The Schmidt-Hammer as a Relative Age Dating Tool for Rock Glacier Surfaces: Examples from Northern and Central Europe

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Abstract

This paper presents new data of measurements of Schmidt-hammer rebound values (*R*-values) on rock glacier surfaces and adjacent landforms from one site in northern Norway (Lakselv) and two sites in central Austria (Dösen and Weissenkar). The obtained *R*-values reveal long and complex rock glacier formation histories with initiations in the early Holocene. At least the large studied rock glaciers were formed continuously during most of the Holocene, whereas for small rock glaciers this is more difficult to prove. This implies that the Schmidt-hammer method seems to be a powerful tool in surface dating, particularly for large rock glaciers where multiple measurement sites along a longitudinal profile are possible to sample. *R*-values from such profiles enable the establishment of relative chronologies with high temporal resolution. Reliable absolute dating is possible when surfaces of known age with similar vegetation and climate history and comparable lithology are available. The more surfaces of known age are available, the better is a resulting age-calibration curve.

Keywords: Holocene landscape development; rock glacier formation; rock glacier surface dating; Schmidt-hammer.

Introduction

Rock glaciers originate from thick debris accumulations (talus and/or till) in high-relief environments that are under cryogenic conditions for a substantial period of time. Surface morphology, extent, and shape are the cumulative result of their entire genesis and thus climatic past. Temporal dates regarding their initiation and evolution period are the key to valuable palaeoclimatic information. Precise dating of rock glaciers is difficult but can be best achieved by applying an integrated approach, using a combination of relative—thereby distinguishing between fieldwork-based approaches (Schmidt-hammer rebound value, lichenometry, and weathering-rind thickness) and photogrammetry-based approaches (displacement rates and interpolated streamlines)—and absolute (luminescence, exposure/cosmogenic, and radiocarbon) dating methods (Haeberli et al. 2003). Absolute dating methods for rock glacier surfaces are still at an initial stage (Haeberli et al. 1999), are time-consuming, and have their own suites of assumptions and errors (cf. Shakesby et al. 2006), whereas relative dating methods are used more frequently (e.g., Haeberli et al. 2003, Frauenfelder et al. 2005, Kellerer-Pirklbauer et al. 2007). The combination of the Schmidt-hammer and photogrammetry-based approaches seems to be a powerful relative age-dating approach allowing—up to a certain extent—also absolute age estimations (Frauenfelder et al. 2005, Kellerer-Pirklbauer et al. 2007). However, Kellerer-Pirklbauer et al. (2007) pointed out that the main drawback of photogrammetry-based calculations of displacement rates and, derived from that, interpolated streamlines, is the crude assumption of constant velocity during the entire period of formation. Age estimations derived from Schmidt-hammer measurements seem to substantially reduce this drawback.

In this study the Schmidt-hammer method was applied at five rock glaciers and adjacent landforms in different environmental and geological settings. Results and age estimates are presented and compared with each other. The study areas are located at the following sites in Europe:

(1) One rock glacier near Lakselv, Gaissane Mountains, northern Norway (69°57′N, 24°47′E). Age dating based on cosmogenic isotope analysis is currently in progress from surface samples of a nearby rock glacier (LA-B in Fig. 1A) by Frauenfelder (pers. com.). No results are available so far.

(2) Three rock glaciers in the Dösen Valley, Ankogel Mountains, central Austria (46°59′N, 13°26′E). No detailed age estimations have been reported previously from there.

(3) One rock glacier in the Weissenkar Cirque, Schober Mountains, central Austria (46°57′N, 12°45′E). Crude age estimations were reported previously by Buchenauer (1990) suggesting a postglacial formation age.

Study Areas

Northern Norway – Lakselv

The study area near Lakselv, Gaissane Mountains, is characterised by a steep escarpment (caused by faulting) with some hundreds of meters in vertical dimension. This escarpment separates a high plateau from the broad glacially modified Balgesvag´gi valley (Fig. 1A). The high plateau is gently dipping towards the west with smooth summits reaching elevations above 800 m a.s.l. The bedrock at the study area consists of Precambrian and Palaezoic sandstones and silts. A number of gravitationally induced landforms can be identified at the foot of this escarpment reaching a lower elevation of ca. 380–400 m a.s.l. Such landforms are in particular two talus-derived, lobated rock glaciers (LA-A and LA-B in Fig. 1A) and four distinct avalanche boulder tongues (ABT in Fig. 1A). At this study area the intact (i.e. containing permafrost but presumably no current movement; Farbrot 2007), monomorphic and lobated rock glacier LA-A with a surface area of 0.09 km² was studied. For a detailed site description refer to Farbrot (2007).

