The effect of weathering on Alpine rock instability

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Abstract

Weathering affects joint or fault gouge material in the Swiss Alps, leading to the formation of smectite, which changes the mechanical properties of fault gouge and degrades slope performance. Analysis of recent rockslides in gneissic rocks in Switzerland indicates that accelerations of movements are linked to precipitation, without the development of excess pore water pressure. Processes such as weathering and crushing induce soil-like behaviour of the infilling material and explain rockslide movements induced by water seepage in both fault and joint gouges.

Keywords: weathering, fault gouge, rock instability, soil mechanics

Estimating the hazard associated with unstable rock masses is very difficult. The usual methods use a relative scale that rarely gives information concerning the time scale of the processes (Cancelli & Crosta 1993; Mazzoccola & Hudson 1996; Rouiller *et al*. 1998). Other methods of estimating hazard are based on inventories (Pierson *et al*. 1990; Hungr *et al*. 1999). However, the processes leading to failure in rock slopes are still difficult to understand. The change of the safety factor with time is dependent on both fatigue and weathering of the rock mass. As a consequence, improvements in estimating the variables governing the change of the stability of a rock mass with time will improve hazard assessment. The present paper discusses the impact of weathering and crushing processes that cause the gouge material to behave more like soil (Leroueil 2001).

In rock mechanics, the role of excess groundwater pressure is often proposed as a triggering factor for rockslides (Terzaghi 1962; Hoek & Bray 1984). Although it is a frequent process, it does not explain the change of the peak strength of material with time. Weathering is often recognized as one of the processes destabilizing slopes (Piteau & Peckover 1978), or taken into account in geomechanical classifications (Romana 1993). However, most of the studies of jointed and faulted rocks do not take chemical weathering into account as a factor of slope evolution (Rossmanith 1998).

Gerber & Scheidegger (1969) postulated that fractured rock cropping out in steep slopes is submitted to more intense weathering caused by pre-existing stresses, which favours the degradation of rock strength. Piteau & Peckover (1978) reported that the occurrence of montmorillonites led to rockslides in some cases. In the Swiss Alps, Girod (1999) indicated that the gneissic rock mass before the Randa rockfall was strongly affected by chemical weathering (Sartori *et al*. 2004). This observation is supported by the fact that chemical weathering occurring in crystalline rock in sub-arctic climate conditions can produce smectite by alteration of feldspars (Hermance 1989).

The effects of chemical weathering and development of montmorillonite are more generally known in landslides such as the debris-flows of Calabria (Calcaterra *et al*. 1998).

Recent observations from three rockslides in Switzerland, described in the case studies below, indicate that rock mass movements are controlled by rainfall or snowmelt. For the two rockslides with the smallest volume, the development of excess pore water pressure was not possible, because the rock mass was completely cut by largely open fractures, precluding the rise of the water table. Thus, the acceleration of movements with rainfall has to be explained by a soil-like behaviour of the basal slip surface, with chemical weathering and crushing as the main processes for strength decrease. In contrast, excess pore water pressure is certainly the triggering factor for the largest rockslide, the Randa rockfall. However, the increase in pore water pressure was promoted by the decrease in permeability caused by weathering and crushing since the last glaciation.

Case studies

Three case studies involving rock instabilities are described, located within the Mattertal (Wallis, Switzerland), 20 km north of Zermatt. They occur within the 'Randa orthogneiss', a massive augengneiss (Fig. 1). The orthogneiss is an intrusion of Permian age that underwent Alpine deformation and the development of a light schistosity. This lithology is competent in comparison with the surrounding lithologies.

