and latitudes have produced mean surface lowering rates mostly within the range 0.2-1.0 mm per thousand years (André, 1996, 2002; Nicholson, 2008, 2009; but see Matthews and Owen, 2011). Other indices and estimates based, for example, on weathering rind thicknesses, pit depths and water chemistry (Dahl, 1967; Rapp, 1960; André, 1996, 2002; Darmody et al., 2000; Nicholson, 2008, 2009; Thorn et al., 2011; Beylich and Laute, 2012, 2021) generally support the concepts of slow rates of chemical weathering in periglacial environments and the dominance of local over regional climatic controls.

5.2. Implications of R-value variations for Schmidt-hammer exposure-age dating (SHD)

SHD fundamentally depends on the rate of chemical weathering of the rock surface and age-calibration of R-values from that surface (Matthews and Winkler, 2022). Age-calibration involves establishing the numerical relationship between mean R-values and exposure age from surfaces of known exposure age (control points) for a specific lithology. In practice, exposure-age estimates for surfaces of unknown age from that lithology are then interpolated. SHD age estimates are dependent on the variability of the mean R-values from rock surfaces of both known and unknown age. As our field experiment involves two potential control points (inside and outside sites), the known age difference of ~10,000 years between them determines the potential age range of any resulting SHD age estimates. However, it is the variability of the R-values that determines the age resolution. The chronological implications of our results therefore apply to the age-resolution of SHD on the Holocene timescale.

In the context of SHD, R-value variability is best summarised by the 95% confidence intervals associated with the (corrected) regional-mean R-values; i.e. ±0.6 units for inside sites and ±0.9 units for outside sites in both Jotunheimen and Jostedalsbreen regions (Table 2). These R-value confidence intervals can be converted into time intervals using the *b* coefficients from the published age-calibration equations of Matthews and Owen (2010) for Jotunheimen (Equation 3) and Jostedalsbreen (Equation 4), where y = surface age and x = mean R-value:

$$y = 22986.956 - 347.82608x \qquad (\textit{Equation 3})$$

$$y = 19617.379 - 291.17379x \qquad (\textit{Equation 4})$$

The implied age-resolution of 420–625 years for Jotunheimen and 350–520 years for Jostedalen are based entirely on the calibration error (C_c). As the age resolution of SHD ages is also affected by the sampling error (Cs), our estimates should be regarded as minimum estimates. Although age resolution can, in principle, be increased by increasing the sample size, a significant increase in age resolution would require a very large, possibly impractical, sample size beyond the n = 300 in use here (cf. Matthews and Winkler, 2022).

The age range of SHD (in the context of crystalline rock surfaces in southern Norway) can be estimated from our calculated weathering rates of 2.8–3.0 R-value units per millennium (Table 2). Applying this rate to the mean R-values of 65.9–66.9 from our inside sites (Table 2), which represent unweathered rock surfaces, suggests a maximum age-range for SHD of little more than ~20,000 years. This is consistent with the time frame of most applications of SHD, which have focused on the Holocene and the Late Glacial (see Matthews and Winkler, 2022), though occasionally the effective age range has been extended further (e.g. Tomkins et al., 2018).

Close similarity in mean R-values obtained from surfaces of the same age in different lithologies and climatic environments has implications for the application of calibration equations. Particular calibration equations may well have wider than local applicability subject, of course, to the extent of lithological variability. The degree to which mean R-values from sites characterised by pyroxene-granulite gneiss in Jotunheimen and granitic rocks of the Jostedalsbreen region are in agreement is perhaps surprising. Closer study may reveal that this conclusion can be extended to certain other lithologies that commonly occur in southern Norway and beyond, such as augen gneiss and migmatitic gneiss (cf. Matthews et al., 2016), leading to wider application of SHD.

