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Weathering rind measurements and relative age dating of rockglacier surfaces in crystalline regions of the Eastern Swiss Alps

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ABSTRACT: Selected rockglaciers on granites and gneisses in the Swiss Alps have been investigated with respect to the development of the weathering rind of rock debris. The resulting weathering mapping has been compared to other relative methods of rockglacier surface dating such as Schmidt-hammer measurements and photogrammetric determinations of flow trajectories. A close relationship could be found between the thickness of weathering rinds and the Schmidt-hammer rebound value, which correlates with absolute age determination methods. A logistic model was applied to the modal values to describe the correlation between time and weathering rind development. Rock weathering rinds found in the Upper Engadine were usually much thinner than those observed by other authors on sandstones (New Zealand). Chemical analyses of the weathering rinds gave a steady increase of dithionite-extractable Fe with age. This easily determinable Fe fraction also seems therefore to be a suitable indicator of the age of the weathering rind.

1 INTRODUCTION

Rockglacier surfaces reflect debris accumulations produced, deposited and deformed during historical and Holocene time periods. With time, the surface is increasingly subject to weathering processes. Usually, the older the surface of the rock debris the more pronounced the imprint of weathering. The weathering rind thickness, a reddish outer crust-layer around the rock, increases with time and offers a simple tool to obtain relative chronologies. Relative and absolute age dating by measuring the weathering rind thickness was successfully performed on moraines and rockglaciers developed on sandstones in New Zealand (Chinn 1981, Gellatly 1984, McSaveney 1992, Ricker et al. 1993, Whitehouse et al. 1986) and basaltic and andesitic boulders in North America (Colman & Pierce 1984).

During the past decades, several studies have been carried out in order to determine the age of rockglaciers in the European Alps (Barsch & King 1975, Haeberli et al. 1998, Haeberli et al. 1999, Kaufmann 1998, Winkler & Shakesby 1995). Kääb et al. (1997) used photogrammetric methods to obtain flow trajectories and to estimate ages of rockglacier surfaces. Castelli (2000) and Haeberli et al. (this issue) demonstrate the possibility for relative age dating with Schmidt-hammer measurements. No data is, however, available for weathering rind thickness of rock debris for the late-glacial and post-glacial period in the Alps.

2 RESEARCH LOCATIONS

The study sites around Piz Julier are located in a granitic part of the Err-Bernina-Nappe in the Upper Engadine (Fig. 1). Sites with a predominance of schistose rock types were not investigated due to the fact that these rocks produce unreliable rates of weathering rind growth (Gellatly 1984).

At least four of these rockglaciers are still active (A, B, D, F), whereas the surfaces of rockglacier C and E show little movement according to creep measurements.

For all selected rockglacier sites, relative age dating results were available from Schmidt-hammer measurements or photogrammetric analysis. According to these interpretations the rockglaciers developed in the late-glacial or post-glacial period.

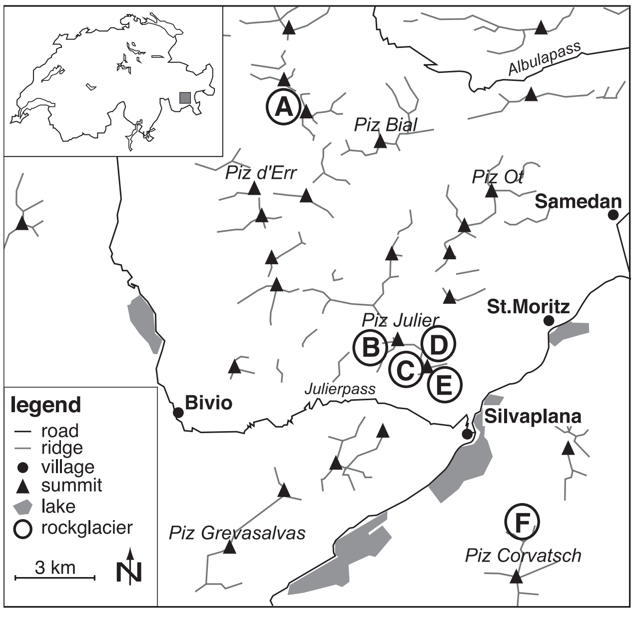


Figure 1. Test region in the Upper Engadine showing the studied rockglaciers: A = Blais Marscha, B = Gianda Grischa, C = Munteratsch, D = Suvretta, E = Albana, F = Murtèl.