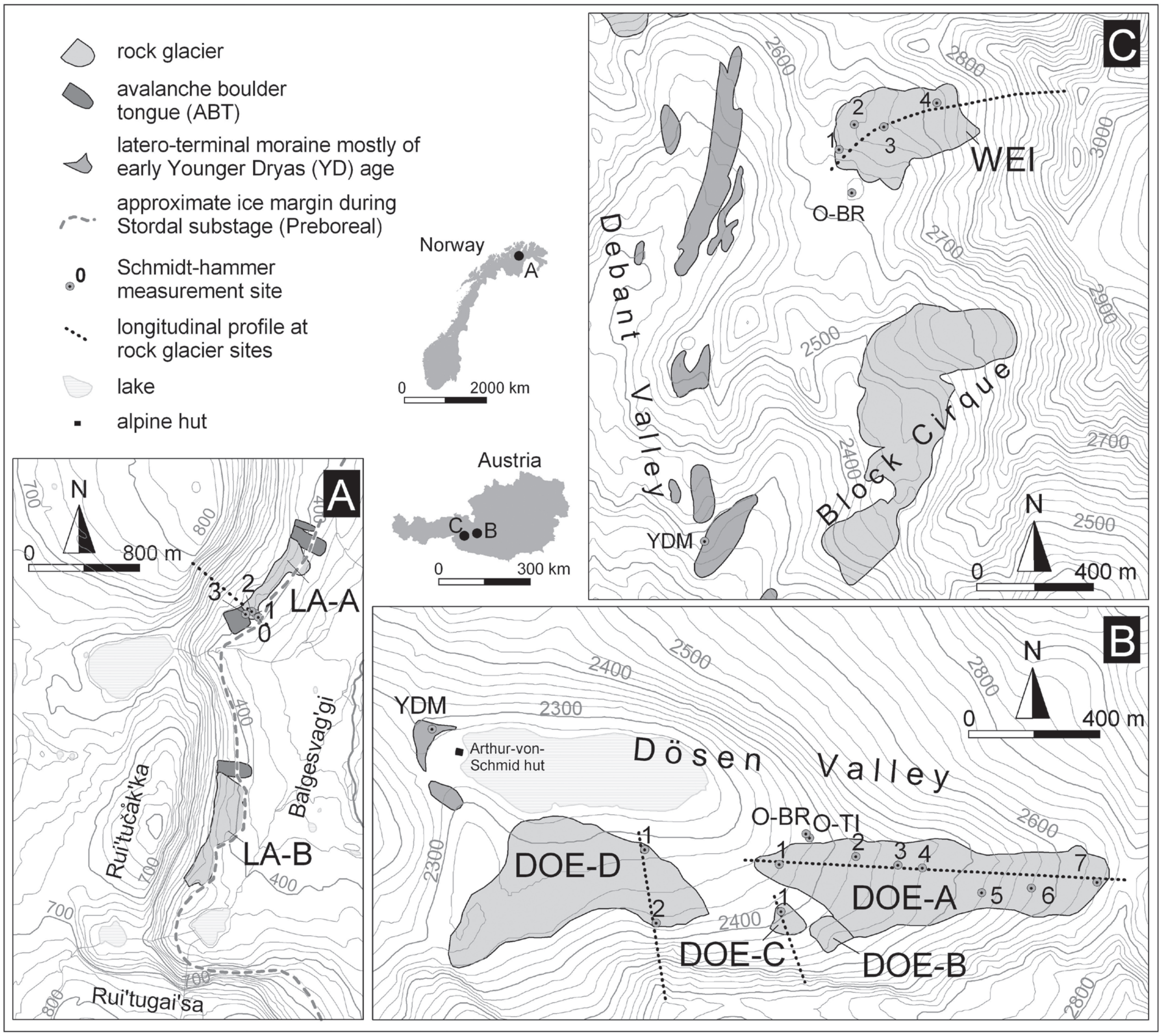

Figure 1. The study areas near (A) Lakselv, Gaissane Mountains in northern Norway and (B) Dösen Valley and (C) Weissenkar Cirque, both in central Austria: (A) Both rock glaciers (LA-A and LA-B=rock glacier Lakselv A and B) occur in close vicinity to avalanche boulder tongues indicating their close genetic relationship. Two Schmidt-hammer measurement sites are located at LA-A (1 & 2) and two nearby (0 & 3). The margin of the Fennoscandian Ice Sheet during the Stordal substage (Preboreal) was at the foot of the escarpment coming from east as indicated in the map. Age dating based on cosmogenic isotope analysis is currently in progress at LA-B. (B): Schmidt-hammer readings were carried out at two active, monomorphic, tongue-shaped (DOE-A and DOE-B) and one intact, monomorphic, lobated rock glacier (DOE-D) in the Dösen Valley. Dots at the rock glaciers, near rock glacier DOE-A (O-BR=bedrock outside rock glacier; O-TI=till boulders outside rock glacier) and at the terminal moraine of early Younger Dryas age (YDM) indicate sites of Schmidt-hammer measurements. (C) Schmidt-hammer readings were carried out at the surface of Weissenkar Rock Glacier (WEI), slightly outside the rock glacier at a roche moutonée (O-BR) and at a latero-terminal moraine ridge of early Younger Dryas age (YDM). Depicted landforms based on (A & B) field work and aerial photograph interpretation, and on (C) Buchenauer (1990). Dotted lines in the maps indicate longitudinal profiles.

Central Austria – Dösen

The second study area is situated in the Ankogel Mountains at the inner part of the glacially shaped, E-W trending Dösen Valley. This part of the valley is characterised by four north-to-west facing rock glaciers, a cirque floor with a tarn lake, and distinct terminal moraines (Fig. 1B). The moraines were presumably formed during the Egesen-maximum advance and are thus of early Younger Dryas (YD) age (Lieb 1996). The elevation ranges between 2270 m a.s.l. at the cirque threshold to more than 3000 m a.s.l. at the nearby Säuleck peak. The four rock glaciers predominantly consist of granitic gneiss (Kaufmann et al. 2007). Three of these rock glaciers (DOE-A, B, and C in Fig. 1B) are considered to be active, and one (DOE-D in Fig. 1B) is regarded as climatic inactive (Lieb 1996). In this study, the focus was on the two active and monomorphic rock glaciers, DOE-A (0.19 km²) and DOE-C (0.007 km²), and on the inactive and monomorphic rock glacier DOE-D (0.17 km²). Previous permafrost research—including velocity measurements—focused particularly on the rock glacier DOE-A (for details see Lieb 1996 or Kaufmann et al. 2007).

Central Austria – Weissenkar

The third study area is located in the Schober Mountains at a west-exposed cirque in the Debant Valley. As indicated by the high number of rock glaciers (*n*=126), the Schober Mountains provide suitable topoclimatic and geological (crystalline rocks) conditions for rock glacier formation (Lieb 1996). The cirque is dominated by the tongue-shaped Weissenkar Rock Glacier (WEI in Fig. 1C) which is fed by active scree slopes. Until the late 1990s, the rooting zone of WEI was occupied by a large perennial snow field. WEI consists of an active upper lobe overriding an inactive lower lobe. Different types of mica schist form the lithological component of the rock glacier. WEI is characterized by well developed furrows and ridges at its entire lower half, a lower limit at 2615 m a.s.l., a length of 500 m, and a surface area of 0.11 km². WEI creeps from the cirque to a plateau-like area composed of roches moutonées. Latero-terminal moraine ridges of Late Glacial age are frequent in the area. At this study area the rock glacier, one roche moutonée, and a distinct moraine ridge of supposed Egesen/early YD age located at the lower end of the Block Cirque were studied (cf. Buchenauer 1990, Lieb 1996, Kaufmann et al. 2006).

Methods

A Schmidt-hammer (or sclerometer) is a light and portable instrument traditionally used for concrete stability testing by recording a rebound value (*R*-value) of a spring-loaded bolt impacting a surface. Beginning in the 1980s (e.g., Matthews & Shakesby 1984, McCarroll 1989), this method has been increasingly applied in glacial and periglacial studies for relative rock surface dating. The obtained *R*-value is proportional to the compressive strength of the rock surface and gives a relative measure of the surface hardness and thus provides information on the time since surface exposure and the degree of weathering. High values are indicative of a lower age and vice-versa.