Conclusion

Comparison of Schmidt-hammer R-values from pairs of glacially-scoured bedrock outcrops located inside and outside of Little Ice Age glacier-foreland boundaries in two regions of southern Norway constitute a field experiment to assess rates of chemical weathering over centennial to millennial timescales. Mean R-values (± 95% confidence intervals) from inside sites deglacierized for <300 years of 65.9 ± 0.6 (Jotunheimen) and 66.9 ± 0.6 (Jostedalsbreen) were found to be consistently higher

than the corresponding mean values of 39.9 ± 0.9 and 39.0 ± 0.9 from outside sites deglacierized for ~10,000 years. These differences translate into weathering rate indices of 2.8 and 3.0 R-value units per 1000 years, respectively. Controlled sampling and the characteristics of the rock surfaces enabled the significant R-value differences between inside and outside sites to be attributed primarily to the higher degree of chemical weathering at the outside sites. In contrast, regional differences in lithology (gneissic versus granitic) and altitudinal differences of up to 1000 m were found to have little effect on the inferred weathering rates within the alpine and boreal environments of the study area. Our approach focusing on differences in R-values from surfaces that differ appreciably in exposure age but are located in similar environments may have wider application in the study of weathering rates beyond the glacier-foreland context. The results also have implications for Schmidt-hammer exposure-age dating of rock surfaces. These include an estimated minimum age-resolution of ~350–625 years and a maximum exposure age that can be determined of ~20,000 years.

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Table 1. Glacier-foreland sites in the Jotunheimen and Jostedalsbreen regions

Glacier	Inside site		Outside site	
	Altitude[1] (m)	Distance[2] (m)	Altitude[1] (m)	Distance[2] (m)
Jotunheimen				
Bøverbrean	1340	200	1360	40
Hurrbrean	1100	150	990	600
Koldedalsbreen	1240	200	1180	150
Sandelvbrean	1350	150	1320	80
Storbrean N[3]	1160	100	1160	100
Storbrean S[3]	1350	300	1320	250
Styggedalesbreen	1270	200	1300	300
Jostedalsbreen				
Austerdalsbreen	350	150	320	500
Bødalsbreen	620	200	600	1000
Fåbergstolsbreen N[3]	520	200	520	40
Fåbergstolsbreen S[3]	510	150	520	30
Nigardsbreen	310	400	270	200
Tuftebreen	430	150	450	150

[1] Altitude = metres above sea level
[2] Distance = metres from the glacier-foreland boundary
[3] N and S = north and south

Table 2. R-values from sites inside and outside the glacier-foreland boundaries (n = 300) and weathering indices. Corrected averages refer to the exclusion of inside sites that represent statistical outliers (see text for further explanation).

Glacier foreland	Inside site			Outside site			Δ Mean	IRW (%)	WR (per ka)
	Mean	SD	CI	Mean	SD	CI			
Jotunheimen									
Bøverbrean	61.1	6.2	0.7	38.3	7.8	0.9	22.8	37.3	2.4
Hurrbrean	65.8	4.8	0.5	38.8	7.9	0.9	27.0	41.0	2.9
Koldedalsbreen	65.1	4.3	0.5	39.9	6.9	0.8	25.2	38.7	2.7
Sandelvbrean	66.5	5.7	0.7	41.5	8.8	1.0	25.0	37.6	2.7
Storbrean N	63.1	4.0	0.5	40.3	7.8	0.9	22.8	36.1	2.4
Storbrean S	67.4	5.3	0.6	41.4	9.0	1.0	26.0	38.6	2.8
Styggedalesbreen	64.5	4.3	0.5	39.3	7.3	0.8	25.2	39.1	2.7
Regional average	***64.8***	***5.0***	***0.6***	***39.9***	***7.9***	***0.9***	***24.9***	***38.4***	***2.6***
Corrected average	***65.9***	***4.9***	***0.6***	--	--	--	***26.0***	***39.0***	***2.8***
Jostedalsbreen									
Austerdalsbreen	62.9	6.3	0.7	38.5	6.7	0.8	24.4	38.8	2.6
Bødalsbreen	67.9	5.0	0.6	39.0	7.6	0.9	28.9	42.6	3.1
Fåbergstølsbreen N	67.5	7.4	0.8	37.9	8.3	1.0	29.6	43.9	3.1
Fåbergstølsbreen S	65.4	5.0	0.6	40.0	8.8	1.0	25.4	38.8	2.7
Nigardsbreen	66.8	3.7	0.4	39.3	8.7	1.0	27.5	41.2	2.9
Tuftebreen	60.5	8.5	1.9	39.2	9.2	1.1	21.3	35.2	2.3
Regional average	***65.2***	***6.0***	***0.8***	***39.0***	***8.2***	***0.9***	***26.2***	***40.2***	***2.8***
Corrected average	***66.9***	***5.3***	***0.6***	--	--	--	***27.9***	***41.6***	***3.0***