3 METHODS

3.1 *Weathering rind measurements*

The weathering rind thickness corresponds to the extent to which oxidation of the minerals has penetrated below the surface of a clast (Gellatly 1984). Chinn (1981), Gellatly (1984), Kirkbride & Brazier (1995), McSaveney (1992), Ricker et al. (1993) and Whitehouse et al. (1980) studied several moraines and rockglaciers in the Alps of New Zealand and pointed out the possibility of relative and even absolute age dating with rind measurements on sandstones. Colman & Pierce (1984) used the method for differentiating glacial deposits by age in several areas in North America.

At suitable sites with surface-exposed clasts, around 50 to 100 rind samples were chipped from boulders and cobbles with a hammer. Rind thicknesses were measured normal to the surface, to the innermost discernible edge of weathering using a 0.1 mm scale graduated magnifying glass. Samples were measured at strictly defined transects along profiles from the root zone to the front of the rockglaciers.

The measured values >0.5 mm were classified, following past research, to the nearest 0.2 mm. The data ≤ 0.5 mm were taken as measured and the data set plotted in a frequency histogram which displays distribution patterns and modal values.

The first studies of weathering rind thicknesses were based on the average rind thickness (Burke & Birkeland 1979). Usually, the modal value of thickness is taken as an indicator of the surface age. In this paper, the median was used as an additional value for relative age dating. In general, the thickness range increases with time and the shape of distribution changes from one to several or more modes together with broader peaks.

3.2 *Chemical analysis*

Fitze (1982), Witzig (2000) and Egli & Mirabella (2001) tried to date Holocene soils in the Swiss Alps with the Al_d/Fe_d-ratio.

The dithionite reagent extracts various forms of organic and inorganic Al and Fe. The following forms of Al are reported to be dissolved (Wada 1977, Shoji & Fujiwara 1984, Borggaard 1988, Dahlgren & Ugolini 1991): organic Al, noncrystalline and crystalline oxyhydroxides (e.g. Al substituted in ferrihydrite and goethite), some Al in hydroxy interlayers and allophanes. The dithionite procedure usually extracts organically-bound Fe, noncrystalline and crystalline Fe-oxyhydroxides and also to a small extent Fe-bearing silicates, especially nontronite (Borggaard 1988). Organic forms of Fe and Al are negligible for the investigated samples.

Chemical analysis have been performed for the Blais Marscha rockglacier (site A in Fig. 1). From each transect W2 (youngest) to W5 (oldest), part of the rind and the unweathered inner part of a representative sample was cut off with a hammer and a chisel. The samples were ground to a fraction of <2 mm. From each sample two replicates were analysed.

The dithionite-extractable fraction was measured for the elements Fe and Al. Elemental concentrations were analysed by atomic absorption spectroscopy (AAS). Relative contents of Fe and Al in the microscale were analysed by means of microprobe measurements of weathered plagioclase. Additionally, the analysis of thin sections was performed.

4 RESULTS

4.1 *Weathering mapping*

Figures 2a–f give the modal and median values of weathering rind thicknesses of six investigated rockglacier profiles.

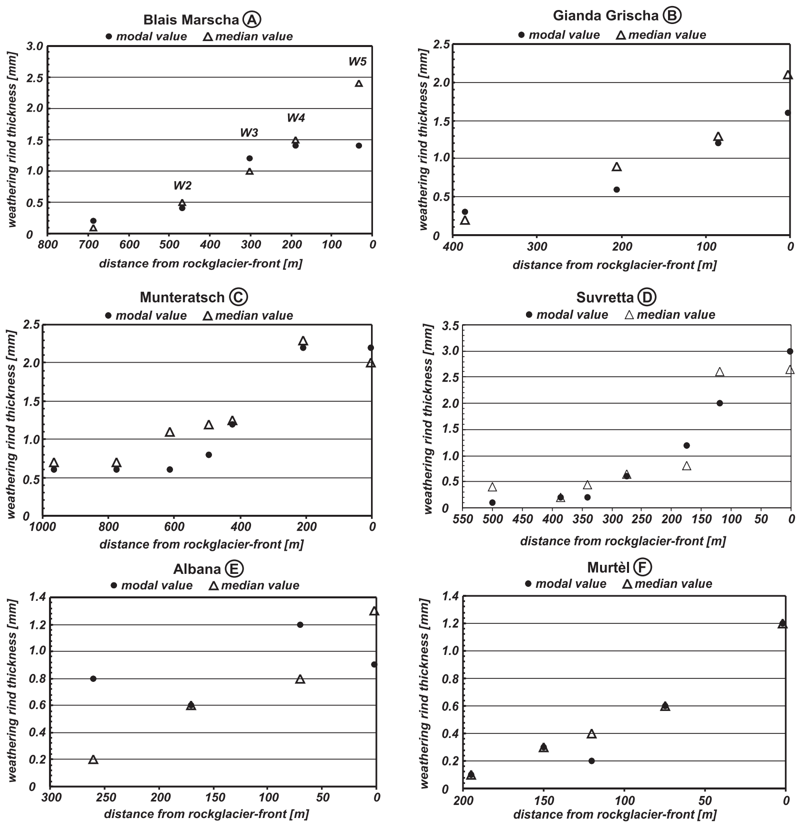
The Blais Marscha rockglacier (site A in Fig. 1) appears as a single stream with different lobes and furrows. Its steep front is mostly vegetation covered and probably relict. The tongue lies within two lateral moraines which are supposed to be from a Younger Dryas glacier advance (Frauenfelder et al. 2001). An older relict front cannot be discerned by weathering rind data so distinctly as on the rockglacier Munteratsch. Nevertheless, the increasing weathering rind thickness is more clearly documented by the median values (Fig. 2a). W2–W5 refer to the chemical analysis (cf. Table 1).

