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Frost weathering and rockwall erosion in the southeastern Swiss Alps: Long-term (1994–2006) observations

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Abstract

Rates and processes of frost weathering in the Alps were investigated by visual observations of intensively shattered rocks, continuous monitoring of frost wedging and rock temperatures in bedrock and measurements of rockfall activity. Rapid frost weathering of hard-intact rocks occurs along lakes and streams where seasonal freezing promotes ice segregation in the rock. Otherwise, rocks require pre-existing weakness or a long exposure period for intensively shattered. Automated monitoring shows that crack opening occurs at three scales, including small opening accompanying short-term frost cycles, slightly larger movements during seasonal freezing and occasional large opening originating from refreezing of snow-melt water during seasonal thawing. The opening events require at least partial water saturation in the crack. The repetition of crack opening (frost wedging) results in permanent opening and finally debris dislocation. Debris collections below fractured rockwalls show that pebble falls occur at an average rate of about 0.1 mm a^{-1} with significant spatial and inter-annual variations. Occasional large boulder falls significantly raise the rockwall erosion rates, controlled by such factors as the joint distribution in the bedrock, repetition of annual freeze–thaw cycles and extraordinary summer thaw.

Keywords: Periglacial processes; Frost weathering; Rockfall; Rock slope instability; Field monitoring; Swiss Alps

1. Introduction

Physical rock weathering is an important geomorphic process in high mountains, where steep slopes and the lack of vegetation directly expose rocks to changes in temperature and humidity. Under cold climate, frost weathering promotes rock breakdown where subfreezing temperature and moisture availability allow ice formation in pores and fractures in the bedrock (e.g. Rapp, 1960; Matthews et al., 1986; Matsuoka, 2001a; Sass, 2005a, Murton et al., 2006), which eventually affects long-term evolution of mountain slopes (e.g. Anderson, 2002; Hales and Roering, 2005). Yet the efficacy of frost weathering is often overestimated from the visual evidence such as closely fractured bedrock and angular rock debris, the origin being also attributable to thermal, wet–dry, salt or biological weathering (e.g. Andrè, 1997; Hall et al., 2002). The dominant process varies with climatic and geological factors. Chemical weathering also significantly contributes to denudation of cold mountains, directly by producing dissolved materials and indirectly by increasing pores and microcracks that are susceptible to physical processes (e.g. Whalley et al., 1982; Thorn et al., 2001). These conditions demonstrate that the precise evaluation of weathering process requires dynamic observations of in-situ fracturing or detachment of rocks and controlling parameters.

In this context, the last 30 years have witnessed an increase in quantitative studies based on field monitoring or numerical modelling of weathering processes in high mountains (e.g. Thorn, 1979; Fahey and Lefebure, 1988; Matsuoka, 1990a; Davies et al., 2001; Gruber et al., 2004a; Hales and Roering, 2007). In contrast to numeral data on rock temperatures, however, few data have highlighted bedrock fracturing and resulting rockfall processes (e.g. Matsuoka and Sakai, 1999; Matsuoka, 2001a).

The situation is not exceptional in the Alps, where recent studies have focused on the impacts of climate change on rock

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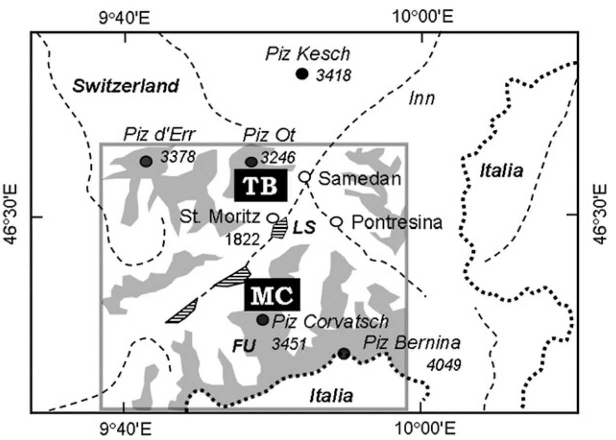

Fig. 1. Location map of the Upper Engadin. TB: Trais Fluors–Büz area. MC: Murtèl–Corvatsch area. LS: Lake St. Moritz. FU: Furchellas. Thin broken line denotes major streams. The shaded area represents ground covered with glacier or underlain by permafrost, after 'Glaziologische Karte Julier-Bernina': information confined within the inner square excluding the Italian part.

falls and avalanches associated with frost cycles (e.g. Stoffel et al., 2005; Frayssines and Hantz, 2006) or permafrost thawing (e.g. Wegmann et al., 1998; Gruber et al., 2004a,b; Gruber and Haeberli, 2007). Indeed, only a few detailed observations have been undertaken on rock fracturing (Wegmann and Gudmundsson, 1999) and associated small-scale rockfalls (Sass, 2005a,b). Such dynamic observations are essential in the evaluation of frost weathering, because rock temperature data alone do not indicate fracturing due to ice formation (Matsuoka, 2001b).

