Methods for absolute and relative age dating of rock-glacier surfaces in alpine permafrost

W. Haeberli, D. Brandova, C. Burga, M. Egli, R. Frauenfelder, A. Kääb & M. Maisch
Geography Department, University of Zurich, Switzerland

B. Mauz and R. Dikau
Geography Department, University of Bonn, Germany

ABSTRACT: Rock glacier surfaces reflect debris accumulations produced, deposited and deformed during historical and Holocene time periods. Dating of such surfaces is difficult but can best be achieved by using a combination of absolute and relative age-determination methods. Photogrammetry of present-day flow fields yields trajectories along which inverse velocities can be integrated and compared with radiocarbon dates from organic samples providing absolute ages. Weathering rinds and Schmidt hammer rebound values can be calibrated with the time scales calibrated in this manner. This helps to interpret lichen-cover distribution under marginal growth conditions. Luminescence dating of fine material becoming exposed in upper parts of rock-glacier fronts has the potential of providing true travel times. Relict “rock glacierised” features can be dated by cosmogenic (exposure) effects.

1 BACKGROUND AND CONCEPT

The formation and preservation of ground ice over the typical time scales (millennia) involved with the steady flow over long time intervals of large and well-developed rock glaciers require the existence of perennially negative ground temperatures, i.e., permafrost by definition (Haeberli, 2001). This climatically determined ground thermal condition makes rock glaciers interesting in view of quantitative palaeoclimatic reconstructions (Frauenfelder et al., 2001). Moreover, the debris accumulated in rock glaciers reflects centuries and millennia of past frost weathering and rock-fall activity (Barsch, 1977; Olyphant, 1987). In order to decipher the corresponding information, rock glaciers must be dated.

The following briefly outlines a strategy which combines a variety of applicable methods. It uses a basic concept of permafrost creep, which relates to results from extensive drilling, borehole observation, geophysical soundings, photogrammetric analyses, permafrost mapping etc., at Murtel rock glacier (Figure 1; Haeberli et al., 1998). The initial condition is a talus cone with characteristic vertical sorting of grain sizes. Frost heave and creep of the ice-supersaturated finer material originally deposited on the upper part of the talus cone then forms a bulge (protalus rampart) which steadily develops into a larger rock glacier. Coarse blocks continue to accumulate at the base of the talus cone and are carried along on the back of the further advancing rock glacier until reaching its front. There, they fall down the oversteepened scree of re-exposed and thawed fine material. These coarse blocks from the rock-glacier surface are subsequently overridden by the creeping ice-super-saturated fine material. In contrast to the latter with ages increasing along flow paths, they form a stiff basal layer in which age decreases towards the rock glacier front. The age distribution at depth in rock-glacier permafrost, therefore, is likely to contain sharp time inversions.

2 METHODS

2.1 Photogrammetry

A first indication of age distributions is provided by surface-flow fields using modern photogrammetric methods (Kääb et al., 1997, 1998; Kääb & Vollmer, 2001). Such measurements enable time (age) to be integrated for particle paths along flow trajectories constructed for present-day conditions assuming a
steady-flow condition as a first-order approximation. On the Murtel rock glacier (Figure 2), this approximation seems to be justified by the fact that the curvature of the isochrones is similar to the curvature of the ogive-like transverse ridges, the formation and cumulative deformation of which obviously takes up several millennia; their wavelength of about 20 m corresponds to an age difference between ridges of about 300 to 400 years (Kääb et al., 1998).

The surface age at the rock glacier front as calculated from the present-day velocity field amounts to approximately 5–6 ka. Similar velocities and flow fields measured on other rock glaciers indicate that this result is probably of general significance for comparable forms of actively creeping permafrost (Frauenfelder and Kääb, 2000; Kääb et al., 1997, 2002). The example shown in Figure 2 demonstrates that photogrammetrically derived estimates yield highly detailed spatial patterns of age distribution and thus represent a unique tool for interpolating results from other dating methods. The main concerns are temporal variations in rates of permafrost creep and the behaviour during initial stages of rock glacier development with flow velocities growing from zero to present-day values. The latter point makes photogrammetrically determined ages minimum rather than maximum values.

