PERMAFROST AND PERIGLACIAL PROCESSES
Permafrost Periglac. Process. **13**: 117–135 (2002)

Borehole Deformation Measurements and Internal Structure of Some Rock Glaciers in Switzerland

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ABSTRACT

In order to understand the mechanical processes that influence the deformation patterns of active rock glaciers, information about local horizontal and vertical deformations as well as knowledge of the internal structure and the temperature distribution is necessary. Results from borehole deformation measurements of three sites in the Swiss Alps show that despite different internal structures, similar phenomena can be observed. In contrast to temperate glaciers, permafrost within rock glaciers has distinct shear zones where horizontal and vertical differential movements are concentrated. In addition, a reduction in volume can be caused by compressive flow due to the presence of air voids within the permafrost. The flow velocity depends on the temperature, the surface and bedrock slopes of the rock glacier, and the composition of the ice-rich frozen ground. Within degrading permafrost, the ice content decreases, the creep velocity increases and the shear zone rises towards the surface, where seasonal temperature changes and the presence of liquid water might also influence deformation. Copyright © 2002 John Wiley & Sons, Ltd.

KEY WORDS: rock glacier; creep; deformation measurements; internal structure

INTRODUCTION

Rock glaciers can be found in Alpine environments on slopes, which are at an elevation higher than about 2400 metres above sea level (mASL), depending on their exposure (Haeberli, 1975; Barsch, 1978; Keller *et al.*, 1998). These rock glaciers are a special geomorphological form of creeping mountain permafrost. Information about the kinematics of active rock glaciers is very important if the history of rock glacier behaviour is to be understood and predictions of future response are to be made. In Switzerland, it is of increasing concern that instability of a significant mass might be induced by the melting of the ice within the permafrost body due to global warming (Haeberli *et al.*, 1997, 1999). This is of vital importance, since elevated mountain areas are increasingly used for tourism, communication networks, hydroelectric power stations or strategic purposes (Haeberli, 1992).

Permafrost creep has been a major research area in the northern hemisphere for a long time. However, few field measurements exist. Savigny and Morgenstern (1986) confirmed with borehole inclinometer data in ice-rich soils from the Canadian Arctic that the creep deformation rate is higher as the component of ice increases. There is also an extensive source of literature concerning mechanical behaviour of frozen soils, based on a range of laboratory and field tests, e.g. Vialov

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Received 12 December 2001
Revised 2 April 2002
Accepted 4 April 2002

et al. (1962), Ting (1983), Domaschuk *et al.* (1991) or Andersland and Ladanyi (1994) just to name a few.

In mountain environments, the movement patterns of rock glaciers have often caused speculation, even though deformation measurements have been carried out in various forms for more than 80 years (e.g. Chaix 1919, 1923). In the early days of these investigations, the position of the front was measured in relation to a fixed point. Later, better results were gained by marking profile lines (e.g. Wahrhaftig and Cox, 1959; White, 1987). Since the thirties, terrestrial photogrammetric measurements have been performed in rock glacier research with ongoing improvements in accuracy (for summary cf. Kääb and Vollmer, 2000).

Although these deformation measurement techniques help in observing long-term, surficial changes of rock glacier geometry, such as thickness or horizontal extent, they do not reveal the internal deformation processes. Furthermore, seasonal changes are difficult to measure, since thick snow cover prevents the exact location of the markers or distinct boulders, which are necessary for using photogrammetric methods during the winter months. The net movements over some months may also be so small that they cannot be resolved accurately by the measurement system.

In contrast to glaciers, where a continuous deformation profile can be observed (e.g. Paterson, 1994) rock glaciers show a distinct shear horizon where most of the deformation takes place (e.g. Haeberli *et al.*, 1998). Why such distinct shear zones develop preferentially at a specific depth within the inhomogeneous mass is still not fully understood (Hoelzle *et al.*, 1998). These uncertainties result in general statements, such as rock glaciers must be avoided as a founding stratum for essentially all structures (Burger *et al.*, 1999), or that constructions on rock glaciers are engineering hazards (Giardino and Vick, 1985). Therefore, more specific knowledge is necessary, which may be obtained from the analyses of core samples, geophysical investigations and precise deformation measurements. All this information adds to existing research and helps to form a better insight into the deformation behaviour of rock glaciers.

Vertical and horizontal borehole deformations have been measured in three rock glaciers in Switzerland. The results are compared in this paper. In addition, the results of two recent drilling campaigns, one on the Muragl and one on the Murtèl-Corvatsch rock glacier, are presented.

