Pollen analysis and ^{14}C age of moss remains in a permafrost core recovered from the active rock glacier Murtèl–Corvatsch, Swiss Alps: geomorphological and glaciological implications

WILFRIED HAEBERLI,[1] ANDREAS KÄÄB,[1] STEPHAN WAGNER,[2*] DANIEL VONDER MÜHLL,[2]
PATRICIA GEISSLER,[3] JEAN NICOLAS HAAS,[4†] HOLGER GLATZEL-MATTHEIER,[5] DIETMAR WAGENBACH[5]

[1]*Department of Geography, University of Zürich-Irchel, Winterthurerstrasse 190, CH-8057 Zürich, Switzerland*

[2]*Versuchanstalt für Wasserbau, Hydrologie und Glaziologie, Eidgenössische Technische Hochschule, ETH-Zentrum, CH-8092 Zürich, Switzerland*

[3]*Conservatoire et Jardin Botaniques de la Ville de Genève, C.P. 60, CH-1292 Chambésy, Switzerland*

[4]*Department of Botany, University of Basel, Schönbeinstrasse 6, CH-4056 Basel, Switzerland*

[5]*Institut für Umweltphysik, University of Heidelberg, D-69120 Heidelberg, Germany*

ABSTRACT. Within the framework of core-drilling through the permafrost of the active rock glacier Murtèl–Corvatsch in the Swiss Alps, subfossil stem remains of seven different bryophyte species were found at a depth of 6 m below surface and about 3 m below the permafrost table in samples from massive ice. The composition of the moss species points to the former growth of the recovered mosses in the nearest surroundings of the drill site. A total of 127 pollen and spores captured by the mosses and representing 23 taxa were determined. The local vegetation during deposition time must be characterized as a moss-rich alpine grassland meadow rich in Cyperaceae, Poaceae, Chenopodiaceae and Asteraceae, comparable to today's flora present around the study site. For ^{14}C analysis, accelerator mass spectrometry had to be used due to the small sample mass (about 0.5 mg Carbon content). The mean conventional ^{14}C age of 2250 ± 100 years (1σ variability) corresponds to ranges in the calibrated calendar age of 470–170 BC and 800 BC to AD 0 at statistical probabilities of 68% and 95%, respectively. This result is compared with the present-day flow field as determined by high-precision photogrammetry and with information about the thickness, vertical structure and flow of the permafrost from borehole measurements. Total age of the rock glacier as a landform is on the order of 10^4 years; the development of the rock glacier most probably started around the onset of the Holocene, when the area it now occupies became definitely deglaciated. The bulk of the ice/rock mixture within the creeping permafrost must be several thousand years old. Characteristic average values are estimated for (1) surface velocities through time (cm a^{-1}), (2) long-term ice and sediment accretion rates (mm a^{-1}) on the debris cone from which the rock glacier develops, (3) retreat rates (1–2 mm a^{-1}) of the cliff which supplies the debris to the debris cone and rock glacier, and (4) ice content of the creeping ice/rock mixture (50–90% by volume). The pronounced supersaturation of the permafrost explains the steady-state creep mode of the rock glacier.

INTRODUCTION

Permafrost or negative ground temperature throughout the year is characteristic of many high-mountain areas of the world (Cheng and Dramis, 1992; Haeberli and others, 1993). With such ground thermal conditions, large amounts of ice beneath the surface can exist over extended time periods. Ice supersaturation and the existence of massive ice strongly affect geotechnical properties of the frequently occurring perennially frozen scree and moraine deposits, leading to slow viscous flow and the formation of lava-stream-like landforms usually termed rock glaciers (Wahrhaftig and Cox, 1959; Haeberli, 1985; Barsch, 1996). Evidence from outcrops, drillings, borehole logging and geophysical soundings indicates that the ground ice concerned is most likely to be polygenetic in origin, with interstitial, segregation and buried snow-bank ice probably being the predominant components. Measured electrical d.c. resistivity values — a key indicator for variable ice origins — together with the coupled thermodynamic conditions of ice formation and preservation lead to the assumption that the ice types concerned must systematically vary along flow trajectories and form, over characteristic time periods of millennia, on top (permafrost table) of as well as at the bottom (permafrost base) of the creeping rock glaciers (Haeberli and Vonder Mühll, 1996).

In 1987, scientific core-drilling was carried out through the active rock glacier Murtèl–Corvatsch (Figs 1 and 2), eastern Swiss Alps (cf. Haeberli and others, 1988, for information about site selection, goals, drilling logistics and first results). The borehole is situated on the central flowline,

* Present address: Bitzi, CH-9542 Ebnat-Kappel, Switzerland.

† Present address: Department of Botany, University of Toronto, 25 Willcocks Street, Toronto, Ontario M5S 3B2, Canada.

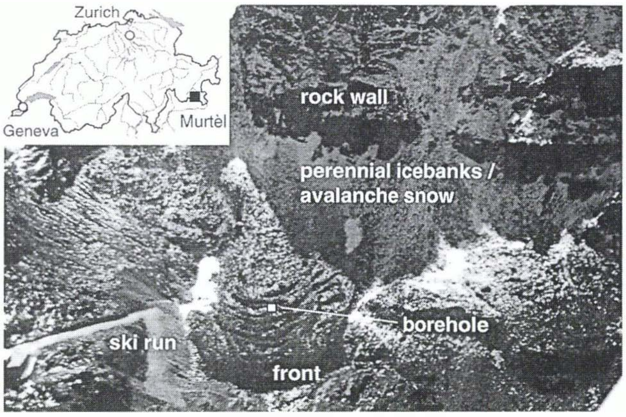

Fig. 1. Location map and oblique view of the Murtèl rock glacier. Photograph taken by M. Hoelzle, 1994.

