EARTH SURFACE PROCESSES AND LANDFORMS
Earth Surf. Process. Landforms **36**, 170–179 (2011)

Published online 22 June 2010 in Wiley Online Library
(wileyonlinelibrary.com) DOI: 10.1002/esp.2029

Surface and sub-surface Schmidt hammer rebound value variation for a granite outcrop

Barbora Černá and Zbyněk Engel
Department of Physical Geography and Geoecology, Faculty of Science, Charles University in Prague, Albertov 6, 128 43 Praha 2, Czech Republic

Received 7 December 2009; Revised 3 March 2010; Accepted 17 March 2010

Correspondence to: Z. Engel, Department of Physical Geography and Geoecology, Faculty of Science, Charles University in Prague, Albertov 6, 128 43 Praha 2, Czech Republic. Email: engel@natur.cuni.cz

ESPL
Earth Surface Processes and Landforms

ABSTRACT: This study presents rock strength variations at granite outcrops and in subsurface vertical profiles in the Jizerské hory Mountains, Czech Republic. Schmidt hammer rebound values in subsurface profiles change gradually from the bedrock surface downward. An exponential relation has been observed between the R-values and depth in rock outcrops to a depth of around 4·5 m. The exponential nature of the curve indicates that rock hardness increases more rapidly with depth in the uppermost 1 m section of the rock profile. A detailed study of rebound values obtained from both intact and polished rock exposures reveal effects of surface grinding on results of the Schmidt hammer method. The range of data collected increases after grinding, allowing more precise discrimination of rock surfaces in respect of age and weathering. The Schmidt hammer method may be used effectively as a relative-age dating tool for rock surfaces that originated during the Late Pleistocene. It is concluded that this time limitation can be significantly mitigated by surface grinding before measurement. Copyright © 2010 John Wiley & Sons, Ltd.

KEYWORDS: weathering; granite; Schmidt hammer; Quaternary; Jizerské hory Mountains

Introduction

Weathering changes the physical and chemical properties of exposed rock surfaces. The extent of change reflects the duration of exogenic action factors and this indicates relative age of rock surfaces. Hardness is a characteristic commonly used for estimating the relative age of surfaces and can be measured using the Schmidt hammer (SH). Emphasis has been laid on a set of operating guidelines designed to eliminate error in SH measurements. The instrument is calibrated for horizontal impact directions, although measured R-values for non-horizontal impacts could be corrected (Proceq, 1977). Measurement should be made on surfaces free of lichens, avoiding places near cracks or edges of a rock mass (Day and Goudie, 1977). Some authors have recommended polishing the surface using a carborundum wheel or electric grinder before measurement (Malhotra, 1976; Katz *et al.*, 2000). The latter technique is rarely adopted because the measurement becomes time-consuming, and there are doubts as to the influence of such an alteration of the rock on the resulting measurements: 'If the surface is first prepared by removal of weathered material, the hammer is then testing rock that is fresher than the original surface' (Nicholas and Butler, 1996).

The SH has been used as a dating tool for recent to Middle Pleistocene rock surfaces. Relative dates have been obtained for Holocene surfaces, including various anthropogenic features, moraines, rock glaciers, rock-falls, avalanches, debris flow and deltaic deposits. SH has been used only sporadically to estimate the relative age of older features, for example, glacial landforms (Sumner *et al.*, 2002), periglacial trimlines (Ballantyne, 1997; Anderson *et al.*, 1998), rock glaciers (Humlum, 1998; Frauenfelder *et al.*, 2005), raised beaches (Sjöberg, 1990) and lake shorelines (Matthews *et al.*, 1986). Limitations of the method itself have been described (McCarroll, 1989; Goudie, 2006). However, data on the effective range of geological time for which the SH dating technique is useful are not available.

This paper presents SH measurements on intact and prepared surfaces in the Jizerské hory Mountains, Czech Republic. SH R-values were collected from granite outcrop surfaces and from vertical profiles below rock surface. The main aims of this study were (1) to verify the influence of surface grinding on the results of SH measurements; (2) to uncover how rock hardness changes with depth; and (3) to identify the age limitations of the SH dating technique.

Study Area

The Jizerské hory Mountains lie in the northern part of the Bohemian Massif in Central Europe. The bedrock in the study area is composed of granite which was differentiated by Chaloupský (1989) into two types: porphyritic coarse-grained biotitic granite and a porphyritic medium-grained granite. Both types have uniform petrographical composition and their grain sizes are also similar. Thus, properties of two granite types may not differ enough to affect the SH measurements.

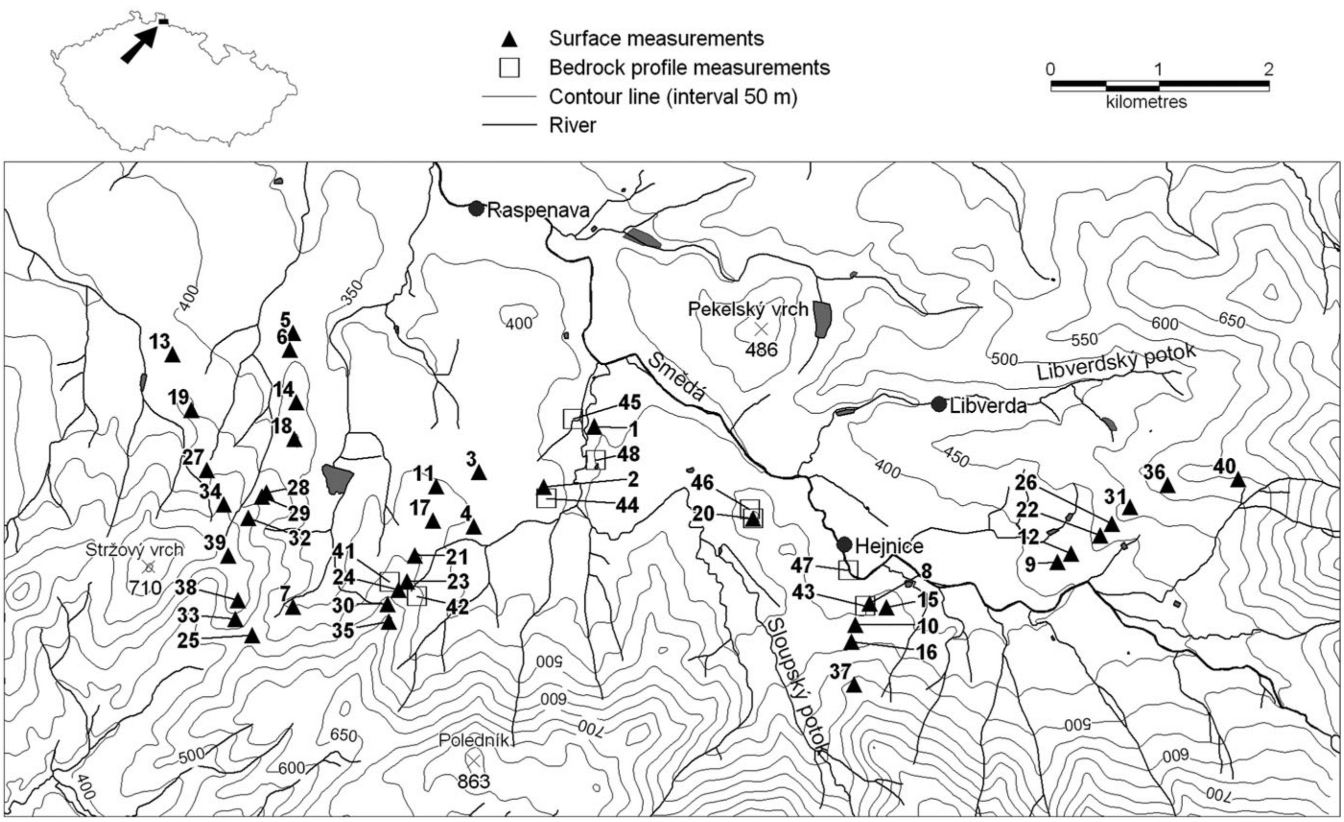

Figure 1. Location of SH measurement sites in the study area.