Mean = Site mean R-value
SD = Standard deviation
CI = 95% confidence interval
Δ Mean = Difference in site mean R-values between inside and outside sites
IRW = Index of Rock Weathering (see text for explanation)
WR = Weathering Rate (see text for explanation)

FIGURE CAPTIONS

Fig. 1. Location of the glacier forelands investigated in two regions of southern Norway: (A) Jotunheimen and (B) Jostedalsbreen.

Fig. 2. The sampling design on an idealised Little Ice Age glacier foreland in southern Norway where deglacierization commenced <300 years ago and the landscape beyond the glacier foreland boundary was deglaciated ~10,000 years ago. The rock outcrops shown represent potential study sites. These are located inside, outside and crossing the glacier foreland boundary. Unacceptable inside sites are located in the marginal zone, defined here as the outermost 100 m of the glacier foreland. Acceptable inside sites (intended to avoid pre-weathered rock surfaces) are located >100 m from the glacier-foreland boundary. All outside sites are shown as acceptable. One ideal pair of sites is shown where (a) inside and (b) outside sites are available from the same contiguous bedrock outcrop that extends across the glacier-foreland boundary.

Fig. 3. Representative examples of glacially-scoured bedrock outcrops from inside and outside of glacier-foreland boundaries (A-D, Jotunheimen; E-H, Jostedalsbreen): A, Bøverbrean (inside site); B, Bøverbrean (outside site); C, Styggedalsbreen (inside site); D, Storbrean (outside site – Little Ice Age moraine ridge in the middle ground a few metres from the site); E, Austerdalsbreen (inside site); F, Austerdalsbreen (outside site); G, Bødalsbreen (inside site); H, Tuftebreen (outside site).

Fig. 4. Site-mean and regional-mean R-values for sites located inside and outside sites of glacier-foreland boundaries in the Jotunheimen and Jostedalsbreen regions. Site-

mean R-values are represented by points with 95% confidence intervals shown as horizontal bars. Regional-mean R-values are represented by vertical lines with their 95% confidence intervals shown as vertical shaded bands.

Fig. 5. Distributions (frequency histograms; n = 300 each) of R-values from sites located inside and outside of Nigardsbreen glacier foreland. The inside site is shown in red and the outside site in green. The site from the marginal zone (blue with grey shading) is transitional due to pre-weathering effects.