TEST SITES

Deformation measurements were performed in three rock glaciers in the Upper Engadin, Switzerland, after the drillings and additional borehole measurements, such as borehole logging (Vonder Mühll and Holub, 1992), cross-hole geophysics (Musil *et al.*, in press) or pressuremeter tests (Arenson and Springman, 2000) were finished (Figure 1). Even though all three rock glaciers are active, and have similar inner deformation patterns and surface characteristics, their internal structures are quite different.

Several boreholes were drilled into these rock glaciers during the last two decades (Table 1). The locations of the holes were always chosen to be in the lower part of the rock glaciers, where the flow region is compressive, as evidenced by transverse ridges and furrows that are present. The elevation lies between 2549 and 2755 mASL for all of the rock glaciers. Figures 2a-c show pictures of the three sites, all annotated with borehole locations. The internal temperature profiles are plotted in Figure 3.

Internal Structure

Due to the inaccessibility and the difficulties of excavating in mountain permafrost, only a few direct observations have been made from large exposures (e.g. Fisch *et al.*, 1977; Elconin and LaChapelle, 1997) to help determine the internal structure of a rock glacier. An overview of internal structures of some rock glaciers can be found in Table 4 of Burger *et al.* (1999). Great improvements have been made with geophysical investigations (Lehmann and

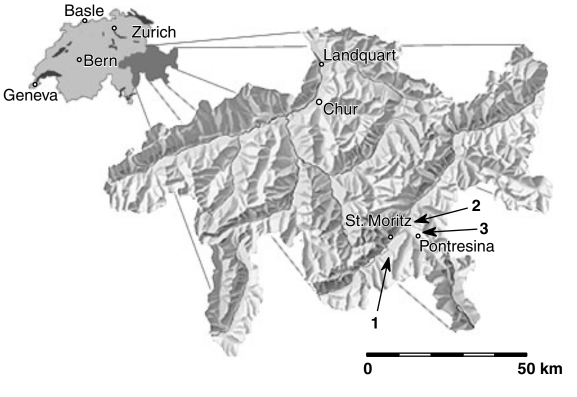


Figure 1 Location of the rock glaciers in Switzerland as studied in this project: Murtèl-Corvatsch (1), Muragl (2) and Pontresina-Schafberg (3).

Table 1 Overview of the boreholes of the three rock glaciers presented in this study.

	Murtèl-Corvatsch			Muragl			Pontresina-Schafberg	
	2/1987	1/2000	2/2000	2/1999	3/1999	4/1999	1/1990	2/1990
Elevation[mASL]	2670	2673	2672	2538	2558	2549	2755	2733
Depth of borehole[m]	62.0	51.9	63.2	64.0	72.0	71.0	67.0	37.0
Approx. depth of bedrock[m]	51 (?)	Not reached		37	38	32	16	30
Lower boundary of permafrost layer[m]	54(talik)	50	57	na[1]	20	20	60	38 (extrapolated)
Approx. depth of zero annual amplitude (ZAA)[2] [m]	18	na	na	na	16	16	20	17
Temperature at zero annual amplitude[°C]	−1.8	na	na	na	−0.2	−0.3	−0.9	−0.3
Year of reading	2000	na	na	na	2001	2001	1992	1992
Thermal gradient[°C/m]	0.051	na	na	na	na	na	0.027	0.01
Surface slope[3][°]	14			21	22		20	

[1] na: not available.

[2] The ZAA is defined as the depth where the annual temperature changes are smaller than 0.1 °C.

[3] The surface slope is defined as the mean slope between a point at the surface approximately 100 m up-slope and a point at the surface approx. 100 m downslope of the borehole.

Green, 2000; Hauck *et al.*, 2001; Vonder Mühll *et al.*, 2001; Musil *et al.*, in press) in order to detect or investigate the spatial distribution within a rock glacier. However, assumptions are always required in predicting the internal structure from geophysical data, and this should be calibrated by drilling, which (when carefully carried out) is the only reliable method for determining the strata within the body of permafrost.

Murtèl-Corvatsch.

The first deep borehole was drilled in an Alpine rock glacier in 1987 to extract cores from mountain permafrost. A range of interesting features was discovered subsequently (Haeberli *et al.*, 1988, 1998; Vonder Mühll, 1992; Vonder Mühll and Holub, 1992; Kääb *et al.*, 1997; Vonder Mühll *et al.*, 1998). These investigations show three distinct layers. A 25 m thick ice-rich layer was found underneath a 2.5–3 m thick active layer, which contains mainly large boulders. Underneath the ice-rich layer, there is a 4 m thick intermediate zone where the ice content decreases with depth and solid particles, mainly of silt or sand-size, are present to a greater degree so that particle—particle contact and interlocking increases with depth. The ice is only present in the pores within a blocky, gravel body below this layer.