The study area includes the steep northern flank of the mountains, as well as glacially transformed foothills (Figure 1). Incised valleys dissect the flank, isolating prominent ridges with a variety of rock outcrops. In the lower foothill area, low outcrops (extensive isolated rock outcrops with height less than 2 m) and roches moutonnées predominate. Boulder piles (outcrops that fell to pieces and consist of *in situ* boulders) are the most frequent type of outcrop occurring at all altitudes. Tors are found at all altitudes, but their heights differ. Low tors (less than 3 m high) are frequent below 470 m whereas the highest tors (more than 5 m) predominate above 520 m a.s.l.

Apart from the above mentioned landforms a variety of other granite forms including mushroom rocks, balanced boulders, pseudokarst caves, potholes and weathering pits have developed in the study area. The distribution, size and shape of landforms are influenced by differences in lithology and structure of the Jizera granite (Letošník, 1962). Ginzel and Novák (1962) have shown that porphyritic structure and fracture patterns control the morphology of tors and rock walls in the study area. Minor granite landforms relate to the presence of fractures and vein rocks such as aplite or kersantite (Žitný, 1966). The two-stage model of landform evolution defined by Jahn (1962) may be applied to granite landforms located above the upper limit of continental glaciation. These landforms have formed under the influence of long-term weathering which affected the landscape since the tectonic composition of the Hejnice Basin in the Tertiary (Chaloupský, 1989). The last stage of granite landforms development may be attributed to the cold conditions in the Quaternary (Migoń, 2007).

The morphostratigraphic study of Králík (1989) indicates that the ice sheet reached the northern part of the Jizerské hory Mts three times, twice during the Elsterian glaciation and once in the Saalian (OIS 6 or 8). However, more recently both Polish and German authors consider all ice sheet advances to have taken place during the Elsterian (=OIS 12) (Eissmann, 1995; Badura and Przybylski, 1998; Michniewicz, 1998). Contrasting hypotheses have important implications for ice-sheet trimline studies. The more recent the retreat of the glaciation, the higher the probability that the trimline can be reconstructed from landform evidence including measurement of rock surfaces hardness. The altitudinal limit of glaciation was estimated by Králík (1989) at 400–500 m, by Traczyk and Engel (2006) at around 425 m and by Janásková (2010) at 470–490 m (±20 m).

Methods

SH recording technique was applied to the naturally weathered surface at the sites of 40 rock outcrops along six transects from the foothills (350 m a.s.l.) upslope to 600 m a.s.l. (Figure 1, Table 1). The surfaces were then prepared using an electric grinder and re-examined with a hammer. The grinding was used to reduce surface roughness removing 3–4 mm of the rock. All the outcrops where measurements were taken are situated on parallel ridges with similar geomorphic positions and evolution.

Below rock surface measurements were made throughout the bedrock at nine sites (Table 2). At five outcrops SH measurements were taken along subsurface vertical profiles (down to a 5 cm depth) using an electric saw. A series of vertical cuts were made and a sequence of horizontal cuts at 1 cm intervals was then cut into the profile. The top surface of each horizontal cut was tested in sequence as the cuts were made. At four remaining sites rebound values (R-values) of deeper sections were measured down to a 50 cm depth at horizontal cuts using a 5 cm interval (Figure 2a). Similar measurements were subsequently made at quarries on prepared horizontal sur-

Table 1. Results of SH measurement on naturally and prepared surfaces of rock outcrops

Site No.	Landform	Landform height (m)	Coarse/medium grained granite	Altitude	Natural surface R-value	Natural surface Standard deviation	Natural surface Coefficient of variation	Prepared surface R-value	Prepared surface Standard deviation	Prepared surface Coefficient of variation
1	Roche moutonnée	1·5	M	346	26·0	2·4	9·3	44·6	1·6	3·6
2	Boulder pile	2·8	C	359	29·6	2·1	7·2	46·0	2·7	5·9
3	Boulder pile	2·0	C	377	23·6	2·8	11·8	41·4	1·3	3·1
4	Boulder pile	2·6	C	390	27·4	2·1	7·6	36·3	2·0	5·6
5	Low outcrop	2·0	M	392	25·8	3·9	15·0	37·3	1·6	4·2
6	Low outcrop	2·0	M	394	31·0	2·8	8·9	48·9	1·5	3·0
7	Tor	4·0	C	401	22·8	2·1	9·4	25·8	1·1	4·2
8	Roche moutonnée	2·0	C	405	30·8	2·9	9·3	54·3	1·9	3·6
9	Roche moutonnée	4·0	C	413	28·4	2·5	9·0	42·6	3·2	11·8
10	Roche moutonnée	6·0	M	413	34·3	4·2	12·3	50·6	2·1	4·2
11	Tor	3·0	C	416	31·3	4·1	13·2	48·1	2·5	5·1
12	Roche moutonnée	0·2	C	417	34·4	2·1	6·1	41·4	2·0	4·7
13	Boulder pile	2·0	M	417	24·8	2·6	10·6	37·9	1·5	4·0
14	Low outcrop	1·2	M	426	29·5	3·3	11·3	42·9	2·3	5·3
15	Tor	4·5	C	434	29·5	2·9	9·7	40·6	1·4	3·4
16	Boulder pile	2·0	M	438	27·1	3·2	11·8	59·7	2·1	4·4
17	Tor	5·0	C	441	26·6	2·6	9·8	36·0	1·5	4·3
18	Tor	5·0	M	452	21·1	2·0	9·6	32·8	1·7	5·3
19	Low outcrop	1·8	M	452	21·7	3·0	13·9	30·5	1·4	4·7
20	Tor	2·5	C	454	24·3	2·9	12·1	33·3	1·3	3·9
21	Tor	6·0	C	454	31·3	3·7	11·7	43·5	2·6	5·9
22	Tor	3·8	C	461	24·5	1·9	7·8	37·7	1·3	3·6
23	Low outcrop	1·5	C	465	25·2	2·8	11·0	42·8	3·1	7·1
24	Tor	4·0	C	477	21·5	2·4	11·3	28·2	1·3	4·5
25	Low outcrop	1·2	C	482	21·0	2·7	13·0	38·5	1·9	5·0
26	Tor	2·0	C	486	25·6	2·2	8·6	35·7	1·3	3·6
27	Boulder pile	3·0	M	491	28·0	3·2	11·3	44·1	1·7	3·9
28	Low outcrop	1·8	C	495	26·0	3·0	11·6	47·1	1·3	2·9
29	Boulder pile	1·2	C	496	25·3	1·7	6·9	49·3	2·1	4·4
30	Tor	10·0	C	518	22·9	2·8	12·2	35·2	1·5	4·3
31	Tor	2·5	C	520	23·8	1·7	7·3	32·8	1·7	5·3
32	Tor	7·0	C	520	20·6	1·4	7·2	27·8	1·1	5·9
33	Tor	5·0	C	535	24·3	2·6	11·8	31·5	1·4	5·6
34	Tor	11·0	C	547	23·0	2·1	8·9	29·7	2·1	3·0
35	Tor	12·0	C	556	20·7	1·8	12·3	25·1	0·9	13·2
36	Tor	3·4	M	570	22·7	2·0	8·7	32·4	1·3	4·0
37	Tor	15·0	M	583	25·1	1·6	6·3	27·2	1·3	4·7
38	Tor	12·0	C	588	20·1	2·0	9·9	21·1	1·1	4·2
39	Tor	6·0	C	593	23·3	1·5	6·4	29·1	1·7	5·9
40	Tor	15·0	M	596	21·6	1·6	7·6	28·6	1·2	4·2

