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# Characteristics and potential climatic significance of "miniature ice caps" (crest- and cornice-type low-altitude ice archives)

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ABSTRACT. Long-term ice-core records of Alpine glaciers are usually taken from cold-firn areas at high altitudes, as on Mont Blanc and Monte Rosa. Perennial ice bodies at lower altitudes, however, also bear information about the past. Recent findings from the remains of such ice (the Oetztal iceman found in Austria; wooden bows at Lötschen Pass, Switzerland) clearly indicate the hitherto little-recognized fact that small, more-or-less static perennial ice bodies which are cold and frozen to the underlying bedrock may contain very old ice and, hence, important palaeoclimatic information about warm periods with minimum ice extent in the Alps. Since autumn 1998, investigations have been initiated on a crest-type location or "miniature ice cap" at Piz Murtèl, Engadine, Swiss Alps. First results from shallow drilling, temperature data-logging, geodetic surveying, visual observation, finite-element modelling of simplified basic two-dimensional configurations and comparison to earlier measurements at similar sites provide promising perspectives concerning a little-studied phenomenon with considerable scientific-environmental research potential. Specific characteristics of the investigated site, and probably of many other comparable mountain sites, are: cold ice (about $-4^{\circ}$C at 10 m depth), no basal sliding, small mass turnover, striking lack of a firn zone, accumulation mainly by superimposed ice, and direct access to old layers (centuries, millennia?) at the ice/bedrock interface.

## INTRODUCTION

The largest and most conspicuous ice bodies in the Alps are the numerous glaciers. Characteristic lengths are in kilometres, and characteristic flow velocities vary from metres to tens of metres per year. The age of the ice in these glaciers is usually limited to a few centuries. Much older ice (Holocene to possibly late-Pleistocene) can be found at very high altitudes where cold-firn layers accumulate (e.g. Oeschger and others, 1978; Haeberli and others, 1983; Alean and others, 1984; Haeberli and Alean, 1985; Haeberli and Funk, 1991; Lüthi and Funk, 2000; Suter and others, 2001). These cold-firn/ice archives are highly suitable for deriving information on earlier atmospheric compositions by the study of their ice cores. Long-term ice-core records from sites such as Colle Gnifetti, Monte Rosa, and Col du Dôme, Mont Blanc, better reflect the continental source regions of concern because of their intimate connection to them (cf. Wagenbach, 1989; Haeberli and Stauffer, 1993; Wagenbach and others, 1996; Lavanchy and others, 1999; Schwikowsky and others, 1999).

Holocene ice is also known to exist in the permafrost of rock glaciers (Haeberli, 1990; Haeberli and others, 1999b; Konrad and others, 1999). Moreover, wind-exposed ice crests and firn/ice divides are not temperate, but cold and frozen to the underlying (permafrost) bedrock (Haeberli and Alean, 1985; Haeberli and Funk, 1991). Recent findings (the Oetztal iceman found in Austria and wooden bows from Lötschental, Switzerland) from similar situations reveal that small and more-or-less static perennial ice bodies which are slightly cold and frozen to the underlying bedrock may well contain very old ice. This is highly relevant for palaeoclimatic assessments. The reconstruction of former glacier advances on the basis of mapped and analyzed morainic deposits enables definition of past maximum stages of glacierization. Such reconstructions provide important information on the "cool" (low-energy) boundary of pre-industrial ice and climate variability (Haeberli and others, 1999a). Strategies for early climate-change detection, however, require information about minimum ice extents or the "warm" (high-energy) limits of such Holocene ice and climate variability. Besides other techniques such as the dendrochronological analyses of formerly glacier-buried tree trunks, the investigation of small and more-or-less static perennial ice bodies could therefore provide important palaeoclimatic information on warm periods with minimum ice extent in the Alps.

Perennial snowbanks and glacierets frozen to the ground constitute virtually unexplored low-altitude ice archives which contain potentially important information on Holocene climatic variability. They are now being investigated, the main goals being to

(1) describe their glaciological characteristics (thickness, temperature, structure, flow, age, ice accumulation) and

(2) analyze the information contained within the ice (stable isotopes, impurities, organic matter, etc.) with a view to helping with climatic interpretations.

The present paper briefly reviews the limited information available from earlier studies, reports results from first measurements and observations from an ice crest in the Engadine (Piz Murtèl) and provides conclusions and recommendations about the climate-related significance of such sites.