Analogue L-type Schmidt-hammers have been used at all three study areas using products of the companies “PROCEQ,” Switzerland (Norwegian site) and “Controls,” Italy (Austrian sites). On each of the larger rock glaciers (LA-A, DOE-A, DOE-D, and WEI), two to seven locations close to the central flow line between the frontal ridge and the rooting zone were measured. Sites were kept as small as possible. Measurements on rock glaciers were made on ridge crests and high spots to minimise the possible influence of late-lying snow on weathering rates.

Complementary measurements were carried out on a smaller rock glacier (DOE-C), on boulders at the active talus of the rooting zone of DOE-A, on an active ABT (LA-A3), and at outside sites located adjacent or down-valley from the rock glacier termini. These outside sites were located twice on bedrock (2 x O-BR: Dösen and Weissenkar) and four times on glacigenic boulders (LA-A0, O-TI and 2 x YDM: Dösen and Weissenkar). Sampled stable boulders and bedrock sites in each of the three study areas were selected on the basis of comparable lithology with dry, flat and clean surface, free of lichens, visual fissures and cracks (McCarroll 1989, Haeberli et al. 2003, Shakesby et al. 2006).

Arithmetic means of 50 individual readings (4 impacts per boulder; only the two middle values were noted) with 95% confidence interval were examined at all sites (Matthews & Shakesby 1984, Shakesby et al. 2006). Arithmetic means are representative for the effective hardness of the analyzed surface. The 95% confidence interval is indicative for the standard error and statistically significant age differences between measurement sites.

Results

The Schmidt-hammer results of all three study areas are summarised in Fig. 2A to 2C. Frequency distribution of only one sample shows low bimodality (LA-A3), and skewness is generally low to moderate. Negative skewness may point to a somewhat lower mean *R*-value (higher age) than observed; positive skewness may indicate a somewhat higher mean *R*-value (lower age) than observed.

Rock glaciers near Laksekv

Mean *R*-values range from 48.8 outside LA-A (LA-A0) to 54.8 at the active ABT (LA-A3) adjacent to the rock glacier with low 95% confidence limits. The four samples cover a *R*-value range of only 6.0. *R*-values taken at the rock glacier surface are significantly higher than the ones taken from the outside site close to a moraine ridge of Preboreal age, and they are significantly lower than the ones from the ABT.

Rock glaciers in the Dösen Valley

Mean R-values range from 29.7 at the YDM site to 47.7 at the active talus above DOE-A (DOE-A7) covering a *R*-value range of 18.0. The 95% confidence limits are generally below ±1.00. A decrease in *R*-values can be discerned at the inactive rock glacier DOE-D and, in particular, at the active rock glacier DOE-A (δ*R*-value 12.3).

Rock glacier in the Weissenkar Cirque

Mean *R*-values range from 21.5 at the YDM site to 38.0 at site WEI4 located in the active rooting zone of the rock glacier covering a *R*-value range of 16.4. The rooting zone was occupied by a glacier during the Little Ice Age (~1850 AD) and a large perennial snow field until the late 1990s indicating a rather young age of the deposits at site WEI4. The 95% confidence limit at site WEI4 (1.77) is the highest of all 23 measured sites. A clear decrease in *R*-values can be discerned at the rock glacier WEI (δ*R*-value 13.5).

Discussion

When analyzing Schmidt-hammer literature, it becomes obvious that *R*-value decrease over time is quite heterogeneous in alpine climates and in different lithologies. However, *R*-value differences of >10 suggest time periods of some thousands to more than ten thousand years even in competent rocks such as gneiss (e.g., Aa & Sjåstad 2000, Frauenfelder et al. 2005, Kellerer-Pirklbauer et al. 2007).