Table 2. Schmidt Hammer R-values measured on prepared surfaces and below rock surfaces

Site No.	Landform	Landform height (m)	Coarse/medium grained granite	Altitude (m)	Depth of measurement (cm)	Depth interval (cm)	Surface R-value (prepared)	Maximum R-value
41	Tor	3·0	C	474	5	1	31·4	23·1
42	Tor	2·0	C	471	5	1	51·0	49·9
43	Low outcrop	1·2	M	397	5	1	37·1	34·5
44	Low outcrop	1·5	C	363	5	1	41·2	42·2
45	Roche moutonnée	1·5	M	345	5	1	44·4	46·9
20	Tor	2·5	C	454	50	1–5	33·3	32·0
47	River channel	-	C	365	50	5	62·2	67·1
46	Quarry	-	C	449	450	25–75	39·9	62·6
48	Quarry	-	C	350	380	1–75	39·4	66·5

faces of quarry steps down to a depth of 4·5 m at 25 to 75 cm intervals. The quarry at Site 48 is cut into bedrock located 12 m above the surroundings in the glacier-covered area. The small quarry at Site 46 is situated close to the summit of a hill which lies about 90 m above the surrounding relief. The estimated trimline indicates that a thin sheet of ice might have covered it for some time during the glaciation.

The supplementary measurement of density of cracks was done in a vertical profile at Site 20. The density of cracks was measured along 5 cm deep vertical cuts below each SH tested horizontal surface. The crack density was expressed as ratio of crack length and relevant areas of the vertical cuts (Figure 2b).

The standard N-type of SH was chosen and used in accordance with the operating guidelines recommended by Day and Goudie (1977). 25 hammer impacts were taken on each horizontal surface. The data were processed following the guidelines presented by Matthews and Shakesby (1984) and

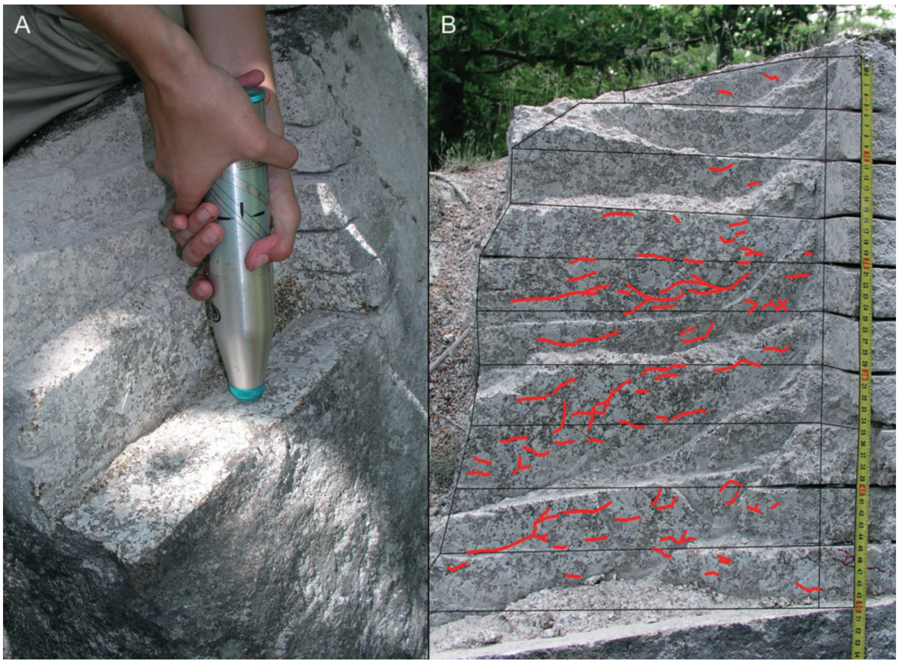

Figure 2. SH applied to horizontal surfaces along 50 cm deep vertical profiles (A). Vertical cuts with marked cracks (B). This figure is available in colour online at wileyonlinelibrary.com

extended by Moon (1984). First, the mean and the standard deviation of the recorded readings were calculated. Then, the five values with the greatest deviation for each surface were excluded from the dataset and new mean values for R were calculated from the remaining 20 values. The resulting mean R-values for the intact and prepared surfaces measured at 40 sites were compared for each measurement site. Coefficients of variation were calculated for each of the intact and prepared datasets. R-values for the naturally weathered surfaces were correlated with the test values for prepared surfaces using the least squares regression method. The equation for the line of best fit, the 95% confidence limits and the correlation coefficient were determined for the regression. R-values for subsurface horizontal flats were determined using the same statistical techniques as for data from intact and prepared surfaces. Subsequently the mean R-values of subsurface horizontal flats were plotted against depth. Regression curves were constructed for the datasets derived from sampling Sites 46 and 48.

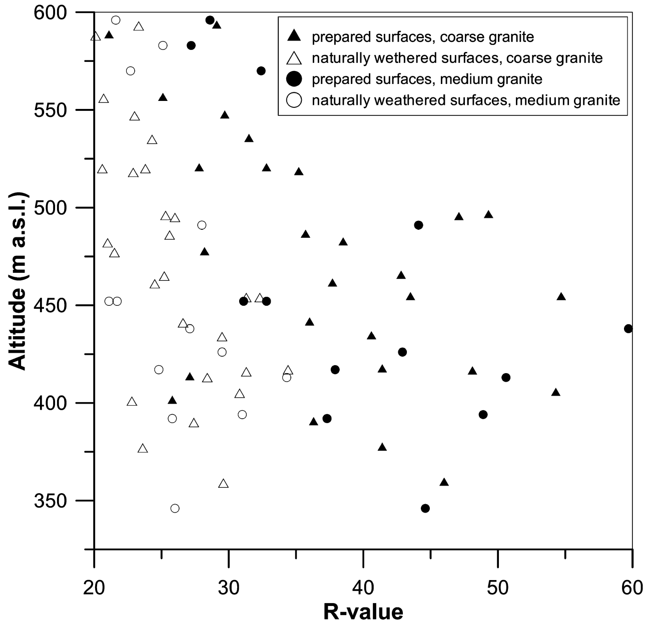

Figure 3. R-values versus altitude in the study area.

Results

Rock outcrop surfaces

R-values for rock outcrop surfaces are given in Table 1. The average R-values for natural surfaces range from 20·1 to 34·4 for coarse-grained granite, and 21·1 to 34·3 for medium-grained granite. The coefficients of variation range from 6·1% to 13·2% for coarse-grained granite, and from 6·3% to 15·0% for medium-grained granite. The results of measurements on prepared surfaces show considerably higher R-values than those on natural surfaces, as well as a wider range of measured values (Figure 3). The average R-values range from 21·1 to 54·7 for coarse-grained granite, and from 27·2 to 59·7 for medium-grained granite. The coefficients of variation range from 2·9% to 13·2% for coarse-grained granite, and from 3·0% to 5·3% for medium-grained granite. The coefficients of variation are high for coarse-grained granite in both natural and prepared datasets whereas for medium-grained granite the average value of the coefficient is lower for prepared surfaces. R-values measured on prepared surfaces are higher on average by nearly 12 points (10·8 for coarse-grained and 13·7 for medium-grained granite) than values obtained before grinding. The relation between R-values on intact and prepared surfaces (Figure 4) is described by linear regression. Nevertheless, its reliability is relatively low (R-squared value 0·539) which means that R-values on natural surface can hardly be used to predict the R-values on prepared surface.