## OLD COLD ICE AT LOW ALTITUDE

Extraordinarily important evidence about minimum glacierization has recently emerged from ice sites at low altitudes, one of the most spectacular cases being the finding of the Oetztal iceman. Special glaciological conditions explain the perfect conservation (cf. Sjøvold, 1996) of this body which had been buried by snow and ice in a small topographic bedrock depression on a crest/saddle site at Hauslabjoch, Austrian Alps (3200 m a.s.l.), more than 5000 years ago and which remained in place until it melted free in 1991 (Spindler and others, 1995; Baroni and Orombelli, 1996). Burial of the Oetztal iceman most likely happened in a storm with a rapid accumulation of cold snow within the topographic depression where the body rested on bare bedrock. The theory that it is a fake (Heim and Nosko, 1993) is unconvincing because artificial production of such a large mass of ice around the body would not have gone undetected. The lack of animal traces on the skin indicates that the body was rapidly buried under a snow layer and quickly froze solid. This condition persisted for many millennia (the probability level of such coincidences is astonishing). As the site is within the Alpine permafrost belt today, temperatures at the base of the winter snow cover must have been several degrees below 0°C (Haeberli, 1973; Keller and Gubler, 1993; Hoelzle and others, 1999), enabling an effective freeze-drying of the body. Refreezing of spring meltwater in cold snow probably caused an ice crust to form around the body which perfectly protected it against water and air during the summer. Later, the build-up of cold ice above the body is likely to have prevented surface meltwater percolation and, hence, kept the body well frozen and isolated from the air and meltwater. Significant basal sliding could not take place at the base of this thin, cold ice frozen to the bedrock, and low to zero basal shear stress at the firn/ice divide limited ice deformation (Haeberli and Stauffer, 1993). Besides its outstanding archaeological interest, the Oetztal iceman shed light on glaciological processes of quite unexpected interest and significance. These concerned ice formation and basal-layer evolution within low-altitude ice archives.

Three well-preserved wooden bows and a number of other archaeological objects had been discovered as early as 1934 and 1944 at a saddle site (Lötschen Pass, Swiss Alps) comparable to Hauslabjoch but at an even lower altitude (2700 m a.s.l.). At first the discovery aroused neither archaeological nor glaciological interest. Recent $^{14}$C–accelerator-mass-spectrometry dating of the three bows gave dendrochronologically corrected ages of around 4000 calendar years (Bellwald, 1992). This confirms the remarkable finding from the Oetztal iceman, i.e. that warming periods comparable to those of the 20th century had occurred previously but the extent of glaciers and permafrost in the Alps may be more reduced today than it ever was during the Upper Holocene.

*Fig. 1. The ice crest on the Sphinxgrat, Jungfraujoch, from the north, with the astronomical/meteorological observatory on the (permafrost–) rock summit, before construction of the new restaurant. (Photograph taken from helicopter by W. Haeberli, July 1986.)*

Some basic glaciological information about cold ice on crests and summits is available from earlier consulting work done at the Jungfraujoch and Titlis in the Swiss Alps (Haeberli and others, 1979, 1992).

At the Jungfraujoch (Fig. 1), core drilling from the crest top of the Sphinxgrat, located at about 3500 m a.s.l., down to the level of the train station went through about 10 m of firn/ice, 12 m of granite containing appreciable amounts of ice, 13 m of limestone and, again, about 35 m of granite (Keusen and Amiguet, 1987; cf. Wegmann, 1998, for more recent permafrost investigations at the site). Temperature measurements in this borehole, corrected for thermal drilling disturbances, gave a mean annual bedrock temperature of about −6°C at the ice/bedrock interface. Stake measurements over a 4 month period showed that the south side of the ice moved considerably faster (0.2–0.8 m a$^{-1}$) than the north side (0.1–0.2 m a$^{-1}$). Finite-element modelling was based on the assumptions of plain strain, stress-independent viscosity, uniform density (850 kg m$^{-3}$), incompressibility and no crevasses. Maximum shear stress was calculated to be about 0.05–0.08 MPa in the basal part of the ice crest. Accumulation rates, inferred from an assumed constant geometry, were estimated to be small (centimetres to decimetres per year). At that time the age of the basal layers was of no interest. Zero flow at the ice/bedrock interface and small flow vectors calculated underneath the crest nevertheless demonstrate that the maximum age at the ice/bedrock interface may primarily depend on the past evolution (appearance/disappearance) of the entire ice crest rather than on ice flow in a steady-state mode.

