Schmidt-hammer exposure ages from periglacial patterned ground (sorted circles) in Jotunheimen, Norway, and their interpretative problems

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Abstract

Periglacial patterned ground (sorted circles and polygons) along an altitudinal profile at Juvflya in central Jotunheimen, southern Norway, is investigated using Schmidt-hammer exposure-age dating (SHD). The patterned ground surfaces exhibit R-value distributions with platycurtic modes, broad plateaus, thin tails, and a negative skew. Sample sites located between 1500 and 1925 m a.s.l. indicate a distinct altitudinal gradient of increasing mean R-values towards higher altitudes interpreted as a chronological function. An established regional SHD-calibration curve for Jotunheimen yielded mean boulder exposure ages in the range 6910 ± 510 to 8240 ± 495 years ago. These SHD ages are indicative of the timing of patterned ground formation, representing minimum ages for active boulder upfreezing and maximum ages for the stabilization of boulders in the encircling gutters. Despite uncertainties associated with the calibration curve and the age distribution of the boulders, the early-Holocene age of the patterned ground surfaces, the apparent cessation of major activity during the Holocene Thermal Maximum (HTM) and continuing lack of late-Holocene activity, clarify existing understanding of the process dynamics and palaeoclimatic significance of large-scale sorted patterned ground as an indicator of a permafrost environment. The interpretation of SHD ages from patterned ground surfaces remains challenging, however, owing to their diachronous nature, the potential for a complex history of formation, and the influence of local, non-climatic factors.

Keywords

Sorted circles, periglacial patterned ground, alpine permafrost, Schmidt-hammer exposure-age dating (SHD), RockSchmidt, Holocene climatic variations, Jotunheimen

Introduction

During the past few decades the Schmidt hammer has been applied to estimating the age of landforms of periglacial, glacial, and mass movement origin such as rock glaciers (Frauenfelder *et al.* 2005; Kellerer-Pirklbauer *et al.* 2008; Rode and Kellerer-Pirklbauer 2011; Matthews *et al.* 2013), pronival ramparts (Matthews *et al.* 2011; Matthews and Wilson 2015), snow-avalanche impact ramparts (Matthews *et al.* 2015), moraines (Matthews and Shakesby 1984; Evans *et al.* 1999; Aa and Sjåstad 2000; Winkler 2005, Ffoulkes and Harrison, 2014), rock fall/avalanches (Nesje *et al.* 1994; Aa *et al.* 2007), fluvial terraces (Stahl *et al.* 2013) and boulder streams (Wilson *et al.*, submitted). Initially it was used only as a relative-age dating technique based on the principle of relating compressional strength of a bedrock or boulder surface to its degree of surface weathering and, hence, its exposure age (McCarroll 1994; Goudie 2006; Shakesby *et al.* 2006). Subsequent improvement during the last 10 years has seen the combination of Schmidt-hammer relative-age dating with absolute dating techniques, in particular TCND (terrestrial cosmogenic nuclide dating; Winkler 2009), and the development of Schmidt-hammer exposure-age dating (SHD), which enables the calculation of local or regional calibration curves and provides absolute age estimates for the landforms investigated (Matthews and Owen 2010; Matthews and Winkler 2011; Shakesby *et al.* 2011; Matthews and McEwen 2013; Stahl *et al.* 2013; Winkler 2014). The Schmidt hammer has also been used in integrated, multi-proxy approaches to dating (e.g. Böhlert *et al.* 2011). Apart from the predominant chronological and palaeoenvironmental applications, Schmidt-hammer data may also reveal valuable information about the formation processes and dynamics of the landforms investigated, for example rock glaciers (Scapozza *et al.* 2014) and snow-avalanche impact ramparts (Matthews *et al.* 2015).

Unlike those typical high mountain landforms mentioned above, periglacial patterned ground has not yet been subjected to detailed investigated in the context of SHD. Cook-Talbot (1991) used Schmidt-hammer R-values in her relative-age evaluation of patterned ground in the Glittertinden massif of eastern Jotunheimen, southern Norway, but did not produce exposure ages. Calibrated-age estimates of exposure ages of clasts within patterned ground surfaces potentially provide insights into the processes and dynamics of sorted patterned ground formation as well as their chronology by revealing, for example, for how long the majority of clasts have been exposed at the surface or when the clast-rich margins were established or became inactive (see, for example, Washburn 1956, 1979; Goldthwait 1976; French 1988, 2007; Hallet 1990, 2015; Kessler *et al.* 2001; Matsuoka *et al.* 2003; Peterson and Krantz 2008; Ballantyne 2013; Warburton 2013, for more details of patterned ground formation and its classification).

A well-known, previously described and mapped occurrence of patterned ground on the Juvflya plateau in central Jotunheimen, southern Norway, has been selected as a test area (Ødegård *et al.* 1987, 1988). Various types of sorted patterned ground (circles, polygons, nets, steps and stripes) occur in this area over an altitudinal range of ~ 1950-1500 m a.s.l. extending down towards the relatively gently-dipping upper slopes of Bøverdalen and Visdalen to the north and east, respectively. Supporting the selection of this particular test area is the availability of information about regional permafrost limits (Ødegård *et al.* 1992, 1996; Isaksen *et al.* 2002, 2011; Harris 2009; Lilleøren and Etzelmüller 2011; Lilleøren *et al.* 2012) and an established chronology of regional deglaciation and Holocene climate variability (Follestad and Fredin 2007; Matthews and Dresser 2008; Nesje *et al.* 2008; Nesje 2009). Furthermore, regional (Matthews and Owen 2010) and local (Matthews *et al.* 2014) calibration curves for SHD are available without the necessity to obtain additional local samples for terrestrial cosmogenic nuclide dating (TCND) or other independent dating techniques.

This first study of the potential of SHD in the context of patterned ground was carried out under the reasonably well understood environmental conditions of central Jotunheimen. It has the following specific objectives:

(a) To describe the characteristics of Schmidt-hammer measurements obtained from boulder surfaces associated with sorted circles, and compare the results to those reported from other landforms, especially those characterised by diachronous surfaces or long-term, continuous formation processes (e.g. rock glaciers and pronival ramparts).

(b) To investigate whether Schmidt-hammer measurements associated with sorted circles exhibit variations between sites located at different altitudes, and interpret any altitudinal gradient detected with reference to the timing of deglaciation, rates of rock weathering, periglacial processes, and climate.