Rock glaciers near Lakselv

The formation of the studied rock glaciers in Lakselv

(LA-A) was initiated sometime after the retreat of the Fennoscandian Ice Sheet from the study area. During the YD period, the site of the rock glacier LA-A was situated well inside the glacier limit (Sollid et al. 1973). Marginal moraine ridge systems belonging to the Post-Main (Stordal) substages (Sollid et al. 1973) of suggested Preboreal age (9-10 ka BP, uncalibrated ^{14}C years; Andersen 1979) were deposited in very close vicinity to the present rock glaciers LA-A and LA-B (see Fig. 1A). Later these moraine ridges acted as natural barriers for the development of both lobated rock glaciers and were partly incorporated into them.

The interpretation of the obtained *R*-values is difficult, and the dating here is very speculative. Aa & Sjåstad (2000) calculated for a site in southern Norway that the *R*-value was reduced by 20.5 over a period of 9730 a. Their study site is to some extent climatically comparable to the Lakselv site but with different lithology (gneiss). They inferred a (hypothetical) linear surface weakening rate of 2.1 *R*-values per 1 ka. However, complications arise because the increase in the degree of weathering over time (i.e. weathering rind thickness) and the role of flaking of the weathering rind are not easy to quantify. Schmidt-hammer mean values seem to correlate with weathering rind thickness almost linearly (Laustela et al. 2003) allowing good comparison. Weathering rind thickness increases nonlinearly with time although this nonlinear weathering-time relationship seems to occur on very long timescales often exceeding 100 ka (Skakesby et al. 2006). The role of flaking of weathering rinds might be more important for shorter time periods (Etienne 2002). The *R*-value differences of 3.4 between LA-A1 and LA-A3 (site at the ABT) and 2.6 between LA-A1 and LA-A0 (site close to the Preboreal moraine ridge) is statistically significant. They allow the conclusion that the rock glacier surface is significant younger than Preboreal but significant older than the currently still active ABT. The low δR-value of 6.0 between the ABT site and the site adjacent to the moraine ridge also might be explained by occasional dispersing of rock material over the entire rock glacier LA-A and its foreland by powerful debris-charged snow avalanches. Judging from the morphology of the rock glacier itself, the glacial and periglacial landforms in close vicinity, and the considerations by Kääb (2005) – total age of rock glaciers might be 2–5 times higher than the minimum age obtained for the surface – a long and complex formation history and a rock glacier initiation soon after the Preboreal is suggested.

Rock glaciers in the Dösen Valley

The initiation of all rock glaciers in this study area occurred after the Egesen advance in the early YD period as indicated by the moraines downvalley from the four rock glaciers. In Austria, the early YD is 10Be-dated to around 12.3–12.4 ka (Kerschner & Ivy-Ochs 2007). Thus the maximum and the minimum R-values in this study area can be absolute dated to 12.3–12.4 ka at the YDM site and ~0 a at the active talus site DOE-A7. In this regard, one should not forget the time lag between initial crack formation in the rock face above the rock glacier (exposure to weathering) and the eventual release of a clast to the talus below. Quantification of this period is difficult.

By using a linear relationship between *R*-value and time, a tentative age-calibration curve with a mean decrease of 1.46

