# MONITORING THE LONG-TERM EVOLUTION OF MOUNTAIN PERMAFROST IN THE SWISS ALPS

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Attempts are presently being made to establish a measurement network for monitoring the long-term behaviour of mountain permafrost in the Swiss Alps, especially in view of warming trends. Methods applied include aerial photogrammetry of permafrost creep within selected rock glaciers, borehole measurements for permafrost deformation and temperature, data archiving from geophysical surface soundings for later repetition and qualitative analysis of infrared aerial photography. The investigated permafrost is typically several decameters to more than 100m thick and has mean annual surface temperatures between the melting point and about -3°C. Heat flow within the uppermost 60m of bedrock-reaching permafrost indicates more or less stable surface temperatures between about 1950 and 1980. As a consequence of the exceptionally warm 1980s, permafrost temperatures in the uppermost 10 meters below surface now seem to be rising at rates of 0.5 to more than 1°C per decade. Annual rates of thaw settlement from melting of ground ice in Alpine permafrost may have more than doubled since the 1970s.

## INTRODUCTION

Snow, glaciers and permafrost react sensitively to changes in atmospheric temperature because of the proximity to melting conditions. In addition, mass wasting is most intensive in high mountain areas with steep slopes. As a consequence, climatic changes cause pronounced effects in the glacial and periglacial belts of mountain areas (Haeberli 1990, Wood 1990). The 20th century has seen striking changes in glacierized areas of mountain ranges and, hence, in the extension of periglacial mountain belts all over the world. The changes in surface and ground ice conditions caused a corresponding shift in geomorphic processes such as debris flow activity in freshly exposed or thaw-destabilized moraines and talus. In the Alps, this development was accompanied by increasing human activities. The combination of atmospheric warming and human impact have, in fact, introduced the most striking changes in high mountain landscapes.

Coordinated long-term monitoring of *glaciers* in the Swiss Alps started as early as 1893. The significance of glaciers as key parameters for climate-system monitoring is now widely recognized and the results of long observational series represent convincing evidence of fast climatic change at a global scale (IPCC 1992). Systematic monitoring of *seasonal snow* started considerably later. Because of the large amplitude of year-to-year variations and the lacking "memory" function of seasonal snow as compared to glaciers or permafrost, snow monitoring is more important in view of the ecological and economic consequences of potential changes (water cycle, energy production, tourism) than as a signal of climate change (VAW 1990). Systematic long-term monitoring of *permafrost* only started recently and is still being developed as part of a combined observational programme on changes in the Alpine cryosphere. The goal of the long-term project discussed here on mountain permafrost in the Swiss Alps is to

(a) adequately document ongoing changes;
(b) better understand the processes involved;
(c) improve the basis for assessing consequences of potential warming trends in the near future.

## CONCEPTS AND TECHNIQUES

Changes in permafrost take place at various scales of time and space. Along vertical profiles with depth at individual points, reactions of permafrost to climatic changes are supposed to take place in three main forms:

(1) changes in active layer thickness and thaw settlement/frost heave in supersaturated material at the permafrost table as an immediate response (time scale: year(s);

(2) disturbance of temperature profiles within the permafrost, i.e. between the permafrost table and the permafrost base, as an intermediate response (time scale: years to decades); and

(3) displacements of the permafrost base as a definitive response (time scale: decades to centuries or even millennia).

With regard to the 3-dimensional dynamics of complex landscapes, two more types of reactions at highly variable time scales can be envisaged:

(4) modification of permafrost distribution patterns, involving

(5) adjustment of geomorphic, hydrological and nivo-glaciological processes such as permafrost creep, frost heave/thaw settlement, thermokarst, erosion and slope instability on thaw-destabilized slopes, runoff variations in time, drainage characteristics, snow cover evolution and metamorphism, and avalanche formation.

Hence, the most important *parameters* to be observed are the surface altitude in permafrost areas and the depth to the permafrost table beneath the surface, the vertical temperature profile within the permafrost, the local/ regional distribution pattern of permafrost, the horizontal and vertical deformation of ice-bearing ground, geomorphic forms, and runoff characteristics in the periglacial belt. Evidently, a combination of methods must be applied (cf. King et al. 1992) to appropriately document this entire set of phenomena and associated changes.