Two additional boreholes were drilled in late spring 2000. As before, a triple-tube drilling rig with a cold-air flushing system was used. The compressed air in the tubes above the drilling bit had a temperature of around 0 °C. Due to the expansion through the nozzles in the bit, it is thought that an air temperature of about −10 °C was reached. The new boreholes were drilled up-slope from the 1987 borehole, at distances of 19 m and 32 m respectively. Water was discovered within the permafrost body during the drillings (the depths at which water was encountered are marked with a* in Figure 4). As expected, water was initially reached near the permafrost table, indicating that meltwater flows on top of the permafrost. However, additional water was found at greater depths within the permafrost body. During the night, this water had either drained away or frozen so that no water was found the next morning. While performing one pressuremeter test (BH1/2000: 24.5 m), which lasted about 23 h, some water must have flowed into the borehole (excavated to the depth of 27.15 m at this stage). The pressure transducers measured a residual pressure of about 400 kPa after unloading until removal of the probe. If this was caused by porewater pressure, as suggested by P. Hawkins (personal communication, 2000), this implies an artesian pressure of about 160 kPa (~16 m of water). The origin of this pressure is still unknown.

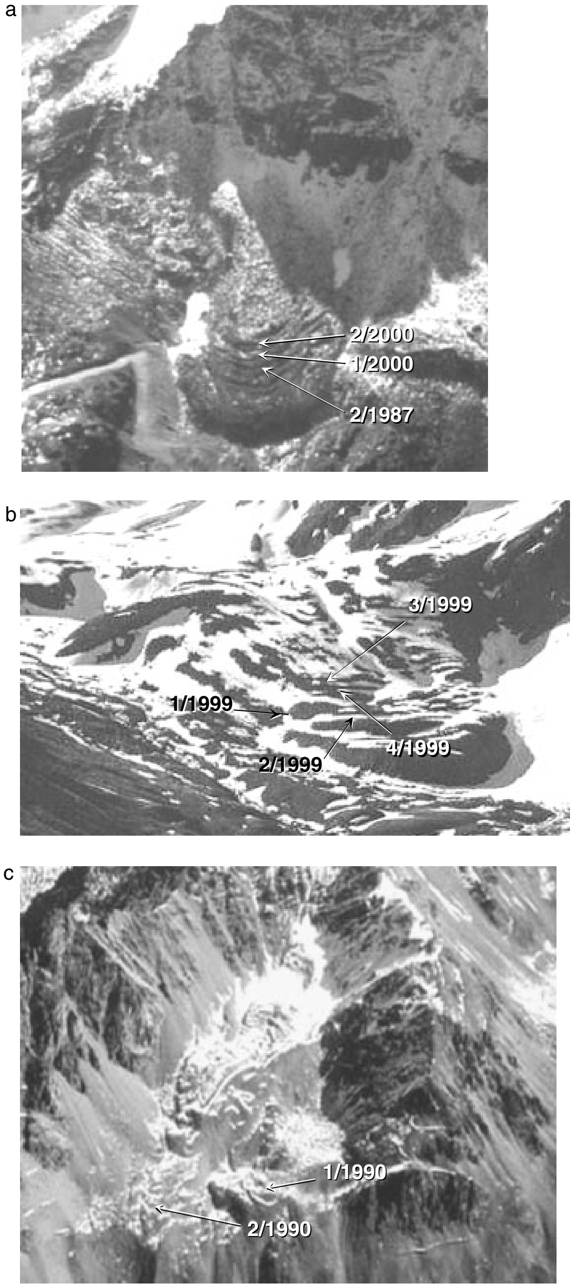


Figure 2 Photographs and location of the boreholes (photos: M. Hoelzle / L. Arenson). a) Rock glacier Murtèl-Corvatsch; b) Rock glacier Muragl; c) Rock glacier Pontresina-Schafberg.

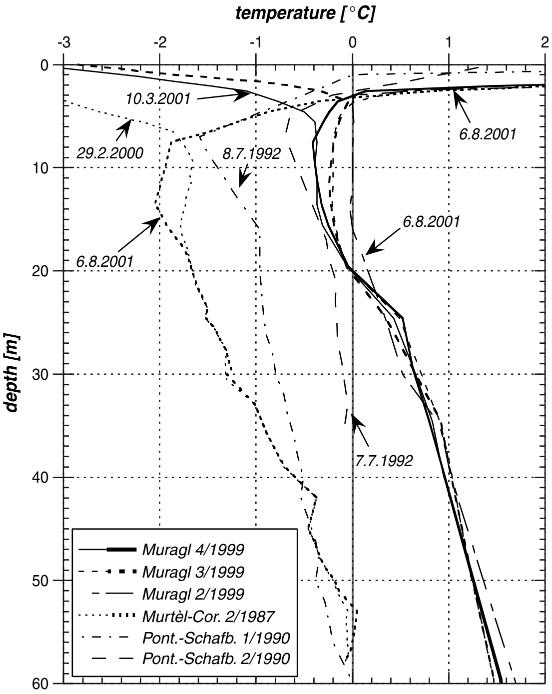


Figure 3 Temperature profiles of the different rock glaciers.