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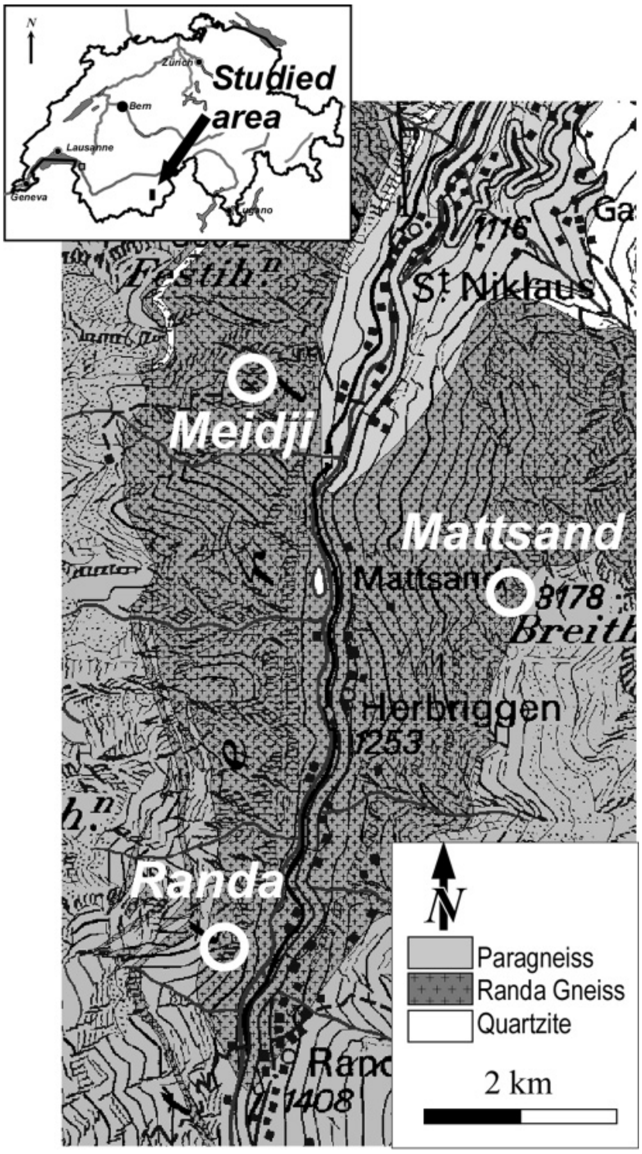


Fig. 1. Location of the three instabilities within the Randa orthogneiss (modified after Steck *et al.* 1999).

The Randa rockslide

The main rockfall of this area occurred in 1991 in Randa (30×10^6 m^3) (Sartori *et al.* 2004). Its mechanism was mainly controlled by the sliding of a rock mass along a fault located at the base of the cliff. The triggering factor was certainly the development of excess pore water pressure caused by a hot wind inducing snowmelt. However, fatigue and the obstruction of the permeability of the fracture caused by chemical weathering within the gouges (i.e. the cementation and build-up of a fine-grained material deposit (Girod & Thélin 1998; Girod 1999)) made excess pore water pressure build-up possible. Subsequently, a gallery used to deviate the river was built below the Randa scar, to prevent floods caused by the damming created by a new rockslide.

The Mattsand rockslide

The second case study described is the rock instability of Mattsand. It is a 400 m^3 column (Cruden & Varnes 1996) (Fig. 2) situated above a 300 m^3 block that toppled on 28 October 1998 (Amatruda *et al.* 2002). This unstable mass is also sliding on its basal surface. The rock mass is completely separated from the massif by open fractures. The displacements measured by extensometers indicate a strong increase of velocities during and after rain (Fig. 3). No excess pore water pressure is possible for such a geometry (Fig. 4). No movement can be attributed to freeze and thaw cycles. This rock block was blasted down for safety reasons in April 2001.

The Medji rockslide

The third case study described is the rockslide of Medji (*c.* 100 000 m^3), which occurred above the town of St-Niklaus on 22 November 2002. The rockslide was composed of a completely fractured spur that slid on a complex basal surface along which it was not possible to develop excess pore water pressure. Detailed information about this event is still confidential, but it is now known that the displacement velocity increased after rain, and remained constant after the rain stopped. The groundwater level (monitored using a borehole) was located below the instability. No significant rise was observed during or after the rain.

Chemical weathering of the Randa gneiss

Observation

A detailed mineralogical analysis on the Randa orthogneiss, the fault gouge and the percolating groundwater was carried out to determine the chemical weathering mechanisms (Girod 1999).

The mineralogical composition of the Randa orthogneiss is classical: K-feldspar (KF), plagioclase, albite, microcline, quartz, white micas, phengite, biotite, and accessory minerals such as pyrite are present.

The chemical analysis of the water indicates that the higher the salinity, the higher the elevation above the gallery. This means that the longer the groundwater path, the longer the time available for mineral dissolution. Furthermore, thermodynamic calculations indicate that those waters are undersaturated in albite and pyrite (Girod 1999), demonstrating that albite and pyrite are potentially dissolved along the entire groundwater path.

The fault gouge material is up to 40 cm thick and is typically fractured material with large rock elements (up to few centimetres) separated by a paste of finer material. The grain-size distribution is as follows: 3% clay and silts; 54% sand; 43% gravel.