The depth to the *permafrost table* can be measured with thermistors in boreholes and with geophysical surface soundings. Seismic refraction and geoelectrical resistivity soundings are best applied in non-consolidated sediments with a high ice content. The permafrost table in such cases often consists of almost pure ice and gives sharp contrasts in P-wave velocity and specific resistivity. The resolution of active layer thickness determination by such measurements may not be better than a meter or two. The commonly encountered coarse, blocky surface layer makes exact definition of surface geometry difficult and introduces considerable heterogeneity in near-surface physical properties over theconsidered profile. For logistic and economic reasons, borehole temperatures can be monitored at a few sites only, whereas geophysical soundings may cover a number of profiles and areas. Fast changes can be expected to exceed the methodological uncertainty range within the time scale of decades. Melting of pure ice at the permafrost table, however, leads to surface lowering rather than to increased active layer thickness.

The vertical profile of *permafrost temperature* should be observed in boreholes (Fig.1) reaching beyond the depth of seasonal temperature variations and - if possible - even penetrating the permafrost base into non-frozen sub-permafrost ground. Periodic recalibration of the installed thermistors by repeated measurements with a thermistor chain lowered into the borehole is essential for assuring measurement accuracy in the 0.1°C range over long

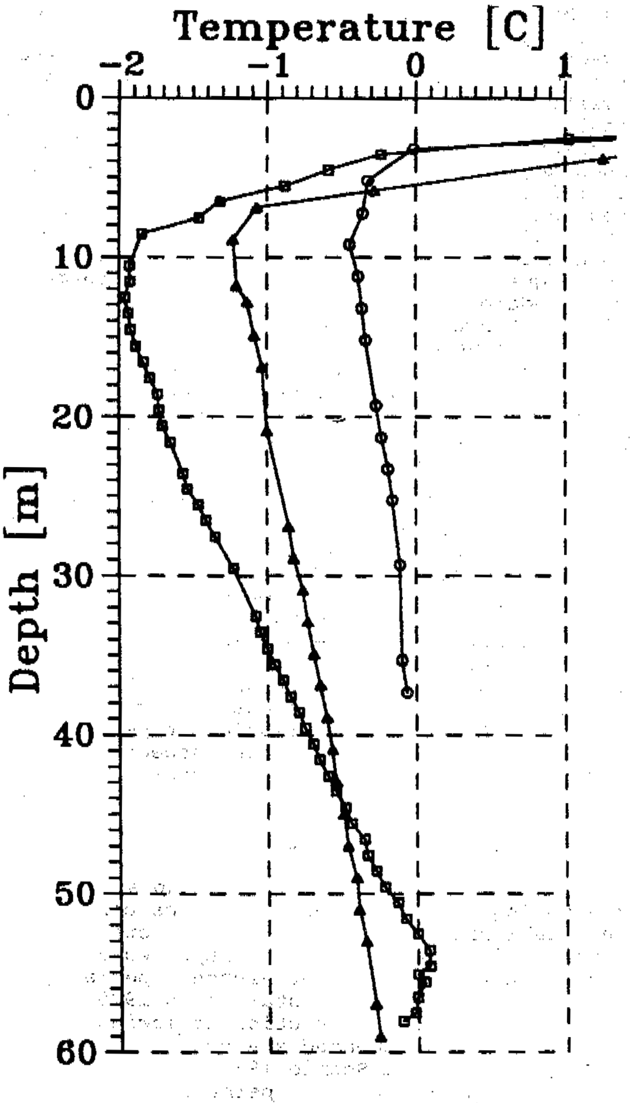

FIGURE 1. Temperature profiles in the permafrost boreholes Murtèl (squares), Ursina 1 (triangles) and Ursina 2 (circles). The date is September 1991.