The above described facts indicate that the measured R-values are not primarily influenced by bedrock types as differentiated by Chaloupský (1989). Instead, the results suggest that weathering histories are of major importance. SH measurements along transects include both weathered and rela-

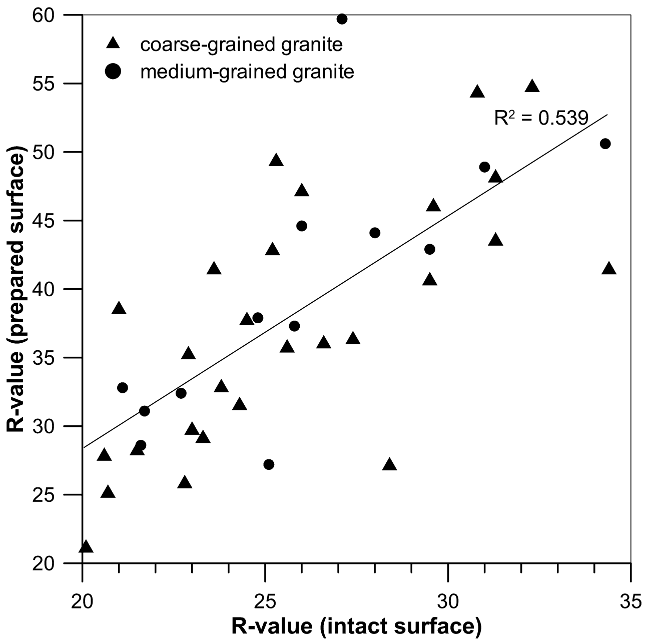

Figure 4. R-values on prepared versus intact surfaces.

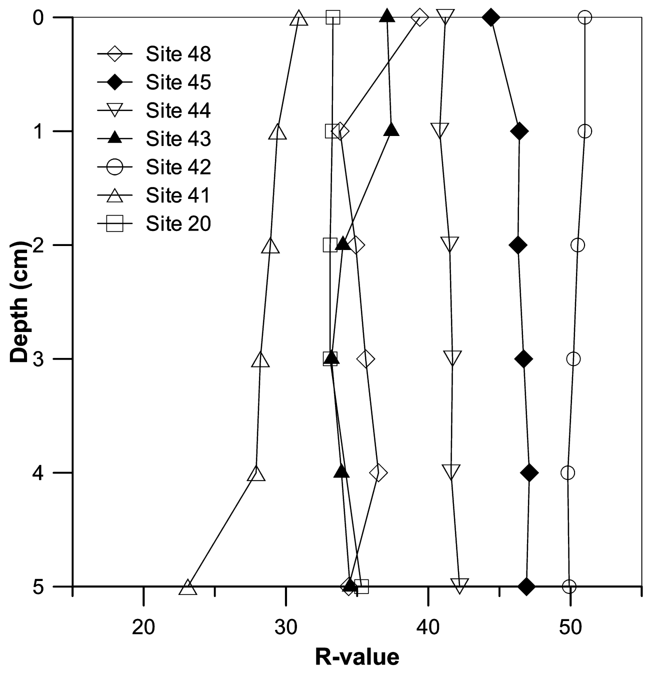

Figure 5. R-values down to 5 cm depth. Solid and unfilled shapes represent coarse- and medium-grained granite, respectively.

tively fresh rock outcrops, representative of weathering conditions in the area. Smaller R-values (of up to 35) represent strongly weathered outcrops even if subjected to grinding, but much higher values were usually obtained from weakly weathered outcrops after polishing (R-value above 50). The progressive increase in the data range after polishing emphasizes the contrast between measurements on recently exposed and older surfaces. The increased variation enables easier recognition of outcrops in various stages of weathering. In terms of variation among sites, there are higher mean R-values at the recent river channel (mean R-value 39·8 intact / 62·2 prepared surface) and on roches moutonnées (mean R-value 30·8 / 46·7 prepared surface), with lower values being characteristic for outcrops situated above the altitudinal limit (500 m a.s.l.) of the Quaternary ice sheet (mean R-value 22·5 intact / 29·1 prepared surface).

Bedrock profiles

Stable or slightly varying R-values were recorded in shallow subsurface vertical profiles down to a depth of 5 cm (Figure 5). The coefficients of variation range from 2·4% to 10·0% for coarse-grained granite and from 3·1% to 6·4% for medium-grained granite. The lower hardness of subsurface sections is thought to be due to increased presence of rock cracks. Sub-horizontal cracks invisible on naturally weathered surfaces seem to affect the measurement according to their density. SH data from all subsurface measurements show a similar hardness to R-values recorded at the surface.

The data presented in Figure 6 show the change of R-values in lower sections of coarse-grained granite down to 4·5 m. The R-values vary widely depending upon the depth of the rock surface tested within the profile. The average R-values range from 34·4 to 66·5 for Site 48 and from 39·9 to 66·9 for Site 46. The R-values in the Site 47 profile vary from 60·5 to 69·8, a restricted range compared with the previous two sites. Coefficients of variation range from 2·0% to 10·4% (Site 48), from 1·9% to 5·6% (Site 46) and from 1·5% to 4·0 % (Site 47), with an overall average of 4·6%, 3·6% and 2·4%. An exponential relation between the R-values and depth was found, as was a similar exponential fit. The high value of the coefficient of determination is the result of a correlation between R-values and depth in both deep vertical profiles (Sites 48 and 47).

SH measurements at Site 20 revealed an anomalous trend in surface hardness for the upper 0·5 m section. The highest R-value was recorded 5 cm below the surface (34·9). The data show a decreasing trend between 5 and 20 cm, followed by a slight increase down to 50 cm (Figure 7A). The data scatter is due to irregular cracking in the rock, which is sub-horizontal and invisible on the bedrock surface. The higher the density of cracks below the measured horizontal surfaces, the lower the R-value (Figure 7B).

Discussion

Impact of surface grinding on R-value

The variation of R-values among the subsurface 5 cm sections is low irrespective of the surface hardness and the degree of rock weathering. The measurements carried out suggest that if the unevenness is removed from the surface the variable depth of grinding does not significantly affect the measured R-value. Thus, concerns about the negative influence of rock surface preparation expressed by Nicholas and Butler (1996) do not apply. Results of SH measurements are more prone to be affected by discontinuities in the rock, decreasing R-values substantially. Sub-horizontal cracks, in particular, present a problem because these are invisible on the surface, prohibiting the operator from avoiding incorrect readings. This source of error can be eliminated by using measurements on a more extensive area of the surfaces being tested. The measurements undertaken evidence a relation between R-values and cracks and confirm that SH is highly sensitive to discontinuities in the rock, as noted by Goudie (2006). The results also support the recommendations of Malhotra (1976) on the application of grinding before SH measurements.