(c) To apply regional and local SHD calibration curves, and hence obtain absolute-age estimates, for the boulder surfaces, determine the active or relict status of the sorted circles, and interpret the landforms in the light of existing palaeoclimatic evidence and current understanding their dynamics.

Study area

The study area, Juvflya, is a small high-level plateau typical of the southern Norwegian mountain area of central Jotunheimen (Figure 1). These plateaux are usually related to a pre-glacial 'paleic surface' (Gjessing 1978; Nesje and Whillans 1994) and contrast sharply with the surrounding deeply-incised valleys and the overshadowing mountain peaks and cirques of Pleistocene origin (Figure 2a). The central part of Juvflya constitutes flat to gently sloping terrain of some 8 – 10 km^2 at an altitude between 1850 and 1950 m a.s.l. (Figure 2b). Towards the edge of the plateau, there is a transition towards the upper slopes of Bøverdalen to the north (Figure 2a) and Visdalen to the east with gradually increasing slope angles but also several small 'benches' of flatter terrain (e.g. Dugurdsmålkampen and Svartkampan).

A variety of patterned ground features dominate the surface of Juvflya, the benches and the adjacent transitional upper valley slopes (Figures 2c, d). Between 1750 and 2000 m a.s.l. Ødegård *et al.* (1987, 1988) report a 15 – 50 % surface cover of patterned ground at slope angles less than 10°. Whereas they show the flat terrain is dominated by sorted circles and sorted polygons, sorted stripes and boulder tongues dominate where slope angles are between 3 and 17°. Sorted steps are reported from slopes between 2 and 11° but as Ødegård *et al.* (1988) point out, the complex interaction of factors – surface material (substrate), vegetation, soil moisture content etc. – make it difficult to relate specific patterned ground features to specific slope angle thresholds.

The study was restricted to sorted circles and polygons (simplifying the term "sorted nets and polygons" used by Ødegård *et al.* 1988) on flat terrain. This decision was primarily driven by the fact that sorted stripe dynamics are affected by slope-related processes that potentially complicate any interpretations of landform age and origins (Harris 1988; French 2007; Feuillet *et al.* 2012). An isolated occurrence of patterned ground at 1500 m a.s.l. was selected as the lower end of an altitudinal profile that includes an additional four sites at altitudes of 1550, 1750, 1850 and 1925 m a.s.l. respectively (Figure 1). The diameters of the fine-grained centres of the sorted circles at the study sites usually vary between 2 to 4 m and are encircled by coarse (stone) gutters filled with clasts with an average long axis between 30 and 80 cm (Figures 2e,f). The width of the gutters between the fine-grained centres at most sites range between 1 and 2 m. The diameters of individual sorted circles are therefore up to about 6 m and rarely less than 3m. Individual boulders within the gutters may project above the fine-grained circles by 10 – 30 cm (never > 50 cm). The widest gutters commonly exhibit a depth of a few tens of cm.

At the lower two sites, the fine centres tend to be covered by mid-alpine tundra-like vegetation and the boulders are heavily covered by a variety of lichen species. The sorted circles at these two sites are therefore clearly relict. Although their centres have a sparser cover of high-alpine species, the patterned ground at the higher altitude sites also appear to be relict (cf. Ødegård *et al.* 1992) with little evidence of recent cryoturbation disturbing the boulder distribution. With the exception of a small area around Juvasshøi, all the patterned ground below about 2000 m a.s.l. has developed in till (Ødegård *et al.* 1987; see below),

A meteorological station at Juvasshøi (1894 m a.s.l.) reports a average mean annual air temperature (MAAT) of –3.5°C for the period AD 2000 to 2014 with annual variability ranging from –2.49°C (2014) to –5.37°C (2010; eKlima data base by met.no). Ødegård *et al.* (1992) calculated a MAAT of –2.6°C at 1500 m a.s.l. to –6.4°C at 2200 m a.s.l. These data correspond quite well to the 1km-grided MAAT normals (1971 – 2000) between –2.0 and –4.0°C given for our five study sites by the SeNorge data base (met.no). Ødegård *et al.* (1992) measured a mean annual ground temperature (MAGT) between –2.1 and –2.3°C in a borehole near Juvasshytta and gave additional data for shallow MAGT from Dugurdsmålkampen (–0,7°C), Galdehøi (–4.2 to –4.4°C) and a site near Juvvatnet, the lake close to Vesle-Juvbreen (–1.7 to –1.9°C). They also mention strong winds typical for Juvflya resulting in little snow cover and a (late) maximum snow depth of 0.5 m in May. During field work for this study in late July 2015, all of Juvflya was largely snow-free whereas in most other parts of central Jotunheimen the terrain above about 1200 m a.s.l. retained snow-cover after a snowy winter and an unusual cold spring season. Isaksen *et al.* (2011) give 800 to 1000 mm as mean annual precipitation (MAP) for the Galdhøpiggen area including Juvflya.

A number of studies have concluded that the lower limit of discontinuous permafrost in Jotunheimen lies at about 1450 m a.s.l. (Ødegård *et al.* 1992, 1996; Isaksen *et al.* 2002, 2011; Farbrot *et al.* 2011, Lilleøren *et al.*, 2012). Ødegård *et al.* (1987) report an active layer thickness of 1.5 – 2.0 m for the central Juvflya area, which is similar to the range of 1.95 – 2.45 m annual thickness reported by Harris *et al.* (2009) from recent borehole monitoring.

Central Jotunheimen has been at or near the culmination centre/ice divide of the Late Weichselian Scandinavian ice sheet (Mangerud *et al.* 2011). As a consequence, the study area experienced a relative late deglaciation and the till in which the patterned ground has been developed is of local origin. The exact date when Juyflya and the upper slopes of Bøverdalen and Visdalen became ice-free has not precisely been determined, but an early Holocene (Preboreal) deglaciation with a date of c. 9,700 cal. yr BP seems very likely. This is consistent with deglaciation following the Erdalen Event in the late Preboreal (Dahl *et al.* 2002; Matthews and Dressser 2008; Nesje 2009; Stroeven *et al.* 2015) and is supported by the size of the well-developed sorted circles (Cook-Talbot 1991; Falch 2001) and recent permafrost studies (Lilleøren *et al.* 2012). Owing to its wind-exposed, leeward position in relation to a dominant westerly air flow and in the light of some studies from the more continental part of southern Norway (Dahl *et al.* 1997; Lie *et al.* 2004) it cannot completely be excluded that ice-free conditions prevailed slightly earlier. A previous deglaciation model of the region predicted, however, a middle- to late-Preboreal deglaciation (Sollid and Trollvika 1991; Holmsen 1982; Sollid and Reite 1983).