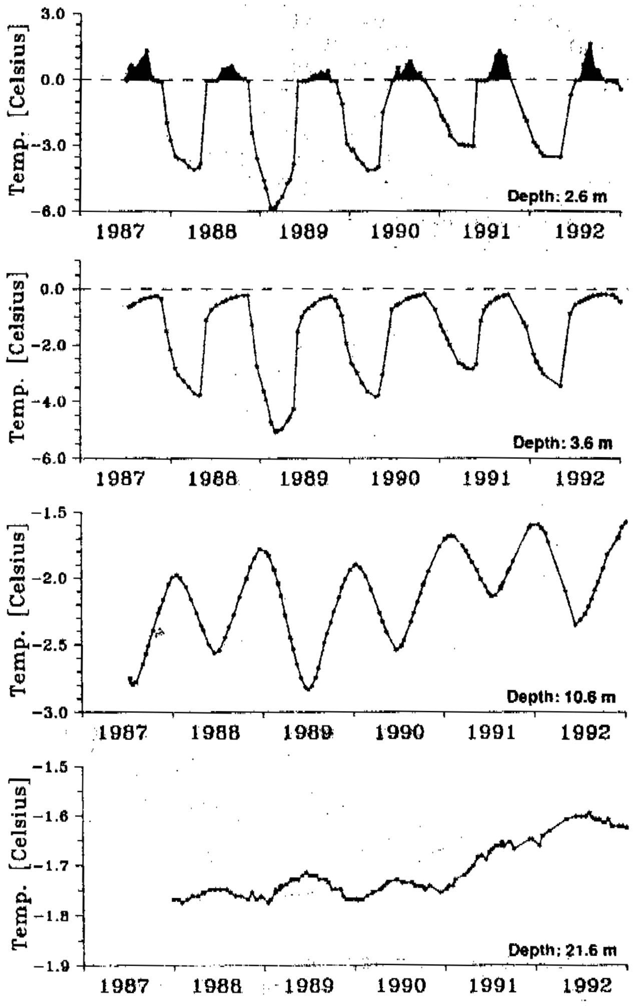

FIGURE 2. Borehole temperatures in the permafrost of the active rock glacier Murtèl/ Corvatsch (Grisons) at various depths. The permafrost table is between 2.6 and 3.6 m depth. Recent warming trends from the exceptionally hot 1980s and early 1990s are most clearly visible at 10.6 and 21.6 m depth. The accuracy of the measurements is about ± 0.05°C.

time-periods (Vonder Mühll and Haeberli 1990, Vonder Mühll 1992). Clear signals can be observed after a few years (Fig.2). Interpretation can be based on heat conduction theory as long as water flow remains negligible. The vertical temperature profile in permafrost is, indeed, the clearest information available at present but the representativity of observations in a few expensive boreholes must be assessed using complementary methods. Interpretation of geophysical soundings with respect to displacements of the permafrost base are difficult and uncertain (cf. Haeberli 1985). Long-term changes are, therefore, only detectable with precise borehole temperature measurements. Even with this method, problems exist due to borehole depths not reaching the permafrost base, slow and small rates of change at the considered depth range, and effects of freezing-point depressions or complicated influences of groundwater (Vonder Mühll 1992).

Patterns of *permafrost distribution* in mountain areas with a thick enough cover of winter snow are best mapped using the BTS method (Fig. 3) if possible in combination with geophysical soundings at representative sites. The great number of point measurements collected in this way enables the development of statistically calibrated models of permafrost occurrence as a function of energy balance parameters and topographic effects on snow redistribution by avalanches and wind (cf. Hoelzle et al. 1993). Such models can also be used to simulate spatial effects of changing climatic conditions for various scenarios and, thus, point to the most sensitive sites. Repetition of regional mapping could reveal marked changes in the observed patterns of permafrost existence within time intervals of decades.