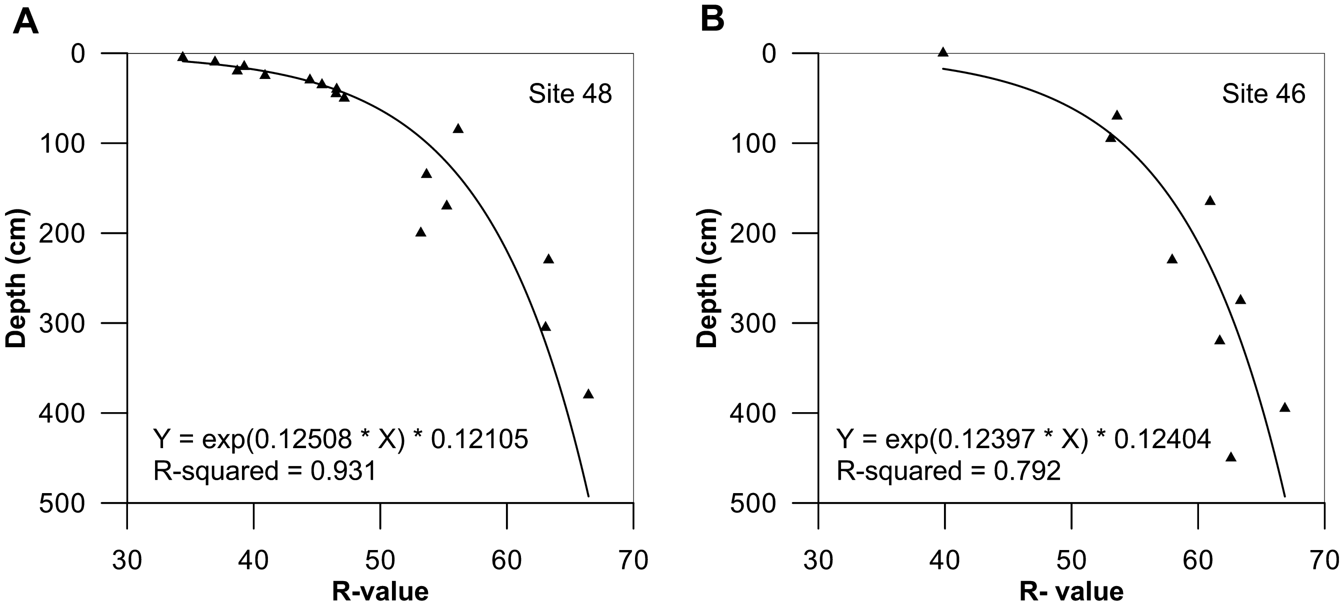

Figure 6. R-values versus depth at Sites 48 and 46.

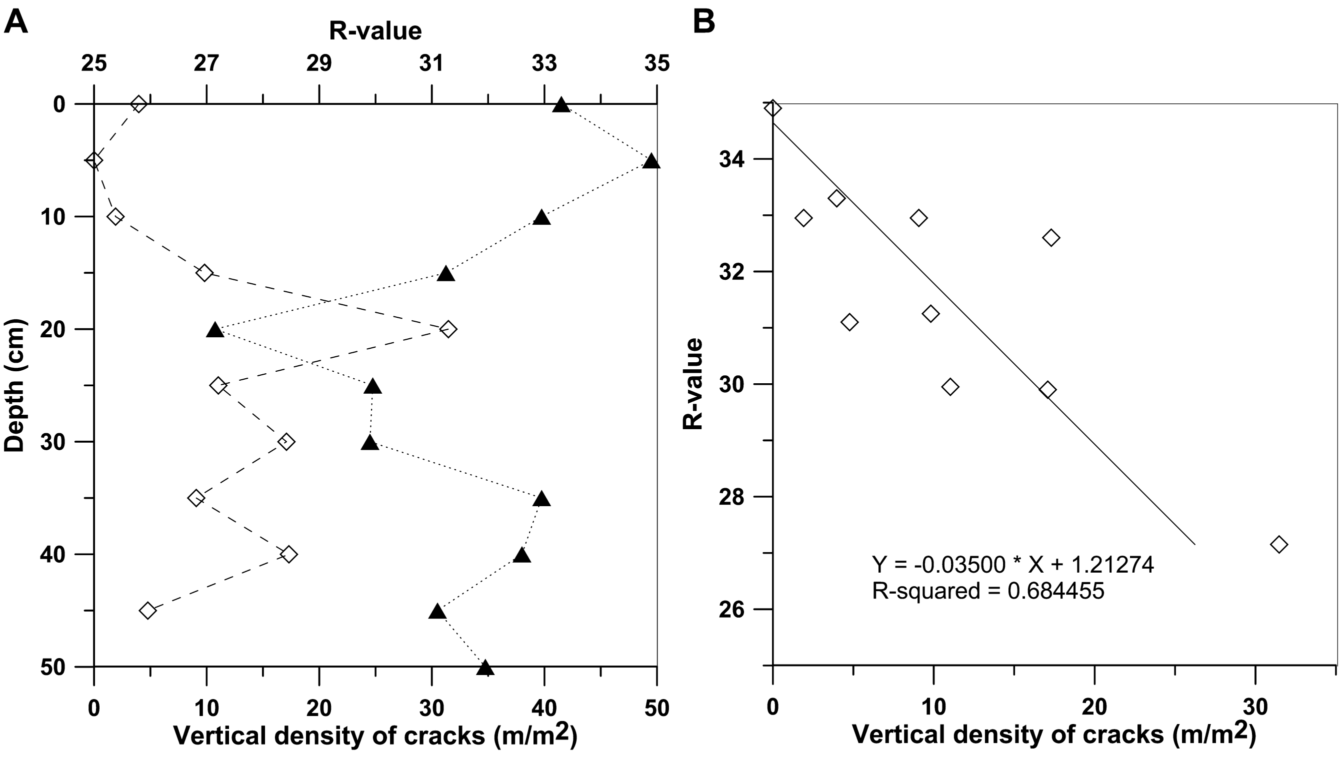

Figure 7. R-values and density of cracks versus depth at Site 20. Solid and unfilled shapes represent Rvalues and cracks, respectively.

The results obtained demonstrate contrasting readings from two different weathering zones (Figure 8). Rock surfaces affected by glacial erosion (roches moutonnées) yielded generally higher and more scattered R-values than tors above the upper limit of ice-sheet glaciation. The decrease in surface hardness with altitude probably results from different landscape evolution above and below the glacial trimline located around 500 m a.s.l. (Janásková, 2010). Although both R-value datasets markedly overlap, the aggregate results point to different degrees of surface weathering. A comparison of R-value sets obtained on intact and prepared surfaces emphasizes the weathering contrast. The difference between mean R-values from intact and prepared surfaces is more than twice as high for rock surfaces below 500 m a.s.l. as for outcrops situated higher up which feature greater weathering.

Figure 8 also demonstrates the benefits of grinding. While on natural surfaces R-values from roches moutonnées (21–50) largely overlap with the group of tors (17–30), on prepared surfaces, the overlapping is negligible (33–57 roches moutonnées, 18–35 tors). If SH is used to differentiate these groups, only the measurements on prepared surfaces are reliable data.

Natural surfaces, which yielded R-values between 20 and 25, give R-values between 22 and 42 after polishing. This expansion of data range after polishing significantly improves resolution of the SH method. Measurements on prepared surfaces allow comparison and differentiation of outcrops with