Our study sites are located in the central part of Jotunheimen, on rocks of the early-Proterozoic Jotunheimen complex, which is dominated by pyroxene-granulite gneiss (Lutro and Tveten 1996). This local bedrock type is also the predominant lithology of the till in which the patterned ground has developed at our study sites. A few boulders of different lithology do, however, occur within the till; for example peridotites that crop out in small areas throughout Jotunheimen. They develop a distinct reddish-rusty surface colour when exposed to subaerial weathering and were easily detected and avoided during Schmidt-hammer testing. Furthermore, lithological and mineralogical heterogeneity within the pyroxene-granulite gneiss has not previously limited the application of Schmidt-hammer calibration curves in the region (Matthews and Owen 2010; Matthews and Winkler 2011).

Methods

Schmidt-hammer measurements were performed at all five sites covering the altitudinal range from 1500 to 1925 m a.s.l. (see Figure 1). Tests were restricted to boulders in the coarse gutters of the sorted circles (the fine-grained centres being free of larger clasts with very few exceptions). Gutters were randomly sampled from every suitable boulder (central gutter depressions as well as gutter edges). This sampling design was consistently applied to all sites and Schmidt hammer impacts were made on horizontal or near-horizontal upper surfaces of boulders. Thus, spatial or seasonal variation in snow distribution, depth or duration (and hence long-term weathering rate) are unlikely to have affected the data. Between 190 and 260 individual boulders were tested with one impact each at all sites using mechanical N-type Schmidt hammers with an impact energy of 2.207 Nm for the plunger (Proceq 2004; see also Shakesby *et al.*, 2006 for more technical details). The instruments were tested on a manufacturer's test anvil prior to and after the measurements to ensure proper calibration. All tests were performed on lichen-free areas, avoiding any visible cracks or weaknesses in the boulder surfaces. The requirement of boulders not to move during impacts restricted tests to those with a minimum long axis of 40 cm, but those were numerous and randomly distributed through the gutters. The sparsity of much larger boulders did, however, prevent the application of any test design involving multiple impacts on each boulder.

The data from each test site were treated as a homogeneous sample. Sample mean R(Rebound)-values and their 95 % confidence intervals (α = 0.05) were calculated using the equation:

$$\bar{X} \pm ts/\sqrt{(n-1)} \quad (1)$$

where $\bar{X}$ = arithmetic mean, s = sample standard deviation, t = Student's t statistic, and n = number of impacts (sample size) following Shakesby *et al.* (2006). Because each area of sorted circles was expected to resemble a diachronous rather than a single-age or synchronous surface (i.e. with a considerable spread of exposure ages as revealed by their R-values), detailed histograms were produced for all sites for further interpretation. Standard statistical analysis of R-values included Kolmogorov-Smirnov tests for normality and Mann-Whitney or Kruskal-Wallis ANOVA tests of differences between sites (cf. Schönwiese 1992; Sachs 1999; Lehman 2002) using IBM SPSS Statistics software. The statistical significance of the differences between sites using nonparametric analysis of variance (ANOVA) is appropriate even if samples exhibit non-normal distributions (Sachs 1999). Whereas the Mann-Whitney U-test was used to test pairs of samples, the Kruskal-Wallis H-test was applied simultaneously to three or more samples following standard recommendations (Sachs 1999; Lehmann 2002).

At sites 2 – 4, additional Schmidt-hammer testing was carried out using the newly introduced electronic N-type RockSchmidt, which has identical impact energy as the mechanical N-type Schmidt hammer (Proceq 2014). The RockSchmidt is basically an improved version of the electronic SilverSchmidt (Proceq 2012; see also Viles *et al.* 2011) designed for rock testing with more specified software and technical improvements, such as a tighter seal of the impact plunger. A larger sample size (750 boulders) was used at each site, again with one impact per boulder, using the same criteria for boulder selection and raw data processing as for the mechanical Schmidt hammer. Although the R-values obtained with the electronic and mechanical Schmidt hammers are not identical for technical reasons, their results have been shown to be interconvertible (Winkler and Matthews 2014). For this study, no conversion has been considered. Instead, the results are presented separately, the measurements being differentiated by use of the terms 'R-values' and 'R_{Rock}-values' for the mechanical hammer and the RockSchmidt, respectively.

At three locations as near as possible to sites 2, 3, and 4, boulders in fresh road cuts along the access road to Juvasshytta were also measured with the mechanical Schmidt hammer. At these sites, 10 boulders with a non-weathered, fresh appearance were selected with the aim of testing the suitability of the ‘young’ control points (unweathered rock surfaces of zero age) used for calibration of R-values and the production of SHD ages. In order to obtain approximate R-values for non-weathered rock surfaces with the same lithology as boulders in the patterned ground, five impacts from the same spot were recorded on each boulder. Following procedures from engineering geological rock testing (Poole and Farmer 1980; Aoki and Matsukura 2007), the fifth impact was used as an approximation to the R-value of non-weathered rock surfaces (see also, Matthews et al., 2016).

The lack of stable boulders of known age that are sufficiently old for use as an ‘old’ control point, alongside the possible limitations of the boulders from the road cuts as a ‘young’ control point (see below), mean that it has not proved possible to calculate a new local calibration curve for boulders on Juvflya. Instead, two established calibration curves were initially applied: the local Vesl-Juvbreen curve (Matthews et al. 2014) and the regional Jotunheimen curve (Matthews and Owen, 2010). Dating the mean exposure ages of the boulders from the sample sites by using these existing SHD-calibration curves is quite challenging due to uncertainties in their applicability to the specific rock surfaces and environmental conditions that characterize the sorted circles.

In principle, the local Vesl-Juvbreen calibration curve (Matthews *et al.* 2014) would be expected to be the more appropriate of the two curves, because of the proximity of its control point locations to the patterned ground sites and hence the closely similar lithology of its control points. This curve is defined by the equation:

$$y = 28749.610 - 500.77841x \qquad (2)$$

where y = surface age in years and x = mean R-value

The ‘young’ control point for this curve was derived from unweathered, recently deposited boulders on the glacier foreland of Vesl-Juvbreen, whereas the ‘old’ control point was derived from a rare bedrock outcrop outside the glacier foreland.