Glaciological aspects of summit ice or a "miniature ice cap" covering the peak of Chli Titlis (Fig. 2), central Alps, were investigated in connection with the construction of a telecommunication tower having its foundation in perennially frozen bedrock. The summit itself is a kind of cornice

*Fig. 2. The "miniature ice cap" on the summit of Chli Titlis from the summit of Titlis, before construction of the telecommunication tower. (Photograph by W. Haeberli, June 1979.)*

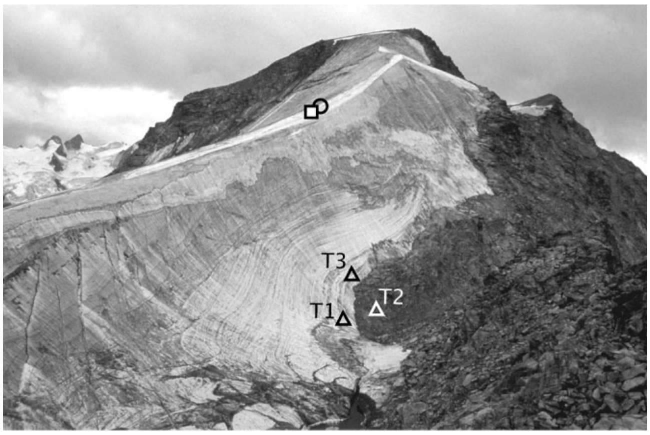


*Fig. 3. The ice crest or "miniature ice cap" at Piz Murtèl (3433 m a.s.l.) from the summit station of the Corvatsch cable car. The ice crest is around 500 m long and slightly asymmetric, with a cornice and a steep, approximately 45 m high leeward slope facing northwestwards. Measurement locations are marked as follows: ○, ice-core drill site; □, borehole for temperature measurements; △, locations of miniature temperature data loggers (UTL1). The drill site and the borehole are located at 3340 m a.s.l. (Photograph by R. Frauenfelder, August 1998.)*

consisting, on the lee side, of well-layered ice roughly 25 m thick and at −0.7°C at 15 m depth in 1979/80. The thickness of the firn layers on the windward side increased downslope from 0 m at the summit to about 15 m at the bergschrund. Bedrock temperatures were measured during the construction of a tunnel through the bedrock, under the summit ice, that connected the cable-car station to the tower. Temperatures increased from −1.5°C, near the cable-car station on the north-exposed slope, to −0.5°C at what was planned to be the tower foundation on the south side. Temperatures in an ice tunnel for tourists (at the northern end of the rock tunnel) varied slightly around −1°C and increased towards the bergschrund, with increasing ice/firn thickness and meltwater percolation through small crevasses at the end of the tunnel. Finite-element modelling, assuming plain strain, stress-independent viscosity and no crevasses, showed that, for an assumed steady state of the summit ice cover, the computed flow vectors indicated a spatial distribution of accumulation which corresponds to a cornice. The largest losses occur due to submergence flow and are compensated for on the lee side (with respect to the predominant winds, coming from west to northwest) during precipitation events. Accumulation rates on the flat summit area generally seem to be low. Negative temperatures reach far into the underlying bedrock, and basal flow velocity approaches zero, making it possible for old ice to exist at depth. Samples taken from the ice/bedrock interface in the ice tunnel for tourists at the northern slope of the summit confirmed a striking shift in $^{18}O/^{16}O$ values (Lorrain and Haeberli, 1990). Even though an Ice Age origin is not necessarily the cause of this interesting shift in isotopic concentration, it is considered probable that the basal layers are of a high age.

Three interesting cases, from non-Alpine countries, are known to the authors. The "miniature ice cap" (the summit ice crest) of Kebnekaise, northern Sweden, sometimes exhibits distinct ice layers (Holmlund, 1998) which resemble those seen at Chli Titlis but exhibit more pronounced lateral variations. Ice considerably older than a few centuries has been detected within perennial snow banks in the Japanese Alps (Yamamoto and Yoshida, 1987; Yoshida and others, 1990). Organic matter from caribou remains, dating back to 2450 ± 50 years BP, was found within the surface layers of perennial ice patches in northern Canada (V. E. Bowyer and others, unpublished information).

## FIRST MEASUREMENTS AT THE MURTÈL–CORVATSCH ICE CREST

Ice summits/crests and more-or-less static perennial ice patches frozen to the ground can contain very old ice and, hence, important palaeoclimatic information. The basic characteristics of such potential low-altitude ice archives must be better understood, however, in order to enable more systematic studies in the future. To this end, an inventory of perennial ice patches was compiled by interpretation of aerial photography and field checking in the dryer parts of the Swiss Alps (Valais and Grisons; Frauenfelder and R.W. Haeberli, unpublished information). One selected site, the ice crest at Piz Murtèl, upper Engadine, eastern Swiss Alps, is now being investigated in more detail. This section reports first results from the investigation at Piz Murtèl, obtained by shallow drilling, borehole temperature measurements, temperature data-logging at the ice/rock interface, geodetic surveying, regular visual observation and preliminary finite-element modelling.

The ice crest or "miniature ice cap" under study is around 500 m long and slightly asymmetric, with a cornice and a steep (35–40°), approximately 45 m high leeward slope facing towards the northwest (Fig. 3). It leads from a wind-exposed firn/ice saddle a few tens of metres below the summit station of the Corvatsch cable car (3295 m a.s.l.) to Piz Murtèl (3433 m a.s.l.). The foundations of the cable-car station are in a small rock summit with mean annual permafrost temperatures of −3 to −4°C and an active-layer thickness of around 2–2.5 m. Vertical heat flow is around 75–100 mW m$^{-2}$, and permafrost thickness probably exceeds 100 m (personal communication from F. Keller, 1999).