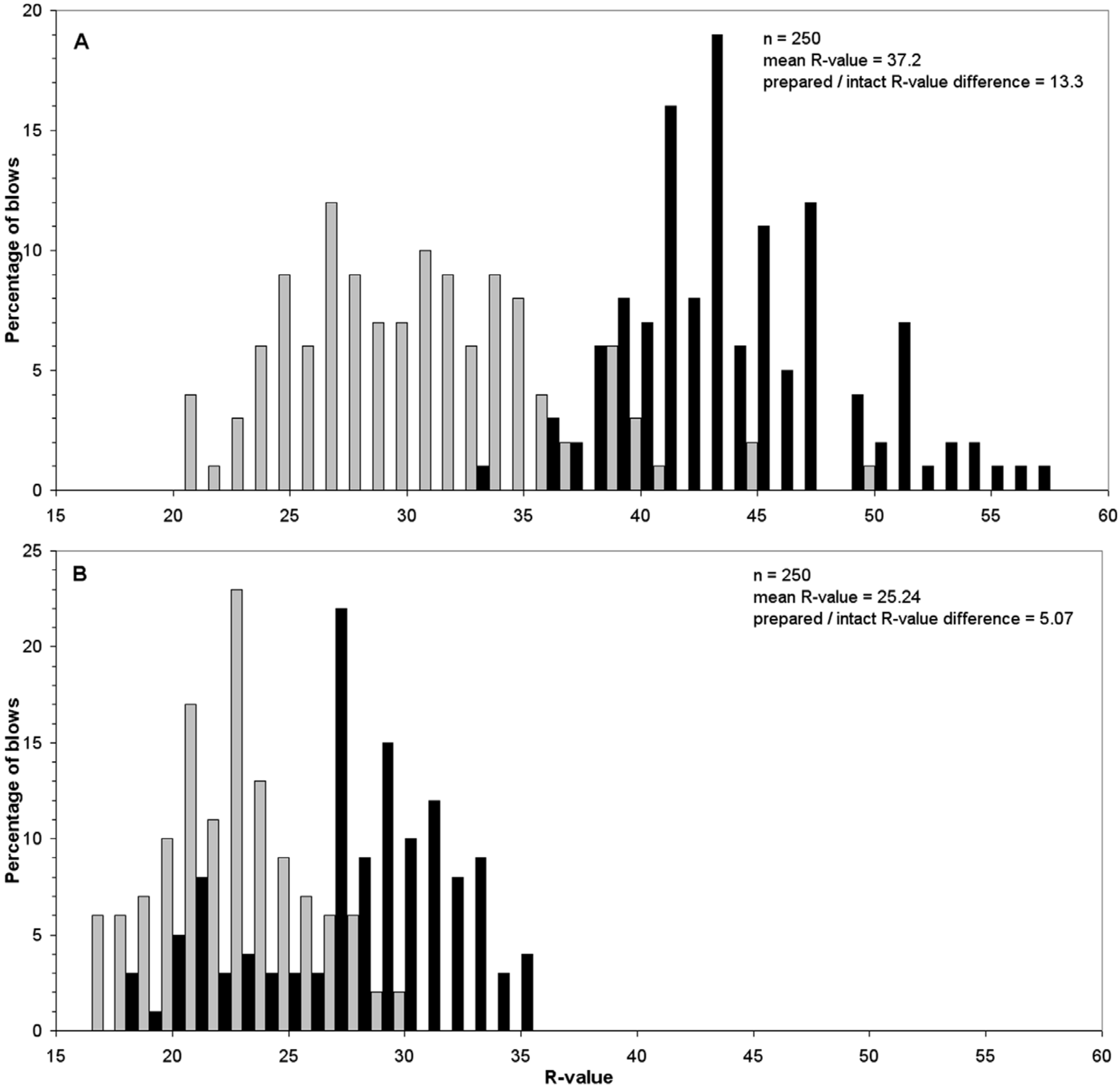

Figure 8. Frequency distributions of Schmidt Hammer single impacts for relatively fresh (A) and weathered (B) surfaces, represented by roches moutonnées and tors above 560 m a.s.l., respectively. Grey bars represent data from natural surfaces and black bars represent prepared surfaces.

similar R-values on intact surfaces. SH measurements of both intact and prepared surfaces is thus advisable, since this will tend to provide a better estimate of the degree of weathering than measurements applied to natural surfaces only. Applying SH to prepared surfaces follows similar principles to repeated hammer impacts at individual points (Poole and Farmer, 1980; Aydin and Basu, 2005) but with higher accuracy. Surface grinding is especially worth the effort when surfaces of similar weathering rate or very old surfaces are compared, if better accuracy is needed or if the data are to be compared with an absolute time scale.

Relationship between depth and R-value

The most important point arising from SH measurement in vertical profiles is the variable decrease of weathering in the granite outcrops. The largest vertical gradient for the R-value marks the upper 0·5 m of the vertical profile, while in lower sections it gradually decreases. The gradual change of rock hardness results in a substantial depth at which the impact of weathering may be recorded and measured using SH. The R-value change in profiles 46 and 48 can be traced lower than 4 m below the surface.

R-values for fresh granite usually reach 50–60 (Goudie, 2006) and may exceptionally exceed 70 (Katz *et al.*, 2000). According to our data from the recent river channel, an R-value of at least 70 seems to be the upper limit of local granite hardness. SH measurements along subsurface vertical profiles in both quarries show similar values. These results suggest that an R-value of at least 70 may be expected at a certain depth below the bedrock surface in the whole study area. As regards the exponential increase in R-value with depth, the maximum hardness for unweathered granite was

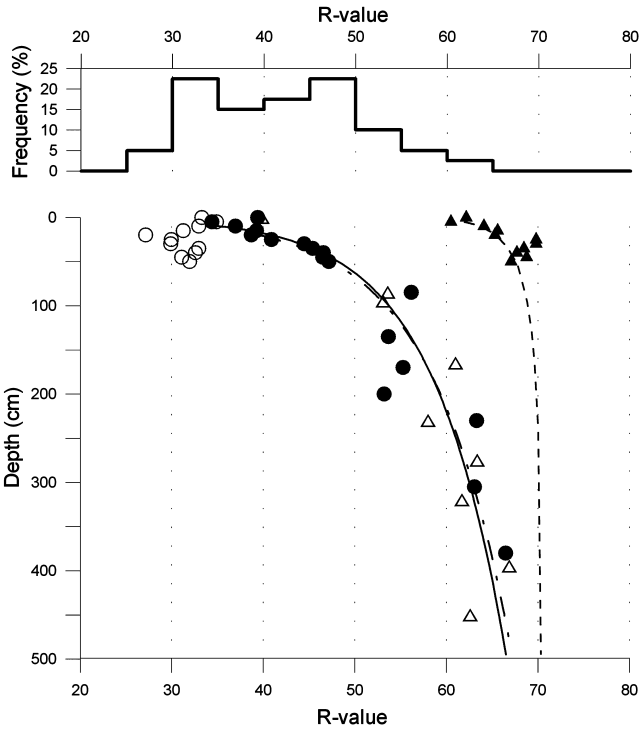

Figure 9. Depth versus R-value plot for vertical profiles and step plot of R-value frequencies measured on prepared surfaces in the study area. Solid triangles, dashed fit – Site 47 (river channel); solid circles, solid fit – Site 48; unfilled triangles, dashed and dotted fit – Site 46; unfilled circles – Site 20.

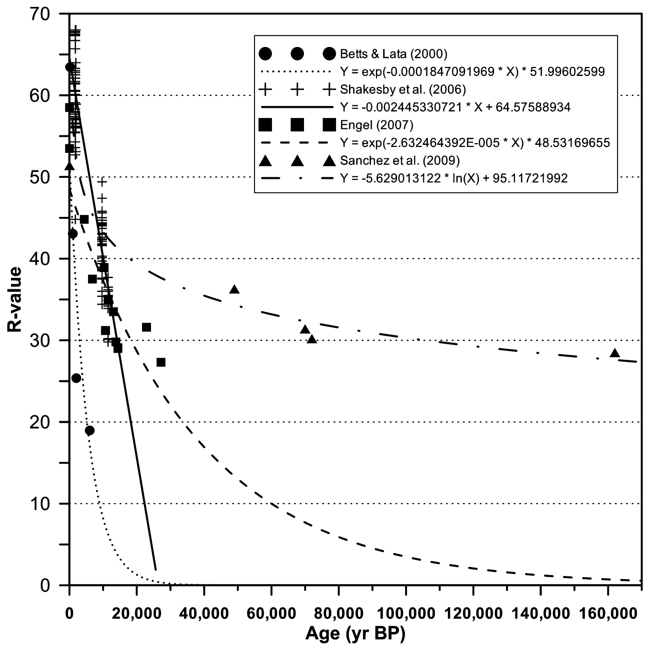

Figure 10. Age-calibration curves for rock surfaces including fitted regression models. Curves are calculated using data from Betts and Latta (2000), Shakesby *et al.* (2006), Engel (2007) and Sánchez *et al.* (2009).

obtained in both profiles at a minimum depth of 8 m. By contrast, in the recent river channel this R-value was recorded 25 cm below the surface (Figure 9). The different course of exponential fits reflects various periods of time over which rock has been affected by weathering. The depth, at which the maximum R-value is reached, decreases with decreasing surface hardness. As the degree of weathering increases, the fit of the curve shifts toward lower R-values, but its overall shape remains exponential.