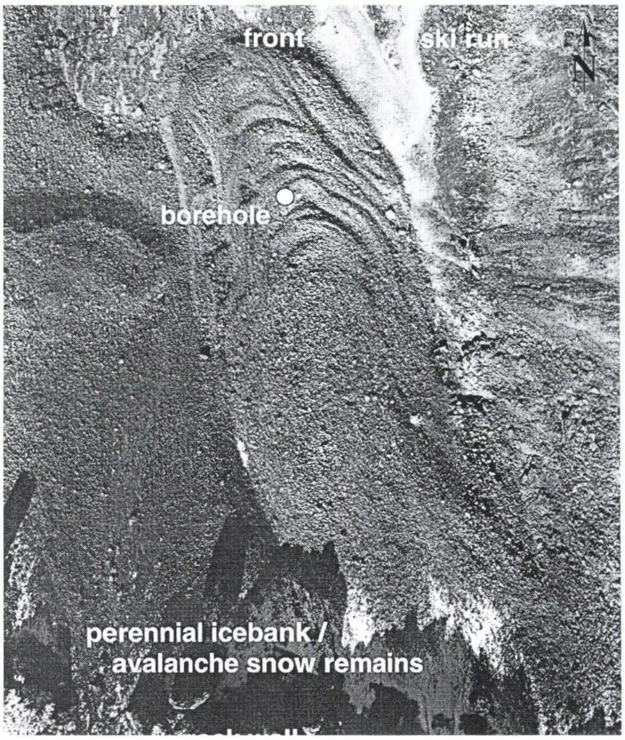

Fig. 2. Aerial photograph of Murtèl rock glacier taken by the Swiss Federal Office of Cadastral Surveys on 11 September 1996, flight-line 066155, photo 2435.

about halfway from the headwall to the front, and reaches bedrock. One of the primary goals of this project was to search for organic remains within the recovered cores in order to directly date ice from mountain permafrost and to acquire evidence about the age of the investigated ground ice. This age determination would be independent of earlier estimates from kinematic considerations. Surprisingly enough, only one layer within massive ice contained moss remains at a depth of about 6 m below surface. The results from ^{14}C dating and botanical analyses confirm the concepts developed so far about the creep of mountain permafrost and enable some general conclusions to be drawn about long-term flow velocities, landform genesis, rates of ice formation, rockfall activity and cliff retreat at an active rock glacier. The present contribution reviews the background of the drill site and core-sampling, documents the botanical/bryological analysis of the recovered moss remains with their pollen spectra, reports on the ^{14}C dating (cf. early ^{14}C datings of Arctic permafrost by Brown, 1965) and briefly discusses the geomorphological and glaciological implications of the result obtained.

SITE AND SAMPLING

The active Murtèl–Corvatsch rock glacier has developed within a former cirque from perennially frozen, north-westerly exposed scree slopes at 2850–2620 m a.s.l. Extending flow characterizes the upper part of the rock glacier, whereas longitudinal compression causes pronounced ogive-like transverse ridges in the lower part. The steep, approximately 20 m high front is largely free of vegetation and slowly advances over permafrost-free granodiorite bedrock. High-resolution vertical aerial photographs were taken by the Swiss Federal Office of Cadastral Surveys in the fall of the years 1987 and 1996. Using special computer-aided photogrammetric techniques (Kääb and others, 1997), the horizontal velocity field (Fig. 3, left side) as well as area-wide changes in surface elevation were determined from these photographs. Horizontal velocities reach maximum values of 15 cm a^{-1} and more in the upper part of the rock glacier just below the rock wall delimiting the creeping permafrost. Along the flowlines, they decrease to about 5 cm a^{-1} behind the front, where increasing surface slopes and sliding or tilting of individual rocks lead to higher surface velocities again. In full agreement with borehole deformation measurements (Wagner, 1992; Vonder Mühll, 1996), the photogrammetric compilations show horizontal surface velocities of about 6–7 cm a^{-1} at the borehole. The changes in surface elevation at the front hint at an advance rate of the rock glacier Murtèl of about 1.5–2 cm a^{-1} over the period 1987–96. Assuming constant creep rates through the last millennia, trajectories were computed from the velocity field 1987–96 for a number of manually selected points (Fig. 3, right side). These trajectories show the time it takes for a particle to travel down the rock-glacier surface under present-day conditions. Because flow must have been quite different from today at the beginning of rock-glacier evolution (Olyphant, 1983, 1987), such a calculation allows only for a rough (probably minimum) age estimate (cf. discussion at the end of the paper).

The 60 m deep borehole on the active rock glacier Murtèl was placed at 2670 m a.s.l. Alpine permafrost in the area surrounding the drill site exhibits a discontinuous distribution pattern (Hoelzle, 1996). Core analyses and borehole measurements (Fig. 4; Vonder Mühll and Haeberli, 1990; Vonder Mühll and Holub, 1992; Wagner, 1992; Vonder Mühll, 1996) showed that the permafrost underneath the 3 m thick active layer essentially consists of two layers: an upper one with an extremely high ice content (90–100% by volume), and a lower one consisting of coarse blocks with ice-filled pores but almost completely without fine rock particles. Seventy-five per cent of the total horizontal displacement (6 cm a^{-1} at the surface) takes place within the transition zone between the two layers at 28–30 m depth, with the upper (strongly supersaturated) layer undergoing steady-state creep and overriding the non-deforming (structured) lower layer. Mean annual ground temperature at 11 m depth increased from −2.3°C (1987) to −1.4°C (1994) but was intermittently cooling again due to thin snow cover in the winters of 1994–95 and 1995–96 (Fig. 5; Vonder Mühll and others, in press). It is reasonable to assume that permafrost conditions existed at the drill site throughout the younger Holocene time period at least. At 52–58 m depth, temperature variations around 0°C are observed in a seasonal talik (Vonder Mühll, 1992). Total permafrost thickness reaches far into the bedrock which underlies the rock-glacier

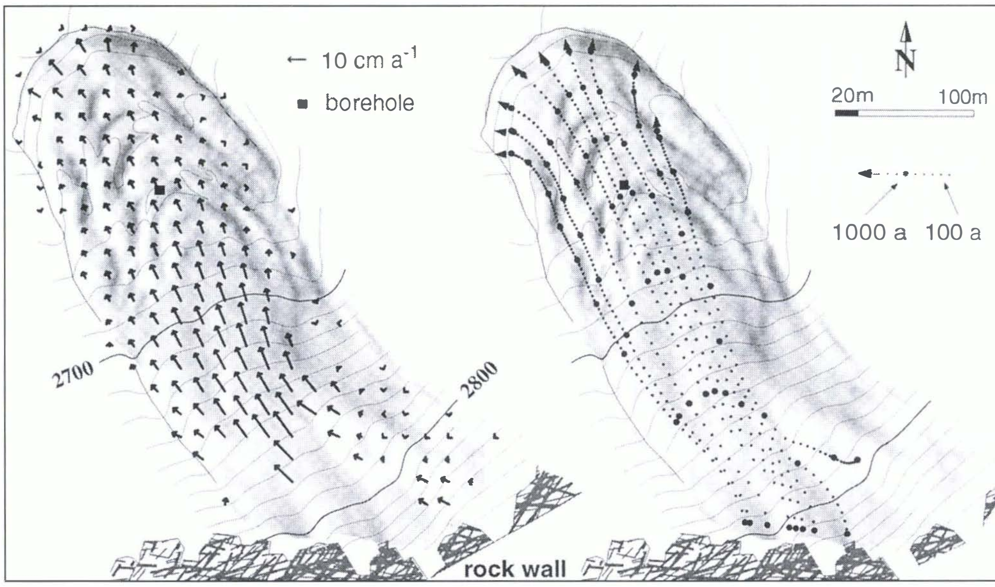

Fig. 3.
and trajectories/surface ages computed from this velocity field (right).