The summer of 1998 was especially hot, and caused extreme ablation and loss of mass from the glaciers in the Swiss Alps (Hoelzle and others, 2000). As a consequence, snow at Piz Murtèl melted right back to the crest, and a striking sequence of more-or-less crest-parallel ice layers



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*Fig. 4. The ice layering and superimposed ice on the lee slope of the Murtèl "miniature ice cap". (Photograph by W. Haeberli, August 1998.)*

was exposed on the leeward slope of the ice crest. The immediate impression was that the snow was transformed into ice on the crest via melting and refreezing of the snow (superimposedice formation) and that the corresponding crest-parallel ice layers were submerged at the top of the ridge but re-emerged at lower parts of the slope due to ice deformation effects (subsidence of the crest/peak and bulging of the lateral slopes). Repeated visual inspection and preliminary finite-element modelling (see below) seem to confirm this hypothesis. The fine stratigraphy exposed in 1998 consisted of strata which thin progressively towards the ice/bedrock interface and indicate that >100 if not

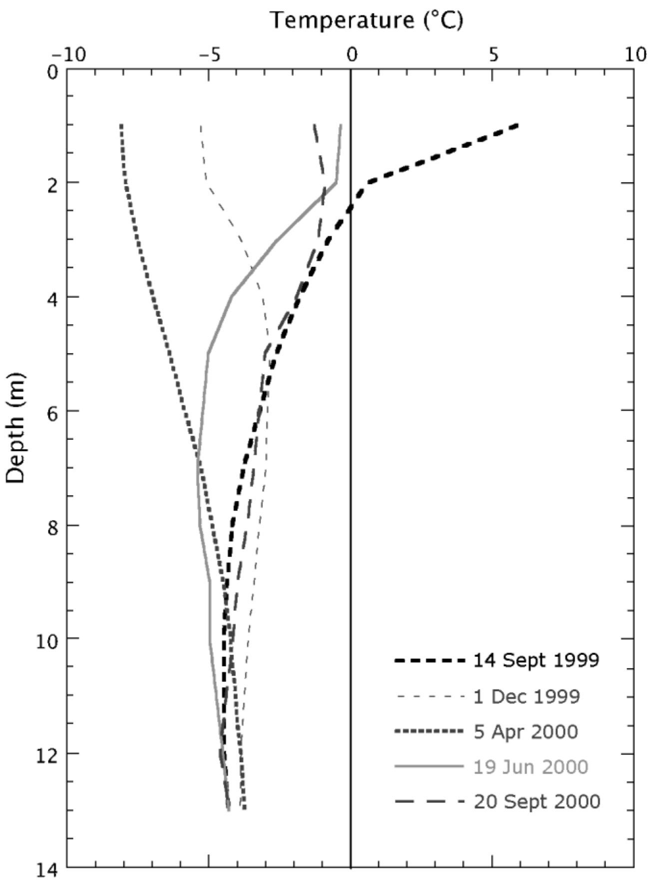


*Fig. 5. Selected examples of seasonal temperature/depth profiles from the borehole on the crest of the Piz Murtèl "miniature ice cap" (April 1999–September 2000).*

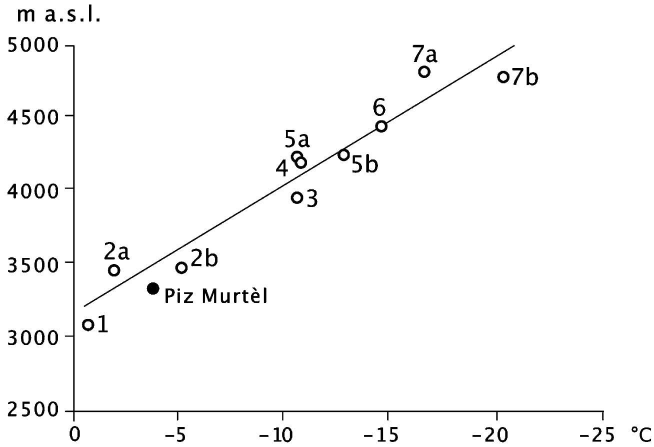


*Fig. 6. Compilation of mean annual temperatures within cold-firn saddles and "miniature ice caps" of the European Alps. Modified after Haeberli and Funk (1991). Numbers in the graph refer to the following sites: 1. Chli Titlis; 2a. Jungfraujoch (saddle); 2b. Jungfraujoch (crest); 3. Fletschhorn; 4. Dufoursattel; 5a/5b. Col du Dôme; 6. Colle Gnifetti; 7a/7b. Mont Blanc. The two sites at Col du Dôme and the two at Mont Blanc illustrate the strong local-scale variability of englacial temperatures under conditions of complex saddle/summit topography. Dufoursattel is a saddle near Dufourspitze, the highest summit of Monte Rosa.*