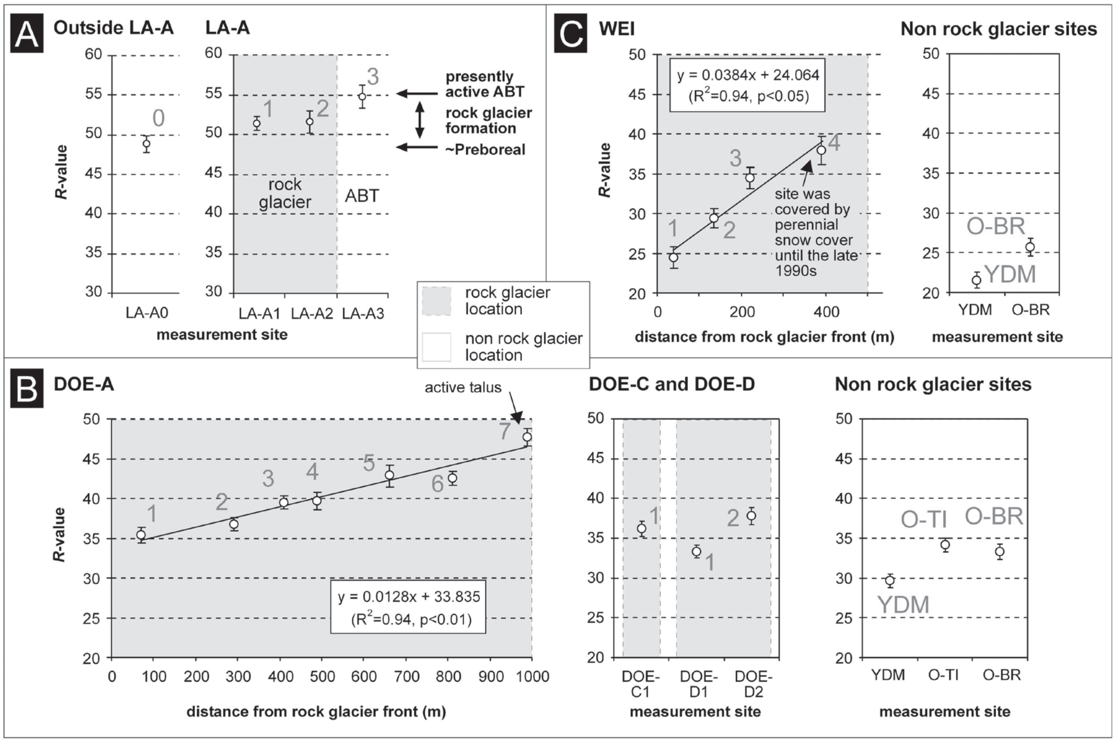

Figure 2. Results of the Schmidt-hammer measurements at the studied rock glaciers and nearby non-rock glacier locations in (A) northern Norway (LA-A) and (B-C) in central Austria (DOE-A, DOE-C, DOE-D and WEI): *R*-values show the arithmetic mean and 95% confidence limits at each measurement site. At the large monomorphic rock glaciers, DOE-A and WEI, *R*-values are plotted against distance from rock glacier front. Best-fit correlations are indicated. Numerals in the graph refer to locations in Figure 1. Estimated age ranges for (A) are given.

R-values per 1 ka can be inferred (Fig. 3A). Skakesby et al. (2006) introduced a simple method to investigate the likely size of error of the absolute age estimates derived by the linear relationship. According to their approach, error limits for the predicted ages are determined separately for the YD and present sites from the corresponding 95% confidence intervals of *R*-values by a straight line. The error limits in the predicted age based on this approach is ±607 years for YDM and ±774 years for DOE-A7. Thus a predicted age error of ca. ±0.7 ka for all sites should be considered.

A substantially and statistically significantly lower mean *R*-value at the YDM site compared to all other sites ($\delta \geq 3.6$) suggests that during the YD and Preboreal periods, the head of the Dösen Valley was covered by a glacier terminating between the YDM and the present rock glacier front. The following glacier retreat deglaciated the bedrock site O-BR and deposited the coarse boulders at site O-TI. Identical *R*-values from site DOE-D1 suggest that the rock glacier DOE-D reached its lower end at a similar time. This further suggests that due to its lower position along the valley axis, this valley stretch was not glaciated in the preceding Preboreal period but allowed the formation of DOE-D.

The insignificant *R*-value difference between the outside site O-TI and the lowest site on DOE-A is difficult to interpret when considering the assumption that the total age of a rock glaciers is 2–5 times higher than the minimum age obtained for the surface (Kääb 2005). The obtained minor difference suggests that the surface and total landform age of DOE-A seems to be similar. The same seems to be true for DOE-C and DOE-D. Explanations might be: (a) a less effective "conveyor belt" mechanism (Haeberli et al. 2003), (b) debris-covered glacier tongues which were later incorporated in the rock glacier, (c) mineral variations in the bedrock, or (d) differences in the surface weakening rate between sites due to different vegetation /snow cover histories in the Holocene.

The regression line at DOE-A indicates that this rock glacier was formed continuously during most of the Holocene. Recent velocity data (1954–2005) from the rock glacier DOE-A show mean annual velocity rates of 13.4–37.4 cm a^{-1} (Kaufmann et al. 2007). If these velocities are taken as (questionable) constant over time and combined with the length of DOE-A, ages of 2.7–7.5 ka are calculated. These age values are lower than the age estimate of the lowest rock glacier site (DOE-A1) obtained by the tentative age-calibration curve presented in Fig. 3A (8.4±0.7 ka).