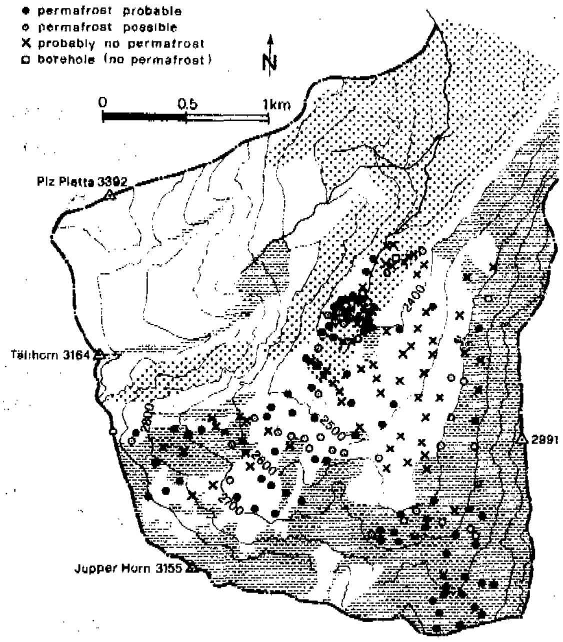

FIGURE 3. Permafrost mapping in the Val Bercla (Grisons) using BTS-measurements. The stippled and dashed screens give permafrost-free areas and areas with probable permafrost as estimated from the empirical "rules of thumb" developed earlier in a nearby test area (cf. Hoelzle et al. 1993). The reliability of the rules is reduced particularly in historical glacier forefields with a complicated recent thermal history (cf. the cirque between Tälihorn and Jupper Horn).

*Thaw settlement and frost heave* as related to permafrost degradation and aggradation cause changes in surface altitude which can be mapped using geodetic and photogrammetric techniques. Direct photogrammetric comparison of specially flown large-scale aerial photographs also serves for monitoring the flow field in creeping rock glacier permafrost (Fig.4). The concepts and procedures have been introduced and illustrated by Haeberli and Schmid (1988). The slow displacement of a coarse, blocky surface with a roughness of the meter scale is the main limitation to the resolution of altitude change determination within a regular grid remaining fixed in time. Averaging over larger areas helps to reduce this uncertainty and gives significant results about marked changes within a time period of a few years to several decades. More detailed interpretation of the observed changes requires that one distiguishe between the "climatic signal" (settlement/heave from melting/freezing) and the "dynamic signal" (vertical strain from 3-dimensional flow) by analysing in detail the fields of vectors and horizontal strain rates. Uncertainties with such detailed calculations are caused mainly by poor local information about permafrost thickness and complex variations of vertical strain rates with depth. Horizontal and vertical borehole deformation using borehole inclinometry and magnetic rings offers essential information with regard to these difficulties (cf. Wagner 1992) but are available for only a few sites.

The evolution of *geomorphic phenomena* associated with Alpine permafrost can be recorded and documented using aerial photographs. High-altitude/small-scale infrared photography is especially suitable for mapping large areas in view of changes in vegetation cover at rock glacier margins (flow activity), scree slopes and cones (rockfall activity), debris flow traces (frequency of occurrence), size and water-level variations in thermokarst lakes (permafrost hydraulics), and growth/disappearance of perennial ice patches. Repetition of mapping seems reasonable at time intervals of one to a few decades. Monitoring the processes of water runoff in areas of mountain permafrost requires classical hydrological equipment with the main difficulty being its maintenance during winter. Monitoring snow characteristics at permafrost sites may also be an important aspect of observing long-term changes at high altitudes (cf. Keller and Gubler 1993).

## PROGRAMME AND FIRST RESULTS

The initial step for building up a long-term monitoring system in the Swiss Alps consisted in establishing survey nets at selected rock glaciers in conjunction with repeated high-precision *photogrammetry*. At Gruben, special flights at low altitude started in 1970 in connection with flood protection following two lake outbursts. Repeated analyses in 1975 and 1979 (Haeberli and Schmid 1988) showed that growth and degradation of permafrost can take place simultaneously at different places within the same rock glacier but that an overall thinning tendency of a few centimeters per year occurred in the purely periglacial part of the