One possible solution might be that melting water infiltrates through the air voids of the rock glacier until it is trapped within larger caverns and slowly freezes. Due to limited available space, the volume increase during the phase change in the freezing process causes the pressure in the porewater to increase.

A borehole camera was lowered down the boreholes and showed that a compact ice-rich layer is present in the upper part (Figure 5a). At a depth of 49 m, however, approximately where the bedrock was assumed to have been reached in 1987, huge boulders and air voids were found (Figure 5b), which made further drilling impossible without a casing.

Pontresina-Schafberg.

No cores were taken from the two boreholes in the Pontresina-Schafberg rock glacier in 1990. Surface seismic and geoelectrical investigations had been performed beforehand in order to determine the bedrock and permafrost distribution (VAW, 1991) and geophysical borehole logging was performed mainly in borehole 1/1990 in order to investigate the internal structure (Vonder Mühll, 1993; Vonder Mühll and Holub, 1992). The results identify that the first layer underneath the active layer has approximately 30% ice by volume. In the next 6 m (until the bedrock was reached), ice content was deduced to be up to 80% by volume. The local geomorphology, data from photogrammetrical analysis and the depth to bedrock obtained from

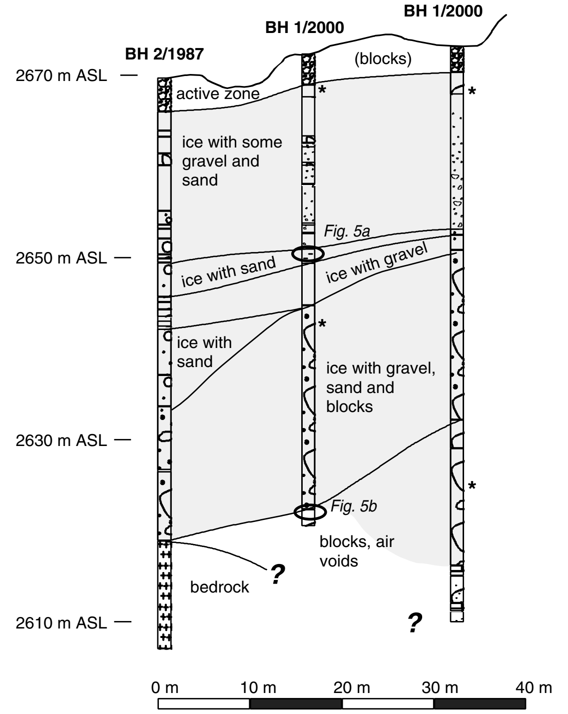


Figure 4 Internal structure of the Murtèl-Corvatsch rock glacier. Water leakage into the borehole (*).

the boreholes indicate that borehole 1/1990 has been drilled over a slight ridge in the rock horizon, in a less active region to one side of the rock glacier. Borehole 2/1990 is located in the second tongue where it is thought that the bedrock will be more or less parallel to the surface.

Muragl.

The Muragl rock glacier has attracted many researchers during the last hundred years (Salomon, 1929; Domaradzki, 1951; Barsch, 1973, 1978; Haeberli, 1992). However, studies concentrated mainly on geomorphology and therefore the composition has remained largely unknown. In contrast to the two sites described previously, the Muragl rock glacier has a much lower ice content and higher air-void ratio. Furthermore, the ice is warmer and close to 0 °C (Figure 3). Information during drilling, such as penetration rate, rotation velocity of the drill bit, borehole cuttings and cores, air loss, and the experience of the drillers, contributed to obtaining details of the strata found in the four boreholes (Figure 6), three of which were cored using a triple-tube drilling system. The geophysical borehole loggings (GEOTEST, 2000), and investigations from the surface and from borehole to borehole (Musil *et al.*, in press), could be calibrated against the borehole data to reveal the spatial distribution of the permafrost body and the bedrock between the holes. No water was found within the frozen ground during drilling, probably because air voids within these layers were so large that any water was able to flow down to the unfrozen gravelly, blocky layers below the permafrost. Drilling without a casing was not possible due to the relatively low ice content and the high air-void ratio.

