Monitoring of water content, water displacement and freeze-thaw processes in alpine rock walls using geoelectric survey lines

MATTHIAS RODE[1] and OLIVER SASS[2]

[1] Institute for Geography and Regional Sciences, Karl-Franzens-University Graz, Austria.
[2] Institute of Geography, University of Innsbruck, Austria.

matthias.rode@uni-graz.at

Abstract

The detachment of rock fragments from alpine rockwalls is mainly assigned to frost weathering. However, the actual process of frost weathering as well as the contribution of further weathering processes (e.g. hydration, thermal fatigue) is poorly understood. Rock moisture distribution during freeze-thaw events is the key to understanding weathering. As freeze-thaw cycles of different duration and intensity can contribute to rock shattering, these events can only be adequately investigated by means of a continuous monitoring program. To achieve this aim, small-scale geoelectric survey lines have been installed in three study areas (Gesäuse, Dachstein, Kitzsteinhorn) in the framework of the initiated ROCKING ALPS project. The here presented results of geoelectric measurements at the Kitzsteinhorn point to high importance of hydrostatic pressures and the generated pore water movement during freezing for the process of freeze-thaw weathering in rock.

Introduction

Rockfall generation is not uniform in space and time and rockfall of all magnitudes is concentrated along pre-formed clefts and faults. Small scale joint density and differences in moisture supply are highly important for debris fall patterns. Furthermore, the presence of permafrost in the rock promotes frost weathering.

According to HUDEC (1980), water displacement during freezing and the resulting adsorption and desorption processes are responsible for "frost" damage in limestones. MCGREEVY and WHALLEY (1985) also favoured ice formations causing hydrostatic pressure in the unfrozen rock as being the main agent of frost weathering; this viewpoint was supported by e.g. FAHEY and LEFEBURE (1988) and COUTARD and FRANCOU (1989). ISHIKAWA et al. (2004) directly observed crack widening caused by water supply and subsequent freezing. High-resolution electrical conductivity measurements (SASS, 2004) showed heightened pore water contents near the margins of ice lenses, which also indicates that hydrostatical pressure is an important factor in frost weathering. Contrastingly, WALDER and HALLETT (1986) postulated that rock shattering is achieved by slow formation of ice lenses (segregation ice) similar to frost heave in soil. The critical point of all these theories is the lack of data on water contents of natural rock and on moisture fluctuations during freezing (MCGREEVY and WHALLEY, 1985; MATSUKURA and TAKAHASHI, 2000; REGMI and WATANABE, 2009).

Recent investigations use 2D-resistivity for monitoring ice in bedrock (e.g. HILBICH et al., 2009; KRAUTBLATTER et al., 2010). Applying this technique to bedrock using drilled-in electrodes is a relatively new approach (SASS, 2003; KRAUTBLATTER et al., 2007). This present paper is focusing on frost weathering and debris fall and by the smaller scale of measurement. This small-scale approach has been only carried out by SASS (2003, 2004) and SASS and VILES (2006, 2010).

Study sites

In the framework of the ROCKING ALPS project investigations are carried out in three areas of the Eastern Alps (Figure 1) of different elevation and lithology. The first study area is the Gesäuse as part of the north-eastern Limestone Alps. The prevailing rock types are the Dachstein limestone and the Wetterstein dolomite. The study sites are at an elevation of 800-1200 m. The Dachstein area is situated west of the Gesäuse and reaches a summit height of up to 2.995 m. The rockwalls are also built up of Dachstein limestone. The existing permafrost in the north-facing rockwalls is a highly interesting comparison area to the geologically similar Gesäuse. The third area is the Kitzsteinhorn (3203 m) in the Hohe Tauern range consisting of calcareous mica-schist with permafrost.