The regional Jotunheimen calibration curve of Matthews and Owen (2010) is defined by the equation:

$$y = 22986.956 - 347.82608x \quad (3)$$

This curve is based on the same general lithology as the patterned ground sites (pyroxene-granulite gneiss) but its 'young' and 'old' control point were both derived from glacially-scoured bedrock outcrops from lower altitudinal zones. The main grounds for regarding the regional Jotunheimen curve as applicable to the boulder surfaces associated with the sorted circles are: (1) the generally similar pyroxene-granulite gneiss bedrock throughout the region; and (2) similarity in roughness characteristics between glacially-scoured bedrock surfaces and glacially-abraded boulder surfaces, which are likely to produce similar R-values after prolonged weathering. See below for further discussion of the appropriateness of the two calibration curves.

Confidence intervals around the predicted SHD ages reflect the total error (C_t), which combines the calibration error of the calibration curve (C_c) with the sampling error of the patterned ground (C_s) (Matthews and Winkler 2011):

$$C_t = \sqrt{(C_s^2 + C_c^2)} \quad (4)$$

C_c is derived from the confidence intervals associated with the old control point (C_o) and the young control point (C_y), where R_o, R_y and R_s are the mean R-values of the old control point, the young control point and the sampled patterned ground, respectively (Matthews and McEwen 2013):

$$C_c = C_o - [(C_o - C_y)(R_s - R_o)/(R_y - R_o)] \quad (5)$$

C_s is derived from the slope of the calibration curve (b), Student's t statistic and the standard error of the mean R-value of the patterned ground, where s is the standard deviation and n is the sample size (Matthews and Owen 2010):

$$Cs = \pm b\,[ts/\sqrt{(n-1)}] \quad (6)$$

Finally, 450 individual boulders were sampled from each of sites 2, 3 and 4 for their clast roundness following the visual comparison method of Powers (1953). The aim was to investigate possible sedimentological differences in the substrate where the patterned ground has developed. Clast roundness differences between the sites were analysed graphically using histograms and compared quantitatively using a numerical index of mean roundness (*ir*) based on assigning a numerical value to each roundness class (very angular, 0.5; angular, 1.5 … to well rounded, 5.5; cf. Powers 1953; Matthews 1987; Tucker 1988).

Results

The statistical distribution of R-values and R_{Rock}-values

R- and R_{Rock}-values from all sites tested are presented as histograms (Figures 3 and 4) as well as numerical parameters (Figure 5, Table 1). R-values from the mechanical Schmidt hammer and R_{Rock}-values obtained by the RockSchmidt are highly comparable in terms of relative differences between sites, the overall trend, and most other parameters, but the 95 % confidence intervals for the R_{Rock}-values are narrower due to the larger sample size. The histograms from both instruments have the same form, confirm the interconvertibility of mechanical and electronic Schmidt-hammer data when allowance is made for the offset in mean values (cf. Winkler and Matthews 2014), and justify SHD using the established calibration curves based on R-values (see below).

Visual inspection of the histograms reveals differences from those typical of Schmidt-hammer measurements from landforms characterized by synchronous rock surfaces, such as moraines, which usually display symmetrical, unimodal, normal distributions (Matthew and Shakesby 1984; Winkler 2014). The histograms from the patterned ground resemble platykurtic distributions with wide plateaus and thin tails, negative skew and (at all but site 1) negative kurtosis. Three of the mechanical Schmidt hammer data sets (sample sites 1, 3, and 4) and all three RockSchmidt data sets do not pass one-sample Kolmogorov-Smirnov and Shapiro-Wilk tests of normality. Furthermore, it should be noted that the asymmetry of sample sites towards higher R- and R_{Rock}-values tends to increase with altitude, whereas the number of values at the lower end of the measured range clearly decreases. The non-normal distributions, their characteristic shape, and the absence of any clear bi- or polymodal pattern, can all be related to the process of formation of sorted circles and polygons and the exposure of individual clasts to subaerial weathering for varying periods of time (see discussion below).

The altitudinal gradient in R-values and R_{Rock}-values

Mean R- and R_{Rock}-values exhibit an increase with altitude and a strong linear trend (Figure 6). However, the 95 % confidence intervals associated with particular sample sites exhibit partial overlap (Table 1, Figure 6). The results for the RockSchmidt are unequivocal, with each pair of samples and also the three samples together showing statistically significant differences between their respective distributions (Tables 2 and 3). In contrast, some sample pairs and two tests involving three samples from the mechanical Schmidt hammer indicate differences that are not statistically significant, especially if those sites are within a limited altitudinal range. In fact, all tests which involve sites differing in altitude by 250 m or more exhibit statistically significant differences in their R-value distributions (Table 2).

The road-cut data

The results from the road cuts are shown in Table 4. For first impacts, overlapping confidence intervals indicate that none of the mean R-values are statistically significantly different. Thus, the three data sets based on first impacts can legitimately be combined to produce the single overall mean R-value of 62.93 ± 2.09. Similar reasoning for fifth impacts leads to an overall mean R-value of 66.03 ± 1.21, which is significantly higher than the overall mean value of the first impacts and therefore the more realistic approximation to the mean R-value of unweathered boulders in the sorted polygons. Nevertheless, owing to the small sample of road-cut boulders, these results should be treated with caution.

SHD ages

SHD results from application of the local (Vest-Juvbreen) and regional (Jotunheimen) calibration curves are shown, together with tests of their efficacy against the ‘young’ road-cut data, in Table 5 where all dates are rounded to the nearest 5 years. SHD ages from all sites range between 7515 ± 940 and 5605 ± 935 years (Vesl-Juvbreen curve) and between

8240 ± 495 and 6910 ± 510 years (Jotunheimen curve). It should be noted that the SHD ages (mean boulder ages) predicted by both curves exhibit a decrease with altitude. This age gradient of ~1900 and ~1300 years, respectively, over the ~400 m altitudinal range of the sites results from the increase in mean R-value with altitude previously demonstrated in Table 1 and Figures 5 and 6. Although none of the mean boulder ages derived from the Vesl-Juvbreen calibration curve are statistically different according to their relatively broad confidence intervals, the narrower confidence intervals associated with the predictions from the Jotunheimen curve yield several statistically significant differences between the uppermost and lowermost sites (Figure 7).