The rockglacier Gianda Grischa (site B in Fig. 1) is comprised of two parts: an active one exhibiting two tongues and an older upper part that is assumed to be inactive. Figure 2b shows a series of four transects measured on the active part of the orographic left front side. The increasing weathering rind thickness with time is indicated by both the modal and median values.

Rockglacier Munteratsch (site C in Fig. 1) has a complex morphology due to the fact that a formerly active part has overridden an older part. The newer part (at about 400 meters from the frontal-talus) is probably inactive according to creep velocity measurements. The weathering rind measurements at a distance of 0–300 m were performed on the older fossil part and are expected to be much older than the other transects above.

The rockglacier Suvretta (site D in Fig. 1) shows a steep relief and fast creep rate reaching up to 2 ma^{-1} (Kääb 2000). Only the two transects at the front of the tongue that are measured on clear ridges give a much older age than the other transects in the upper part.

In the period 1955–1971 the horizontal movement of rockglacier Albana (site E in Fig. 1) nearly stopped



Figures 2a–f. Modal and median values of the measured weathering rind thicknesses at six Alpine rockglaciers. The capital letters refer to the location given in Figure 1. Note the inverse x-axis due to growing weathering rinds towards the front (at 0 meter). W2–W5 = sites with chemical measurements (see Table 1).

Table 1. Concentrations of dithionite-extractable Fe (Fe_d), Al (Al_d) and the corresponding Al_d/Fe_d-ratio.

Sample		Fe_d (mg/kg)	Al_d (mg/kg)	Al_d/Fe_d-ratio
W2*	rock	848	632	0.75
	rock	806	601	0.75
	rind	1733	918	0.53
	rind	1729	945	0.55
W3*	rock	1327	919	0.69
	rock	1340	945	0.71
	rind	1859	848	0.46
	rind	1910	874	0.46
W4*	rock	1114	358	0.32
	rock	1113	336	0.30
	rind	2011	521	0.26
	rind	2064	528	0.26
W5*	rock	1113	603	0.54
	rock	1115	600	0.54
	rind	2730	852	0.31
	rind	2801	866	0.31

* location of W2–W5 see Figure 2a.

(Barsch 1996). According to photogrammetrically derived flow velocity measurements the actual movement acitivities are, at $0.03\,ma^{-1}$, within the uncertainty of the method. The modal values of weathering rind thickness give no susceptible trend despite the relatively simple morphology of the rockglacier. The median values show a clear increase from the youngest part near the rockwall to the frontal talus of the rock glacier.

The petrography of rockglacier Murtèl (site F in Fig. 1) is not uniform and consists of gneisses or basic and ultra-basic rock debris. A complete dataset is available including flow trajectory measurements (Kääb et al. 1998, Frauenfelder & Kääb 2000), Schmidt-hammer investigations (Castelli 2000) and absolute ages from radiocarbon dating of a moss sample in a borehole (Haeberli et al. 1999). The median values and the slightly less uniform modal values of the weathering rind measurements show a clear increase of the thickness towards the tongue of the rockglacier.

4.2 *Chemical composition of weathering rinds*

The results of the dithionite extraction are given in Table 1. Sample W1 was not analysed due to the lack of a well-developed rind.

The variation of Fe_d and Al_d within the replicates were very small. Obviously, a representative part of the weathering rind has been analysed. The content of Fe_d is increasing with the duration of weathering exposure. No such trend could be observed for Al_d (Fig. 3). Consequently, the Al_d/Fe_d-ratio is decreasing with increasing time of weathering exposure.