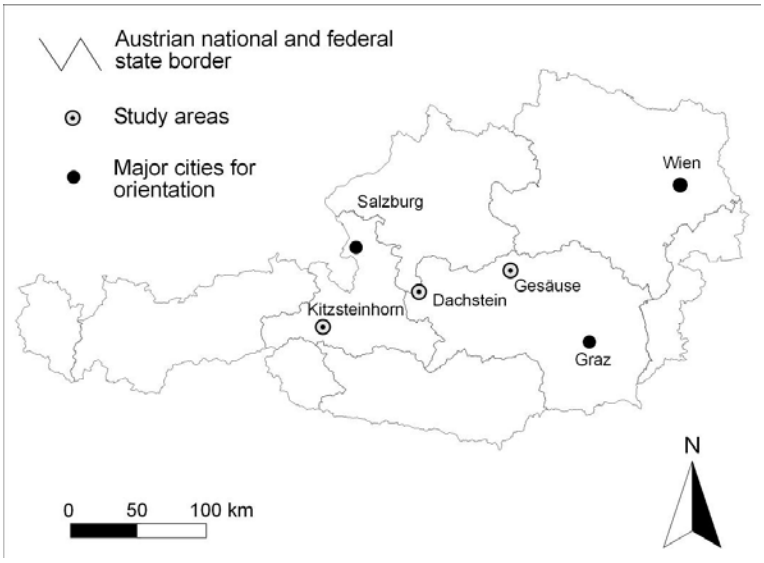

Fig. 1: Study sites of the ROCKING ALPS project.

Project methods

The aims of ROCKING ALPS are (1) to get information on rock moisture at high temporal and spatial resolution, (2) to monitor the pore water movement during freeze-thaw events and (3) to connect moisture and rockfall data obtained by TLS. Therefore, the 2D-resistivity measurements will be combined with rockfall monitoring.

Monitoring of water content, water displacement and freeze-thaw processes is achieved by permanently installed geoelectric survey lines (ERT). The ERT method enables an interesting, graphic general view of the small-scale moisture distribution and allows the assessment of moisture fluctuations during freezing.

Very short-term moisture fluctuations (e.g. those induced by freeze-thaw events) cannot be accurately recorded by geoelectric profiling. Thus, additional temperature and moisture measurements at higher temporal resolution are carried out. Two techniques are applied - transitional resistivity and heat capacity measurements. For investigating the impact of observed moisture fluctuations on weathering, regular laser scans (TLS) are carried out at several monitoring sites in the vicinity of the geoelectric instruments. The datasets allow assessing the dominant controlling factors of rockfall. While datalogger and geoelectrical measurements are performed at fixed sites at high temporal resolution, TLS offers the spatial rockfall distribution within the test sites of some 100 m². To tie these two approaches closer together, georeferenced infrared photos are taken at regular intervals. This enables to visualize temperature patterns and amplitudes. The cross-check with TLS data offers interesting insights into the relevant drivers of weathering.

As freeze-thaw cycles of different duration and intensity can contribute to rock shattering, these events can only be adequately investigated by means of a continuous monitoring program. The design of the survey lines enables detailed observation of small-scale water movement during wetting, drying and freeze-thaw events (50 electrodes, spacing 0.06 m, Wenner-array) while additional longer profiles at the Dachstein will record the presence of frozen rock to a depth of c. 3 m (25 electrodes, spacing 0.5 m, Wenner-Array). The survey lines will be maintained over a period of at least one year each. Considerably different freezing behaviour between north- and south-facing sites, as well as between permafrost and non-permafrost sites is to be expected.

ERT-setup

Several geoelectric measurements were performed on the Magnetköpfl summit (2900 m), in the Kitzsteinhorn area from 27-04-2011 to 29-04-2011 (Figure 2). In the course of this field trip two geoelectric profiles, both equipped with 50 electrodes and a spacing of 0.06 m were drilled into a rock wall. This instrument setup enables to investigate the external layers of the rock wall to c. 0.5 m depth.