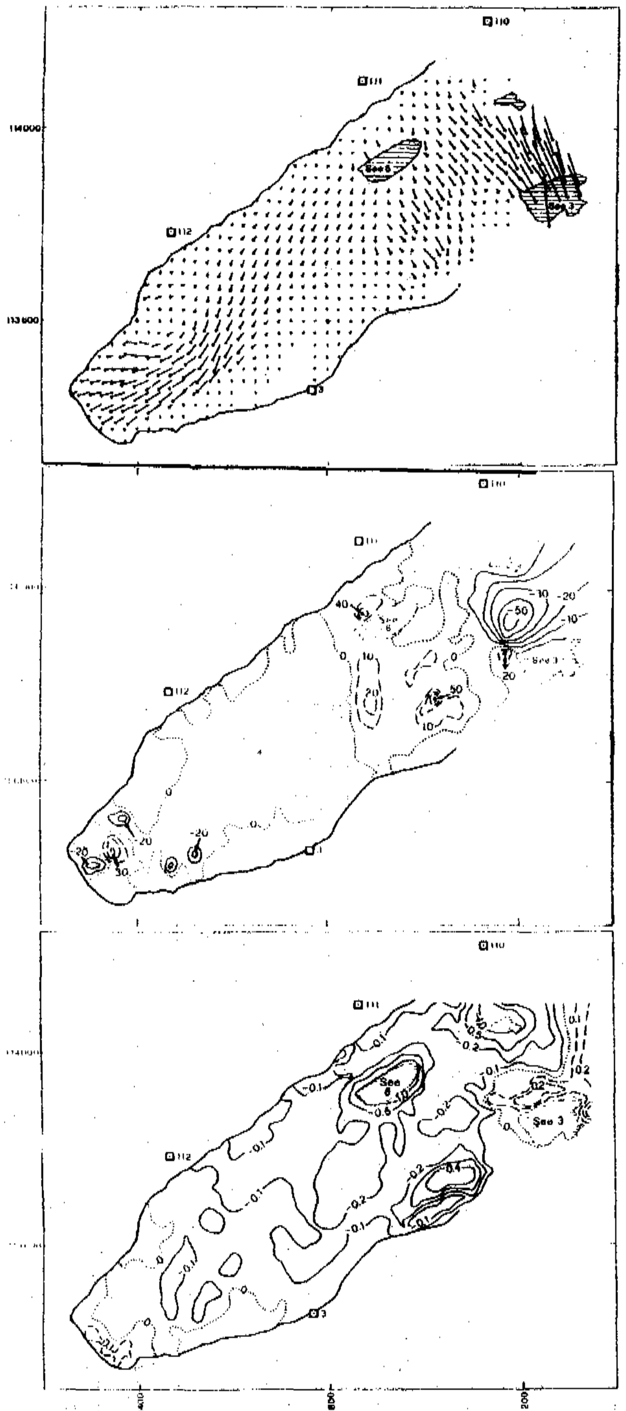

FIGURE 4. Photogrammetrical analysis of creeping permafrost at Gruben rock glacier: (a) vector field 1985-1991, (b) changes in surface altitude (1979-1991, cm/year) and (c) changes in flow velocity 1979-1985/1985-1991 (m/year). Accuracy is about 0.1 to 0.2 m/year. The part to the west of lake 6 is a purely periglacial feature, whereas the remaining parts have been influenced by a glacier advance during the Little Ice Age and carry relics of dead ice on top of the permafrost (cf. Haeberli and Schmid 1988 for more details on the method and the site).

rock glacier and of about 1 decimeter per year in the formerly glacier-covered part with remains of dead ice buried on top of the permafrost. New analyses were carried out from aerial photographs taken in 1985 and 1991 (Fig.4). The number of grid points has now been increased greatly by reducing the mesh width (25m) to half its original value. In comparison with the 1970s, annual thinning rates have accelerated by a factor of 2 to 3 in the warm 1980s to early 1990s (Fig. 5). This is probably caused by increased melting of ice at the permafrost table and may therefore be superimposed onto an assumed long-term trend of slow melting at the permafrost base. Results from similar surveys since 1981 are available from Muragl rock glacier in the Grisons (Vonder Mühll and Schmid 1993) and confirm the generally small rates of geometric change in Alpine permafrost. Additional results from repeated photogrammetry can soon be expected from the rock glaciers Réchy, Furggen/Gemmi and Gufer/Aletsch in the Valais and from Murtèl/Corvatsch and Ursina/Pontresina in the Grisons (Fig.6).