several hundreds of layers could have formed in this way. Visual observations during frequent visits, together with comparisons of photographs taken at regular time intervals, showed that processes on the lee slope include (a) snow erosion at the saddle below the cable-car station by northeasterly winds that blow when there is a stable anticyclonic pressure distribution, (b) cornice break-offs and snow avalanches in dry as well as wet snow and (c) superimposed-ice formation partially to entirely covering the foot of the slope (Fig. 4).

In February 1999, a 6 m long core was drilled on the crest at 3340 m a.s.l. (about halfway up to Piz Murtèl; cf. fig. 3). Initial visual inspections of the cores (R. Frauenfelder and others, unpublished information) indicate that the ice contains few visible impurities but is rich in large air bubbles of a mostly rounded, non-orientated nature and having diameters of 1–4 mm. This caused the density of the ice to vary and gave an average of 850 kg m$^{-3}$. Such characteristics are unusual for (glacier) ice formation through temperate firn metamorphosis (e.g. Post and LaChapelle, 1971; Stauffer, 1982) and suggest an origin of superimposed-ice formation. Additional evidence is provided by slightly edged but still round ice crystals of the same diameter (several mm), a characteristic product of freeze–thaw metamorphosis.

An additional 14 m deep borehole was steam-drilled at the same site and prepared for borehole-temperature measurements using Fenwall and YSI4000 thermistors. Monthly readings during the first year of measurement clearly demonstrate that the ice is cold (Fig. 5). The pronounced temperature shifts 2 m below the original surface in the borehole at Piz Murtèl reflect the snow/ice interface where thermal properties change drastically. From April 1999 to April 2000, ice temperatures at 13 m depth varied by about 0.7°C around a mean of −3.86°C. This result relates well to earlier ice-temperature measurements from other Alpine firn and ice summits (Fig. 6). The site at Piz Murtèl may well be compared to the other mid- to low-altitude sites such as


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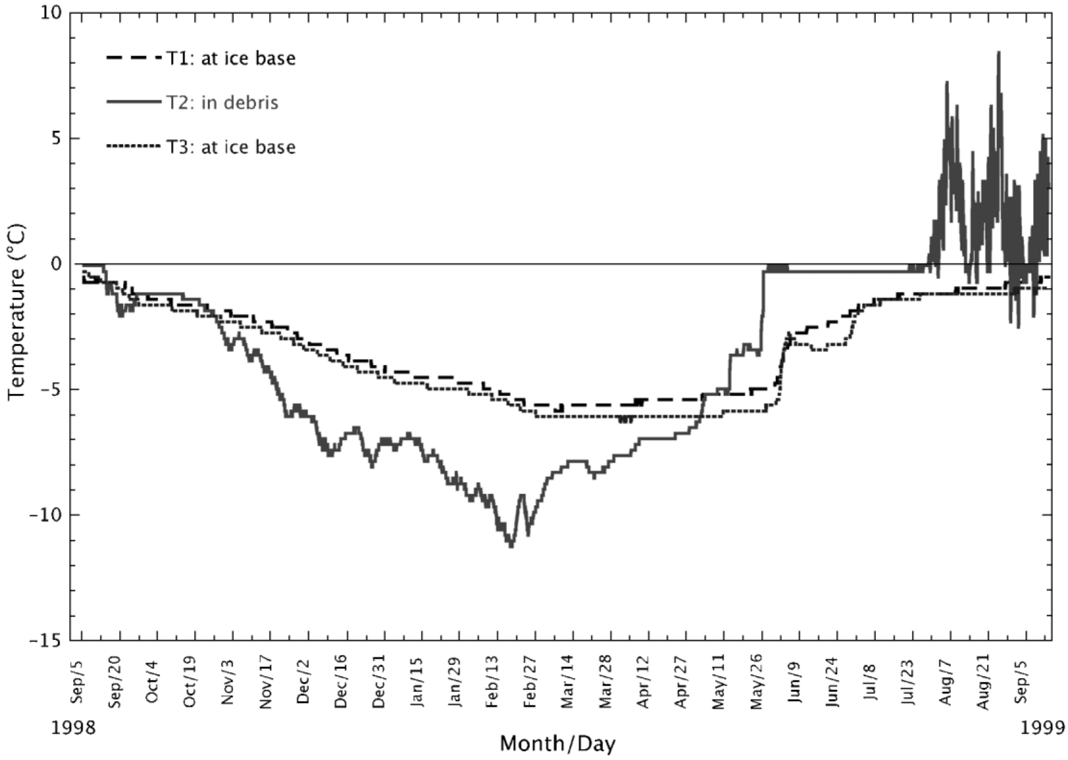