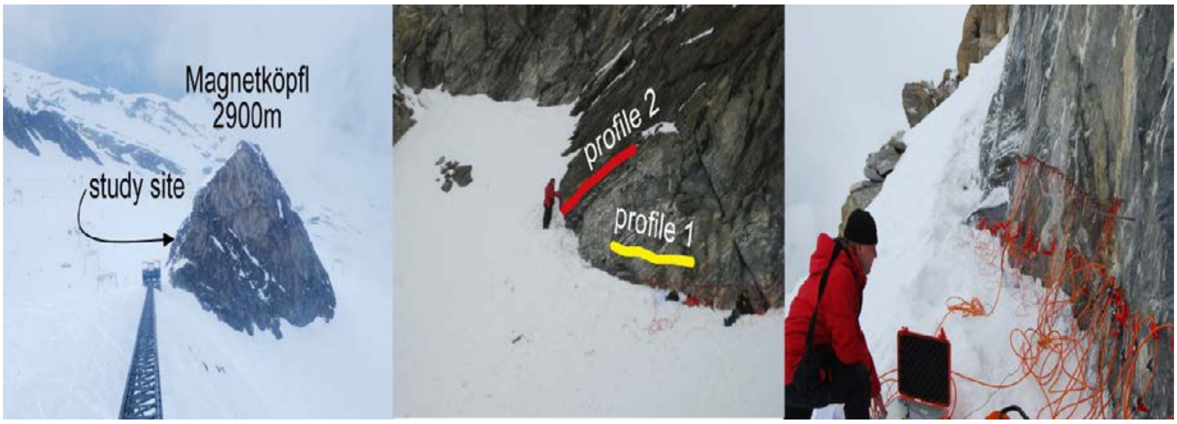

Fig. 2: ERT measurements at two profiles on a rock wall at the Magnetköpfl (Kitzsteinhorn).

On both survey lines measurements were taken on 28-04 from 09:00 to 20:00 and on 29-04 from 06:00 to 09:00. In the following, two data sets per profile are presented: the condition before freezing inside the rock wall (t1 – 28-04-2011, 19:30) and the frozen condition in the next morning (t2 – 29-04-2011, 07:30). During this time, the air temperatures decreased continuously from +1.8°C at t1 to -4.3°C at t2 (Figure 3).

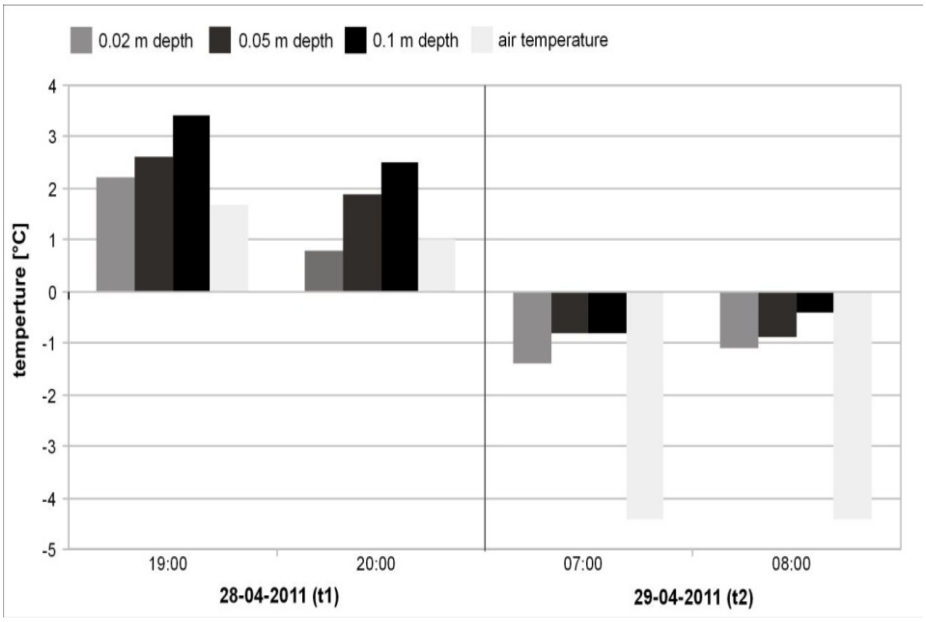

Fig. 3: Mean rock and air temperature at the two measurement dates t1 and t2.

First results

At profile 1 (Figure 4), increasing resistivity values between t1 and t2 are recognizable near the surface which is due to freezing of the pore water. However, at c. 1.92 m and at a depth of about 0.2 m, a decrease of resistivity values can be observed. This resistivity drop (blue zone) is caused by heightened pore water content underneath the frozen layer. This presumably indicates displaced pore water during freezing.

Profile 2 (Figure 4) yielded similar results. This profile was installed along a horizontal fissure in the rock wall. During the day, melted snow impounded in this fissure. Due to the night frost this water got frozen. This phenomenon is clearly mirrored by the increase in resistivity between t1 and t2. Due to freezing heat, caused by a higher amount of water at the surface than in dryer layers deeper inside the rock, not the entire surface got frozen. The RMS error of both profiles is fairly low in the unfrozen state (3.6-4.1%) and is markedly higher at subzero temperatures (4.8-14.2%). This is due to the extreme contrast between frozen and unfrozen rock areas.