With the 1987 *drilling* through the permafrost

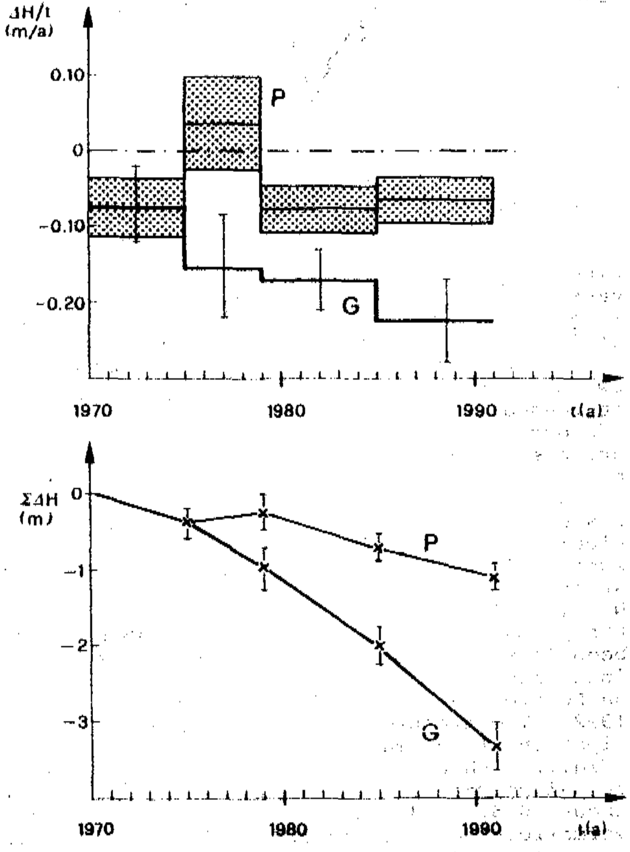

FIGURE 5. Changes in surface altitude at Gruben rock glacier from aerial photogrammetry since 1970: annual velocities (top) and cumulative effect (bottom). P = periglacial part, G = glacier-affected part with dead ice remains. Surface lowering (thaw settlement) is significant in both parts and considerably faster in the warm 1980s than in the 1970s.