Rock glacier in the Weissenkar Cirque

The *R*-values from the third study area suggest a comparable landscape history to the one from the Dösen Valley. The initiation of the rock glacier WEI occurred after the Egesen advance in the early YD period as indicated by the YD moraines downvalley from the cirque. The linear relationship between the *R*-value of the YD moraine site (YDM: 21.5) and the uppermost measurement site in the rooting zone of the rock glacier (WEI4: 38.0) reveals a mean decrease of 1.33 R-values per 1 ka (Fig. 3B).

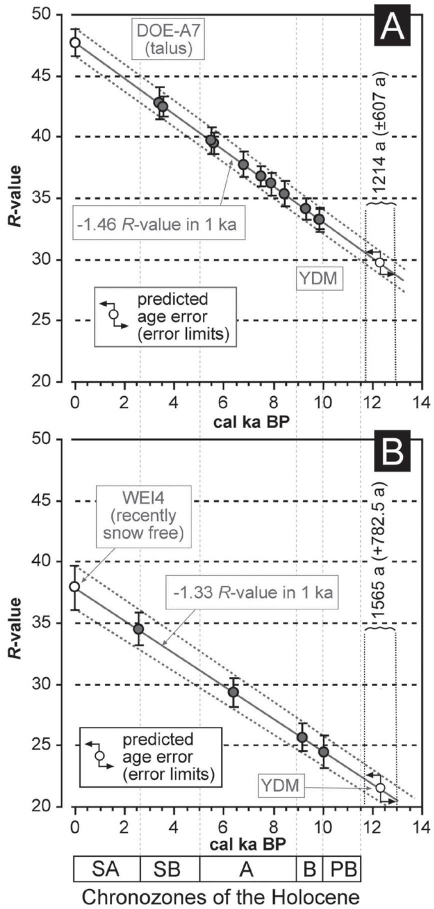

Figure 3. Tentative age-calibration curves for the *R*-values of the study areas Dösen (A) and Weissenkar (B) based on two surfaces of known age indicated as open circles. The calculation of predicted age error including error limits is illustrated for the YDM locations. Grey circles indicate calculated ages based on this approach. Holocene chronozones: SA=Subatlantic, SB=Suboreal, A=Atlantic, B=Boreal and PB=Preboreal.

This rate is only slightly less than the one from the Dösen Valley which indicates that the reduction in the mean *R*-value during the Holocene in central Austria was similar for granitic gneiss (Dösen) and mica schist (Weissenkar) despite substantially different absolute *R*-values.

At Weissenkar Cirque the bedrock site just outside the rock glacier (O-BR) suggests a younger age than the lowest site at the rock glacier (WEI1). Reasons for that might be explanations (a) to (d) presented above. The statistically significant decrease in R-values along a profile at WEI points to a long formation history of the landform starting in the early Holocene. At WEI, the lowest measurement site reveals an age of about 10 ka (cf. Fig. 3B). Therefore, WEI might be even older than the large rock glacier DOE-A in the Dösen Valley. Recent velocity data (1974–2004) from WEI were summarised by Kaufmann et al. (2006) showing low mean annual velocity rates of 1.6–11.6 cm a^{-1}. Assuming constant velocities and using a length of 500 m, rock glacier ages of 4.3–31.1 ka can be estimated. This maximum age is certainly far too high, highlighting the weakness of the assumption of constant surface velocity.

Conclusions

The Schmidt-hammer method seems to be a powerful tool in rock glacier dating, particularly for large rock glaciers where multiple measurement sites along a longitudinal profile are sampled. *R*-value data from such profiles enable the establishment of relative chronologies with high temporal resolution. For small and short rock glaciers this method is more difficult to apply, and additional palaeoclimatic information is required to constrain age estimates. At the study sites in Austria it was possible to estimate relatively accurately the age for Holocene features. However, possible incorporation of older clasts in the rock glacier surface or dispersing of "fresh" rock material by powerful debris-charged snow avalanches can lead to errors. Furthermore, mineral variations in the bedrock or differences in the rate of surface weakening between sites due to different vegetation/snow cover histories might significantly influence *R*-values. Reliable absolute surface age dating is only possible when surfaces of known age with similar vegetation and climate history, and comparable lithology are available. The more surfaces of known age are available, the better is a resulting age-calibration curve.

Acknowledgments

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