Testing of the two calibration curves against the ‘young’ road cut data interestingly reveals contrasting results (Table 5). Using the Vesl-Juvbreen curve, the unweathered boulders are predicted to have futuristic SHD ages of –2765 ± 1140 years based on first-impact data and –4315 ± 740 years based on fifth impacts. These age estimates deviate widely from the expected result of zero age. In contrast, the Jotunheimen curve predicts SHD ages of 1100 ± 735 years based on first impacts and only 20 ± 435 years based on fifth impacts. Thus, only the Jotunheimen curve in combination with fifth-impact data successfully predicts the zero age of the road-cut boulders.

At each of the five sites, moreover, the differences in the estimated mean SHD ages using the two curves decreases with altitude from 1305 years for site 2 to 725 years at site 5 (Table 5). Errors in estimating the true exposure age of the boulders in the sorted circles are therefore unlikely to be as great as the underestimates of ~3000–4000 years for the boulders in the road cuts derived from the Vesl-Juvbreen calibration curve. The differences of ~700–1300 years in the predicted SHD ages between the two curves are, moreover, almost wholly the result of differences in the R-values associated with their ‘young’ control points. This must be the case because the mean R-values of the ‘old’ control points for the Jotunheimen and Vesl-Juvbreen curves are almost identical: 38.20 ± 0.56 and 38.04 ± 1.43, for the Jotunheimen and Vesl-Juvbreen curves, respectively, whereas the mean R-values of the ‘young’ control points are 65.80 ± 0.33 and 57.31 ± 1.03, respectively (Matthews and Owen 2010; Matthews *et al.* 2014). These test results suggest, therefore, that the Jotunheimen curve is by far the better of the two calibration curves for estimating the exposure ages of the boulders in the sorted circles (see detailed discussion below).

Clast (boulder) roundness

Results of clast roundness measurements are plotted on Figure 8 and show no significant differences between sites. All samples display a sub-angular mode with considerable quantities of sub-rounded and angular clasts but hardly any very angular clasts. Site 4 (at 1550 m a.s.l.) has the lowest *ir* index but there is no altitudinal trend as site 3 (at 1750 m a.s.l.) reveals the highest *ir* index. The sub-angular mode of the surface material coincides roughly with what is expected for tills in mountain environments (Evans and Benn 2004; Lukas *et al.* 2013), perhaps with some local effects resulting from the limited availability of rock outcrops and supraglacial debris, which could provide sources of very angular boulders.

Discussion

Methodological considerations

Testing both calibration curves against the road-cut boulders demonstrates that it is the young control point used to construct the Jotunheimen curve that renders this curve preferable to the Vesl-Juvbreen curve in the context of SHD dating of the patterned ground landforms at Juvflya. This interpretation is based on the more accurate prediction of the age of the road-cut boulders by the Jotunheimen curve than the Vesl-Juvbreen curve (see above). The reason for this lies in the nature of the boulder surfaces. The boulders in the sorted circles and the boulders in the road cuts are derived from a similar till substrate and are subangular to subrounded (Figure 8). Such boulders have been glacially abraded (Boulton 1978; McCarroll 1991; Shakesby *et al.* 2006; Lukas *et al.* 2013) and are therefore relatively smooth compared to the relatively rough angular and subangular boulders characteristic of the young control point used in construction of the Vesl-Juvbreen calibration curve (Matthews *et al.*, 2014). In contrast, the boulders in the road cuts and the sorted circles both yield relatively high mean R-values that are numerically similar to those derived from the glacially-abraded bedrock used in construction of the Jotunheimen calibration curve (Matthews and Owen 2010).

Furthermore, the fifth-impact mean R-value from the road cuts (66.03 ± 1.21; Table 4) is numerically very close to the mean R-value of the young control point used in the regional Jotunheimen curve (65.80 ± 0.33; Matthews and Owen 2010). The fact that the difference between the means of the first and fifth impacts is appreciable (though not quite a statistically significant difference according to the 95 % confidence intervals; Table 4) indicates, however, that there has been some weathering of the boulder surfaces in the road cuts despite their recent excavation. Matthews *et al.* (2016) has shown that the difference between the mean values of the first and fifth impacts of unweathered *abraded* rock surfaces of this rock type should be negligible. The road cut data themselves do not therefore appear to provide suitable boulders for use as young control points, most likely due to subsurface weathering of boulder surfaces that were buried at shallow depth for most of the Holocene prior to their excavation during construction of the road cuts.

Thus, only the Jotunheimen calibration curve can be regarded as yielding meaningful SHD ages from the sorted circles. Our results demonstrate, moreover, some of the interpretive problems associated with dating these asynchronous land surfaces.

SHD ages in relation to the dynamics of sorted circles

The interpretation of SHD ages from patterned ground is far from straightforward. Whereas the boulder exposure ages of synchronous landforms, such as moraines and till sheets, can be clearly related to a single time of formation, the mean boulder exposure age of asynchronous landforms, such as sorted circles, are much more likely to be affected by a relatively long history of development and such factors as inheritance and post-depositional disturbance.

The starting point for sorted circle formation on Juvflya is assumed to be a till sheet of heterogenic grain-size distribution exposed during deglaciation in the late Preboreal,~9700 years ago. In theory, the oldest boulder exposure ages should therefore coincide with deglaciation as a number of boulders would by exposed on the surface of this till deposit. With the process of patterned ground formation mainly related to active layer dynamics above permafrost (Washburn 1956; French 1988) it is likely to have started immediately after local deglaciation (Lilleøren *et al.* 2012). The significant difference in age of at least ~1,500 years between deglaciation and the oldest of the patterned ground landforms according to the Jotunheimen calibration curve is consistent with an appreciable time lag between deglaciation and stabilization of these features.

Although some aspects of the detailed mechanics of sorted circle formation are still not fully resolved, upfreezing and lateral frost sorting of boulders are the main processes to be considered when interpreting boulder exposure ages (cf. Washburn 1979; Mackay 1984; Williams and Smith 1989; Hallet 1990, 2015; Van Vliet-Lanoë 1991; Ballantyne and Harris 1994; Kessler *et al.* 2001; French 2007; Kääb *et al.* 2014). Upfreezing, involves boulders that were previously buried below the surface becoming exposed to subaerial weathering. Subsequent lateral frost sorting (migration of boulders towards the coarse zones encircling the fine centres) may involve the boulders being tilted or rotated (Kääb *et al.* 2014) prior to their deposition and stabilization as they wedge together. Both upfreezing and lateral frost sorting can occur quite fast, resulting in the formation of well developed patterned ground within a few decades (Ballantyne and Matthews 1982; Harris 1988; Haugland 2004, 2006). However, given a thick till cover with a plentiful boulder content, and suitable environmental conditions, formation may take much longer.