sediments, and is estimated at about 100 m. This is in sharp contrast with the absence of permafrost in front of the rock glacier and indicates marked horizontal gradients in ground thermal conditions. Electrical d.c. resistivity of the perennially frozen material is up to 2 MΩm in the massive ice, decreasing to around 10 kΩm or even less above bedrock. Together with the short distance (200 m) between the rock wall and the drill site, such resistivities exclude the possibility of a predominant sedimentary ("firn") origin for the massive ice encountered (Haeberli and Vonder Mühll, 1996). It is much more plausible to assume a polygenetic origin of the massive ice with burial of superimposed ice from small perennial snow banks fed by snow avalanches (Figs 1 and 2), probably in combination with later addition of ice from secondary frost heave within the permafrost and from freezing processes taking place at the permafrost table (cf. Haeberli and Vonder Mühll, 1996; Elconin and LaChapelle, 1997).

Careful visual inspection connected to the melting of

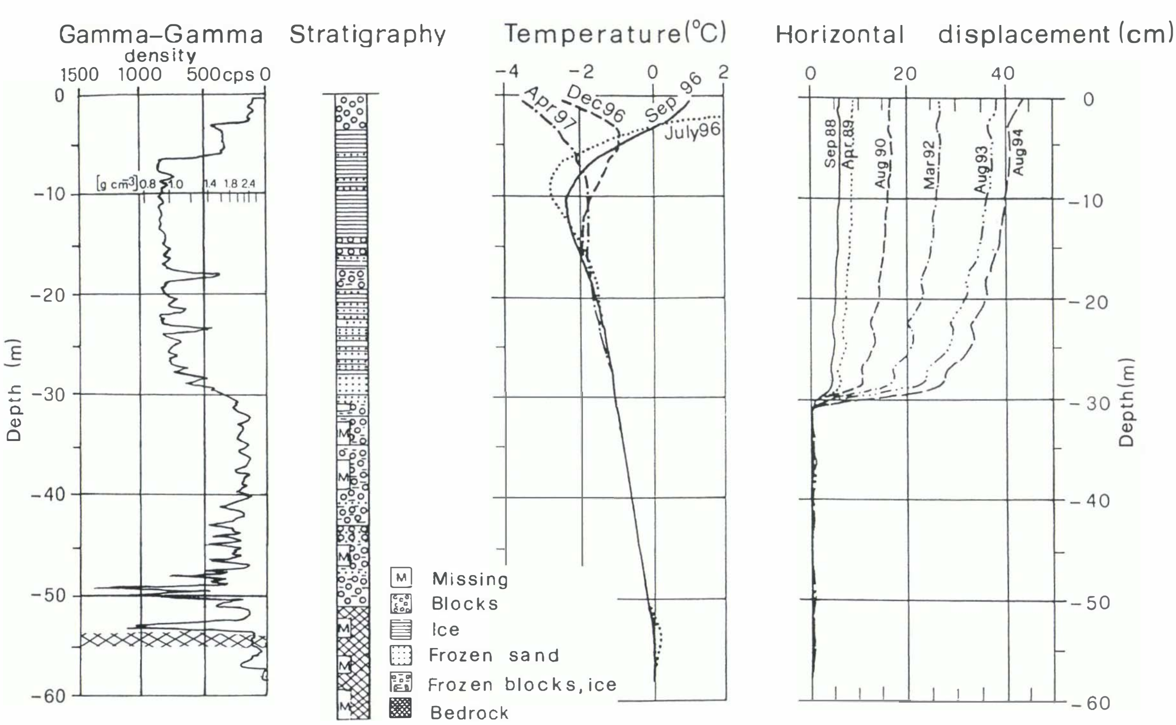

Fig. 4. Principal results from core analyses and borehole measurements at the active rock glacier Murtèl–Corvatsch.
the 3 m thick active layer with coarse blocks, the density log ($\gamma-\gamma$) and the stratigraphy show two main layers: (1) massive ice (90–100% ice content by volume) with thin layers of
almost completely without fine rock particles down to bedrock at about 57 m depth. Three-quarters of the total horizontal displacement (6 cm a^{-1} at the surface) takes place within a pronounced shear horizon in the transition zone between the two layers at 28–30 m depth as revealed by the borehole defor
by overrides the non-deforming (structured) lower layer. Seasonal temperature variations are well developed within approximately the uppermost 20 m, and mean annual permafrost temperature at the permafrost table (3 m depth) is estimated at −2.5° to −3°C.

