Comparison of Exposure Ages and Spectral Properties of Rock Surfaces in Steep, High Alpine Rock Walls of Aiguille du Midi, France

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Abstract

Among various factors, permafrost and frost-thaw cycles play an important role for the stability of steep rock slopes in high alpine regions. Climate change in general and local temperature and precipitation trends in particular are likely to influence permafrost and, consequently, also the stability of rock walls. As stress relief following deglaciation can be excluded at Aguille du Midi (France), rockfall activity is mainly related to changes in permafrost and frost-thaw cycles. To put modern observations of possible climate-induced rockfalls into perspective, information on past rockfall activity is required. In this study, we investigated a combination of surface exposure dating and spectrometry to derive a correlation between rock surface ages and their spectral properties in homogenous lithology. The surface ages found varied from less than 2,000 years to around 40,000 years, and showed a clear correlation with reflectance behavior in the range 380–580 nm. These results may be a first step towards the possible generation of spatial data fields of age distribution in steep rock walls. This may provide deeper insights into spatial and temporal rock-wall development of permafrost in high alpine permafrost environments.

Keywords: cosmogenic nuclide dating; permafrost; reflectance spectroscopy; steep rock slope stability; surface exposure dating.

Introduction

Permafrost thaw is an important process which affects the stability of steep bedrock slopes in many alpine areas (cf. Haeberli et al. 1997, Gruber & Haeberli 2007). Slope failures, like rockfalls, landslides and debris flows, that are assumed to be triggered by changes in the permafrost conditions are known from numerous locations in high mountains and especially in the Alps (e.g., Haeberli 1992, Deline 2001, Noetzli et al. 2003, Schiermeier 2003, Gruber et al. 2004a). These processes cover magnitudes from small rockfalls to huge rockslides (Bergsturz). In comparison with debris-covered slopes, rock faces react quickly to climate change. This is due to the absence of a block layer (Mittaz et al. 2000, Hoelzle et al. 2001) and corresponding direct coupling of surface and subsurface conditions, combined with low water content and small transfer of latent heat during melt. This rapid reaction, together with the effect of destabilization, makes rockfalls due to permafrost degradation a likely and perceivable impact of climate change in the near future (Gruber et al. 2004a).

While recent advances in permafrost modeling have enabled the derivation of permafrost maps for steep bedrock (Gruber et al. 2004b), information about long-term rockfall activity is required to put recent observations and changes in temperature into a long-term perspective.

Besides radiocarbon dating and luminescence methods, the usage of cosmogenic nuclides has become a central technique to gain information about landform ages and landform-modification processes such as rockfalls. An overview of the spectrum of dated landforms and commonly used nuclides is given, for instance, in Gosse & Phillips (2001) and in Ivy-Ochs & Kober (2006). In relation to glacio-geomorphological questions, the determination of $^{10}$Be- and $^{26}$Al-concentrations in the surface of moraine boulders and polished bedrock is of great interest. Ivy-Ochs et al. (2006) summarized results from the European Alps. Whereas, numerous ages from late glacial moraines are available, data from polished bedrock (indicating deglaciation at higher altitudes) or from areas that were not glaciated during the Last Glacial Maximum (LGM) are sparse. Except for investigations in the Grimsel Pass region in central Switzerland (Ivy-Ochs 1996, Kelly et al. 2006), so far no dating has been carried out at higher-elevation sites.

Remote sensing techniques with multispectral and hyperspectral sensors are widely used to investigate different aspects of mountain areas. Kääb et al. (2005) provide an overview of air- and spaceborn remote sensing methods that are applicable for glacier and permafrost hazard assessment and disaster management. Other approaches discuss methodologies for mapping glacio-geological features such as trim lines or terminal moraines in order to reconstruct glacier changes and related past climate (e.g., Huh et al. 2006). Spectral field measurements and airborn
hyperspectral data have enabled an approach to date and map other geomorphic features such as arid and semi-arid alluvial fans (Crouvi et al. 2006). The development of a rock coating significantly influences the overall reflectance of the surface. The redness of rock material or soil is directly related to the age. In oxidizing environments and increasing weathering time, color hues become redder and chromas become brighter (rubification). This fact is, among others, used in the calculation of the profile development index which gives a direct indication of soil age (e.g., Harden, 1982, Goodman et al., 2001).