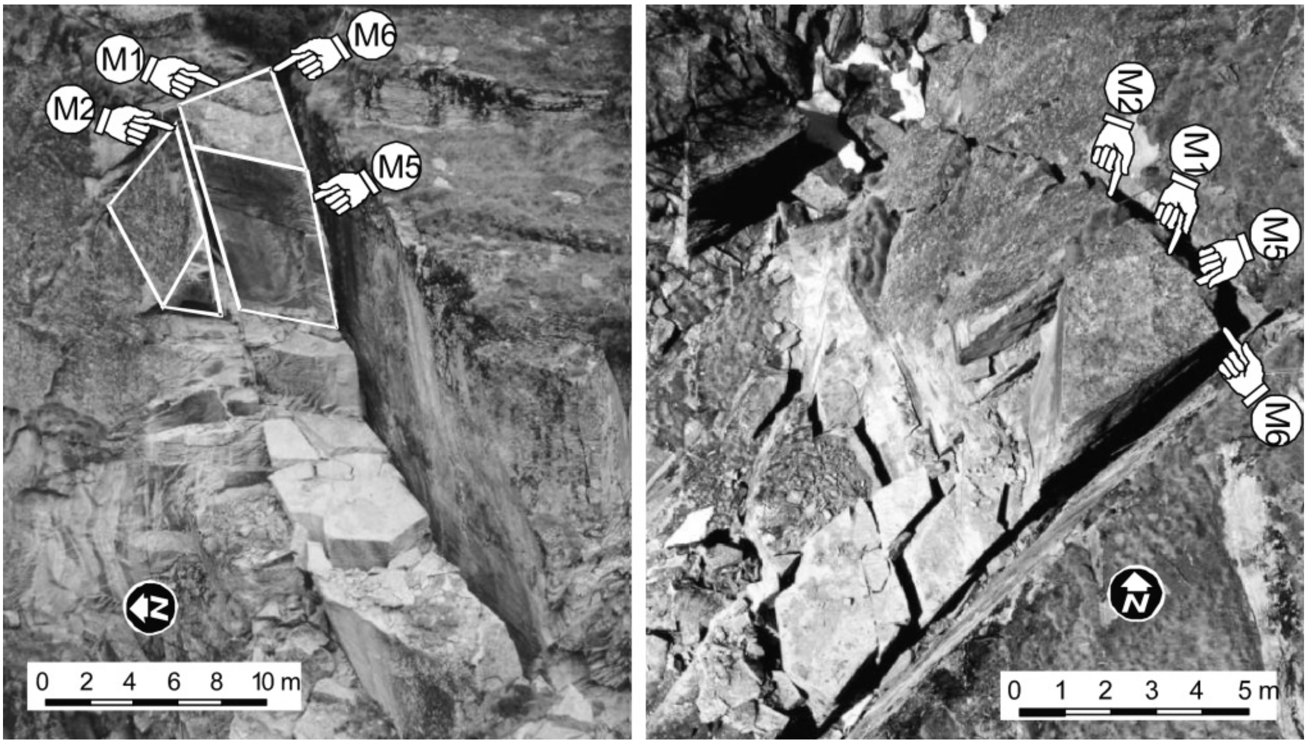


Fig. 2. Picture of the instability of Mattsand. M, locations of the extensometers (data from these are displayed in Fig. 3).