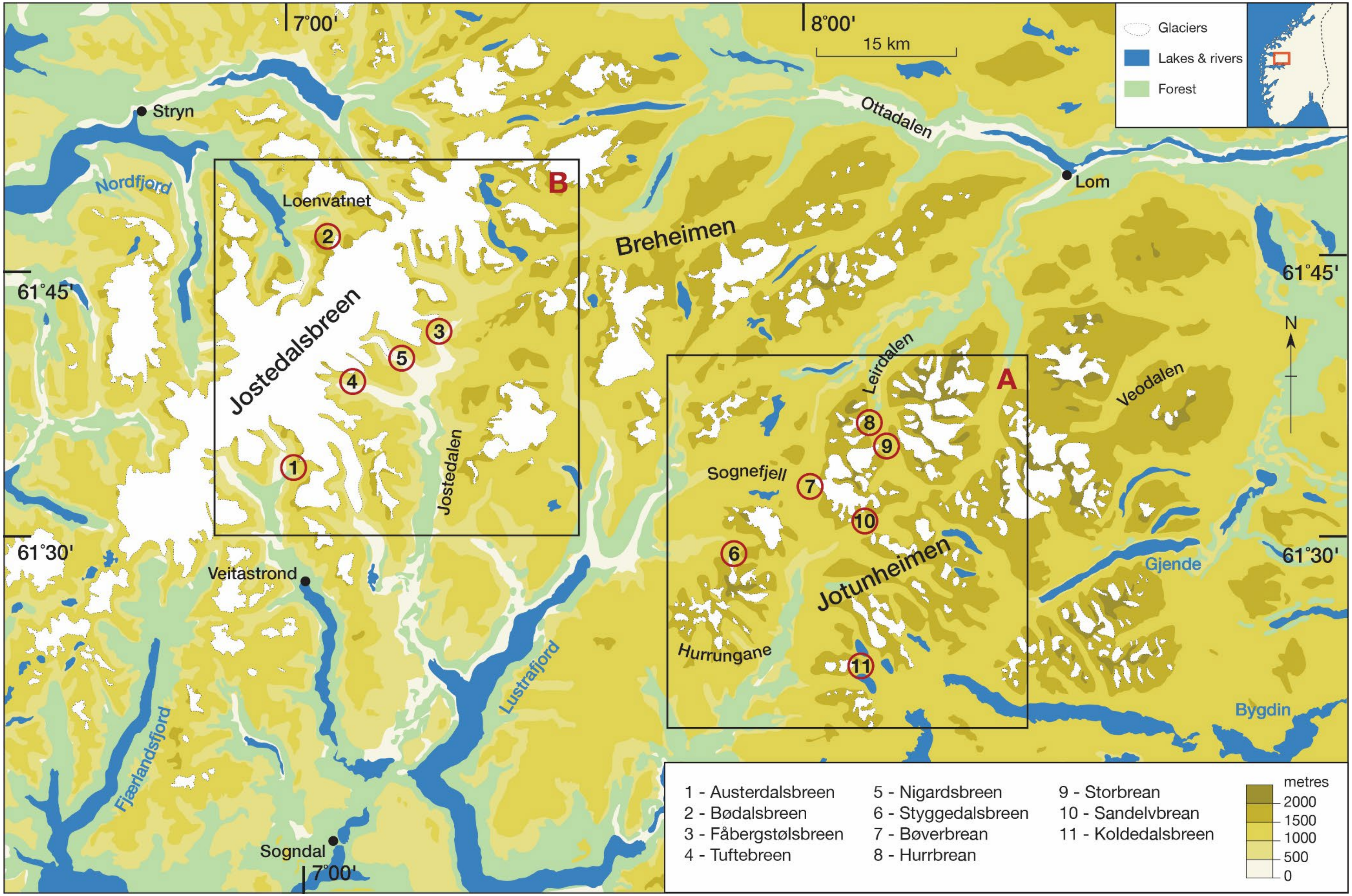
7°00'
8°00'
15 km
Glaciers
Lakes & rivers
Forest
Stryn
Nordfjord
Ottadalen
Lom
B
Loenvatnet
Breheimen
61°45'
61°45'
Jostedalsbreen
Leirdalen
A
Veodalen
N
Jostedalen
Sognefjell
Jotunheimen
61°30'
61°30'
Veitastrond
Gjende
Hurrungane
Lustrafjord
Bygdin
Fjærlandsfjord
Sogndal
7°00'
1 - Austerdalsbreen
2 - Bødalsbreen
3 - Fåbergstølsbreen
4 - Tuftebreen
5 - Nigardsbreen
6 - Styggedalsbreen
7 - Bøverbrean
8 - Hurrbrean
9 - Storbrean
10 - Sandelvbrean
11 - Koldedalsbreen
metres
2000
1500
1000
500
0

Fig. 1.