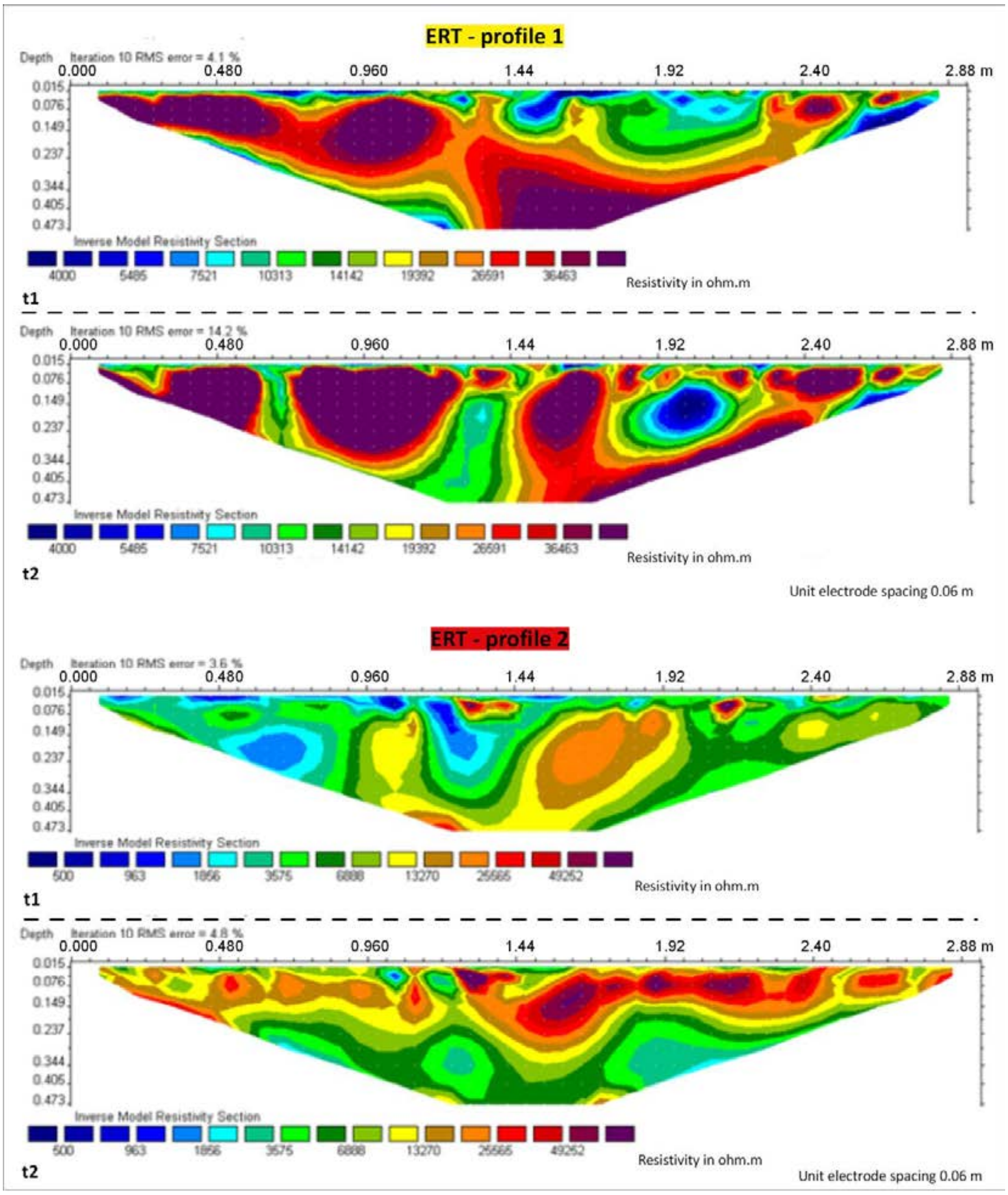

Fig. 4: Inversion models (Wenner-array) of the resistivity values at profile 1 and 2. RMS error: (root-mean-squared-error) = Difference between the calculated and the apparent measured resistivity.