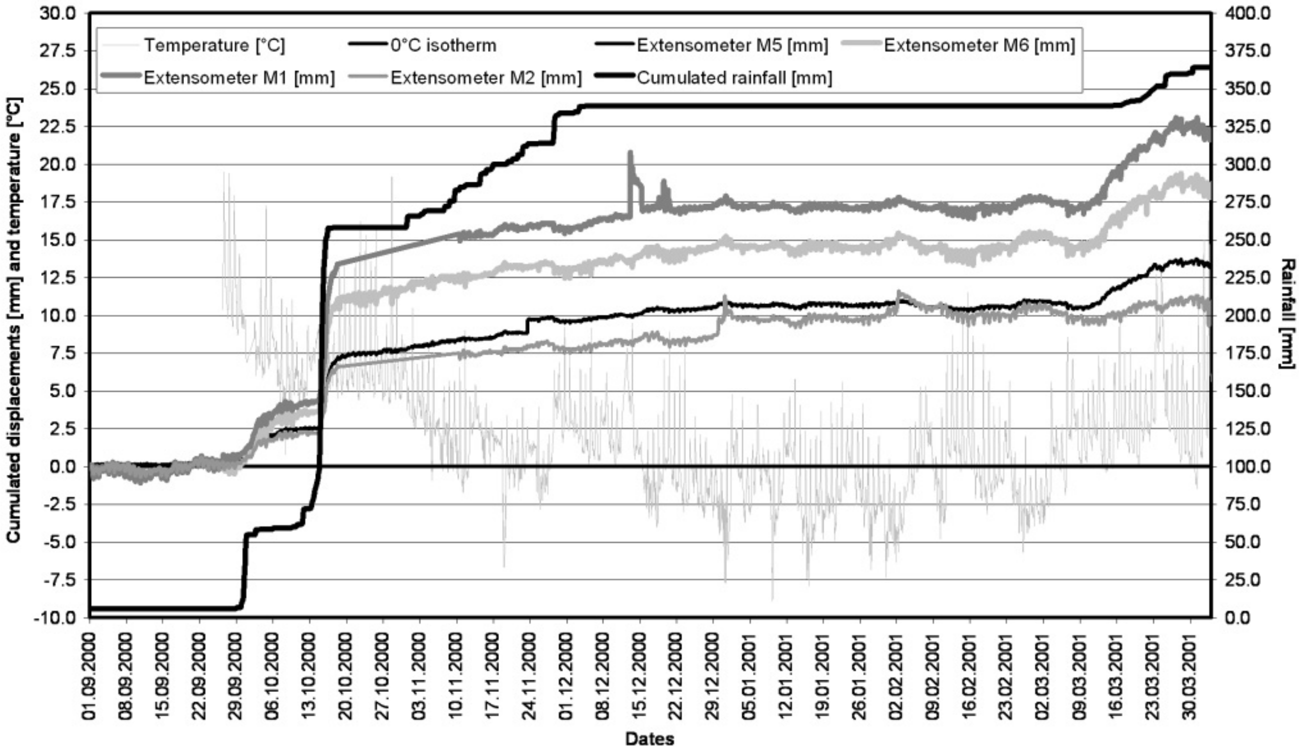


Fig. 3. Cumulative rain, temperature and displacements recorded by the extensometers. The effect of the rain on the displacements and the delay before stabilization should be noted.

Scanning Electron Microscopy (SEM) shows dissolution figures of minerals such as pyrite and feldspars (i.e albite and KF) (Fig. 5). Smectite (more precisely true montmorillonite) is identified by scanning electron micrographs and electron-dispersive X-ray spectrometry analysis, and also by X-ray diffraction analysis of the <2 μm size fraction. Mineral precipitation of iron hydroxide is also reported.

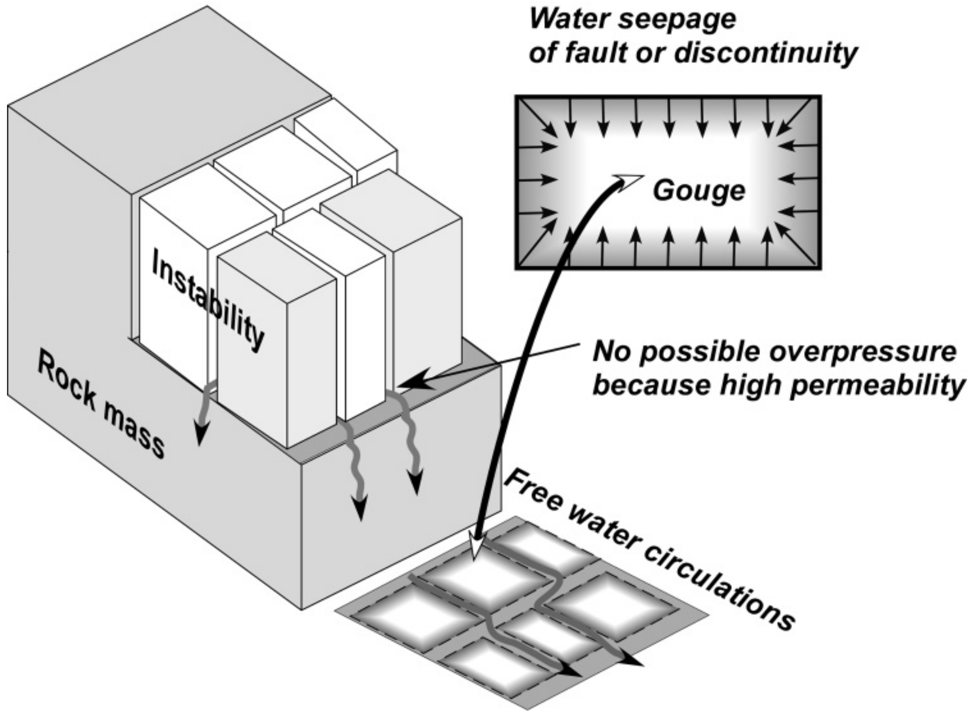


Fig. 4. Scheme of an instability with a water seepage, but with no possibility of excess pore water pressure.