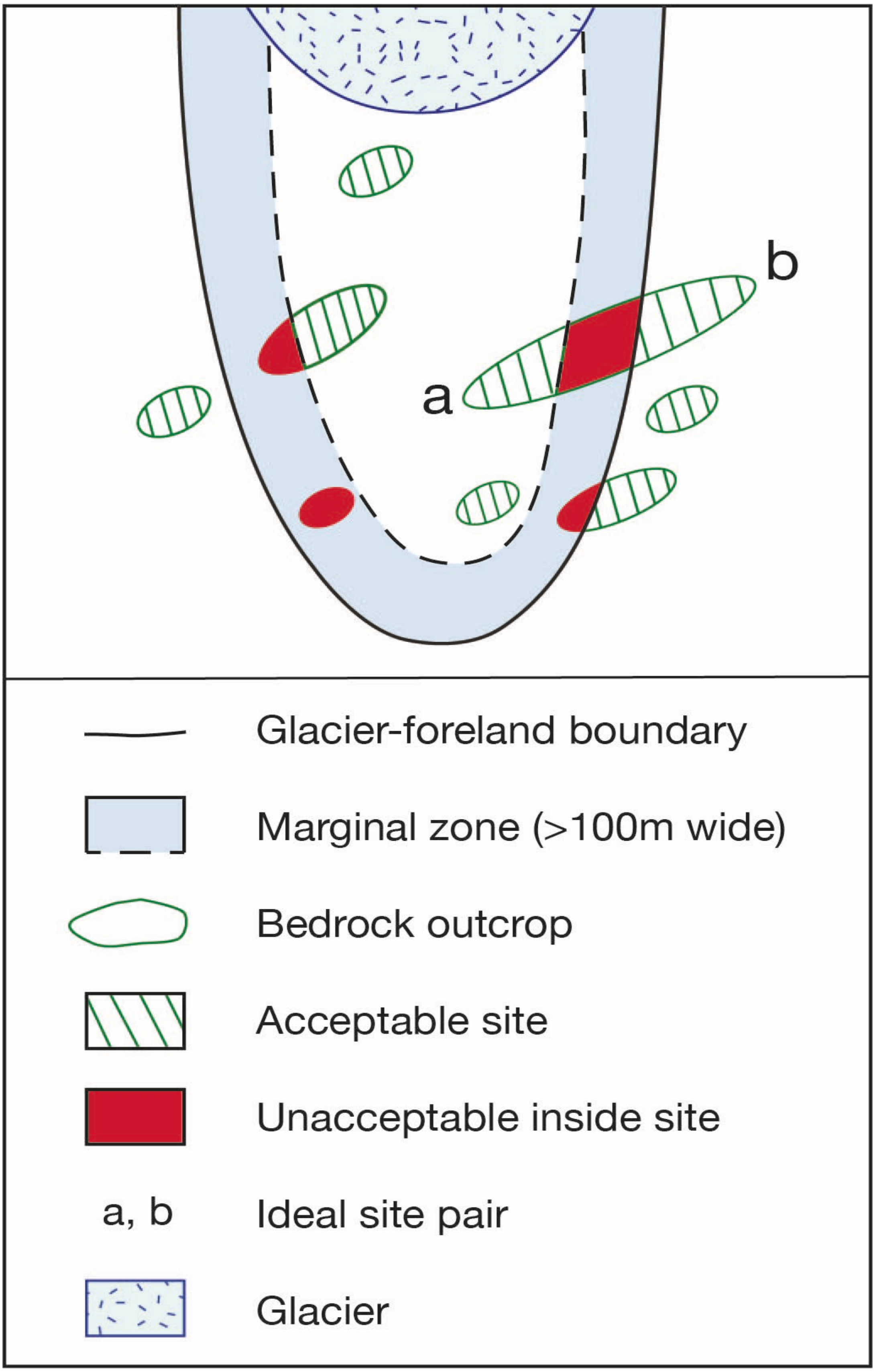
b
a
Glacier-foreland boundary
Marginal zone (>100m wide)
Bedrock outcrop
Acceptable site
Unacceptable inside site
a, b
Ideal site pair
Glacier

Fig. 2.