In this paper, we present a pilot study to investigate the potential of combined imaging spectrometry and exposure dating to derive approximate surface ages in steep bedrock walls of homogeneous lithology. The geometric and radiometric correction of hyperspectral imagery over steep terrain is challenging but generally possible (cf. Gruber et al. 2003). The spatial data fields of estimated age resulting from this method would allow deriving the area and relative frequency of surfaces that belong to a certain age class and that are uninterrupted by older surfaces over a certain distance. This information is related to the frequency of rockfall events during a certain period and is a useful long-term background for assessing whether presently observable, large rockfall shows an unusual abundance as suggested by the relevance of permafrost for slope stability.

Our hypothesis is that the surface ages in this high alpine region can be directly related to the redness of the rocks. The redder a rock surface is, the higher the age that should be measured.

**Geological and Physical Setting**

Aiguille du Midi (3842 m a.s.l.) is situated some four kilometres south of Chamonix in the Western Alps in France. Whereas most of the peaks surrounding Chamonix are only reachable by making trips of several days with high alpine equipment, Aiguille du Midi is easily accessible by cable car and therefore an ideal study site.

Geologically, this area is part of the Mont-Blanc massif (Spicher 1980) and is made up of the so-called Mont-Blanc Granite with an age of roughly 300 Ma (von Raumer & Bussy 2004, Bussy et al. 2000). This granite type is of a very quartz-rich quality and thus suitable for surface exposure dating with $^{10}$Be.

During LGM, the uppermost part of the Aiguille du Midi SSE-face, where the samples were taken, was most probably not glaciated. Paleogeographical reconstructions based on trimline mapping by Coutterand & Buoncristiani (2006) and Kelly et al. (2004) showed that Aiguille du Midi was, during this time, a Nunatak bounded in the east by the Mer de Glace, in the north by the Glacier de l’Arve, and in the west by the Glacier des Bossons. Apart from local glaciations in the less steep parts of the wall, the influence of glacial ice masses on exposure ages can be excluded.

We chose our sampling sites based on visually identifiable differences in color on photographs taken from a helicopter.

The hypothesis was that intensively red-colored parts in the rock wall were exposed to weathering over a longer time period than fresh gray ones, and consequently should have a higher age. This assumption is based on field observations at the adjacent Drus, where, besides several smaller events, a huge rockfall occurred in 2005 (Ravanel 2006). The gray-colored area that came to light clearly contrasts to the surrounding, more or less reddish, and obviously older parts of the wall.

Sample AdM1 was taken at a conspicuously red spot, whereas AdM2 was gathered from a gray part of the wall, where no red coloring was seen. AdM4 and AdM5 can be placed somewhere in between with respect to color. Thereby, sample AdM5 presented a more intensive coloration than AdM4. All these sampling places had a slope ≥ 79°. The slope at AdM3 was, however, only 49°. This sample was the only one that was partly covered by lichen, probably due to an increased water availability resulting from melting snow. For this reason spectral analysis was not applicable, and AdM3 was not taken into account for further interpretation. We concluded that the rock surfaces should have the following order of age: AdM1 > AdM5 > AdM4 > AdM2.

Rock samples were taken with hammer, chisel, and a drilling machine. After Masarik & Wieler (2003), marginal sampling places were excluded in order to avoid edge effects. To calculate the influence of shielding caused by the surrounding topography, azimuth-dependent angles were extracted from the map.
Methodology

Surface exposure dating

Approximately 500–1000 g of each rock sample were crushed and sieved. A grain-size fraction of 0.5 to 1 mm was used. Pure quartz was separated by selective chemical dissolution (Kohl & Nishiizumi 1992, Ivy-Ochs 1996). This method is based on the fact that feldspars and micas dissolve in 4% HF more quickly than quartz does. At least six HF steps were used to obtain very pure quartz as reflected by the low Al concentration (less than 100 ppm).