Process

Girod (1999) interpreted the dissolution of pyrite as a source of water acidification, which allows the dissolution of albite. Thus, assuming that Mg^{2+} is provided by chlorite dissolution, smectite can be interpreted to be the weathering product of albite dissolution (Berner 1971):

$$Mg^{2++} + 3\ Na\ Al\ Si_3\ O_{8(albite)} + 4\ H_2O \rightarrow$$

$$2\ Na_{0.5}Al_{1.5}Mg_{0.5}Si_4O_{10}(OH)_{2(montmorillonite)} +$$

$$2Na^{+} + H_4SiO_{4aq}.$$

The oxidation of pyrite can also lead to further albite dissolution (Berner & Berner 1996). The crystallization of smectite requires slow water flow rates, because saturation in montmorillonite must be reached. This condition is found within the gouges. In open fractures, water simply dissolves the walls without material precipitation. It removes the cations from the system, as is demonstrated by the correlation between the length of percolation path and the water salinity.

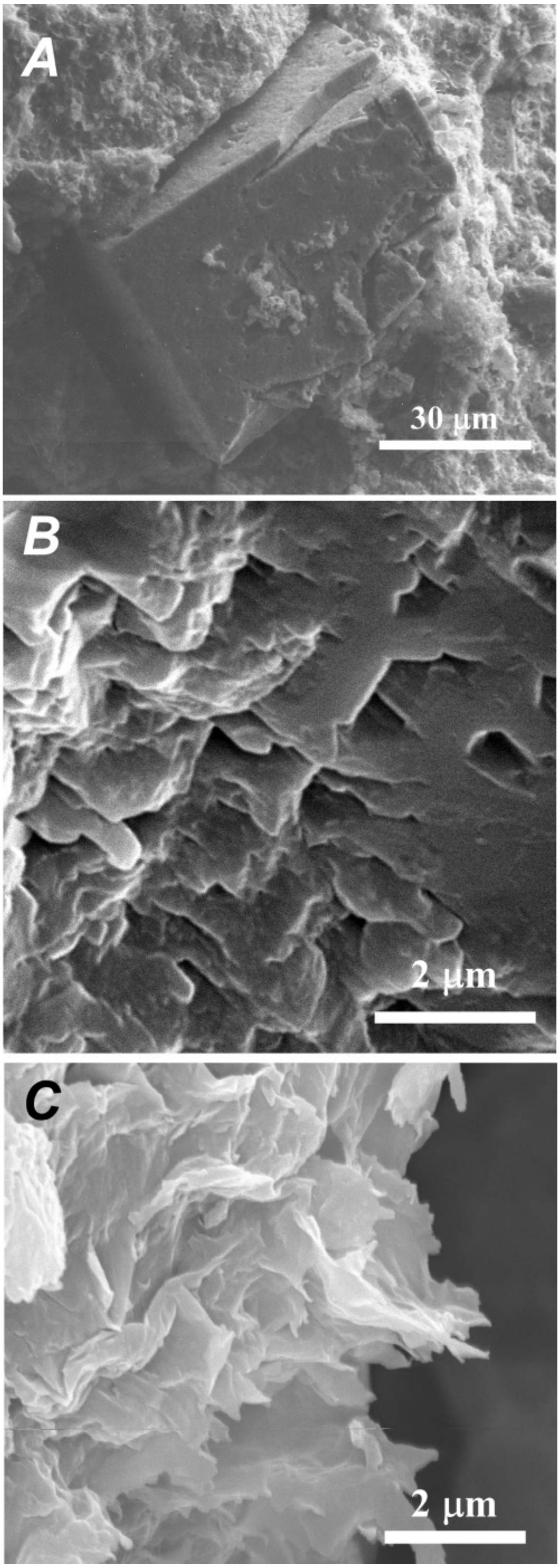
To sum up, the fractured rock mass system can ideally be divided into two subsystems: (1) a highly permeable fracture network, which simply leads to rapid dissolution of minerals (Sausse *et al.* 1998); (2) a less permeable one, which makes mineralogical changes, such as precipitation and dissolution of minerals, possible (Girod 1999) because saturation is reached. The second system leads to changes in mechanical properties of the gouge and the rock, whereas the first opens pores slowly and increases the permeability by dissolution.

Proposed explanation

Argument for unsaturated soil behaviour

From observations of movements caused by rain without the build-up of excess pore water pressure, it must be assumed that the material infilling fracture interfaces or gouges behaves like a soil. Such behaviour cannot be attributed to other types of materials, because one of the few possibilities is to change the mechanical properties by water seepage, which is similar to the behaviour of unsaturated soil (Fredlund *et al.* 1978, 1995; Leroueil 2001; Leroueil & Hight 2003).