In an attempt to evaluate 'when and how weathering and rockfalls happen' and 'how these processes contribute to rockwall erosion', a long-term field study has continued in periglacial mountains of the Swiss Alps since 1994 (Matsuoka et al., 1997, 1998, 2003a). The field programme involves dynamic approaches to rock fracturing and debris production, as well as visual observations of in-situ bedrock shattering. This paper summarizes the results over 12 years (1994–2006). The first part of the paper describes in-situ fractured rocks. The second part presents the results of automated monitoring of frost wedging and near-surface rock temperatures. The third part highlights measurements of rockfalls at two scales. Synthesizing these three observations, discussion focuses on the timing, thermal conditions and processes of frost weathering, as well as coupling of weathering processes and long-term rockwall erosion.

2. The study area and sites

The major study area is located in the Upper Engadin (Fig. 1), southeastern part of the Swiss Alps, which consists of high mountains (2700–4000 m ASL), gentle upper slopes (2200–2700 m ASL), steep lower slopes (1800–2200 m ASL) and formally glaciated valley floors (1600–1800 m ASL). The whole area but some isolated nunataks experienced Pleistocene glaciations (e.g. Florineth and Schlüchter, 2000) and mountains over 3000 m ASL still preserve local glaciers. Permafrost is widespread above 2400 m on northern to western slopes and above 3000 m on southern to eastern slopes (e.g. Keller et al., 1998). The timberline is located at about 2100 m ASL and the 0 °C isotherm of mean annual air temperature (MAAT) is at about 2200 m ASL. The alpine zone above the timberline displays active periglacial landforms including solifluction lobes, patterned ground and rock glaciers (e.g. Matsuoka et al., 2003b, 2005).

The study was concentrated in two mountain areas, Murtèl–Corvatsch and Trais Fluors, located south and north of St. Moritz, respectively (Fig. 1). The study sites lie at similar elevations (2800–2950 m) but differ in geology and aspect (Table 1). The Murtèl rockwall, which constitutes the northern face of Piz (peak) Corvatsch, is composed of crystalline rocks, mainly gneiss in the upper part and schist in the lower part (Fig. 2A), which tend to produce coarse blocks. The major monitoring site (the MW site, 2890 m ASL) is located near the foot of a rockwall 100–300 m in height. The rockwall composes part of an ice-free cirque that acts as a large trap of rockfall debris. In fact, a large volume of coarse debris derived from the rockwall has developed talus cones and the underlying bouldery rock glaciers (the Murtèl rock glaciers) during the Holocene (e.g. Barsch, 1996; Haeberli et al., 1999).

Trais Fluors is a west-to-east extending mountain composed of two kinds of sedimentary rocks, massive calcareous rocks (dolomite/limestone) and closely fractured shale. The major monitoring site (the BN site, 2900 m ASL) lies at the north-facing rockwall of Piz dal Büz, a small peak located at the western end of Trais Fluors. The rockwall consists mainly of shale capped by a dolomite peak (Fig. 2B). The BN rockwall provides fine debris onto a small pebbly rock glacier (the BNU rock glacier) that is rapidly moving downslope at a rate of about 1 m a^{-1} (Ikeda et al., 2003). Two other sites, TFN and TFS, are respectively located on the northern and southern faces of the central part of Trais Fluors, which are composed mostly of massive dolomite. The TFN rockwall (2850 m ASL) provides

Table 1
Characteristics of monitored rockwalls

Site	Area	Altitude (m ASL)	Lithology	Aspect	Slope angle (°)	Mean crack width (mm)	Crack direction [a]	Monitoring period	
								Crack opening	Rock temperature
MW	Murtèl–Corvatsch	2890	Greenschist	N	65	5	35°	1994–2006	1994–2006
TFS	Trais Fluors (S-face)	2850	Dolomite	S	60	2	~90°	1996–1998	1994–1998
TFN	Trais Fluors (N-face)	2850	Dolomite	NW	75	–	–	–	1994–1999
BN	Trais Fluors (Büz)	2900	Shale	N	50	5	~90°	2000–2006	2000–2006

[a] With reference to the rock face.