In contrast to the three other boreholes, no ice was found within borehole 1/1999 (Figure 6), which has been drilled closer to the side boundary of the rock glacier (Figure 2b). The volumetric ice content is relatively low (40–70% by volume) within the frozen layers in boreholes 2–4/1999 and is very heterogeneous. A decreasing trend of ice content

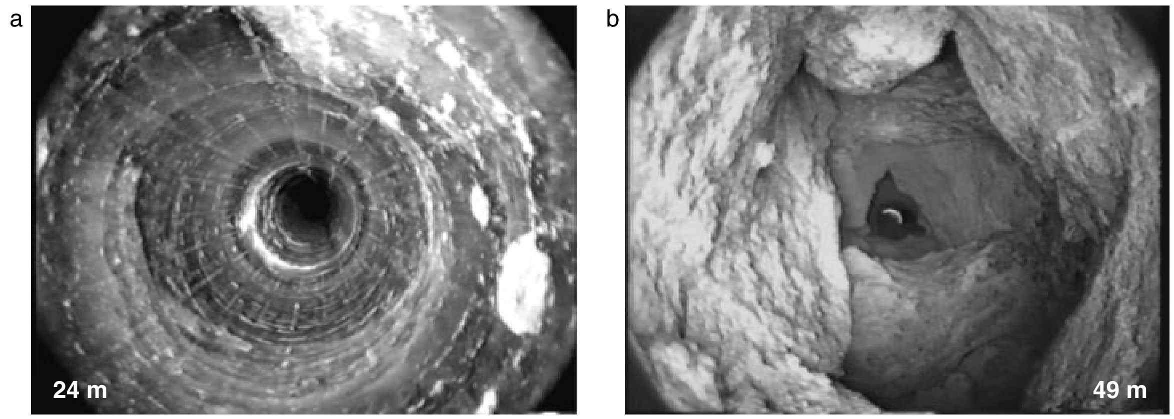


Figure 5 Photographs from a borehole camera (Murtèl-Corvatsch 1/2000) at a) 24 m and b) 49 m depth. The vertical marks at the depth of 24 m originate from steel strips ('Chinese lanterns'), which protect the rubber membrane of the pressuremeter device.

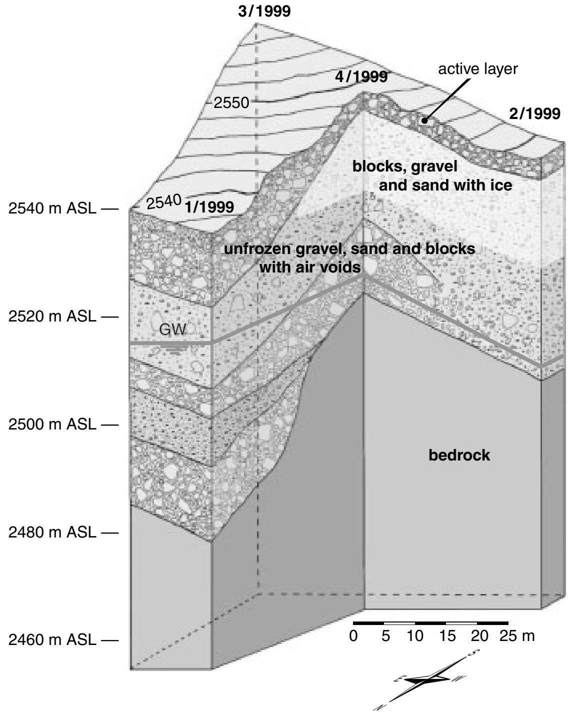


Figure 6 Internal structure of the Muragl rock glacier.

with depth can be observed. The lower boundary of the permafrost (as defined by a temperature less than 0 °C for more than one year) is deeper than the lower boundary of the ice actually found in the pores between the solid particles, i.e. the depth of the ice-bearing permafrost is less than the depth of the 0 °C isotherm. Since large air voids were found underneath the icy layers, where the flushing air vanished completely during the drilling operation, no water accumulated at this depth. Therefore, the ice that melted from the bottom of the permafrost during a warmer period cannot be regained. The groundwater table, which was observed to be constant during the year (1999–2000), is about 2 m above bedrock. The temperatures in borehole 2/1999 (Figure 3) show a 'zero-curtain' effect, which means that a constant temperature of just less than 0 °C exists within the frozen soil at depths between 3 and 16 m. This implies that this section of the rock glacier is close to melting. Permafrost distribution modelling with PERMAMAP (Hoelzle and Haeberli, 1995; Hoelzle, 1996) indicates that the lower part of the rock glacier is in a region where permafrost is unlikely to form under current climatic conditions. There is a high probability that the ice found at the drill sites was formed initially at higher altitudes and has been transported within the rock glacier below the expected lower altitude limit of permafrost for that area.