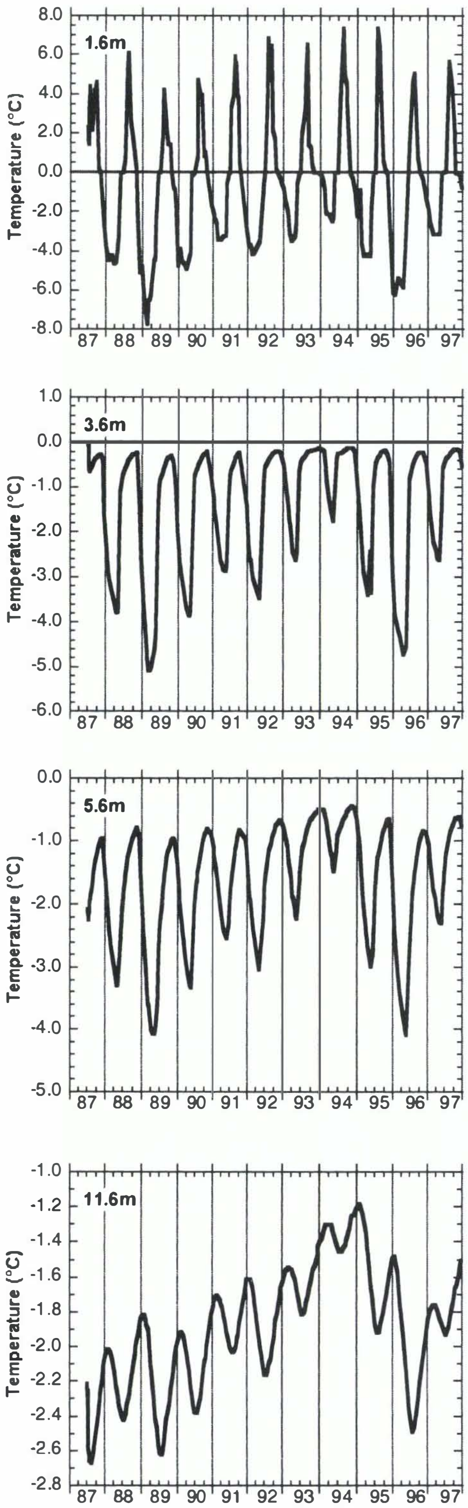

Fig. 5. Borehole temperatures within the active Murtèl–Corvatsch rock glacier between July 1987 and July 1997, at depths of 1.6 m (active layer), 3.6 m (underneath the permafrost table), 5.6 m (nearest thermistor with respect to the moss) and 11.6 m (time-phase lag about half a year). Permafrost temperatures are strongly influenced by snow conditions in individual years (especially thin snow cover in 1988–89 and 1995–96).

ice-core samples for water isotope analyses revealed one piece of moss remains within core Murtèl 2/II/4 at a depth of 5.94 m below surface. The sample was put into double-distilled water within a cleaned, dried and sealed small glass bottle and sent to the Department of Botany of the University of Basel for further analysis. Moss identification was performed at the Botanical Garden of Geneva. Thereafter, the moss remains were prepared for radiocarbon dating at the Institute of Environmental Physics of the University of Heidelberg. Analysis of the final target was done at ETH Zürich.

BOTANICAL/BRYOLOGICAL ANALYSIS

Subfossil stem remains of seven different bryophyte species were found. Table 1 lists the number of individuals counted for each species, together with short descriptions of their ecological preferences following Amann and others (1918) and Meylan (1924), as well as personal observations by one of the authors (P.G.). All considered species commonly occur within Alpine to nival altitude belts. The composition of the moss species points to the growth of the recovered mosses in the nearest surroundings of the drill site Murtèl. Although the individual ecological preferences reflect different habitats, the small-scale density of bryophyte niches may well allow the conclusion that the seven moss species grew close together before they were eroded and subsequently embedded within the rock-glacier permafrost by a process which is not known (snow avalanche, soil erosion, debris flow, rockfall?). Since the sample was found in good preservation conditions, the mosses appear to have been trapped in the ice of the rock-glacier permafrost immediately after deposition. The large amount of *Blindia acuta* remains may indicate that the main original stand was a moist rock.

All stems found were photographed after identification and before being used for pollen analysis and ^{14}C dating. Figure 6 shows the species *Distichium inclinatum* as an example. The extremely good preservation of the moss remains within the permafrost core is obvious: the stems still carry remains of leaflets, showing that secondary processes of deformation were minimal during and after sedimentation. Because leafy mosses serve as ideal pollen traps by concentrating pollen and spores in between leaflets and stems, a pollen analysis was performed on detritic material extracted by a paint-brush, following classical palynological techniques (Moore and others, 1991) at a magnification of 400 and 630 by using phase-contrast microscopy.

A total of 127 pollen and spores representing 23 taxa were determined (Table 2). Percentages of 58% arboreal pollen and 31% non-arboreal pollen and spores (ferns and mosses) were found. This ratio represents well the pollen flora typical for sites above timberline in the region (Heitz, 1975). The arboreal pollen had, therefore, all been blown up to the study site from lower altitudes and represents the regional vegetation composition during the time of sedimentation. The local vegetation during deposition time must be characterized as a moss-rich alpine grassland meadow rich in Cyperaceae, Poaceae, Chenopodiaceae and Asteraceae, comparable to the flora present around the study site today.

This glimpse into the former vegetation mosaic facilitated the characterization of the relative importance of arboreal and non-arboreal pollen influx, and the dating of the moss remains by comparison with results from pollen-analytical investigations on past vegetation at nearby sites (Kleiber, 1974; Heitz, 1975; Welten, 1982; Punchakunnel, 1983; Zoller and Brombacher, 1984; Burga, 1987). The appearance of pollen from fir (*Abies alba*) and spruce (*Picea abies*) made it possible to set a maximum age of the moss remains at approximately 8000 BP. Based on the lack of plant species typical for the

Table 1. Description and present-day ecological characteristics of moss remains found in the permafrost core of the active rock glacier Murtèl–Corvatsch at 5.94 m depth

Species	Family	Numbers found	Distribution	Ecology
Anastrophyllum minutum (Schreb.) Schust.	Lophoziaceae	1	Subalpine–alpine, up to 3000 m a.s.l.	On siliceous rocks, rarely soil
Blindia acuta (Hedw.) Bruch et Schimp.	Seligeriaceae	34	Subalpine–nival, up to 3500 m a.s.l., relatively common, subarctic–alpine floral element	On humid to very wet rocks
Desmatodon latifolius (Hedw.) Brid.	Pottiaceae	3	Subalpine–nival, up to 3500 m a.s.l., very common species, boreal–subalpine floral element	On rich soil and open ground, also on dry and luminous places
Distichium inclinatum (Hedw.) Bruch et Schimp	Ditrichaeae	5	Common in montane regions, 650–3300 m a.s.l., subarctic–subalpine floral element	On damp soil, in rock crevices, often on soil in late-snow areas
Pohlia cf. filum (Schimp.) Mårt.	Bryaceae	2	The specimen probably belongs to the group of bulbiferous Pohlia species often growing on soil in late-snow areas. No propagules were preserved, so it was not possible to identify the specimen to species level	
Racomitrium heterostichum (Hedw.) Brid. s.l.	Grimmiaceae	1	Subalpine–nival regions, up to 3300 m a.s.l., common species, boreal–montane floral element	On dry, often exposed siliceous rocks
Tritomaria scitula (Tayl.) Jorg.	Lophoziaceae	3	Subalpine–alpine, relatively rare species	On humous soil or open siliceous rocks

Roman Age Period, such as walnut (*Juglans regia*) and chestnut (*Castanea sativa*) — both very well distributed by atmospheric currents (Peeters and Zoller, 1988) — a minimum age of 2000 BP was attributed to the moss remains. This younger age limit was later confirmed by the ^{14}C dating of the moss remains to the Iron Age Period.