Shear strength is dependent on water saturation. The suction or the pressure that links grains decreases with saturation. Thus, the shear strength is at a maximum for an intermediate saturation value depending on the soil type (Fredlund *et al.* 1995). In a τ–σ_n plot (shear stress–normal stress), a rock instability sliding on a discontinuity is a fixed point (Fig. 6), if no excess pore water pressure is considered. The suction can be considered as a contribution to an apparent cohesion. For simplification, let $c''(u_w)$ be the cohesion, including the effect of suction depending on the saturation or water pressure (u_w). Thus, the strength is given by $\tau = c''(u_w) - \sigma_n \tan \varphi'$ (where φ' is the friction angle). The distance of the discontinuity stress state from the



strength limit varies with the fluctuation of saturation, leading to fatigue (Leroueil 2001). The suction does not change φ′, and has a limited effect: it alone cannot lead to failure. However, the gouge is subjected to cycles that can lead to the decrease of the mechanical strength by fatigue (Demers *et al.* 1999). If small movements occur within the gouge, the shear band can modify shear strength and permeability, by slowly changing the grain layout. The process leading to failure is then the progressive decrease of φ′ by chemical weathering and alteration.

Origin of the soil-like behaviour

The discontinuities have an ancient tectonic origin. The material in the discontinuities has suffered displacements and crushing, leading to the formation of gouge material, or simply of a small amount of fine-grained material, between the discontinuity walls. The gouge material can be created by displacement as small as 10 cm (Girod 1999).

The crushing of the material during fault formation increases the surface area of the crushed material, resulting in an increase in permeability and facilitating chemical weathering. The weathering rate increases with both water content and circulation (Matsukura & Hirose 1999). Both dissolution and precipitation of minerals occur in the gouge. The soil-like behaviour is consistent with the properties of the small grain size of precipitated minerals and with the relatively low permeability that is necessary for the precipitation of smectite.

The occurrence of montmorillonite in the fault gouges of the Randa orthogneiss has resulted from the effect of weathering on alpine rocks (Girod 1999) and implies large changes in grain superficial tension. This has led to an increase of the suction (u_w), and thus an increase in shear strength if the gouge is unsaturated, or conversely a decrease if the gouge is saturated (Fredlund *et al.* 1995; Nishimura & Toyota 2002; Leroueil & Hight 2003).

Discussion

The effects of chemical weathering on the gouge material have been compared in the three case studies presented above. The existence of faults with thick gouges has played a very important role in the destabilization of the 1991 Randa rockslide (Sartori *et al.* 2004). The action of weathering decreases stability progressively by slowly decreasing φ′ and producing small variations of c''. Numerical analysis of the Randa rockslide by Eberhardt

Fig. 5. Scanning electron micrograph of the weathered minerals and of the neoformed smectite. (a) Weathered pyrite (dissolution pits); (b) weathered etched albite (dissolution pits); (c) neoformed smectite.

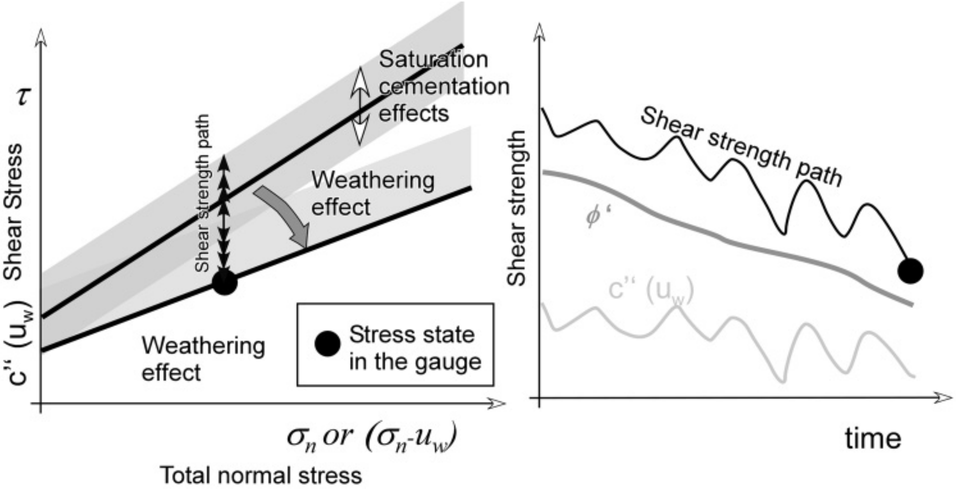


Fig. 6. Effect of changes in saturation on the apparent cohesion $c''(u_w)$ and the effect of weathering on φ'. Left: evolution of the shear strength with time (modified from Leroueil 2001). Right: evolution of the shear strength and of the two variables, c'' and φ' with time (modified after Demers *et al.* (1999) and Locat *et al.* (2000)).