To assess the change in resistivity between t1 and t2, a time-lapse inversion model was calculated in *Res2Dinv*. Thereby, the visual interpretation could be underpinned by relative numerical values. Time-lapse inversion models of the same measurements (Figure 5) also show an increase in resistivity near the surface and a decrease deeper inside the rock. The colors green to purple of the color bar represent the percentage decrease or increase, respectively, of the resistivity values.

At 1.94 m of profile 1, pore water freezing could be clearly recognized by the observed increase of 160% at 0.15 m depth. At greater depth the percentage increase gets smaller, until at 0.25 m a decrease of the resistivity values becomes apparent.

The percentage increase in resistivity at profile 2 amounts 189% on average for nearly the whole section down to 0.14 m. The depth of freezing reaches down to 0.3 m. This pronounced increase is caused by the large amount of water impounded during the day in the horizontal fissure.

From 0.3 m depth on, a decrease of 35% of the resistivity values between t1 and t2 was observed. It is concluded that similar to profile 1, pore water was displaced during freezing.

The time-lapse inversions clearly show that the spatial patterns of resistivity changes is quite heterogeneous for both profiles, which is mainly due to the different geomorphic situation between the two profiles. The highly jointed surface of the rock wall at profile 2 caused a higher moisture level inside the rock than the compact and plain rock surface at profile 1.

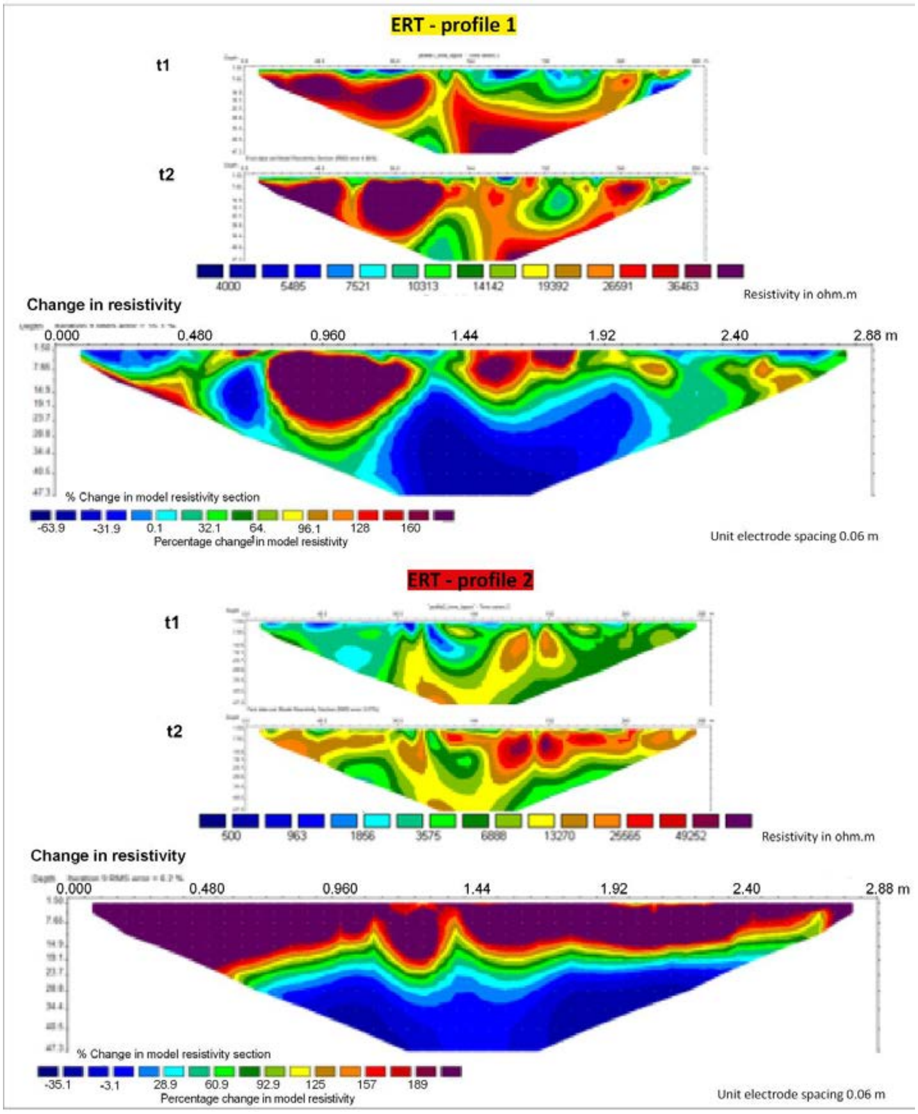

Fig. 5: Time-lapse inversion models at t1 and t2, as well as the percentage change of resistivity between t1 and t2 of the profiles 1 and 2.