Grain Size Characteristics of the Frozen Debris. Grain size distribution and standard soil classification tests have been performed on solid particles obtained from the cores of the Muragl and Murtèl-Corvatsch (drilling 2000) rock glaciers. Even though the maximum grain size is difficult to estimate due to the limited core diameter of 74 mm, in which some particles have been cut smaller by the drilling process, the results indicate a typical Fuller-distribution (Figure 7). In addition, the curves look

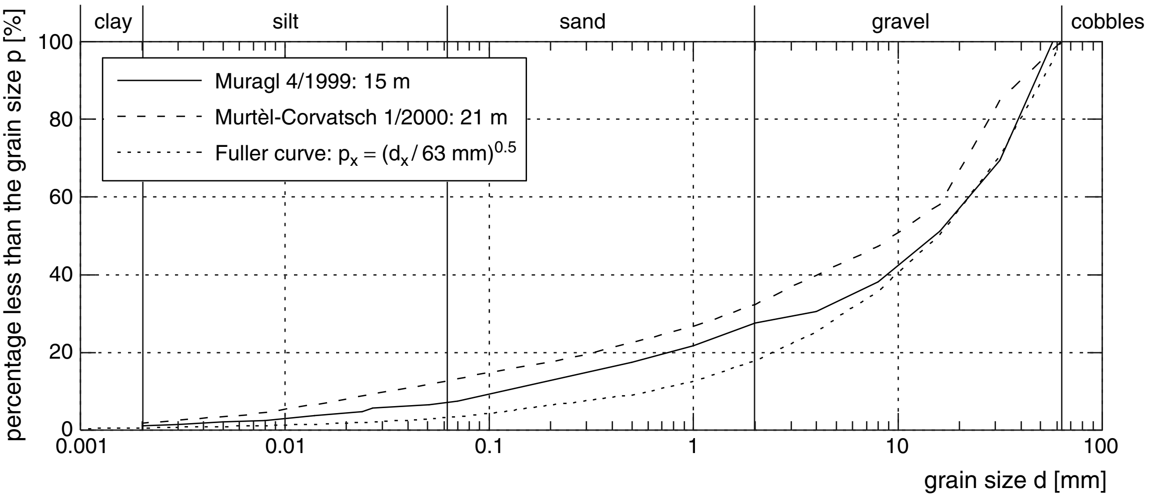


Figure 7 Grain size distribution.

very similar and can be classified as sandy, well-graded gravels with silt (GW-GM (SN 670008a, 1997)). Virtually no clay-size particles were found, largely because insufficient degradation or weathering had occurred at these altitudes. The particles are very angular and the specific density of the material was determined to be between 2.75 and 2.77 g/cm^3.

In contrast, Barsch *et al.* (1979) found much finer material within the active Gruben rock glacier. Unfortunately, they only obtained samples from depths between 2 and 3 m, which is the zone directly underneath the active layer, where the finer particles that might be washed out of the coarse top layer during the summer months may have accumulated. It is not certain, therefore, that this layer is representative of the rock glacier as a whole, since rock glaciers are very heterogeneous and it is difficult to find a representative layer. Considering the variation in grain size, which includes large boulders with diameters up to 5 m, about 1000 t of soil material is necessary to obtain a representative sieve analysis (SN 670810c, 1986).

DEFORMATION MEASUREMENTS

Different systems were installed in order to measure the internal horizontal and nominally vertical movements. Good results were obtained from slope inclinometer measurements with the SINCO Digitilt system for determining horizontal movements. Two different types of settlement measurement system (i.e. vertical deformation) were used for the three sites. However, a PVC-tube is necessary for all systems in order to guide the measurement probes and to protect the borehole from collapsing. The tube was placed within the borehole and a soft grout or water, which then sets and/or freezes, was placed around it to refill the space between the PVC-tube and the borehole wall. Within the very unstable boreholes of the Muragl rock glacier, the PVC-tube and grouting hoses were first placed into the steel casing used during the drilling, which was then pulled out of the ground and the remaining cavities were grouted (Arenson, 2000). However, the first readings have to be used with care, since some rearrangement within the hole due to the grouting process is still possible.

All readings were taken three times in order to increase accuracy of the measurement. An initial zero reading serves for the determination, subsequently, of relative movements.

Horizontal Deformations

A special PVC-tube of 71 mm external diameter, with two sets of diametrically opposed internal channels, guides the inclinometer probe that measures the inclinations in two orthogonal directions every 2 ft (0.61 m) along the tube (Figure 8). The probe uses null-balance accelerometers as sensing elements. Since the accuracy in the guided 'A-direction' is slightly better, the tubes are oriented in a way that the 'A-direction' represents the direction of the primary deformations. A set of two readings is taken from the bottom to the top in the A0 and A180 directions with the aim of eliminating the zero offset of the instrument.