2.2 Radiocarbon

The ice within the perennially frozen material may contain well-preserved organic remains which allow for direct and absolute dating by the radiocarbon method. The primary problem consists in the necessity to drill or dig through the active layer which is often composed of coarse blocks. Moreover, only very small amounts of organic remains may indeed exist in the ice. In the core recovered from the drilling through the permafrost of the active rock glacier Murtel (Figure 2), only one layer within massive ice contained moss remains at a depth of about 6 metres below surface, providing a mean conventional $^{14}$C age of 2250 $\pm$ 100 years. The relatively well-preserved habitus of the moss as well as of the pollen scavenged by them suggest an insignificant residence time of the material on the rock glacier surface before isolation from its ambient environment by incorporation into the ice matrix. Hence, the $^{14}$C age of the moss may not be too strongly influenced by other carbon pools and is expected to represent the age of the hosting ice layer well. These results confirm that the photogrammetrically estimated ages on Murtel are reasonable, that rock glacier surfaces are indeed millennia old and that the flow of the creeping permafrost was quite constant over this time period (Haeberli et al., 1999). Similar results have been obtained by Konrad et al. (2001) for Galena Creek rock glacier (US), a feature of relatively warm ($-1^\circ C$?) permafrost probably affected in its upper part by a former (possibly Little Ice Age, Holocene) glacier or glacieret. It is interesting to note that perennially frozen, “rock-glacierized” ice-cored (push) moraines in northern Sweden provided radiocarbon dates of quite similar age (Östrem, 1965).

2.3 Weathering rinds

Rock particles are increasingly subjected to weathering processes along the flowpaths of rock-glacier surfaces. The thickness of the weathering rind, a reddish outer crust-layer around individual rock components, should therefore increase along flow trajectories. The use of weathering rates from rinds on sandstones, basalts, andesite boulders, etc., for relative to absolute age dating of quaternary deposits have been discussed, for instance, by Chinn (1981), Gellatly (1984), Ricker et al. (1993), Ivy Ochs et al. (1996) or Oguchi (2001). First measurements on rock glaciers of the Upper Engadine (Swiss Alps) were carried out for surface-exposed clasts selected at a series of cross-sectional transects along flowlines from the talus to the front. Around 50 to 100 rind samples per transect were chipped with a hammer from gneiss or granite rock debris and rind thicknesses were measured normal to the surface to the innermost discernible edge of weathering using a 0.1 mm scale-graded magnifying glass. The median as well as the modal values are equally suitable to delineate the increasing tendency of weathering rind thickness on gneiss or granite with the
duration of exposure to weathering. The chronofunctions developed by Laustela et al. (2003) show that the weathering rinds tend to follow a logistic trend with an asymptotic value after $t = +\infty$ and are closely correlated with Schmidt-hammer rebound values (cf. below and Fig. 3). Chemical analyses of the weathering rinds show a continuous formation of iron oxihydroxides and a steady increase of dithionite-extractable Fe with age (Laustela et al., 2003). Rock weathering rinds found in the Swiss Alps however, were usually thinner than those observed on sandstones (New Zealand) and reached characteristic growth rates of 0.2 mm/ky (Murtèl site), 0.3 mm/ky (Gianda Grischa site) or 1 mm/ky (Suvretta site).

2.4 Schmidt-hammer rebound

The Schmidt-hammer is a portable instrument originally designed to measure the surface strength of concrete by recording the rebound of a spring-loaded bolt impacting a surface (Schmidt, 1951). The rebound value ($r$) gives a relative measure of the surface hardness and as such provides information on the time of surface exposure and the degree of weathering. The method has been successfully applied for relative age dating of moraines (e.g. Matthews & Shakesby, 1984; Winkler & Shakesby, 1995; Rune & Sjästad, 2000), rockfall deposits (Nesje et al., 1994) and debris flow deposits (Lippert, 2001). A random sample of fifty measurements is usually recorded on as many different boulders as possible, selecting surfaces which have comparable lithology and which are dry, flat, clean and free of lichens, visual fissures and cracks (cf. Williams & Robinson, 1983). The mean or the median of the values can then be considered representative for the effective hardness of the analysed surface. On the Murtèl rock glacier, mainly composed of gneisses, basica and ultrabasica and with surfaces up to several millennia old (Haeberli et al., 1999; Frauenfelder & Kääb, 2000), $r$ values measured by Castelli (2001) closely correlate with the chronology estimated by photogrammetry and radiocarbon dating. Furthermore, the results are in good agreement with weathering rind measurements effectuated on the same transects (Figure 3; cf. Laustela et al., 2003). These promising results provide an opportunity to calibrate age dating by Schmidt-hammer measurements for assessing at least relative chronologies for Holocene debris surfaces at other sites.