During the Iron Age (2800–2000 BP), the upper tree limit was composed of larch (*Larix decidua*), pine (*Pinus cembra*) and birch (*Betula spec.*) and must have been at an altitude of <2300 m a.s.l. At that time, it was already heavily influenced by human activities and grazing (Zoller and Haas, 1995).

RADIOCARBON DATING

In order to narrow down the botanical age estimates of the moss sample, an attempt was made to date the specimen instrumentally by the ^{14}C method. In this process, the age is determined from the decay of the cosmogenic ^{14}C isotope incorporated by the moss during its assimilation period and from an assumption about the original ^{14}C content of the atmospheric CO_2. In our case, specific error sources to be accounted for relate to possible sample contaminations by other carbon pools (carbonate and organic soil components). Furthermore, due to the small sample mass (about 0.5 mg Carbon content) positive or negative age shifts may arise from very old or from modern laboratory blanks, respectively. For ^{14}C analysis, accelerator mass spectrometry (AMS) had to be used instead of conventional beta-counting due to the small sample size. The sample preparation procedure and carbon isotope analyses outlined below were carefully cross-checked by processing a series of auxiliary samples (modern sugar coal, ^{14}C free charcoal and recent moss species) along with the Murtèl sample.

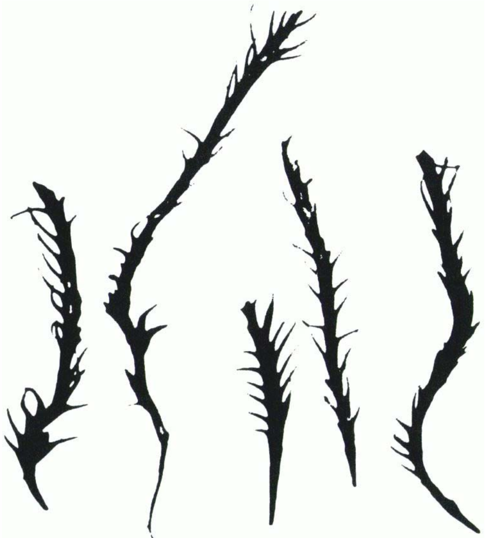

Fig. 6. Moss stems of Distichum inclinatum *from the permafrost core drilling Murtèl–Corvatsch found at a depth of 5.94 m. (Magnification 6.)*

According to various test runs on recent moss specimens, the following procedure was applied for the Murtèl sample at the Heidelberg Laboratory:

1. pooling of all plant fragments into one bulk sample which was then washed, dried, weighted and ground in a mortar to a fine powder;
2. acid treatment of the powder in diluted HCl to remove carbonates. More rigorous steps to extract the organic fraction not associated with the moss (pollen) matrix were avoided in order not to dissolve the sample;
3. stepwise transfer of the suspension onto two small, prefired quartz fiber filters which were gently heated under purified air until dry.

In this way, two practically identical aliquots of the Murtèl moss were obtained with a dry weight of 2.9 and 2.7 mg, respectively. Combustion of the quartz filter samples within a pure O_2 atmosphere was initiated by an external heat source. The resulting CO_2 amount was manometrically determined after purification by an activated charcoal trap and then cryogenically transferred into a glass vial for sub-

Table 2 [illegible] *found on the subfossil moss remains from the permafrost core-drilling Murtèl–Corvatsch*

Species	*Number found*	*Percentage* %
Trees and Shrubs		
Abies alba (Fir)	8	6.3
Alnus (Alder)	11	8.7
Betula (Birch)	1	0.8
Corylus avellana (Hazel)	8	6.3
Juniperus (Juniper)	2	1.6
Picea abies (Spruce)	6	4.7
Pinus (Pine)	30	23.6
Quercus (Oak)	1	0.8
Salix (Willow)	4	3.1
Tilia cordata-type (Lime)	1	0.8
Ulmus (Elm)	2	1.6
Total	**74**	**58.3**
Herbs		
Artemisia (Mugwort)	1	0.8
Asteraceae (Composits)	2	1.6
Chenopodiaceae (Chenopods)	2	1.6
Cyperaceae (Sedges)	11	8.7
Ericaceae (Heaths)	1	0.8
Poaceae (Grasses)	7	5.5
Rosaceae (Roses)	1	0.8
Urtica (Nettle)	2	1.6
Total	**27**	**21.4**
Ferns and Mosses		
Pteridophyta (Fern-spores)	5	3.9
Lycopodium (Clubmoss-spores)	1	0.8
Bryophyta-trilete (Moss-spores)	3	2.4
Bryophyta-inaperturate (Moss-spores)	3	2.4
Total	**12**	**9.5**
Varia and Indeterminata		
Varia	6	4.7
Indeterminata	8	6.3
Total	14	11.0
Fungal spores and Charcoal particles		
Fungal spores	5	
Charcoal particles (<50 μm)	15	
Total	**20**	

sequent $\delta^{13}C$ analysis. Pilot runs on recent moss samples from the Heidelberg area gave yields of approximately 65–98%, with a systematic enrichment of the $\delta^{13}C$ values towards higher yields by up to 0.5 per mil. No large isotope-fractionation effects were observed otherwise. Elemental carbon required for the AMS measurement was obtained by catalytic reduction of the CO_2 sample in H_2 at 570°C (Schlosser and others, 1987). Procedures for preparation and analysis of the final target at the ETH Zürich AMS facility are described by Suter (1990).