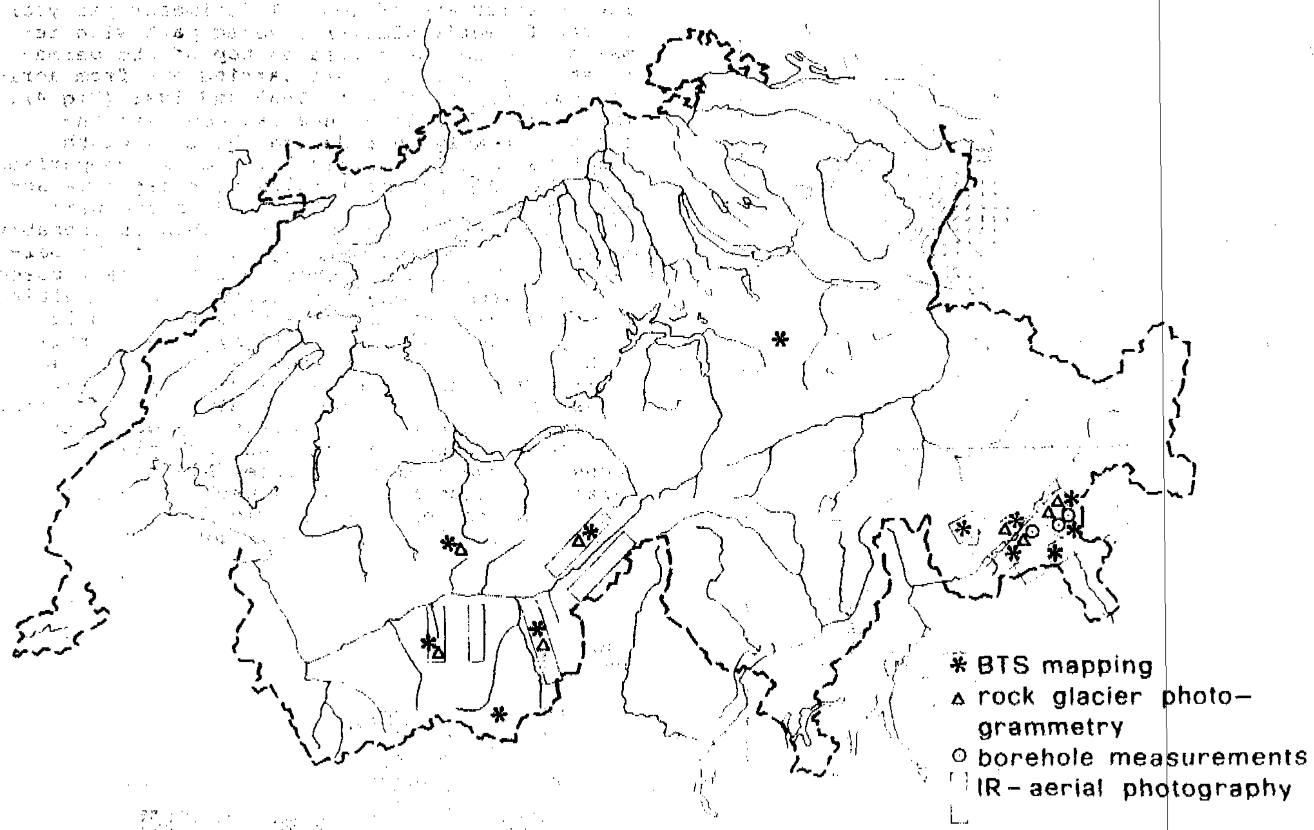

FIGURE 6. Location map of permafrost monitoring activities in the Swiss Alps.

within the active rock glacier Murtèl/Corvatsch, the first borehole was equipped for long-term observations in the Swiss Alps (Haeberli et al. 1988, Vonder Mühll and Haeberli 1990). Up to 1992, permafrost temperatures between the permafrost table and 10m depth have increased at rates of a few tenths to nearly 2°C per decade. This fast warming of near-surface permafrost is a consequence of the especially warm late 1980s and early 1990s. Results of bore-hole deformation measurements are discussed by Wagner (1992). Horizontal and vertical strain rates vary with depth in an unexpectedly complicated and still poorly understood way but remain fairly constant in time. No significant effects of thaw settlement at the permafrost base or permafrost table have been detected so far. Two more boreholes were installed in 1990 at the nearby site of Ursina/Pontresina (cf. Vonder Mühll and Holub 1992). Temperature profiles measured after dissipation of thermal disturbance from drilling (Fig.1) within all three boreholes give mean annual permafrost temperatures at 10m depth of about -0.5, -1.3 and -2°C with corresponding permafrost thicknesses of 40, 70 and possibly more than 100m. The last value is a rough estimate based on a discussion of groundwater influence in a talik at 53m depth, which can also be assumed to be the cause of the strongly elevated value for the overall temperature gradient and vertical heat flow in the Murtèl borehole (Vonder Mühll 1992). The less disturbed temperature gradients in the two Ursina boreholes indicate vertical heat flow values close to steady state conditions and, hence, point to relatively stable surface temperatures between about 1950 and the early 1980s.

Systematic permafrost *mapping* has been carried out in a number of test areas (Fig.3, cf. Haeberli 1992, King 1990, Hoelzle 1992, Tenthorey 1992). The corresponding information is being stored in the data archive GIS/Kryo (Keller 1992) enabling comparison with later repetitions of mapping and sounding programmes.

Collection of *infrared aerial photography* flown at high altitude started in the Goms (Upper Valais) and the Poschiavo regions (Grisons) as part of a governmental research programme on debris flows from the 1987 flood catastrophes and continued in the Upper Engadin (Grisons, 1988/1990) and in the Saas, Turtmann and Réchy/Lona valleys (Valais, 1991). First steps to investigate the long-term evolution of *runoff characteristics* using discharge measurements and tracer experiments in Alpine mountain areas have been undertaken recently in the Réchy area (Monbaron and Tenthorey 1989). The goal of such studies is to assess the influence of Alpine permafrost and its potential future changes on flow paths and discharge variations of water in non-glacierized areas at high altitudes.

## CONCLUSIONS AND RECOMMENDATIONS

First attempts to document climate-induced permafrost changes at various scales in time and space in the Swiss Alps indicate accelerated warming and degradation of Alpine permafrost since about 1980. Long-term monitoring efforts, expansion of similar observations to other countries, and systematic comparison with already existing measurements in other mountain ranges are needed to assess whether information from Switzerland is representative in the more general context of ongoing global warming trends. It is recommended that international coordination encourage and strengthen such efforts.

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