2.5 Lichenometry

The radial growth of crustose lichens as an indicator of substrate age (Beschel, 1950; Locke et al., 1979) has been most widely used in dating glacial deposits in tundra environments where lichens often form the dominant vegetation cover (cf., for instance, Beschel, 1961; Andersen & Sollid, 1971; Erikstad & Sollid, 1986; Matthews, 1992). Growth rates vary from one region to another and may decline after initial colonization to an almost constant value. Lichenometry has a useful range of ca. 500 years (Innes, 1985) with exceptional lifetimes up to 4500 years or more under cold and dry continental conditions (Beschel, 1958). The crustose lichen *Rhizocarpon geographicum* has been most commonly used (see growth curves of *Rhizocarpon geographicum* and *R. alpicola* e.g. in King & Lehmann, 1973; Bradley, 1985). Climate type (mainly moisture supply, solar radiation/rock temperatures and altitude a.s.l.) is a major factor affecting lichen growth rates (see e.g. Calkin & Ellis, 1980). Permanent snow cover and unstable blocks within zones of extending flow on rock glaciers may lead to reduced or lichen-free zones (Haeberli et al., 1979). Lichens on the surface of Alpine rock glaciers have been studied by Haeberli et al. (1979) and Burga (1987). Detailed mapping on the surface of the active rock glacier Murtèl by Ruffet (2001) clearly demonstrated that lichen diameters correlate with relative age differences as estimated from photogrammetric flow determinations. However, lichen growth is limited to the frontal parts of the rock glacier, whereas no lichens of major size can be found in its upper part. This striking feature is most probably due to the adverse effects of rock-fall activity, extending flow and long snow-cover duration within the root zone of the rock glacier. Much larger lichen diameters and denser surface cover can be observed on inactive and relict features.

2.6 Luminescence

Luminescence is used for dating purposes, because natural minerals such as quartz and feldspars are dosimeters. These minerals are capable of accumulating some
of the environmental and cosmic ionising radiation to which they are exposed. By stimulating the dosimeter using light (optically stimulated luminescence, OSL) a luminescence signal is monitored which is proportional to the absorbed dose. The event that can be dated (where t = 0) is the last exposure to daylight. Essential preconditions for successful dating are (i) sufficient reduction of the latent luminescence signal at time of deposition, (ii) thermal stability of the luminescence signal during burial, (iii) signal growth according to the energy absorbed and (iv) radioactive equilibrium in the burial environment. Precondition (i) is crucial for dating rock glaciers. It should be satisfied if flows start from a talus cone, which is fed by sand falling from the rock wall above the cone. The sand is subsequently buried by new material and migrates to the upper part of the front where it is again exposed to daylight (cf. Figure 1). Thus, OSL-ages of samples from the frontal debris (Figure 4) should provide true travel times of buried near-surface particles which have participated in the long-term creep process of the perennially frozen talus.

In future, spatially high-resolution positioning of OSL samples and successful dating could give detailed information about the flow behaviour in time.

Samples from the rock glaciers Muratél, Muragl and La Veduta were collected in 2001 using tubes under a black cover shielding the sampling site from daylight. In the laboratory sample preparation focused on extracting quartz grains of 90–200 μm size. Routine procedures were used which are described in detail elsewhere (Mauz et al., in press).

The OSL-study of the samples are in progress. First results indicate that some samples are datable, others are not. All datable samples give Holocene ages between ~8 ka and ~4 ka. This preliminary result clearly confirms the concept of rock glaciers developing at time scales of millennia as deduced from flow measurements and radiocarbon dating. To estimate accurate and precise OSL-ages, problems have still to be solved concerning the low sensitivity of the quartz to ionising radiation, the extremely inhomogeneous radiation field surrounding the dosimeter and the absorption of ionising energy alternately by water and ice in a not-constant pore volume.