The carbon-isotope results from the two Murtèl moss subsamples are summarized in Table 3 along with the respective reference samples. As illustrated by Figure 7, the mean conventional ^{14}C age of the Murtèl moss of 2250 ± 100 years (1σ variability) corresponds to ranges in the calibrated calendar age of 470–170 BC and 800 BC to AD 0 at statistical probabilities of 68% and 95%, respectively. The $\delta^{14}C$ values from the recent moss and the recent sugar-coal reference sample appear to be underestimated by up to 60‰, suggesting a contamination by some old carbon components. This systematic deviation was depicted from comparisons with the current atmospheric $^{14}CO_2$ record at Heidelberg (personal communication from I. Levin, 1995) and with low-level counting results giving $\delta^{14}C$ = 362‰ ±3‰ for the sugar-coal sample (personal communication from B. Kromer, 1995). As shown by the low process blank of the ^{14}C free Tremonia coal, no significant contamination by modern carbon has to be considered, however. On the other hand, referring to the adopted overall analytical uncertainty in the ^{14}C analysis of approximately 10 per mil, there is perfect agreement between the ^{14}C values of the two Murtèl aliquots, making random contamination less likely. For this reason, no downward correction of the Murtèl ^{14}C ages due to dead carbon contamination (which would account for a maximum of 500 years) was performed.

Table 3. ^{14}C results of Murtèl and the two respective test samples. ^{13}C values are given in δ notation as the deviation of $^{13}C/^{12}C$ ratios relative to the VPDB standard in per mil. ^{14}C activities as ^{13}C corrected ratios relative to NBS–oxalic acid in per mil

Sample name	$\delta^{13}C$ % VPDB	$\delta^{14}C$ %	^{14}C *age* years BP
Tremonia coal*	−24.97	−984.5	33100 ± 100
Sugar coal	−19.5	312	−2130 ± 100
Recent moss	−27.97	40	−235 ± 100
Murtèl I (ETH-Nr. 14228)	−21.27	-258	2340 ± 100
Murtèl II (ETH-Nr. 14229)	−21.19	−242	2165 ± 100
Murtèl average I/II			2250 ± 100

* Process-blank value for moss correction.

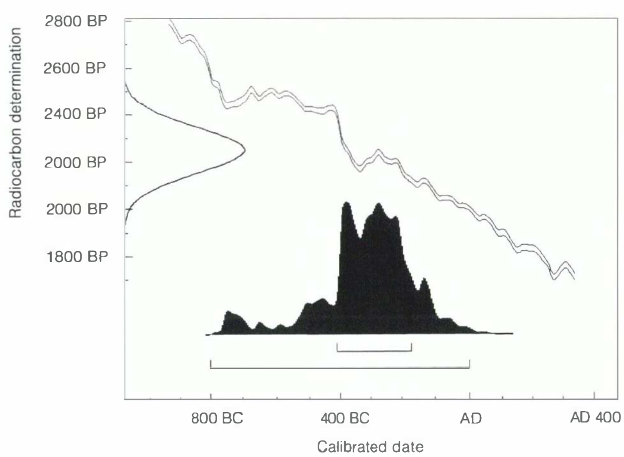

Fig. 7. Calibration of conventional ^{14}C age of moss sample (2250 ± 100 BP) after Stuiver and Reimer (1993) giving calibrated date ranges of 400 BC–160 BC at 1σ (short horizontal bar) and 800 BC–AD 0 at 2σ (long bar) confidence levels; normally distributed ^{14}C ages are indicated at the ordinate.

The relatively well-preserved habitus of the moss remains as well as of the pollen scavenged by them suggests an insignificant residence time of the material on the rock-glacier surface before becoming ultimately isolated from its ambient environment by incorporation into the ice matrix. Hence, the ^{14}C age of the moss may not be much influenced by other carbon pools and is expected to be well representative of the age of the hosting ice layer. Although no further macroscopic plant fragments have been detected so far in the Murtèl cores, micro-plant debris may be abundant (though not easily recognized on visual inspection). Hence, extracting this material by selective concentration steps would lead to bulk particulate organic carbon (POC) samples, sufficiently large for further AMS ^{14}C datings. The same is expected for dissolved organic carbon (DOC) components eventually washed down from overlying soil patches or even from sparsely colonized rock debris.

GEOMORPHOLOGICAL AND GLACIOLOGICAL INTERPRETATION

The ^{14}C dating of the moss remains found in the permafrost core recovered from the active rock glacier Murtèl now constitutes the first absolute age determination of creeping Alpine permafrost available: ground ice at the site of the core-drilling within Murtèl rock glacier has existed for at least 2000 years. Earlier estimates from flow considerations are, thus, clearly confirmed: the ice within active rock glaciers is thousands of years old and by far predates recent climatic events such as the Little Ice Age. Moreover, this absolute age determination of a permafrost layer allows some general conclusions to be drawn about long-term flow velocities, landform genesis, rates of ice formation, rockfall activity and cliff retreat at an active rock glacier as well as about conditions for preservation of old ice in cold mountain areas.

With the time of existence of the sample being known, the average flow velocity of the creeping permafrost during the considered time period can be estimated if the place of moss deposition and, hence, the travel distance to the drill site can be defined. A (hardly realistic) minimum travel distance and long-term flow velocity (both 0) are given by the assumption that the moss had been directly deposited at the drill site in its present-day position. A corresponding maximum limit can be established by assuming that the moss had been deposited at the very foot of the rock wall at the head of the rock glacier and then traveled by permafrost creep over the full distance to today's borehole. In such a case, the average flow velocity along the trajectory to the borehole would have been some 25% higher than at present. The most plausible case is in between the two extremes: the moss may have been transported from the headwall to the rock-glacier surface by a rockfall event or a snow avalanche traveling over some runout distance but not reaching the drill site in the current position. The present-day flow field (Fig. 3), in fact, indicates that the moss remains may have been deposited some 100 m from the foot of the rock wall. In any case, the characteristic average long-term flow velocity is in the range of cm a^{-1}, closely corresponding to values measured at present.

Such an estimated long-term surface velocity of a few cm a^{-1} confirms that the flow of the rock-glacier permafrost indeed corresponds to a secondary (steady-state) viscous-flow mode of ice-supersaturated debris, where constant stress leads to constant strain rates (Olyphant, 1983, 1987; Haeberli, 1985; Wagner, 1992). The constant rate of the flow over long time periods thereby indicates that, during the past two millennia, dramatic changes in rheological characteristics as influenced by material properties or thermal conditions are unlikely to have taken place and that surface slope and permafrost thickness which exert a predominant influence on the stress field within the creeping ice/rock mixture must have remained quite similar to the present ones. The rock glacier as a landform expressing the cumulative straining of perennially frozen, ice-rich debris must, therefore, be considerably older than 2000 years.