To get a better quantitative overview of the change in resistivity at certain depths it is helpful to consider the numerical values. Figure 6 shows the mean resistivity values at different depths at t1 and t2. At a depth of 0.1 m the increase in resistivity in the morning (t2), comparing to the evening before (t1), is plain to see in both profiles. A slight increase of the mean resistivity values happened at a depth of 0.3 m at profile 2. Once again, this pattern is due to freezing near the surface and increased water content underneath the frozen layer.

Comparing t2 to t1, increasing resistivity down to about -0.23 m is evident at both profiles, which represents the frost penetration depth during the night and the freezing of moisture. In contrast, from -0.28m depth on, the resistivity values at t2 are getting lower than at t1. The decrease in resistivity was particularly evident at profile 1 at about 0.47 m depth. Considering the assumed frost penetration depth, the moisture in those deeper layers should be frozen, but the results again indicate heightened pore water pressure under the freezing front. At profile 2 the decrease in resistivity values was not that pronounced, but in principle, the same phenomena of frozen and unfrozen moisture in different rock layers occurred.

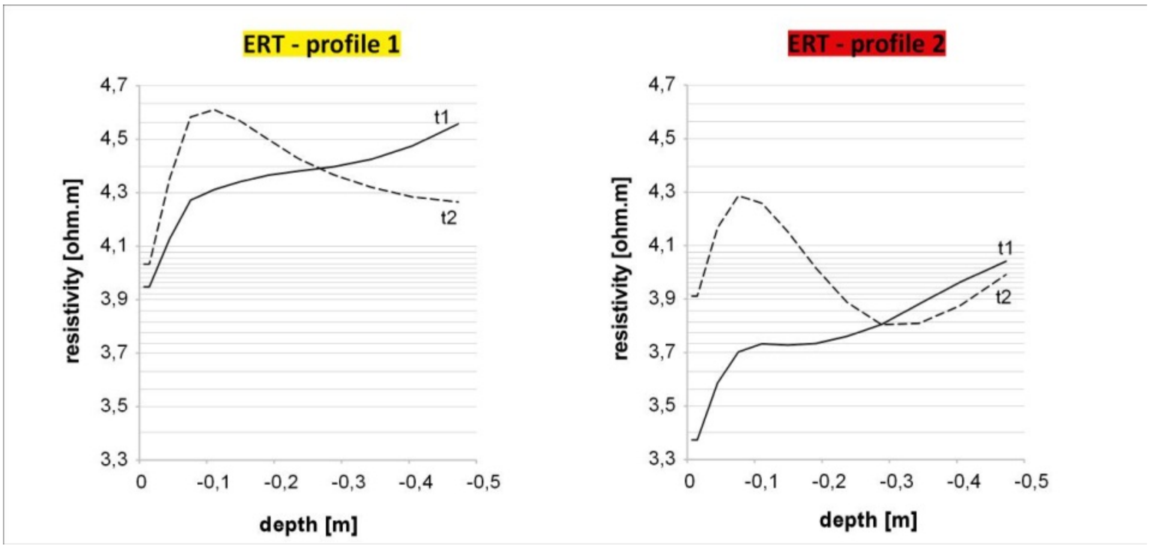

Fig. 6: Change of mean resistivity values at different depths for t1 and t2 at the profiles 1 and 2.

Discussion

The results point to a high importance of hydrostatic pressures during freezing and the generated pore water movement for the process of freeze-thaw weathering in rock walls (Sass 2004). This principally confirms the ideas on frost weathering as conceptualised by McGreevy and Whalley, with ice formations causing hydrostatic pressure in the unfrozen rock being the main agent of frost weathering. However, the idea of slow moisture movement towards the freezing front during long spells of subzero temperatures cannot be confirmed or disconfirmed, as longer measurements are necessary.

The reliability of the results has to be carefully assessed in the future. The surprising resistivity drop under the freezing front might be in parts attributed to an over-compensation artefact of the inversion routine, caused by extremely high resistivity in the frozen area. Therefore additional ERT-measurements, with a reduced current flow to enable reliable measurements under high electrical resistances, are carried out. An accurate analysis of future results in matters of arisen artefacts due to inversion calculations will be done.