et al. (2002) is based on a decrease of cohesion attributed to the progressive failure of the rock bridges (fresh rock between discontinuities). Weathering and water seepage cycles certainly assisted this progressive rock bridge failure by inducing small movements within the gouge. Because of the size of the Randa rockslide, the action of weathering and seepage has been slow, as the percolation takes more time and the time of response to seepage variations is longer. If the residence time of water within the gouge is long (because of the size of the instability) there is a greater chance of the formation of montmorillonite. Thus, both small movements and chemical weathering products are the sources of decrease in permeability that produced the excess pore water pressure considered as the triggering factor for the Randa rockslide (Sartori *et al.* 2004). The effects of smectite on mechanical behaviour are significant. We may recall that a pressure equivalent to more than 20 km of rock pile at surface temperature is necessary to expel the bonded H_2O in the montmorillonite interlayer (Van Olphen 1963). This underlines the role of the water adsorbed at the surface of fine-grained material, whether newly formed or not, which must have a significant effect on local strength within joint gouges. This will lead to small displacements favouring rock mass destabilization.

In contrast to the Randa rockslide, the triggering factor of the two other rockslides appears to be a coupled phenomenon of chemical weathering and unsaturated soil-like behaviour. The 1998 Mattsand rock instability clearly demonstrates a rapid response to the rains. Movements are linked to seepage and cease rapidly, because the size of the basal sliding surface is limited. Thus, the water circulates rapidly, and the unsaturated state is quickly reached during or after the end of the rains, again increasing the strength. The safety factor of the instability decreases with the saturation (Fig. 7).

The 2002 Medji rockslide is of intermediate size between Randa and Mattsand. Its behaviour is slightly different. After the rains ended, the movements did not cease, but continued at the same rate. This can be explained by a longer delay before the gouge once more reached an unsaturated state. In this case, the chemical weathering leads to instability with a safety factor very close to one, even in unsaturated condition. However, the period of saturated state is sufficiently long to promote movements that irreversibly damage the mechanical properties of the gouge by crushing the grains and changing their arrangement (Leroueil 2001).

The 'weathered gouge' system process in the Randa orthogneiss seems to be an important factor for rock slope stability, even in the Alpine climate (Fig. 8). The soil-like behaviour underlines this effect. However, the preliminary results on the grain-size distribution of these gouges (Girod 1999) is surprisingly very similar to those for the weathered crystalline rocks from Calabria (Italy) and their associate debris-flow fans (Calcaterra *et al.* 1998; Parise & Calcaterra 2000). More surprising is the presence of smectite in the debris-flow fans in the Swiss Alps and in Calabria (Parise & Calcaterra 2000). This finding is very important, because it shows that a limiting chemical weathering state may exist. This would be the limit beyond which chemical weathering affects the mechanical properties of the rocks leading, as for instance in gouges, to a particular soil-like behaviour. The material can then be subject to rapid changes in mechanical characteristics because of its high chemical and mechanical reactivity.

Conclusion

(1) This study demonstrates that the chemical weathering of granite–gneisses in an Alpine climate plays an