The total age of the rock glacier, i.e. the beginning of its formation, can be estimated only roughly. In terms of specifics, many questions remain unanswered. Estimates can be based on (1) consideration of the obvious inertia and long-term stability of the flow field, and (2) extrapolation of the vertical time-scale to greater depth. The photogrammetrically determined velocities along the central trajectories of Murtèl rock glacier indicate a surface age of about 3000 years at the borehole, where the moss remains were found, and a surface age of about 6000 years at the actively advancing front. Integration of the currently measured ratio between the rate of advance and the surface velocities over present flow trajectories yields an age estimate for the Murtèl rock glacier of roughly 10^4 years. Assuming that 6 m of ice (3 m) and debris (3 m) had accumulated above the moss remains and that the rate of ice and debris accumulation (3 mm a^{-1}) remained constant through time, the age of the layers within the shear horizon at 30 m depths can, again, be estimated at some 10^4 years. It appears quite reasonable to assume that rock-glacier formation may have started during the final stages of the last Ice Age or with the onset of the Holocene. The bulk of the creeping ice/rock mixture is likely to be several thousand years old.

Ice formation above the moss remains could have taken place at a characteristic rate of mm a^{-1} by means of freezing processes at the permafrost table during the building up of the surficial debris layer (at a comparable rate of mm a^{-1}). This part of ground ice formation would represent syngenetic permafrost aggradation. The most likely process thereby involved is refreezing of snow meltwater percolating into the still cold active layer during spring (Keller and Gubler, 1993) and producing high-resistivity ice with a relatively low ion content (Haeberli and Vonder Mühll, 1996). Taking into account the porosity of the coarse blocks at the surface, the ice content by volume over the total ice/debris thickness above the moss remains is about 50–70%. Such a supersaturation is commonly observed in Alpine permafrost boreholes (Vonder Mühll and Holub, 1992; Vonder Mühll, 1996) and constitutes the basis for the observed steady-state creep of the rock-glacier permafrost. The amount of debris which has been deposited at the rock-glacier surface over the past 2000 years along the central flowline to the borehole roughly corresponds to a retreat of the 200 m high rock headwall of 3 m or 1–2 mm a^{-1}. Based on an average width of the rock glacier and the rock headwall of 150–250 m, some 30–100 m^3 of rocks are likely to have fallen onto the rock-glacier surface every year. During the entire Holocene time period, this would add up to a total of 300 000–1 000 000 m^3 of debris. Assuming that the rock-glacier permafrost acts as a perfect sediment trap (no loss of rock material from meltwater erosion) and comparing it with a total rock-glacier volume of $2–3 \times 10^6$ m^3 provides again a characteristic ice content by volume of 50–90%.

The largest and most conspicuous ice bodies in the Alps are the surface ice masses of the numerous glaciers. With characteristic lengths of kilometers and characteristic flow velocities of meters to tens of meters per year, however, the age of such ice in glaciers is usually limited to a few centuries. Much older ice can be found in cold-based parts of glaciers on wind-exposed crests and at very high altitudes. Examples are the summit ice of Titlis (Lorrain and Haeberli, 1990), the ice-core drilling site on Colle Gnifetti, Monte

Rosa (Haeberli, 1994; Wagenbach, 1994; Wagner, 1994), or the ice on saddles, which, for instance, contained the Ötztal ice man at Hauslabjoch or the archeological bows at Lötschental (Haeberli, 1994; Baroni and Orombelli, 1996). Ice considerably older than a few centuries has also been detected in perennial snow banks of the Japanese Alps (Yamamoto and Yoshida, 1987; Yoshida and others, 1990). All these occurrences concern surface ice within an environment of mountain permafrost. The present study confirms that old ice also exists within the permafrost itself. The scientific investigation of such old ice archives in mountain areas is at its very beginning and deserves more attention.

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REFERENCES

Amann, J., Ch. Meylan and P. Culmann. 1918. *Flore des mousses de la Suisse.* Lausanne, Imprimeries Réunies S.A.

Baroni, C. and G. Orombelli. 1996. The Alpine "iceman" and Holocene climatic change. *Quat. Res.*, **46**(1), 78–83.

Barsch, D. 1996. *Rockglaciers: indicators for the present and former geoecology in high mountain environments.* Berlin, etc., Springer-Verlag. (Springer Series in Physical Environment 16.)

Brown, J. 1965. Radiocarbon dating, Barrow, Alaska. *Arctic*, **18**(1), 37–48.

Burga, C. A. 1987. Gletscher- und Vegetationsgeschichte der Südrätischen Alpen seit der Späteiszeit (Puschlav, Livigno, Bormiese). *Denkschr. Schweiz. Naturforsch. Ges.*, **101**, 1–162.

Cheng Guodong and F. Dramis. 1992. Distribution of mountain permafrost and climate. *Permafrost and Periglacial Processes*, 3(2), 83–91.

Elconin, R. F. and E. R. LaChapelle. 1997. Flow and internal structure of a rock glacier. *J. Glaciol.*, **43**(144), 238–244.

Haeberli, W. 1985. Creep of mountain permafrost: internal structure and flow of Alpine rock glaciers. *Eidg. Tech. Hochschule, Zürich. Versuchsanst. Wasserbau, Hydrol. Glaziol. Mitt.* 77.

Haeberli, W. 1994. Glaciological basis of ice-core drilling on mid-latitude glaciers. *VAW/ETHZ Arbeitsheft* 14, 3–9.

Haeberli, W. and D. Vonder Mühll. 1996. On the characteristics and possible origins of ice in rock glacier permafrost. *Z. Geomorphol.*, Supplementband 104, 43–57.

Haeberli, W., J. Huder, H.-R. Keusen, J. Pika and H. Röthlisberger. 1988. Core drilling through rock glacier–permafrost. *In* Senneset, K., *ed. Permafrost. Fifth International Conference. Proceedings. Vol. 2. August 2–5, 1988.* Trondheim, Tapir Publishers, 937–942.

Haeberli, W., M. Hoelzle, F. Keller, W. Schmid, D. S. Vonder Mühll and S. Wagner. 1993. Monitoring the long-term evolution of mountain permafrost in the Swiss Alps. *In Permafrost. Sixth International Conference. Proceedings, Vol. 1, July 5–9 1993, Beijing, China.* Guangzhou, South China University of Technology Press, 214–219.