2.7 Cosmogenic (exposure) dating

The concentration of “cosmogenic isotopes” such as $^{10}$Be ($t_{1/2} = 1,500,000$ years), $^{26}$Al ($t_{1/2} = 716,000$ years) and $^{36}$Cl ($t_{1/2} = 301,000$ years; cf. Lal, 1991; Cerling & Craig, 1994; Kurz & Brook, 1994; Zreda & Phillips, 1994) depends on the period of time the surface has been exposed, the local production rate, the decay constant of the radionuclide, the rock density, the erosion rate and the cosmic-ray attenuation length. Quartz is well suited to $^{10}$Be- and $^{26}$Al-exposure dating studies because of its inherently low $^{27}$Al content which allows the measurement of the $^{26}$Al/$^{27}$Al ratio (Kohl & Nishiizumi, 1992). Since the method was introduced and tested more profoundly (e.g. Klein et al., 1986; Nishiizumi et al., 1986) it has been applied to more and more specific questions in different geomorphic contexts (Cerling & Craig, 1994; Kurz & Brook, 1994). Applications in Switzerland are quite recent (Ivy-Ochs et al., 1996; Tschudi, 2000) and enable significant improvement in determining the chronology of late-Würmian and Holocene glacier fluctuations. The Egesen moraines of the Lagrev glacier at the Julier Pass were dated and yielded exposure ages of 11,100 years (Ivy-Ochs et al., 1996). The main potential for exposure dating of rock glaciers and other creep phenomena in Alpine permafrost concerns blocks on the surface and blocks from the talus apron at the foot of the front. In the case of relict rock glaciers, dated blocks from the surface provide a minimum time between the deposition of the block at the surface until today, whereas blocks which had fallen – and thereby most probably been turned over – to the talus apron at the foot of the now inactive front indicate the time since rock glacier movement came to a stop. The difference between the two ages could give a minimum travel time of the blocks from deposition at the surface to their present-day position. First samples were analysed from a relict rock-glacierized late-glacial moraine at La Veduta near Julier pass. The exposure age of the top surface of a prominent large boulder on the frontal ridge was determined using the cosmogenic radionuclide $^{10}$Be. It yielded a preliminary mean exposure age of 6800 years, which may possibly indicate continued creep of perennially frozen late-glacial morainic material well into the Holocene. Two other boulders contained various kinds of minerals which could not be eliminated from the quartz fraction, making it impossible to prepare pure quartz so that $^{10}$Be could not be measured. The interpretation of cosmogenic dating at the investigated rock-glacierized feature, therefore, remains uncertain.
3 RECOMMENDED STRATEGY AND CONCLUSIONS

The key and starting point for the proposed dating strategy is the fact that the thermal inertia of ice-rich permafrost causes active rock glaciers to flow and develop steadily over centuries and millennia of relatively constant (Holocene) climatic conditions. Time since clast release and deposition through rock fall onto the rock-glacier surface systematically increases along flow trajectories, enabling highly differentiated age patterns to be derived from photogrammetric flow analysis. Such patterns can be calibrated by luminescence dating of fine material reappearing at the oversteepened front, and by radiocarbon dating of (sparse) organic matter found in drillings or excavations in the permafrost itself. This helps limiting the uncertainty about effects from past changes in flow rates. Weathering-rind thicknesses and Schmidt-hammer rebound values can now be tied to the thus defined time scales. These easily applied field methods in turn facilitate the selection of blocks which have been overturned when falling from the surface over the steep front to the frontal talus of relict rock glaciers immediately before movement came to its final stop. Cosmogenic exposure dating of such selected blocks defines the point in time when this important climate- or topography-induced event took place, and luminescence dating of fine material from the front may add information about total travel times and possibly even involved processes (especially the often discussed participation of small glaciers and large rockfalls or landslides in initial debris transport). A thus calibrated methodology involving weathering-rind thicknesses, Schmidt-hammer rebound values, exposure and luminescence dates may also be applied on other characteristic cold-mountain deposits such as moraines, debris flows or rock-fall deposits. It is evident that the long-term creep of mountain permafrost together with a whole set of newly developed dating methodologies opens most interesting perspectives for chronological work about late-glacial and Holocene landscape evolution in climate-sensitive high-mountain areas.

REFERENCES

Haeberli, W., King, L. & Flotron, A. 1979. Surface movement and lichen cover studies at the active rock glacier...