The mean boulder exposure age of the sorted circles is therefore considered to be primarily indicative of the timing of the upfreezing process and the stabilization of the coarse gutters, provided there was no postdepositional remobilisation of the boulders by the convection-like circulation that characterises the active layer (cf, Hallet 1990, 2015; Kessler *et al.* 2001). Today, frost disturbance of this type seems to be restricted to the fine-grained centres, which are characterised to a greater or lesser extent by patches of bare ground that sometimes exhibit nested smaller-scale patterned ground forms. In contrast, the boulders are almost completely lichen covered with no evidence of recent movement. Accepting that post-exposure modification involving boulders is likely to have been unimportant, the mean boulder exposure age of the investigated sorted circles should simultaneously indicate the timing of (1) the most active upfreezing, and (2) the final stabilization of boulders in the coarse gutters.

Platycurtic R-value distributions (Figures 3 and 4) and the corresponding wide confidence intervals associated with the SHD ages (Table 5, Figure 8) are consistent with a relatively long period of boulder upfreezing and stabilization. Compared to similar histograms from synchronous land surfaces, such as moraines (Matthews and Winkler 2011; Winkler 2014), the peak plateau is very wide. Schmidt-hammer measurements on rock glaciers also display much narrower R-value distributions related to talus entrainment (Frauenfelder *et al.* 2005; Kellerer-Pirklbauer *et al.* 2008; Rode and Kellerer-Pirklbauer 2011). R-value distribution from relatively inactive pronival ramparts exhibit somewhat broader plateaus (Matthews and Wilson 2015), as do long-active avalanche-impact ramparts (Matthews *et al.* 2015). Only those distributions presented by Matthews *et al.* (2014) from ice-cored moraines are comparable to our distributions from patterned ground, however.

The rather thin tails towards higher R-values as shown on Figures 3 and 4 support the largely relict status of the sorted circles, and the lichen-encrusted nature of the boulders correspond well with the 'fossil' appearance of the sorted forms on Juvflya mentioned by Ødegård *et al.* (1992). Relict status is also supported by the size of these large sorted forms relative to recently active features, which are much smaller (cf. Ballantyne and Matthews 1982; Cook-Talbot 1991; Haugland 2004). Limited recent active dynamics of the patterned ground may seem inconsistent with the evidence presented by Lilleøren *et al.* (2012) for the continuous existence of mountain permafrost above 1650 – 1700 m in this region throughout the Holocene (see below). With modern permafrost occurrence confirmed for all our sites (see above), the possible reasons for the lack of recent dynamics may, in theory, be related one or more of the following: (a) a decrease of moisture supply within the active layer (Vandenberghe 1988; Van Vliet-Lanoë 1988, 1991; Luoto and Hjort 2004); (b) a change of average freezing rates and/or orientation of the freeze-thaw plane (with slow freezing rates in saturated soils reported as most conducive to upfreezing by Van Vliet-Lanoë 1991); (c) a decrease in frost susceptibility of the surface material (Ødegård *et al.* 1988, mention that the quantity of fines may not be sufficient to support active frost processes); or (d) exhaustion of boulders from the subsurface of the fine-grained centres. The tail on the other end of the distribution towards lower R-values can easily be explained by the presence of boulders exposed shortly after deglaciation or, less likely, inherited from pre-exposure weathering.

The Holocene history of the patterned ground in relation to permafrost

Whereas small patterned ground features do not require permafrost (Goldthwaite, 1976; Grab, 2002; French 2007; Ballantyne, 2013), and have been demonstrated in Jotunheimen to form below the lower altitudinal limit of permafrost in recently deglaciated glacier forelands

(Harris and Cook 1988; Matthews *et al.* 1998; Haugland 2006), the size of the patterned ground features on Juvflya are consistent with formation within the active layer of underlying permafrost. Permafrost conditions became established in the area soon after deglaciation in the early Holocene (Lilleøren *et al.* 2012) and our proposed timing of the onset of patterned ground formation coincides with this.

Our SHD ages suggest, moreover, cessation of major frost sorting activity with the onset of the Holocene Thermal Maximum (HTM) at c. 8,000 years ago (Seppä and Birks 2001; Jansen *et al.* 2008; Renssen *et al.* 2012) when Lilleøren *et al.* (2012) postulate a rise of the lower limit of permafrost to 1650 – 1700 m a.s.l. This rise seems to coincide most closely with the SHD ages of the lower two sites (sites 4 and 5) that are currently located below the supposed HTM lower permafrost limit. However, sorted circle formation also decreased at the higher altitude sites. Sites 1-3 would, according to Lilleøren *et al.* (2012), have remained underlain by permafrost throughout the whole of the Holocene. Neither at the lower, nor at the higher altitude sites are there any signs of a substantial re-activation of patterned ground dynamics during late-Holocene climatic deterioration and neoglaciation, the conventional start of which occurred c. 6,000 years ago (Matthews and Dresser 2008; Nesje 2009; Seppä *et al.* 2009; Matthews 2013). The patterned ground landforms seem to have remained essentially as they are today even during the Little Ice Age (LIA) of the last few centuries when the distribution of permafrost in Jotunheimen attained its greatest Holocene extent (Lilleøren *et al.* 2012). The likely explanation for this is that most boulders had already been removed from the circle centres and immobilized within the gutters.

The gradient involving higher mean R-values with increasing altitude shown by our data seems too robust to be a random artefact of, for example, site selection. The data of Cook-Talbot (1991) does not show any comparable clear altitudinal trend, but her sample sites were not restricted to as small an area as this study. The strength of the gradient is greater than would be expected in relation to chemical weathering (cf. Dahl 1967; André 2002; Nicholson 2008; Matthews and Owen 2011), and the trend of the gradient is the opposite of one based on physical (frost) weathering intensity and efficiency in mountain environments (Caine 1974; Harris 1988). It may therefore be inferred that the altitudinal gradients in R-values and SHD age associated with the sorted circles on Juvflya is determined by chronological factors affecting the stabilization of boulder movement but is not necessarily related in a simple way to climate. It has frequently be pointed out that due to the complex dynamics and the influence of non-climate-related local factors, the palaeoclimatological interpretation of patterned ground is problematic (Washburn 1979; French 1988, 2007; Ødegård *et al.* 1992; Ballantyne and Harris 1994). Our age estimates compared to the Holocene variations of the lower limit and distribution of permafrost in Jotunheimen as described by Lilleøren *et al.* (2012) may be seen as clarifying these concerns.