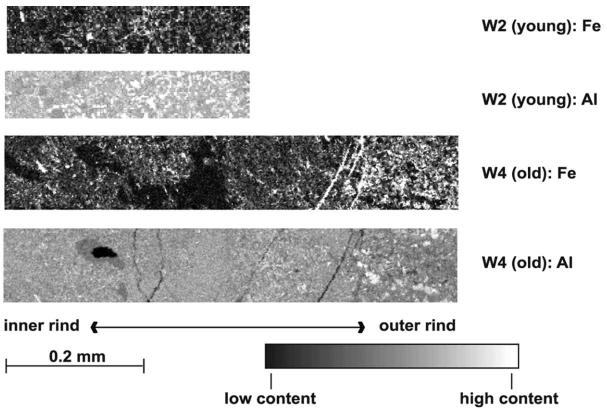


Figure 3. Microprobe measurements (thin sections) of weathered plagioclase of two rocks on transect W2 and W4 of rockglacier Blais Marscha (cf. Fig. 2a). Note the decrease of Fe from the outer rind to the inner rind in W4, expressed in darker colour at the inner rind.

Fitze (1982) and Egli et al. (2001) observed that the Al_d/Fe_d-ratio in the B horizon of soils is a good indicator of their age in the Swiss Alps. The older the soil, the higher this ratio. This means that, with increasing time, more Al is released from the minerals (in order to form secondary phases) through weathering relative to Fe. Young soils ($<$300 a) usually have a ratio of 0.3–0.5, Holocene soils varied between 0.5 and 0.9 and the oldest late-glacial soils showed ratios up to 1.2. The analysis of the weathering rind, however, gives a contradictory result, although the investigated rockglacier has a similar estimated age (around 10 ka) and developed on a comparable geology. The microprobe measurements (Fig. 3) of the outer part of stone W2 (young) and W4 (older) support the Al_d/Fe_d-ratio and the increase in iron in the weathering rind with time analysed with the dithionite reagent.

The decreasing Al_d/Fe_d-ratio in the weathering rind of the Blais Marscha site corresponds to measurements of Oguchi (2001). Those investigations showed that the weathering rind is characterised by higher $FeO + Fe_2O_3$ contents and lower contents of CaO, MgO, Na_2O, K_2O and Al_2O_3 compared to the inner zone of the rock fragments. The oxidation of iron accounts for the red-brown colour of the rind. Iron tends to remain as ferric hydroxides in the outer brown band. Results show the longer the weathering exposure, the higher the amount of these hydroxides.

5 DISCUSSION

The growth of the weathering rind thickness is between c.0.2 mm/1 ka (Murtèl site) and c.1 mm/1 ka (Suvretta site). These values are close to those measured by Burke & Birkeland (1979) for granite (3 mm/10 ka), but much lower than those reported by Birkeland (1973) for another site on granite (45 mm/10 ka).

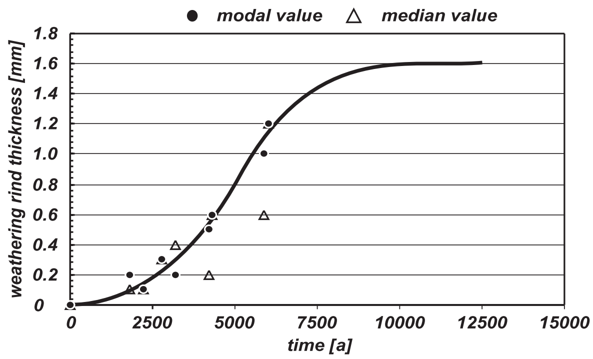


Figure 4. The logistic model (after eq. 2) representing the modal values of the measured weathering rinds on rockglacier Murtèl.

Several equations have been developed during the last few decades in order to describe the relationship between weathering rind thickness and duration of weathering exposure. A power law equation (Chinn 1981) has been replaced by a relaxation law (Whitehouse et al. 1986). McSaveney (1992) found that a relaxation law fails to describe the calibration data below 1 mm and developed the following equation:

$$x_t = x_\infty \left(1 + e^{-\alpha t}\right)\left(1 - e^{-\lambda t}\right) \quad (1)$$

with x_t = rind age, x_∞ = equilibrium thickness, α = rate at which loss of surface material approaches steady state, λ = constant. These curves made an absolute age dating possible with weathering rind measurements.

Similarly, we tried to fit weathering rind thicknesses with the duration of weathering exposure (Fig. 4). For rockglacier Murtèl, weathering rind thicknesses were compared with the ages estimated by photogrammetric analysis (Kääb et al. 1998, Frauenfelder & Kääb 2000) and ^{14}C-dating (Haeberli et al. 1999).