The longest data series presented in this paper are from the Murtèl-Corvatsch rock glacier (Wagner, 1992, 1996). Measurements were made until 1995, when the radius of curvature within the deformed inclinometer casing became smaller than 5.3 m, preventing the probe from passing through the tube. Some results from the Schafberg rock glacier have already been presented in Hoelzle *et al.* (1998), where, in the meantime, the readings in both boreholes had to be stopped due to the excessive deformation. A new series of deformations were recorded on the Muragl rock glacier from the late summer 1999 to early in 2000. The rate of strain, however, was so

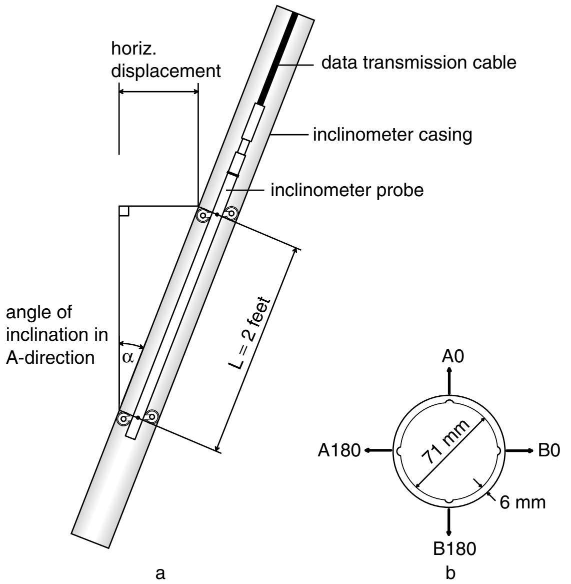


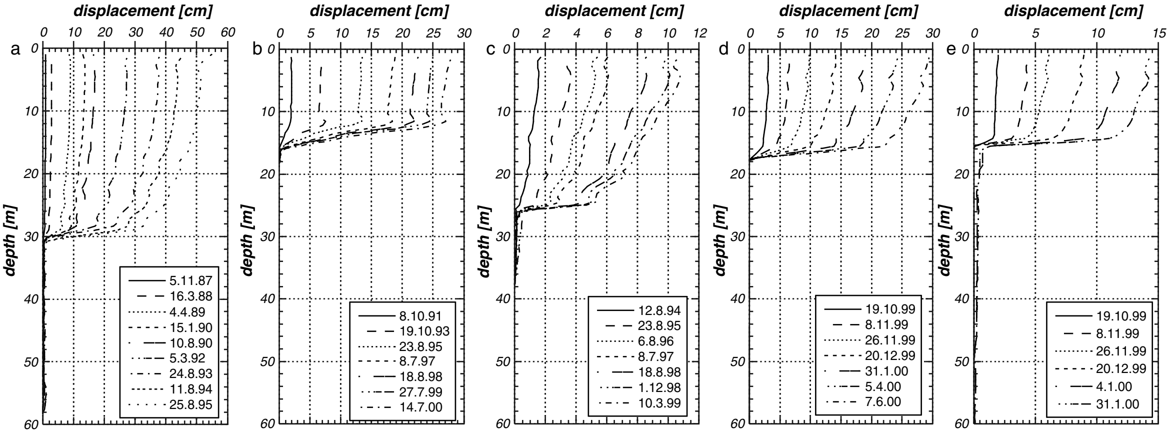
Figure 8 Principle of SINCO Digitilt inclinometer measuring system. a) Longitudinal section through inclinometer casing and probe; b) Cross section through PVC tube, showing the four channels.

large in some zones that the readings could only be carried out for eight and four months, respectively. However, seasonal changes in horizontal deformation rate were observed for the first time.

Usually, it is assumed that the bottom of the borehole is fixed relative to the overlying layers. This assumption allows integration of the differential movements to be carried out from the bottom up, from which a surface movement can be derived. This assumption might not be true for borehole 1/1990 at Pontresina-Schafberg, where the plastic casing is only fixed in the bedrock for 1 m. An inclination can be seen directly at the bottom of the inclinometer casing, which is located at the top of bedrock.

A summary of all horizontal deformation measurements is given in Figure 9a-e. A distinct shear horizon passes through all boreholes, with a zone of no (or limited) deformation in the lower part and a zone with some additional creep above the shear horizon. The velocities, however, are rather different (Table 2). The first readings at Pontresina-Schafberg 2/1990 were ignored since only bedding-in responses were recorded.