$^{9}$Be carrier was added to the dried quartz, which was then completely dissolved with concentrated HF in a microwave. Be and Al were separated using a cation exchange column. The Be hydroxides were precipitated, dried, and calcined at 850°C to BeO.

The $^{10}$Be/$^{9}$Be ratios were measured at the ETH/PSI Zürich Tandem Accelerator Mass Spectrometry (AMS) Facility (Synal et al. 1997).

In order to calculate $^{10}$Be ages, a simple exposure history was assumed, specifically that all $^{10}$Be measured was produced in the rock surface during the latest period of exposure and that the rock surface did not suffer significant erosion. Any earlier exposure, even at greater depth below the original surface, will make the “measured” age an upper limit for the true exposure age of the sample’s surface.

Ages were calculated using the $^{10}$Be production rate of 5.1 ± 0.3 atoms gram⁻¹ year⁻¹ at sea level and high latitude (Stone 2000). Production rates were scaled to the specific sample locations according to Stone (2000) and corrected for sample thickness (assuming an exponential depth profile) and topographical (skyline) shielding (Dunne et al. 1999) (Table 2).

Laboratory reflectance spectroscopy

Rock surface spectra were measured in the laboratory using an ASD FieldSpec Pro Fr spectro-radiometer, a Spectrolon reference panel, and a Thermo Oriel irradiance source. The hematite spectrum was taken from the Jet Propulsion Laboratory (JPL) Spectral Library (HEMATITE 0-1A). In order to identify absorption features for measurement, continuum removal was applied to the data. This is a means of normalizing reflectance spectra to allow comparison of individual features from a common baseline. Continuum removal (Clark & Roush 1984, Kruse et al. 1985, Green & Craig 1985) was performed in ENVI 4.1 to facilitate the comparison of individual absorption features between different objects. In this method, a convex hull (the continuum) of a reflectance spectrum is divided by the spectrum itself and thus results in values ranging from 0-1. The convex hull is built utilizing straight line segments that connect local reflectance maxima.

Elemental composition by X-ray fluorescence measurements

The elemental composition of the rock samples was analyzed by X-ray fluorescence (XRF) spectrometry. After crushing the rock samples to a size of <1mm, around 10 g of rock material were milled to <50 µm in a tungsten carbide disc swing mill (Retsch® RS1, Germany). 4 g of rock powder was mixed with 0.9 g of Licowax® C Micro-Powder PM (Clariant, Switzerland), pressed into a 32 mm pellet, and analyzed using an energy dispersive XRF spectrometer (SPECTRO X-LAB 2000, SPECTRO Analytical Instruments, Germany).

Table 1. Elemental composition of the samples.

<table>
<thead>
<tr>
<th>Element [%]</th>
<th>Samples Aiguille du Midi 1-5</th>
<th>Statistics</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>AdM1</td>
<td>AdM2</td>
</tr>
<tr>
<td>CaO</td>
<td>0.87</td>
<td>0.87</td>
</tr>
<tr>
<td>MgO</td>
<td>0.62</td>
<td>0.60</td>
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<tr>
<td>K₂O</td>
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<tr>
<td>Na₂O</td>
<td>3.12</td>
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</tr>
<tr>
<td>Al₂O₃</td>
<td>16.62</td>
<td>13.58</td>
</tr>
<tr>
<td>Fe₂O₃</td>
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<td>1.64</td>
</tr>
<tr>
<td>SiO₂</td>
<td>70.32</td>
<td>68.73</td>
</tr>
<tr>
<td>MnO</td>
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<td>0.03</td>
</tr>
<tr>
<td>P₂O₅</td>
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<td>0.07</td>
</tr>
<tr>
<td>TiO₂</td>
<td>0.26</td>
<td>0.30</td>
</tr>
<tr>
<td>ZrO₂</td>
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<td>0.02</td>
</tr>
<tr>
<td>BaO</td>
<td>0.07</td>
<td>0.08</td>
</tr>
<tr>
<td>Rb₂O</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>WO₃</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>LOI</td>
<td>3.43</td>
<td>0.55</td>
</tr>
<tr>
<td>Total</td>
<td>99.02</td>
<td>94.61</td>
</tr>
</tbody>
</table>

Elemental composition of the samples based on XRF measurements. Values are converted into oxide contents. LOI = Loss on ignition. The low standard deviation (SD) values indicate a comparable composition and demonstrate the homogeneity of the lithology.
Results

Elemental composition

Results from XRF measurements show after conversion into oxide contents a very similar composition (Table 1.). The high quartz content of the Mont-Blanc granite is represented by high amounts of $\text{SiO}_2$. Other important constituents of the rock samples are $\text{Al}_2\text{O}_3$ and potassium oxide. The total values of over 90% mean that almost all possible compounds were measured.