*Fig. 7. Mini-logger temperatures of the near-surface layer at the ice base (T1, T3) and within adjacent periglacial debris (T2; cf. Fig. 3 for locations) on the lee side of the Piz Murtèl "miniature ice cap" (September 1998–September 1999).*

Jungfraujoch and Chli Titlis described earlier. The zero annual amplitude is expected to be at approximately −16 m depth. Seasonal temperature variations from the surface penetrate to this depth with a time lag of roughly 6 months, an interval which is also typical for corresponding depths within frozen bodies (Vonder Mühll and others, 1998; Van der Veen, 1999). The smooth changes of seasonal temperature fluctuations and the exponential damping of their annual amplitudes at depth is due to heat conduction in ice and excludes the large effects of latent heat from meltwater percolation and refreezing of the firn.

In a sharp ridge the geothermal heat flux is much reduced and the production of deformational heat is minimal. The cold ice ridge, therefore, is assumed to be frozen to its bed, and negative temperatures are likely to reach many tens of metres deep into the underlying bedrock. This result is confirmed by temperature measurements made at the base of the ice crest (ice/rock interface: cf. Fig. 7) with miniature temperature data loggers (UTL1) from September 1998 to September 1999. The bedrock is in a permafrost condition, and the mean annual ground-surface temperatures (MAGTs) are comparable below the glacier (MAGT = −3.4°C) and in the adjacent periglacial permafrost (MAGT = −3.9°C). The slightly lower MAGT in the periglacial debris probably results from the shallow snow depth during the winter in question, which allowed a more pronounced cooling of the ground. As expected with a substrate of ice or permafrost, the temperature at the base of the winter snow cover (BTS) is far below zero (−5.9°C in March/April; cf. Fig. 7).

Leaving surveying stakes in the steep slope throughout the year is difficult (due to avalanches, snow creep, small movements) and, so far, has not provided conclusive results. Stake measurements of surface velocity carried out at six locations during the course of 2 months and their extrapolation to annual values however, yielded small annual velocities (dm per year), predominantly in the direction of the main ridge, and variations in snow-cover thickness of about 2.5 m. A precision survey of the entire "miniature ice cap" was undertaken in summer 2000 for future monitoring but also for comparison with earlier times as documented on aerial photographs and topographic maps.

## PRELIMINARY FINITE-ELEMENT MODELLING

In order to better understand the basic glaciological characteristics of potentially interesting sites, some idealized configurations were modelled using a two-dimensional finite-element scheme assuming, for simplicity, plain strain, stress-independent viscosity, uniform density (900 kg m$^{-3}$), incompressibility, no basal sliding and no crevasses. A symmetric-triangle ice crest, an asymmetric-triangle ice crest, a parabola-shaped "miniature ice cap" on horizontal bedrock and a shallow-inclined ice patch were selected. Flow vectors, flow trajectories, integrated time (age) along the trajectories, surface deformation and accumulation/ablation patterns were estimated as deduced from surface deformation assuming (i) constant geometry (steady state), (ii) no internal shear planes, (iii) no basal melting and (iv) no basal sliding (at present as well as in the past). The steady-state assumption is critical as discussed later. Results are presented in Figure 8a–d and can be summarized as follows.

The case of a symmetric triangle with a flat, horizontal basis shows subsidence (accumulation in the steady-state case) of the crest in the upper third, and a bulging of the emergence flow (ablation in the steady-state case) in the lower two-thirds of the slopes (Fig. 8a). The lower edges of the triangle act as barriers against the flow, because thickness and, hence, shear stress and ice deformation become zero at these points. Consequently, ice accumulating just under the summit is forced to re-emerge on the upper parts