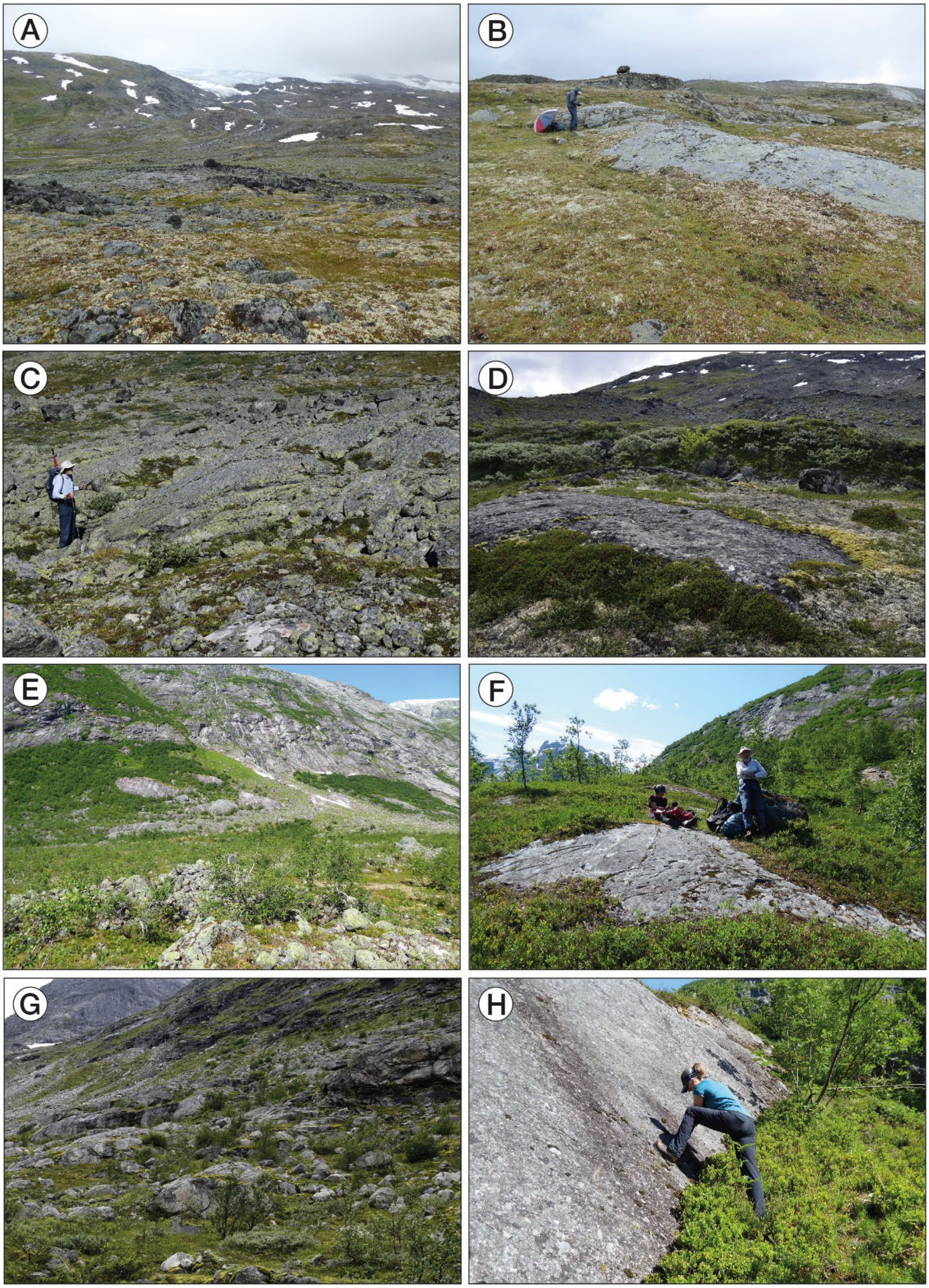

Fig. 3.