For the profile through the tor protruding above the surrounding bedrock, no R-value trend is noticeable at a depth down to 50 cm. In this case, we expect the exponential R-value will increase with depth as well, but beginning below the level of the surrounding surface. The vertical profiles in rock outcrops (Sites 20, 41–45) affected by weathering from both above and the sides differ from bedrock profiles weathered from the surface only (Sites 46, 48). The outcrops tend to display a much more uniform, slowly varying hardness, not only in the first 5 cm of depth but throughout the section protruding above the surroundings.

Comparison of SH measurements performed in vertical profiles with the surface measurements reflects the influence of landform development on surface hardness. Regarding the fact that bedrock conditions vary only slightly within the study area the wide range of surface R-values must be conditioned by various degrees of weathering. Because of the uniform climate within the study area, the impact of different origins and/or ages of rock outcrops are of major interest. The high among-site variance in surface R-values compared with R-values measured in vertical profiles suggests that hardness differences caused by different weathering histories have not yet been obliterated by subsequent weathering.

Effective age range of Schmidt hammer dating

The SH has often been used to evaluate the degree of surface weathering as an indicator of relative age. Until recently, it was considered to be a valid tool for distinguishing recently exposed from much older surfaces. In a few studies, SH measurements were applied directly to surfaces of known age. In such cases, R-values were calibrated with reference to lichenometric or historical data (Matthews *et al.*, 1986; Evans *et al.*, 1999; Winkler, 2005), radiocarbon ages (Aa and Sjåstad, 2000; Betts and Latta, 2000), OSL data (White *et al.*, 1998) and exposure ages (Engel, 2007; Sánchez *et al.*, 2009). Based on the reference R-values, the SH method was subsequently employed to estimate the ages of measured surfaces.

Authors mostly used age estimates based on an inferred linear weathering rate (Nesje *et al.*, 1994; Aa and Sjåstad, 2000; Winkler, 2005; Shakesby *et al.*, 2006). However, such a linear trend was only presumed and its use represents an oversimplification of the relation between rock weathering and time. According to Colman (1981), the rate of weathering is constant only when an equilibrium thickness of the residue is reached. Generally, the rate of weathering changes substantially with climate conditions, oscillating between rapid deterioration of the rock surface during the interglacial period and slow modifications to the rock surface under cold and dry glacial conditions (Goodfellow, 2007). Thus, the linear weathering rate is not valid, at least for evaluating age in surfaces originating prior to the Holocene. The non-linear pattern of weathering was reflected by White *et al.* (1998), Betts and Latta (2000), Engel (2007) and Sánchez *et al.* (2009), who demonstrated that a curvilinear or exponential curve, rather than a straight line, fits the data more precisely. An exponential relation between R-values and depth described in this study supports this view of weathering.

By applying the calibration curves, it is possible to determine the theoretical age range for which SH is applicable on granite surfaces as a dating tool (Figure 10). In considering a linear rate of R-value decline, it is evident that the time span over which SH can be used as a regional dating tool is narrow and its use is restricted to Holocene and last glacial (OIS 2) surfaces only. The period associated with the non-linear relationship between the R-value and time overlaps the Holocene timescale, extending the lower limit at least to the Late Pleistocene. The later view is supported by the conclusions of White *et al.* (1998) and Rae *et al.* (2004), who demonstrated that SH is capable of distinguishing surfaces exposed for more than ten thousand years from those originating during the Holocene. However, a gradual increase in surface degradation caused by weathering processes increasingly restricts SH dating. The exponential nature of the curves indicates that time intervals represented by a single R-value unit increase rapidly with greater age, reducing the resolution of the dating. This limitation can be mitigated by surface grinding, which not only extends the effective measurement range but also increases R-values, enabling the measurement of strongly weathered granite whose R-value for intact surfaces is lower than 20. The SH measurements applied on prepared surfaces of various types of outcrops show, that it is possible to distinguish roches moutonnées of Middle Pleistocene age from older tors above the glacial trimline. This fact indicates a significant extension of the SH effective measurement range after grinding. However, measurements on prepared surfaces of known age are necessary to identify the exact limitations of the SH dating technique.

Conclusions

Comparison of R-values obtained from both intact and prepared surfaces reveals that grinding before measurement provides more accurate data. While the range in data collected increases after grinding, the coefficient of variation decreases. The increase of measured data range markedly emphasizes the variable degree of weathering. Using grinding before measurement enables one to differentiate reliably among the surfaces which display little or no difference using measurements on natural surfaces only. The data suggests that measurement of both intact and prepared surfaces using the SH method is more discriminating in respect of age and weathering and is highly advisable. It was also proved that in the shallow subsurface (first 5 cm) of rock outcrops the R-value is stable. Therefore it does not make any difference to resulting R-values if a few millimetres or 2 cm are ground away before measurement.

Schmidt hammer data obtained in subsurface vertical profiles reflects a gradual change in rock hardness from the bedrock surface downward. The data indicate a decreasing vertical gradient in the R-value of rock outcrops to depths of around 4·5 m. The lowest R-values correspond to subsurface sections and a higher degree of weathering. Simple regression reveals an exponential relation exists between R-values and depth. The exponential nature of the curve indicates that rock hardness increases with depth more rapidly in the uppermost 1 m section of the rock profile. According to SH measurements at the bottom of a river channel and along subsurface profiles, R-values of at least 70 seem to be the upper limit of local unweathered granite hardness.

The exponential relation between R-values and depth supports the hypothesis of non-linear variation of weathering rates over time. This exponential trend indicates that time intervals represented by a single R-value unit increase with greater age. The resolution of the SH as a regional dating tool decreases with increasing age of rock surface. Surface grinding, which increases R-values, is thus advisable for dating of strongly weathered granite because it extends the effective measurement range of the SH method. However, the age limitation of SH remains unclear and further investigations are necessary for its determination.

Acknowledgements—Fieldwork was funded by Charles University in Prague (B-GEO 92908), the Czech Ministry of Education (MSM0021620831) and the Czech Science Foundation (P209/10/0519). We would like to thank Ladislav Žitný (†) for bringing to our attention an interesting study area.

References

Aa AR, Sjåstad JA. 2000. Schmidt hammer age evaluation of the moraine sequence in front of Bøyabreen, western Norway. *Norsk Geologisk Tidsskrift* **80**: 27–32. DOI: 10.1080/002919600750042654

Anderson E, Harrison S, Passmore DG, Mighall TM. 1998. Evidence of Younger Dryas glaciation in the Macgillycuddy's Reeks, southwest Ireland. *Quaternary Proceedings* **6**: 75–90.

Aydin A, Basu A. 2005. The Schmidt hammer in rock material characterization. *Engineering Geology* **81**: 1–14. DOI: 10.1016/j.enggeo.2005.06.006

Badura J, Przybylski B. 1998. Extent of the Pleistocene ice sheets and deglaciation between the Sudeten and the Silesian Rampart. *Biuletyn pnstwowego instytutu geololicznego* **385**: 9–28.

Ballantyne CK. 1997. Periglacial trimlines in the Scottish Highlands. *Quaternary International* **38/39**: 199–136. DOI: 10.1016/S1040-6182(96)00016-X

Betts MW, Latta MA. 2000. Rock surface hardness as an indication of exposure age: an archaeological application of the Schmidt Hammer. *Archaeometry* **42**: 209–223. DOI: 10.1111/j.1475-4754.2000.tb00877.x

Chaloupský J. 1989. *Geologie Krkonoš a Jizerských hor*. Academia: Praha.