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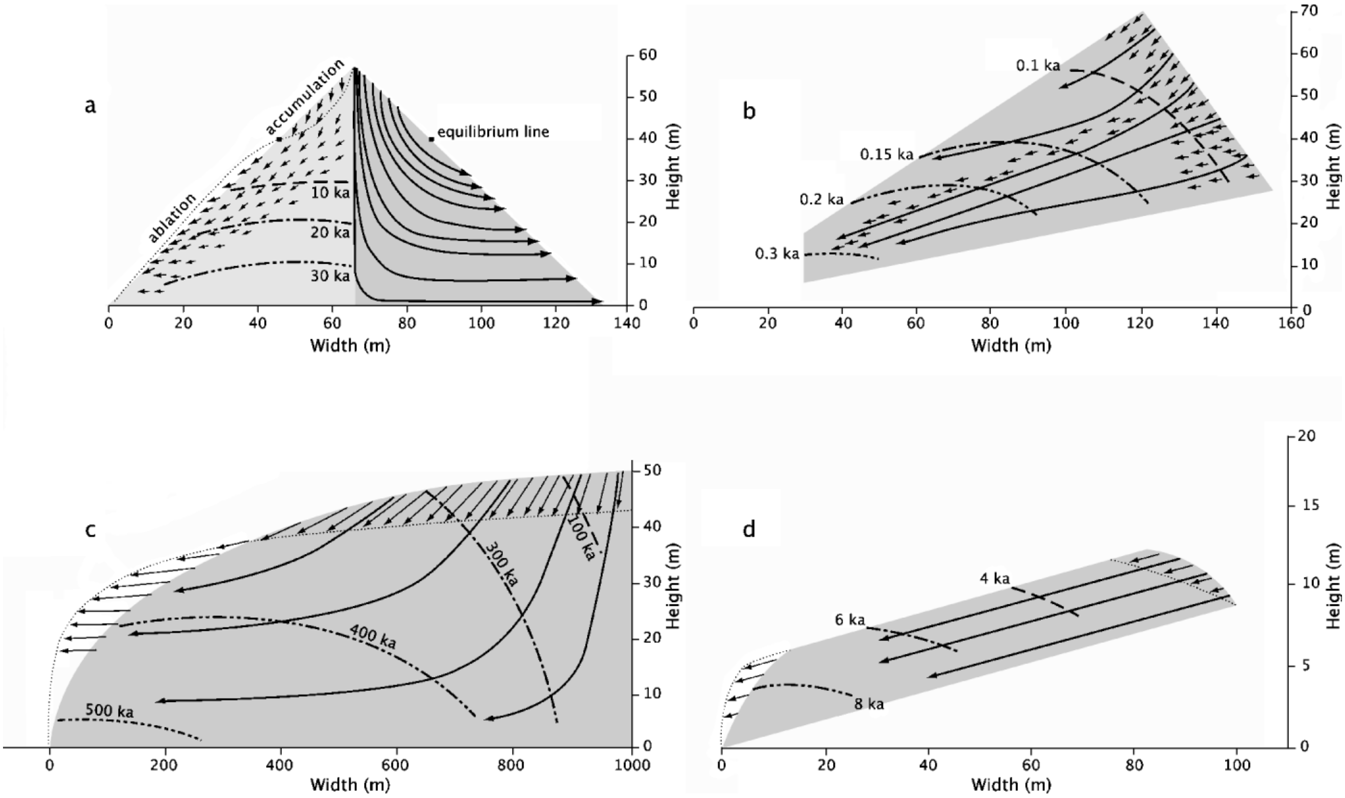


*Fig. 8. Finite-element model calculation (annual displacement vectors, flow trajectories and isochrones) for basic two-dimensional configurations of "miniature ice caps" and perennial ice patches: (a) symmetric triangle with horizontal bed; (b) asymmetric triangle with inclined bed; (c) parabola shape with horizontal bed; and (d) shallow ice patch with inclined bed.*

of the slope and, hence, disappears relatively quickly. Flow trajectories leading to the lower half of the slopes, however, start from a narrow zone at the very summit, and thus must all contain ice accumulated under, more or less, the same topoclimatic conditions. Very high ages are calculated for the ice layers because flow velocity in the central part and near the base of such symmetric triangles is extremely slow under steady-state conditions. Even at a depth of about half the thickness, a surface geometry remaining constant in time would enable ice from the last ice age to exist in the centre of the ice body and on the lateral slopes. This means that old ice from the last ice age would be directly accessible at the base and on the lower-slope parts of such symmetric-triangle shaped ice bodies and, in the case of steady state, through correspondingly extended time periods of the past. Annual-layer thickness would be in the millimetre range.

An asymmetric triangle (Fig. 8b) represents flow conditions where accumulation takes place in the summit area but also over the entire height of the steep leeward slope. This resembles the case of a perennial cornice. Ice movement is away from the steep slope and much faster than in the case of the symmetric triangle. Ice flux at the lower boundary is into the assumed bergschrund area. Ages are centuries rather than millennia, and remains of the older ice may be concentrated in an extremely thin layer at the very bottom of the deforming ice body. On the other hand, information about the industrial time period may be preserved in much thicker annual layers (order of magnitude: decimetres) than in the case of the symmetric triangle. The Murtèl ice crest is assumed to be in between these two cases (symmetric/asymmetric triangle) but with a flat basis near the lee slope. This alone could explain the layering which became apparent in 1998. More sophisticated modelling is envisaged when complete information about three-dimensional ice and bedrock geometry, possibly varying through (recent) time, becomes available.