Alternative interpretations of the formation process and age

Being aware of the limitations of our SHD-approach for determining details of both the formation process and the time constraints on sorted circle formation, our data does not *a priori* exclude alternative and potentially more complex formation histories. The sorted circles on Juvflya seem to be comparatively large for similar high-mountain environments and a Holocene age (e.g. Washburn 1979; Harris 1988; Williams and Smith 1989; Hallet 2015). Such large forms may have required significant thermal-contraction cracking (French 2007), a process that does not appear to be characteristic of the permafrost environment at Juvflya at present. This leads to speculation about possible times when a more severe climate may have pertained (cf. Falch, 2001; Winkler 2001). Two alternative hypotheses are considered here.

The first alternative hypothesis assumes very intense development of sorted circles within a relatively short period of time (several hundred years) during the Younger Dryas-Holocene transition. Permafrost conditions may have been sufficiently severe for thermal-contraction cracking to occur. In this case, at least the general outlines of the features could have been already established at the onset of the Holocene or shortly afterwards during the early Preboreal. Holocene periglacial activity would then merely have modified existing features and led to final stabilization of forms with the onset of the HTM. Although consistent with the lack of any signal for late-Holocene rejuvenation, if this hypothesis was true, older SHD ages would be expected. Without local information about the precise timing of deglaciation at Juvflya this hypothesis must remain speculative. Available regional information (e.g. Barnett et al. 2001; Matthews and Dresser 2008; Nesje *et al.* 2008, Nesje 2009) points firmly to a late-Preboreal deglaciation, although it is possible that the Juvflya plateau areas became ice-free at a time when large glaciers still filled the surrounding valleys (cf. Dahl *et al.* 1997).

The second alternative hypothesis involves the possibility that patterned ground on mountains and plateaux survived glaciation beneath cold-based ice. If this was the case on Juvflya, it is possible that patterned ground formation occurred much earlier and that sorted circles emerged, fully formed, on deglaciation. Until recently, this was considered unlikely as existing reconstructions of the Pleistocene Scandinavian ice-sheet place Jotunheimen in or close to its culmination zone and continuously glaciated even during mild interstadials (Mangerud *et al.* 2011). It was thought, moreover, that the occurrence of block fields and associated 'trimlines' constitute uncontrovertible evidence for the existence of nunataks during the Last Glacial Maximum (LGM; Nesje *et al.* 1988; Nesje and Dahl 1990). However, it is now generally believed that blockfields can be preserved beneath cold-based ice (Hättestrand and Stroeven, 2002; Ballantyne et al., 2011; Rea, 2013), and Juliussen and Humlum (2007) have presented evidence of blockfield survival of more than one ice sheet on mountain tops in eastern Norway. The latter interpretation implies that sorted circle formation may date from before the LGM and may even be of pre-Weichselian age. Such relatively old ages would not be reflected in our SHD results because rock weathering rates would be near zero beneath cold-based ice sheets. Although this second alternative hypothesis cannot be ruled out completely, we regard it as an unnecessarily complex explanation and reject it pending new evidence.

Conclusion

This first study of Schmidt-hammer exposure-age dating in the context of patterned ground surfaces (sorted circles and polygons) along an altitudinal gradient from 1500 to 1925 m a.s.l. on Juvflya in central Jotunheimen demonstrates the potential of the technique and allows the following conclusions to be drawn:

- R-value distributions derived from large samples of boulders exhibit a broad plateau with rather thin tails (platycurtic mode) and are negatively skewed. This distribution reflects the diachronous character of patterned ground that has existed in the landscape over a relatively long period of time.
- The statistical analyses clearly indicate that large sample sizes are necessary to reveal significant differences in R-values and SHD ages between these boulder surfaces. In this respect, the electronic RockSchmidt can be seen as considerably more efficient than the mechanical Schmidt hammer.

- The low proportions of relatively high R-values indicate essentially relict landforms with only minor recent process dynamics affecting the fine centres of the landforms. Convective processes are concluded to have been ineffective in relation to boulders since their stabilization in the coarse gutters, where a lack of fines and good drainage limit frost susceptibility and cryoturbation.
- There is a distinct altitudinal gradient in mean R-values, which increase with altitude, and result in younger SHD ages (mean boulder exposure ages) at higher altitudes.
- Application of the regional Jotunheimen SHD calibration curve (Matthews and Owen 2010) reveals early-Holocene mean boulder exposure ages that range from 6910 ± 510 to 8240 ± 495 years ago. A local Vesl-Juvbreen calibration curve (Matthews *et al.* 2014) produced SHD ages that considerably underestimates the true boulder surface ages because of the unsuitability of its young control point.
- The SHD ages are interpreted in a twofold way: (1) as minimum ages for sorted circle formation and associated intense boulder upfreezing activity; and (2) simultaneously as maximum ages for the cessation of activity associated with the stabilization of boulders in the coarse gutters.
- These SHD ages are consistent with the establishment of regional permafrost shortly after deglaciation in the early Holocene (~9700 years ago) and with subsequent gradual decrease in activity, which affected the sites at the lowest altitudes first following the onset of the Holocene Thermal Maximum ~8,000 years ago.
- Two alternative interpretations are considered: (1) an initial active period of efficient frost sorting during the Younger Dryas-Holocene transition, with completion of sorted circle formation earlier than indicated by the SHD ages; and (2) formation before the Last Glacial Maximum, preservation beneath cold-based ice, and subsequent emergence of sorted circles fully formed following deglaciation. Neither of these alternative hypotheses can be fully rejected on the basis of currently available evidence. .
- Despite lowering of the altitudinal limits of permafrost, there is no evidence to support reactivation of these relict landforms, either during late-Holocene climatic deterioration and the onset of neoglaciation ~6000 years ago, or during the Little Ice Age of the last few centuries.

- The complex geodynamic processes involved in sorted circle formation leave the mean boulder exposure age as reflecting a relatively long process of formation and stabilization rather than a defined event. Additionally, the palaeoclimatic interpretation of patterned ground must still be considered problematic as non-climatic factors are potentially involved in the stabilization process.