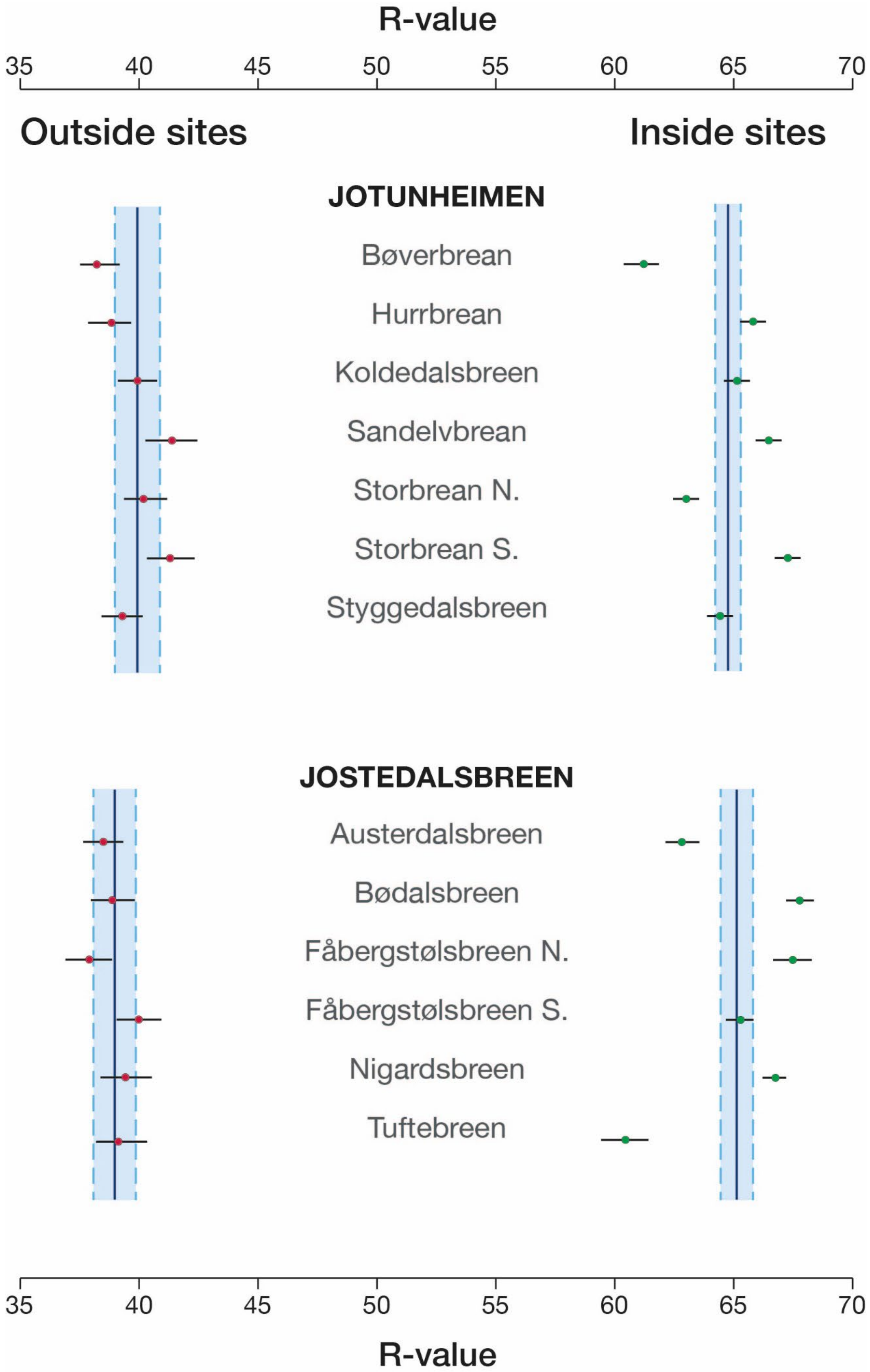
R-value
35
40
45
50
55
60
65
70
Outside sites
Inside sites
JOTUNHEIMEN
Bøverbrean
Hurrbrean
Koldedalsbreen
Sandelvbrean
Storbrean N.
Storbrean S.
Styggedalsbreen
JOSTEDALSBREEN
Austerdalsbreen
Bødalsbreen
Fåbergstølsbreen N.
Fåbergstølsbreen S.
Nigardsbreen
Tuftebreen
35
40
45
50
55
60
65
70
R-value

Fig. 4.