No reasonable fit could be found by means of the published equations however. Regression procedures partially gave very high explained variances, but they were either unable to fit weathering rind thicknesses to the weathering duration with an intercept of 0 or described an infinite increase of weathering rinds with the age. We therefore applied a logistic model to our data (cf. Egli et al. 2001)

$$f(t) = \frac{a}{\left(1 + e^{b(t-c)}\right)} + d \quad (2)$$

with a as the range of the weathering rind property in the chronofunction with $t = -\infty$ to $t = +\infty$, b as the slope coefficient, c as the time (in years) of the maximal rate of change, and d as the asymptotic value ($t = +\infty$). The curve of the calculated model fits well with the modal values of the measured rind thicknesses. The corresponding parameters had values of

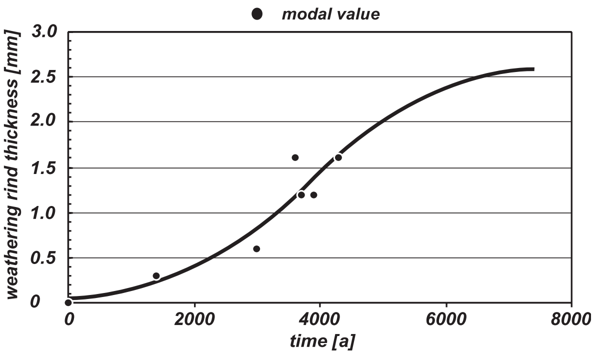


Figure 5. The logistic model (after eq. 2) representing the modal values of the measured weathering rinds on rockglacier Gianda Grischa.

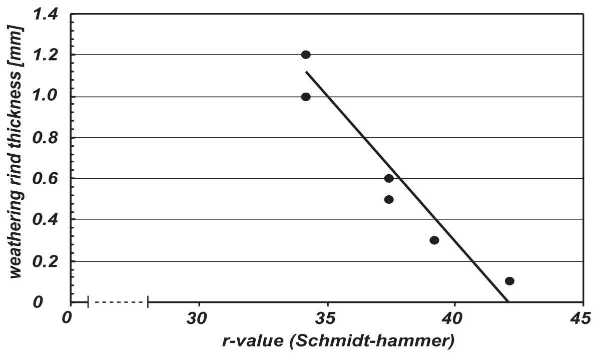


Figure 6. Correspondence between Schmidt-hammer rebound value and weathering rind thickness at various transects at the Murtèl site. Schmidt-hammer values after Castelli (2000).

$a = -1.66$, $b = 7.8 \cdot 10^{-4}$, $c = 5000$ and $d = 1.63$. Additionally the median values were plotted in Figure 4. Due to the absence of corresponding data, the curve in the range >10 ka is uncertain or even speculative. The model however, gives a first impression of weathering rind growth under Swiss alpine circumstances.

In Figure 5 the same logistic model was applied to the rockglacier Gianda Grischa, where a faster increase in weathering rind thickness with time could be observed than at the Murtèl site. Altough the database is rather scarce, the curve gives an impression of the general behaviour of weathering rind growth.

Schmidt-hammer measurements are often used for relative age dating in glacial and periglacial regions (Winkler & Shakesby 1995). This method usually correlates with absolute dating methods. Figure 6 shows the correspondence between the Schmidt-hammer rebound values obtained by Castelli (2000) and the weathering rind thicknesses measured on rockglacier Murtèl. Individual data points in Figure 6 represent mean values (Schmidt-hammer) and modal values (weathering rind thickness), respectively, for corresponding transects on rockglacier Murtèl. The relationship between these two methods is almost linear.

6 CONCLUSION

First measurements of weathering rinds in the alpine region of the Upper Engadine reveal a certain potential for relative age dating possibilities of rockglacier surfaces. The median, as well as the modal values, are equally suitable to delineate the increasing tendency of weathering rind thickness with the duration of exposure. Good correspondence with the Schmidt-hammer method additionally demonstrate the potential of a combined method application in alpine rockglaciers areas.

The analysis of chemical parameters in weathering rinds show a continuous formation of iron oxihydroxides with time. The main reactions include a transformation or dissolution of plagioclase and a formation of epidote ("saussuritisation") along the dominant crystallographic structures giving rise to preferential weathering. Thin sections displayed that oxihydroxides were formed or deposited onto plagioclases. Dithionite-extractable Fe seems to be a good and also easily determinable indicator of the age of a weathering rind and adequately describes the development of oxihydroxides in weathering rinds.

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