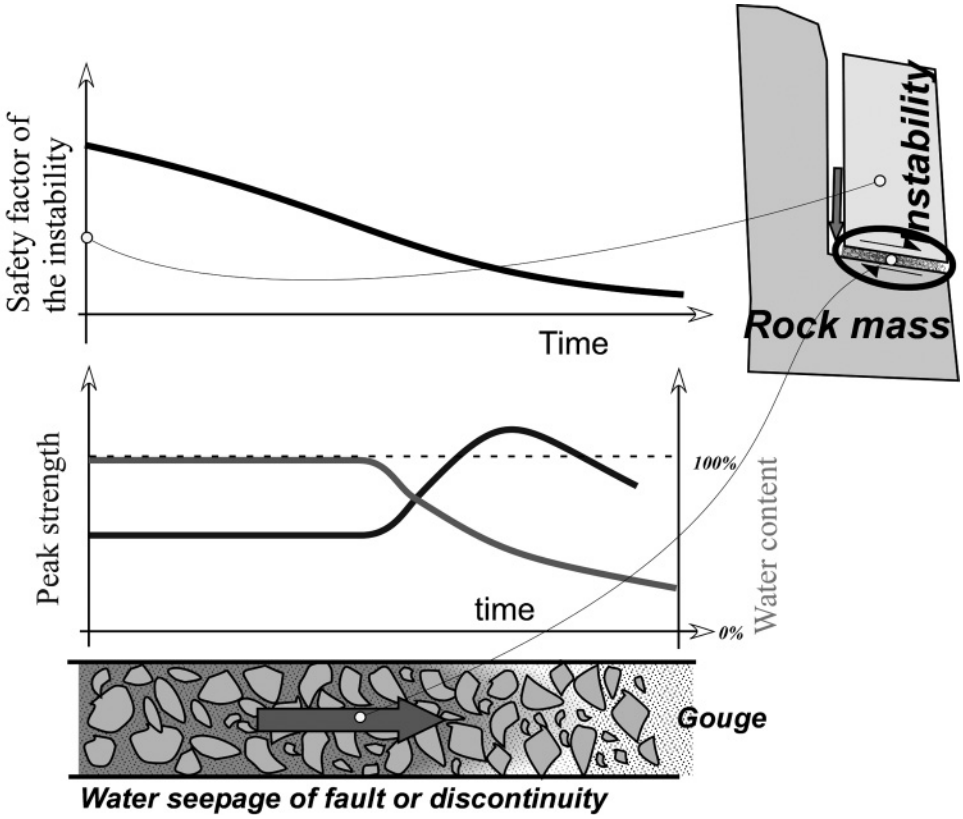


Fig. 7. Decrease in material strength as a result of seepage in fault gouges (loss of suction). This leads to a local decrease in strength, affecting the global safety factor. This can lead to fatigue or failure (see text for symbol explanation).

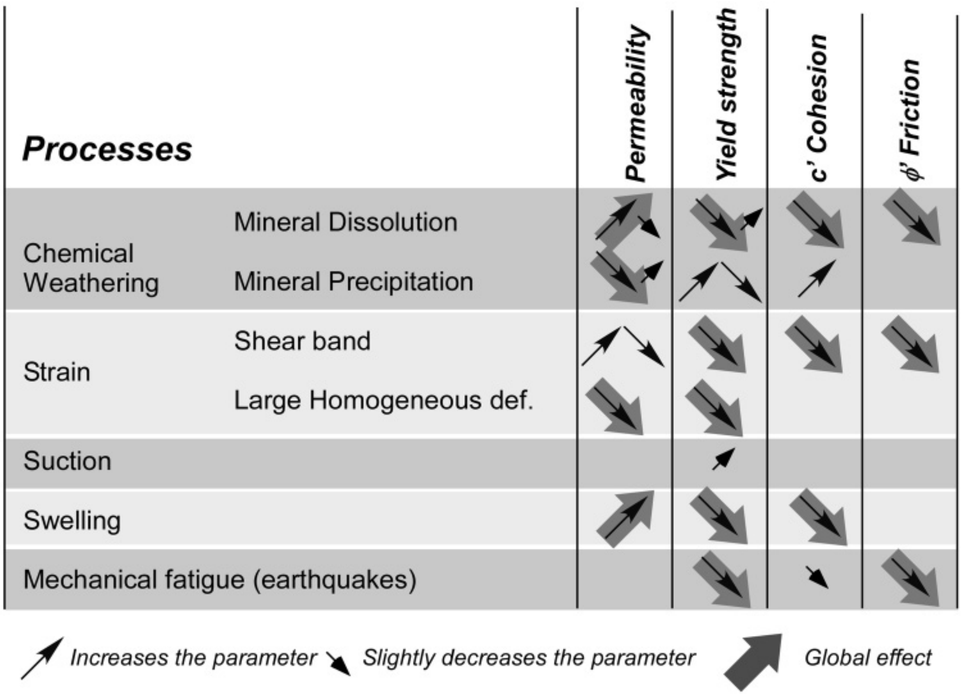


Fig 8. Tentative characterization of the effect of controlling parameters on gouge strength, and interfacial discontinuity surfaces at quasi-constant load. It should be noted that the yield strength can be increased or decreased by mineral precipitation. For instance, calcite precipitation is a cement.

important role in slope processes. Inspection of instabilities within the Randa orthogneiss demonstrates the effect of weathering coupled with unsaturated soil-like behaviour. In addition, the rock bridges gradually disintegrate by the variations of the safety factor of the entire rock mass caused by saturation–unsaturation cycles and weathering.

(2) These results, inferred from the behaviour of rock instabilities, indicate that the effect of chemical weathering, and especially the formation of smectite (Calcaterra *et al.* 1998), is potentially a way to quantify the hazard associated with rock slope processes (Parise & Calcaterra 2000) by assessing the smectite occurrence and its amount.

By studying the weathering grade in rock slopes, a way can be found to quantify the hazard of Alpine rock slope, i.e. rock slope evolution. Geochemical and mineralogical study has to be used. As Perel'man (1972, in Fortescue 1992) wrote about the Russian speciality landscape geochemistry: 'We can therefore say that landscape geochemistry is the history of atoms in the landscape', which means that the dependence of the landscape on chemistry is of primary importance. The mapping of weathering and geochemistry is probably very significant in slope evolution.

Future research should inspect weathering and mechanical behaviour of the fractures and fracture gouges with respect to saturation.

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