Heitz, Ch. 1975. Vegetationsentwicklung und Waldgrenzschwankungen des Spät- und Postglazials im Oberhalbstein (Graubünden/Schweiz) mit besonderer Berücksichtigung der Fichteneinwanderung. *Beiträge zur Geobotanischen Landesaufnahme der Schweiz*, 55, 1–63.

Hoelzle, M. 1996. Mapping and modelling of mountain permafrost distribution in the Alps. *Nor. Geogr. Tidsskr.*, **50**(1), 11–15.

Kääb, A., W. Haeberli and G. Gudmundsson. 1997. Analysing the creep of mountain permafrost using high precision aerial photogrammetry: 25 years of monitoring Gruben Rock Glacier, Swiss Alps. *Permafrost and Periglacial Processes*, **8**(4), 409–426.

Keller, F. and H. U. Gubler. 1993. Interaction between snow cover and high mountain permafrost, Murtèl–Corvatsch, Swiss Alps. *In Permafrost. Sixth International Conference. Proceedings, Vol. 1, July 5–9 1993, Beijing, China.* Guangzhou, South China University of Technology Press, 332–337.

Kleiber, H. 1974. Pollenanalytische Untersuchungen zum Eisrückzug und zur Vegetationsgeschichte im Oberengadin I. *Bot. Jahrb. Syst. Pflanzengesch. Pflanzengeogr.*, **94**(1), 1–53.

Lorrain, R. and W. Haeberli. 1990. Climatic change in a high-altitudinal alpine area suggested by the isotopic composition of cold basal glacier ice. *Ann. Glaciol.*, **14**, 168–171.

Meylan, Ch. 1924. Les hépatiques de la Suisse. *Beitr. zur Kryptogamenflora der Schweiz*, **6**(1).

Moore, P. D., J. A. Webb and M. E. Collinson. 1991. *Pollen analysis.* Oxford, etc., Blackwell Scientific Publications.

Olyphant, G. A. 1983. Computer simulation of rock-glacier development under viscous and pseudo plastic flow. *Geol. Soc. Am. Bull.*, **94**(4), 499–505.

Olyphant, G. A. 1987. Rock glacier response to abrupt changes in talus production. *In* Giardino, J. R., J. F. Shroder, Jr and J. D. Vitek, *eds. Rock glaciers.* London, Allen and Unwin, 55–64.

Peeters, A. G. and H. Zoller. 1988. Long range transport of *Castanea sativa* pollen. *Grana*, **27**, 203–207.

Punchakunnel, P. 1983. Pollenanalytische Untersuchungen zum Eisrückzug und zur Vegetationsgeschichte im Oberengadin II (Lej Marsch, Mauntschas, Stazerwald). (Inauguraldissertation, Universität Basel.)

Schlosser, P. *and 7 others.* 1987. Measurement of small volume oceanic ^{14}C samples by accelerator mass spectrometry. *Radiocarbon*, **29**(3), 347–352.

Stuiver, M. and P. J. Reimer. 1993. Extended ^{14}C data base and revised CALIB 3.0 ^{14}C age calibration program. *Radiocarbon*, **35**(1), 215–230.

Suter, M. 1990. Accelerator mass spectrometry: state of the art in 1990. *Nucl. Instrum. Methods Phys. Res., Ser. B*, **29**, 211–223.

Vonder Mühll, D. S. 1992. Evidence of intrapermafrost groundwater flow beneath an active rock glacier in the Swiss Alps. *Permafrost and Periglacial Processes*, **3**(2), 169–173.

Vonder Mühll, D. S. 1996. Drilling in Alpine permafrost. *Nor. Geogr. Tidsskr.*, **50**(1), 17–24.

Vonder Mühll, D. and W. Haeberli. 1990. Thermal characteristics of the permafrost within an active rock glacier (Murtèl/Corvatsch, Grisons, Swiss Alps). *J. Glaciol.*, **36**(123), 151–158.

Vonder Mühll, D. S. and P. Holub. 1992. Borehole logging in Alpine permafrost, upper Engadine, Swiss Alps. *Permafrost and Periglacial Processes*, **3**(2), 125–132.

Vonder Mühll, D., Th. Stucki and W. Haeberli. In press. Borehole temperatures in Alpine permafrost: a ten-year series. *In 7th International Conference on Permafrost, 23–27 June 1998, Yellowknife, N.W.T., Canada. Proceedings.* Ottawa, Ont., Geological Survey of Canada.

Wagenbach, D. 1994. Results from the Colle Gnifetti ice-core programme. *VAW/ETHZ Arbeitsheft* 14, 19–22.

Wagner, S. 1992. Creep of alpine permafrost investigated on the Murtèl rock glacier. *Permafrost and Periglacial Processes*, **3**(2), 157–162.

Wagner, S. 1994. Three-dimensional flow and age distribution at a high-altitude ice-core drilling site. *VAW/ETHZ Arbeitsheft* 14, 33–39.

Wahrhaftig, C. and A. Cox. 1959. Rock glaciers in the Alaska Range. *Geol. Soc. Am. Bull.*, **70**(4), 383–436.

Welten, M. 1982. Pollenanalytische Untersuchungen zur Vegetationsgeschichte des Schweizerischen Nationalparks. *Ergeb. Wiss. Unters. Schweiz. Nationalpark*, **16**(80), 1–43.

Yamamoto, K. and M. Yoshida. 1987. Impulse radar sounding of fossil ice within the Kuranosuke perennial snow patch, central Japan. *Ann. Glaciol.*, **9**, 218–220.

Yoshida, M., K. Yamamoto, K. Higuchi, H. Iida, T. Ohata and T. Nakamura. 1990. Correspondence. First discovery of fossil ice of 1000–1700 year B.P. in Japan. *J. Glaciol.*, **36**(123), 258–259.

Zoller, H. and Ch. Brombacher. 1984. Das Pollenprofil "Chalavus" bei St. Moritz: ein Beitrag zur Wald- und Landwirtschaftsgeschichte im Oberengadin. *Diss. Bot.* 72, Festschrift Welten, 377–398.

Zoller, H. and J. N. Haas. 1995. War Mitteleuropa ursprünglich eine halboffene Weidelandschaft oder von geschlossenen Wäldern bedeckt? *Schweiz. Z. Forstwes.*, **146**(5), 321–354.

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