Colman SM. 1981. Rock-weathering rates as functions of time. *Quaternary Research* **15**: 250–264. DOI: 10.1016/0033-5894(81)90029-6

Day MJ, Goudie AS. 1977. Field assessment of rock hardness using the Schmidt test hammer. *British Geomorphology Research Group Technical Bulletin* **18**: 19–29.

Eissmann L. 1995. The pre-Elsterian Quaternary deposits of central Germany. In *Glacial Deposits in North-east Europe*, Ehlers J, Kozarski S, Gibbard S (eds). Balkema: Rotterdam; 423–437.

Engel Z. 2007. Measurement and age assignment of intact rock strength in the Krkonoše Mountains, Czech Republic. Zeitschrift für Geomorphologie **51**: Suppl. 1: 69–80. DOI: 10.1127/0372-8854/2007/0051S-0069

Evans DJA, Archer S, Wilson DJH. 1999. A comparsion of the lichenometric and Schmidt hammer dating techniques based on data from the proglacial areas of some Icelandic glaciers. *Quaternary Science Reviews* **18**: 13–41. DOI: 10.1016/S0277-3791(98)00098-5

Frauenfelder R, Laustela M, Kääb A. 2005. Relative age dating of Alpine rock glacier surfaces. *Zeitschrift für Geomorphologie* **49**: 145–166.

Ginzel G, Novák E. 1962. Topografie skal Jizerských hor. Severočeské museum: Liberec.

Goodfellow BW. 2007. Relict non-glacial surfaces in formerly glaciated landscapes. *Earth-Science Reviews* **80**: 47–73. DOI: 10.1016/j.earscirev.2006.08.002

Goudie AS. 2006. The Schmidt Hammer in geomorphological research. *Progress in Physical Geography* **30**: 703–718. DOI: 10.1177/0309133306071954

Humlum O. 1998. Rock glaciers on the Faeroe Islands, the north Atlantic. *Journal of Quaternary Science* **13**: 293–307. DOI: 10.1002/(SICI)1099-1417(199807/08)13: 4

Jahn A. 1962. Geneza skałek granitowych. *Czasopismo Geograficzne* **33**: 19–44.

Janásková B. 2010. Reconstruction of the continental glaciation in the northern slope of the Jizera Mountains. *Sborník geologických věd – Antropozoikum*, in print.

Katz O, Reches Z, Roegiers JC. 2000. Evaluation of mechanical rock properties using a Schmidt Hammer. *International Journal of Rock*

Mechanics and Mining Sciences **37**: 723–28. DOI: 10.1016/S1365-1609(00)00004-6

Králík F 1989. Nové poznatky o kontinentálním zalednění severních Čech. *Sborník geologických věd – Antropozoikum* **19**: 9–74.

Letošník V. 1962. Příspěvek ke studiu skalních tvarů v biotitické žule Jizerských hor. *Sborník Severočeského musea – Přírodní vědy* **2**: 13–22.

Malhotra VM. 1976. Testing hardened concrete: nondestructive methods. In *Project Report: Nondestructive Method for Hardness Evaluation of Mortars*. University Press, Ames: Iowa and The American Concrete Institute: Detroit.

Matthews JA, Shakesby RA. 1984. The status of the 'Little Ice Age' in southern Norway: relative-age dating of Neoglacial moraines with Schmidt Hammer and lichenometry. *Boreas* **13**: 333–46. DOI: 10.1111/j.1502-3885.1984.tb01128.x

Matthews JA, Dawson AG, Shakesby RA. 1986. Lake shoreline development, frost weathering and rock platform erosion in an alpine periglacial environment, Jotunheimen, southern Norway. *Boreas* **15**: 33–50. DOI: 10.1111/j.1502-3885.1986.tb00741.x

McCarroll D. 1989. Potential and limitations of the Schmidt Hammer for relative-age dating: field tests on neoglacial moraines, Jotunheimen, southern Norway. *Arctic and Alpine Research* **21**: 268–275.

Michniewicz M. 1998. The pre-Elsterian valley system in the Western Sudetes, southwestern Poland, and its later transformation. *Geologia Sudetica* **31**: 317–328.

Migoń P. 2007. Geomorphology of granite terrains in Poland. In *Granitoids in Poland*, Kozłowski A, Wiszniewska J (eds). Warsaw University: Warszawa; 355–366.

Moon BP. 1984. Refinement of a technique for determining rock mass strength for geomorphological purposes. *Earth Surface Processes and Landforms* **9**: 189–193. DOI: 10.1002/esp.3290090210

Nesje A, Blikra LH, Anda E. 1994. Dating rockfall-avalanche deposits from degree of rock-surface weathering by Schmidt Hammer tests – a study from Norangsdalen, Sunnmore, Norway. *Norsk Geologisk Tidsskrift* **74**: 108–113.

Nicholas JW, Butler DR. 1996. Application of relative-age dating techniques on rock glaciers of the La Sal Mountains, Utah: an interpretation of Holocene paleoclimates. *Geografiska Annaler* **78A**: 1–18.

Poole RW, Farmer IW. 1980. Consistency and repeatability of Schmidt hammer rebound data during field testing. *International Journal of Rock Mechanics and Mining Sciences and Geomechanics Abstracts* **17**: 167–171.

Proceq. 1977. *Concrete Test Hammer – Types L and R, Operating Instructions*. Proceq SA: Zurich, Switzerland.

Rae AC, Harrison S, Mighall T, Dawson AG. 2004. Periglacial trimlines and nunataks of the Last Glacial Maximum: the Gap of Dunloe, southwest Ireland. *Journal of Quaternary Science* **19**: 87–97. DOI: 10.1002/jqs.807

Sánchez SJ, Mosquera DF, Vidal Romaní JR. 2009. Assessing the age-weathering correspondence of cosmogenic 21Ne dated Pleistocene surfaces by the Schmidt Hammer. *Earth Surface Processes and Landforms* **34**: 1121–1125. DOI: 10.1002/esp.1802

Shakesby RA, Matthews JA, Owen G. 2006. The Schmidt hammer as a relative-age dating tool and its potential for calibrated-age dating in Holocene glaciated environments. *Quaternary Science Reviews* **25**: 2846–2867. DOI: 10.1016/j.quascirev.2006.07.011

Sjöberg R. 1990. Measurement and calibration of weathering processes and lichenometric investigations on a wave washed moraine, Bådamalen, on the upper Norrland coast, Sweden. *Geografiska Annaler* **72**(3–4): 319–327.

Sumner P, Nel W, Holness S, Boelhouwers J. 2002. Rock weathering characteristics as relative-age indicators for glacial and post-glacial landforms on Marion Island. *South African Geographical Journal* **81**: 135–142.

Traczyk A, Engel Z. 2006. Maximální dosah kontinentálního zalednění na úpatí Ořešníku a Poledníku v severním svahu Jizerských hor. *Geografie – Sborník ČGS* **111**(2): 141–151.

White K, Bryant R, Drake N. 1998. Techniques for measuring rock weathering: application to a dated fan segment sequence in southern Tunisia. *Earth Surface Processes and Landforms* **23**: 1031–1043. DOI: 10.1002/(SICI)1096-9837(1998110)

Winkler S. 2005. The Schmidt Hammer as a relative-age dating technique: potential and limitations of its application on Holocene moraines in Mt Cook National Park, Southern Alps, New Zealand. New Zealand *Journal of Geology and Geophysics* **48**: 105–116.

Žitný L. 1966. *Geologie Jizerských hor*. Severočeské museum: Liberec.