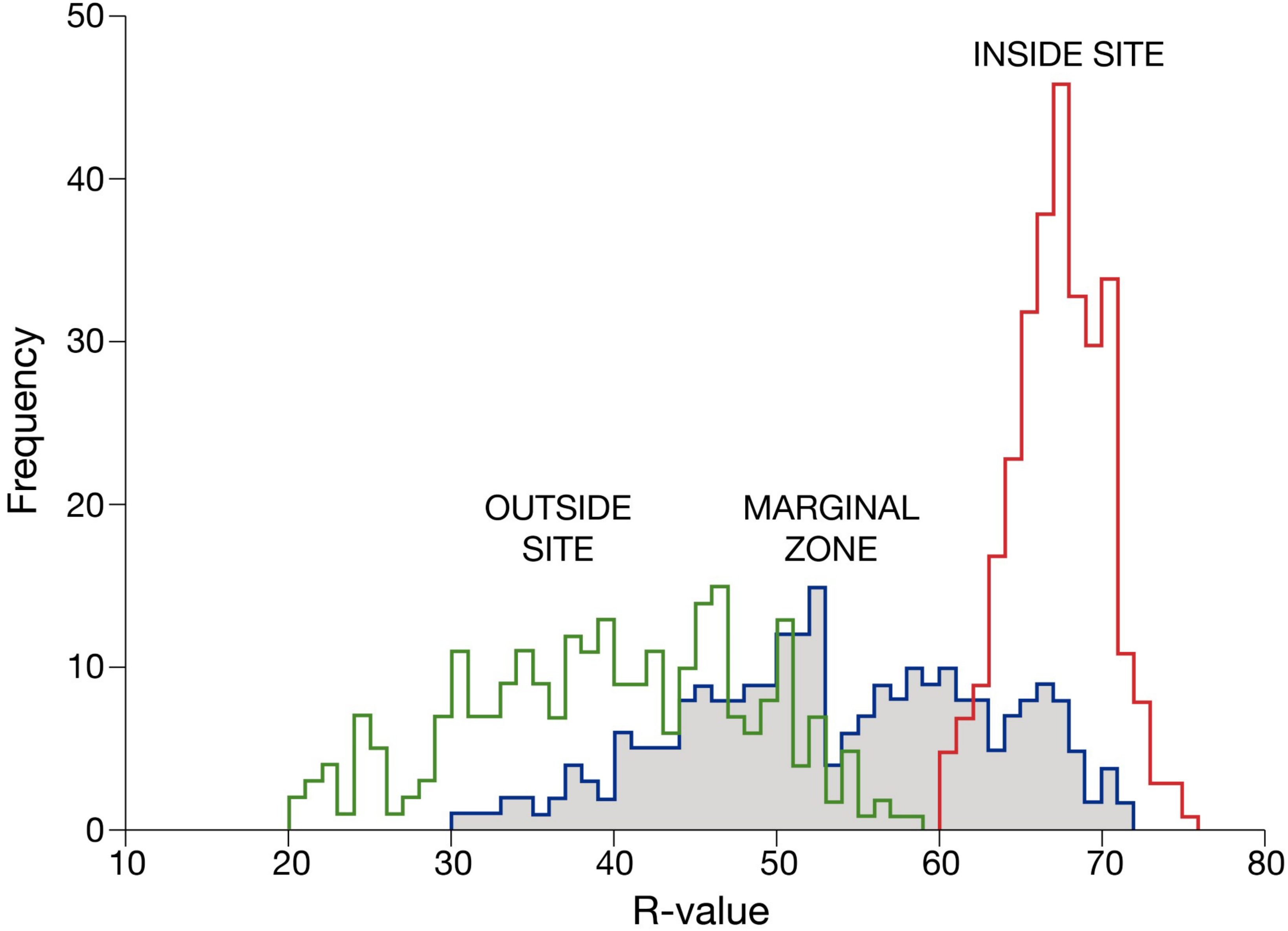
INSIDE SITE
OUTSIDE SITE
MARGINAL ZONE
Frequency
R-value
50
40
30
20
10
0
10
20
30
40
50
60
70
80

Fig. 5.