To get information on the factual moisture content of the rock, it is necessary to convert the resistivity values to moisture graphs through laboratory calibration work. At this stage, only first hypotheses based on the resistivity values could be made to describe the moisture content of the rock. In the near future, fixed moisture, heat-capacity and temperature sensors at different depths will be installed. To assess mechanical changes in the rockwall due to generated hydrostatic pressures, additional piezoelectric sensors will be used.

Acknowledgements

This is a pre-study for the project 'ROCKING ALPS – Rockfall and Weathering in the Eastern Alps' financed by the Austrian Science Fund (FWF) through project no. FWF P24244. Mag. Matthias Rode was funded by a stipend provided by the URBI faculty of the University of Graz, which is gratefully acknowledged.

References

COUTARD, J. and FRANCOU, B., 1989: Rock temperature measurements in two alpine environments: implications for frost shattering. – Arctic and Alpine Research, **21**, 399-416.

FAHEY, B.D. and LEFEBURE, T.H., 1988: The freeze-thaw weathering regime at a section of the Niagara Escarpment on Bruce Peninsula, Canada. – Earth Surface Processes, **13**, 293-304.

HILBICH, C., MARESCOT, L., HAUCK, C., LOKE, M.H. and MÄUSBACHER, R., 2009: Applicability of Electrical Resistivity Tomography Monitoring to Coarse Blocky and Ice-rich Permafrost Landforms. – Permafrost and Periglacial Processes, **20**(3), 269-284

HUDEC, P.P., 1980: Durability of carbonate rocks as function of their thermal expansion, water sorption and mineralogy. – American Society for Testing and Materials, Special Technical Publication, **691**, 497-508.

ISHIKAWA, M., KURASHIGE, Y. and HIRAKAWA, K., 2004: Analysis of crack movements observed in an Alpine bedrock cliff. – Earth Surface Processes and Landforms, **29**, 883-891.

KRAUTBLATTER, M., HAUCK, C. and WOLF, S., 2007: Geophysical 2D and 3D-monitoring of permafrost in rock walls. – Geophysical Research Abstracts, **9**, 09884.

KRAUTBLATTER, M., VERLEYSDONK, S., FORES-OROZCO, A. and KEMNA, A., 2010: Temperature-calibrated imaging of seasonal changes in permafrost rock walls by quantitative electrical resistivity tomography (Zugspitze, German/Austrian Alps). – Journal of Geophysical Resaerch - Earth Surface, **115**, F02003 (doi: 10.1029/2008JF001209).

MATSUKURA, Y. and TAKAHASHI, K., 2000: A new technique for rapid and non-destructive measurement of rock-surface moisture content; preliminary application to weathering studies of sandstone blocks. – Engineering Geology, **55**, 113-120.

MCGREEVY, J.P. and WHALLEY, W.B. 1985: Rock moisture content and frost weathering under natural and experimental conditions: A comparative discussion. – Arctic and alpine research, **17**, 337-346.

REGMI, D. and WATANABE, T., 2009: Rockfall activitiy in the Kangchenjunga Area, Nepal Himalaya. – Permafrost and Periglacial Processes, **20**, 390-398.

SASS, O., 2003: Moisture distribution in rockwalls derived from 2D-resistivity measurements. In: Geophysical applications in geomorphology. – Zeitschrift für Geomorphologie, Supplementband **132**, 51- 69.

SASS, O., 2004: Rock moisture fluctuations during freeze-thaw cycles - preliminary results derived from electrical resistivity measurements. – Polar Geography, **28**(1), 13-31.

SASS, O. and VILES, H.A., 2006: How wet are these walls? Testing a novel technique for measuring moisture in ruined walls. – Journal of Cultural Heritage, **7**, 257-263.

SASS, O. and VILES, H.A., 2010: Wetting and drying of masonry walls: 2D-resistivity monitoring of driving rain experiments on historic stonework in Oxford, UK. – Journal of Applied Geophysics, **70**, 72-83.

WALDER, J.S. and HALLET, B., 1986: The physical basis of frost weathering: Toward a more fundamental and unified perspective. – Arctic and Alpine Research, **18**, 27-32.