Cold "miniature ice caps" (Fig. 8c) with a parabola shape on a flat/horizontal bed, such as exist in the flat-topped mountains in Svalbard, have a separation between submergence (accumulation) and emergence (ablation) at about two-thirds of the slope length. The magnitude of the flow as well as the submergence and emergence vectors very much depend on the thickness at the ice divide. Characteristic length values of hundreds of metres and ice-divide thicknesses of tens of metres lead to ages in the order of tens to hundreds of thousands of years under steady-state conditions, even at shallow depths. Annual-layer thickness would be fractions of a millimetre.

Shallow-inclined ice patches (typically a few metres thick and tens of metres long; cf. Fig. 8d) concentrate emergence flow and ablation on the lower end of their extension and have typical ages of thousands of years towards their base and lower end. The same geometry, but with a topographic depression comparable to the geometry of the site where the Oetztal ice man was found, increases ages by a factor of about two. From the point of view of ice mechanics, the long-term preservation of the Oetztal ice man is not surprising. Average annual-layer thickness would be in the order of millimetres per year.

The critical point in these considerations is the assumption of steady-state conditions. In fact, the reappearance of the Oetztal ice man clearly indicates that non-regular accumulation and ablation, as related to climate forcing, is the decisive factor for age distribution, rather than the steady accumulation and flow through extended time periods. This, in turn, means that the age distribution found in real "miniature ice caps" and perennial ice patches may contain information about earlier periods with extreme melting.



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Such periods would have had warm conditions comparable to the situation at the end of the 20th century or even warmer, and hence have an important potential for palaeoclimatic reconstructions of Holocene/pre-industrial ice and climate variability.

## CONCLUSIONS AND RECOMMENDATIONS

From the described, but still limited, preliminary experiences, the special characteristics of crest- and cornice-type, low-altitude ice archives ("miniature ice caps") can be summarized as follows:

1. Englacial temperatures are cold and the ice is frozen to the permafrost in the underlying bedrock.
2. Rates of annual accumulation are unevenly distributed but in general are small to extremely small.
3. Ice formation is through the refreezing of meltwater (superimposed ice) rather than firn compaction.
4. Close-off probably takes place after a few years rather than after decades to centuries.
5. At the base of the ice bodies (ice/bedrock interface) movement may be close to zero and the age of basal ice layers may be considerable (historical, Holocene, last ice age?).
6. Direct access is possible to layers of different ages and to the ice/bedrock interface.
7. Old ice layers outcropping at the base of lateral slopes follow flow paths which originate in a narrow zone at the very top of crest-type ice bodies.
8. The climate sensitivity of the relatively thin, old and warm ice opens the possibility for monitoring an interesting and potentially excellent indicator of Holocene minimum glacier extent.

Further investigations are planned and underway, both at the Murtèl site and at additional locations. Methods planned are the analysis of ice cores, stake measurements at the ice crest, radio-echo soundings, determination of changes in geometry from precision surveying, three-dimensional flow modelling, temperature measurements (borehole and mini-loggers) and observations with an automatic camera to gain more information about ice formation, movement, thermal conditions, relationship to permafrost, accumulation and age distribution of the site. The fact that ice formation occurs through refreezing of meltwater will probably limit the potential interest of palaeoclimatic information from ice analysis, because the initial information is at least partially destroyed due to fractionation between meltwater and ice. In addition, the specific topographic conditions (exposure to wind and erosion) might cause a hiatus or discontinuity in the depth–age relationship which will render impossible dating by, for example, annual-layer counting. The idea that perhaps very old ice (older than 10 000 years) might exist in the Alps or at other low-altitude sites is nevertheless fascinating.

Dating of basal layers and monitoring of englacial temperatures, as well as of geometric changes, are therefore now of central interest in such crest- and cornice-type ice archives or "miniature ice caps".

*Fig. 9. Photograph of the snow-free "miniature ice cap" at Piz Murtèl, with the entrance of a new tourist tunnel in the foreground. (Photograph by R. Frauenfelder, August 2003.)*

## POSTSCRIPT: EFFECTS OF THE EXTRAORDINARY SUMMER 2003

The summer of 2003 in the European Alps was not only dry but also extremely hot, with mean air temperatures during the time period June–August being about 2°C higher than, and thus far above, extremes measured previously (mainly in 1947; cf. Schär and others, 2004). As a consequence, snow and firn disappeared on many smaller glaciers, and glacier mass losses far exceeded anything reported since the beginning of mass-balance measurements. The exposed borehole thermistor cable and mini-loggers at the Piz Murtèl "miniature ice cap" indicated a net ice-thickness loss of about 3 m or even more at an altitude near the equilibriumline altitude for balance years. The entire ice body would disappear within about 20 years if such conditions continued. The fine layering of the ice described in the present contribution was clearly exposed. Examples can now be investigated in a tunnel constructed for tourists by the cable-car company in the lower part of the ice body (Fig. 9).

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