The comparable composition of the samples is an important indication that observed differences in color are not due to inhomogeneities in lithology.

Surface exposure ages and comparison with measured spectra

The intensively red colored sample AdM1 shows the highest age, followed by AdM5, AdM4, and AdM2, where no coloring occurred. This is in agreement with the above-stated hypothesis and the sample description (Table 2).

Generally, the $^{10}$Be ages, especially AdM1, are remarkably old, and the differences in age are very big. But these ages have to be interpreted as maximum exposure ages of the rock surface, as long as erosional processes can be excluded.

Looking at the measured spectra (Fig. 2), a well-pronounced correlation between surface exposure ages and the corresponding spectral signature in the range of approximately 380–580 nm is identifiable after continuum removal. As a reference, a piece of unweathered fresh rock was also analyzed (AdMf).

According to the visual impression, the curve progression of AdM2 is shaped very similarly to the one of the unweathered sample. With increasing surface exposure ages and thus more pronounced weathering, a decrease in feature depth is ascertainable. A comparison with the continuum-removed spectrum of hematite permits the conclusion that the spectra evolution with increasing age is influenced, at least partly, by hematite formation (Fig. 2). Thus, hematite content and its effects on rock surface color can be interpreted as the main feature required in regard to the generation of spatial data fields of age distribution in rock walls.

Figure 2. Measured and continuum-removed spectra. The arrow indicates the influence of the Fe-Oxide content with age.
Discussion and Conclusions

We showed that analyzing spectral properties of rock surfaces in steep walls with homogeneous lithology may be a tool to estimate the age distribution and related past rockfall activity in high alpine environments. The redder a rock surface, the longer this rock was exposed to weathering. In numerous cases, the correlation of rockfall initiation to changes in the permafrost conditions is rather weak, and related forecast and mitigation possibilities are limited (Gude & Barsch 2005). Not only permafrost thawing but also other processes like general frost-thaw activities (physical weathering), seismic (neotectonic) activity, or stress relief following deglaciation could induce rockfalls. Furthermore, non-erosive cold-based glacier ice can complicate the erosion history of rock surfaces (Briner et al. 2006). Due to the topographic situation of the investigated sites, however, at least one process affecting the stability of rock walls can be excluded. A stress-relief following deglaciation of (cold-based) glacier ice did not occur because no glaciers covered the rock walls during (and after) the LGM. Rockfall is predominantly due to permafrost changes and frost-thaw activities. Although neotectonic activities have been rather low, their influence on rockfalls cannot be fully excluded. The used approach, therefore, will not allow direct reconstruction of past permafrost conditions. However, it can give indications about past and present-day rockfall activities. From this, the influence of permafrost on rock wall stability can be deduced at least partially. Inasmuch as global warming in general and local temperature and precipitation trends in particular are likely to influence the permafrost significantly, the stability of rock walls will also be affected.

The relationships found look promising; however, they certainly represent only a first impression and further investigations in this field will be necessary to establish this approach as a commonly usable application. Doubtless, of great importance is the enlargement of the survey sample size in order to be able to generate statistical correlations between surface exposure ages and spectral properties. Therefore, the latter have to be translated into quantifiable values.

In the present study, we tried to keep as many factors constant as possible. Potential follow-up studies will have to deal with the influence of variable slope aspect and altitudes and different lithologies. Steep places at high elevations should be preferred. Sampling locations that are situated too low are not suitable due to lichen growth disturbing the spectral signal. The same is true for flat spots where snow cover can develop more easily and remain for a longer time. A fundamental problem will be the difficulty in accessing appropriate sites. There is, however, great potential for further efforts.

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References