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Tables

Table 1 – R- and R_{Rock}-values for the sites tested

Site	mean ± 95% CI[1]	σ	skewness	kurtosis	boulders (n)
Mechanical Schmidt					
Site 1 (1,925 m a.s.l.)	45.81 ± 1.24	10.18	-0.822	0.198	260
Site 2 (1,850 m a.s.l.)	46.22 ± 1.37	9.75	-0.260	-0,151	195
Site 3 (1,750 m a.s.l.)	44.64 ± 1.46	10.27	-0.387	-0,457	190
Site 4 (1,550 m a.s.l.)	42.94 ± 1.51	10.93	-0.167	-0.602	200
Site 5 (1,500 m a.s.l.)	42.40 ± 1.31	10.75	-0.189	-0.574	260
RockSchmidt					
Site 2	55.03 ± 0.77	10.71	-0.426	-0.203	750
Site 3	53.37 ± 0.79	11.02	-0.482	-0.265	750
Site 4	51.12 ± 0.86	12.05	-0.216	-0.602	750

[1] Mean of R-values (mechanical Schmidt-hammer) and R_{Rock}-values (RockSchmidt) with 95 % confidence intervals (α = 0.05).

Table 2 – Results of Mann-Whitney ANOVA tests of differences between pairs of sites in R-values and R_{Rock}-values

Sites (paired)	H_0[(1)]	α[(2)]	boulders (n)	Δ altitude
Mechanical Schmidt				
Sites 1-2	retain	0.788	455	75 m
Sites 1-3	retain	0.127	450	175 m
Sites 1-4	reject	0.001	460	375 m
Sites 1-5	reject	0.000	520	425 m
Sites 2-3	retain	0.226	385	100 m
Sites 2-4	reject	0.004	395	300 m
Sites 2-5	reject	0.000	455	350 m
Sites 3-4	retain	0.095	390	200 m
Sites 3-5	reject	0.023	450	250 m
Sites 4-5	retain	0.643	460	50 m
RockSchmidt				
Sites 2-3	reject	0.007	1500	100 m
Sites 2-4	reject	0.000	1500	300 m
Sites 3-4	reject	0.000	1500	200 m

[(1)] H_0 = Distribution of values is the same across both samples (decision at α = 0.05).

[(2)] Asymptotic significance level (2-tailed test)

Table 3 – Results of Kruskal-Wallis ANOVA tests of differences between three or more sites in R-values and R_{Rock}-values

Sites (clustered)	H_0 [(1)]	α [(2)]	boulders (n)	altitudinal range
Mechanical Schmidt				
Sites 1-2-3	Retain	0.278	645	175 m
Sites 2-3-4	Reject	0.014	585	300 m
Sites 3-4-5	Retain	0.066	650	250 m
Sites 1-2-3-4	Reject	0.001	845	375 m
Sites 2-3-4-5	Reject	0.001	845	350 m
Sites 1-2-3-4-5	Reject	0.000	1105	425 m
RockSchmidt				
Sites 2-3-4	Reject	0.000	2500	300 m

(1) H_0 = Distribution of values is the same across both samples (decision at α = 0.05).

(2) Asymptotic significance level (test statistics adjusted for ties)

Table 4 – R-values for boulders surfaces from road cuts ('young' unweathered surfaces)

Road cut	1st impact mean ± 95% CI (1)	5th impact mean ± 95% CI (2)	boulders (n)
Cut near site 2 (1,850 m a.s.l.)	61.2 ± 4.37	64,9 ± 2.64	10
Cut near site 3 (1,750 m a.s.l.)	61.6 ± 3.72	65.9 ± 1.86	10
Cut near site 4 (1,550 m a.s.l.)	66.0 ± 1.78	67.3 ± 1.60	10
Mean (all sites)	62.93 ± 2.09	66.03 ± 1.21	30

(1) Mean R-value with 95 % confidence interval ($\alpha = 0.05$) first impacts of the Schmidt hammer (see text).

(2) Mean of R-value with 95 % confidence interval ($\alpha = 0.05$) for fifth impacts from the same spots as the first impacts.

Table 5 – SHD ages (mean boulder surface exposure ages ± 95% confidence intevals) for sample sites applying two calibration curves

Sites	Vesl-Juvbreen curve	Jotunheimen curve
1	5810 ± 890	7055 ± 465
2	5605 ± 935	6910 ± 510
3	6395 ± 980	7460 ± 540
4	7245 ± 1015	8050 ± 560
5	7515 ± 940	8240 ± 495
1st impacts(1)	-2765 ± 1140	1100 ± 735
5th impacts(2)	-4315 ± 740	20 ± 435

(1) Mean of 1st impacts of all road-cut test sites combined (see Table 4 and text for explanation)

(2) Mean of 5th impacts of all road-cut test sites combined

Figure captions

Figure 1

Study sites (numbered 1 - 5) in the vicinity of the Juvflya plateau area of central Jotunheimen, southern Norway. The locations and view directions of the overview photographs (Figures 2a – d) are indicated.

Figure 2 a - f

Study area, patterned ground features, and Schmidt-hammer test sites: (a) the typical landscape looking northwards towards Bøverdalen from the Juvflya plateau; (b) the central part of Juvflya with its dense patterned ground cover; (c) close-up of typical sorted polygons near Juvasshytta; (d) sorted polygons merging downslope into sorted stripes on the southwest-facing slope of Juvasshøi; (e) sorted polygons at site 2; (f) sorted polygons at site 4 (see Figure 1 for location and view direction of photographs; the location of Figures 2e and f are the same as the place marks for sites 2 and 4, respectively).

Figure 3

Histograms of R-values (mechanical Schmidt hammer) obtained at sites 1 - 5 using a 2-unit class interval.

Figure 4

Histograms of R_{Rock}-values (electronic RockSchmidt) obtained at sites 2 - 4 using a 1-unit class interval.

Figure 5

Mean R- and R_{Rock}-values for the test sites with their 95 % confidence intervals.

Figure 6

The altitudinal gradients in mean R- and R_{Rock}-values for sites 1-5. Linear regression lines, regression equations and coefficients of determination (R^2 values) are depicted, and 95 % confidence interval are shown for each site.

Figure 7

Altitudinal variation in the SHD ages and their 95% confidence intervals for sites 1-5, based on the Jotunheimen calibration curve. The roman numbers refer to the subregional neoglacial events as identified by Matthews and Dresser (2008) in the nearby Smørstabbtindan Massif, Jotunheimen.

Figure 8

Results of the clast roundness measurements at sites 2 - 4. The abbreviations stand for very angular (VA), angular (A), subangular (SA), subrounded (SR), and rounded (R) clasts. The index of roundness (*ir*) is also shown for each site.