The measured deformations in the boreholes of all three rock glaciers show a very good match with the surface deformations derived from digital image analysis (Hoelzle *et al.*, 1998; Kääb *et al.*, 1998; Kääb and Vollmer, 2000). The surface deformations of the Muragl rock glacier were calculated from aerial photographs of 1981 and 1994, assuming the difference between these two years represents average conditions. Within this period, the coordinates of the future boreholes 3/1999 and borehole 4/1999 had moved about 32 cm and 28 cm, respectively. In contrast, surface movements of 45 cm could be calculated for borehole 3/1999, using



Murtèl-Corvatsch 2/1987 (1987-1995) bedrock at >51 m?

Pontresina-Schafberg 1/1990 (1991-2000) bedrock at 16 m

Pontresina-Schafberg 2/1990 (1994-1999) bedrock at 30 m

Muragl 3/1999 (1999-2000) bedrock at 38 m

Muragl 4/1999 (1999-2000) bedrock at 32 m

Figure 9 Horizontal downslope borehole deformation. a) Murtèl-Corvatsch, borehole 2/1987: 1987–1995; b, c) Pontresina-Schafberg, boreholes 1/1990 and 2/1990: 1991–2000, 1994–1999; d, e) Muragl, boreholes 3/1999 and 4/1999: 1999–2000.

Table 2 Shear velocities.

Site		Depth of shear zone [m]	Data reading time [days]	Velocity in shear zone [cm/year]	Deformation in shear zone/tot. surface def.
Murtèl-Corvatsch	2/1987	28.4–31.4	2891	4.0	59%
Pontresina-Schafberg	1/1990	11.4–16.4	3529	2.8	97%
	2/1990	24.4–26.2	2276	0.9	50%
Muragl	3/1999	15.6–17.9	250	32.1	77%
	4/1999	13.7–16.0	122	35.4	82%

an annual shear velocity. Seasonal changes of the available data were fitted with a sinusoidal function and extrapolated, since the horizontal deformation could not be measured for a whole year in the two boreholes. This apparent increase in deformation rate may be due to a possible warming of the permafrost during the last seven years.

The depth to the shear horizons varies from rock glacier to rock glacier. In the Murtèl-Corvatsch rock glacier, the shear zone developed in a sandy layer in the middle of the permafrost, whereas the Muragl rock glacier creeps at the bottom of the frozen body. The main reason for this dissimilarity may be the thermal conditions: permafrost can form today at Murtèl-Corvatsch by freezing water in contrast to the Muragl site, where the permafrost can only exist due to its stored frozen energy. As a consequence, ice, which might have existed at greater depth, melts and the shear horizon moves towards the surface. Relative movement within the unfrozen material will be hindered by interlocking of the particles, which will mobilize peak shearing strengths together with dilatancy along the shear zone. At Muragl however, the warm ice (very close to 0 °C) at the bottom of the frozen soil will creep under some loading conditions. Additional potential energy originates from the slightly steeper (Table 1) and longer slope above the area under observation. These gravity-driven forces combined with reduction of shear resistance due to the warmer temperatures associated with the degradation of an active rock glacier explain why the mean annual velocities are greater than two times than at Murtèl-Corvatsch.

Seasonal changes in permafrost creep rates have been measured by some authors: e.g. for massive ground ice (Dallimore *et al.*, 1996) or at a depth of only 65 cm (Bennett and French 1990, 1991) in arctic permafrost and for the top 3 m in the Tibetan Plateau (Wang and French 1995). However, since these creep deformations occur at shallow depths, effects induced by the active layer, such as solifluction or frost heave affect these processes.

In the Alpine region similar variations are usually difficult to measure since they lie either within the order of the accuracy of the measurement techniques, or they may be non-existent. The cumulative downslope surface deformations of the three rock glaciers are displayed in Figure 10a-c. An increase in the deformation rate from around 6 cm/year up to 9 cm/year could be observed for the measurements at the Murtèl-Corvatsch site taken between 1991 and 1995, which might have been induced by an increase in temperature in the shear zone of about 0.5 °C during the same period (Vonder Mühll *et al.*, 1998). Both boreholes on the Pontresina-Schafberg rock glacier have shown a more or less constant surface velocity during the life of the inclinometer tubes. Surprisingly, the velocity at the surface of borehole 1/1990 is approximately 1.5 times faster than in the second borehole, even though the surface slope inclination is about the same and the temperature in the shear zone of borehole 1/1990 is around 0.6 °C colder. However the bottom of the inclinometer tube might not have been fixed perfectly in the bedrock. The characteristics of the layer just above the bedrock must be different to that which has been described by Haeberli and Vonder Mühll

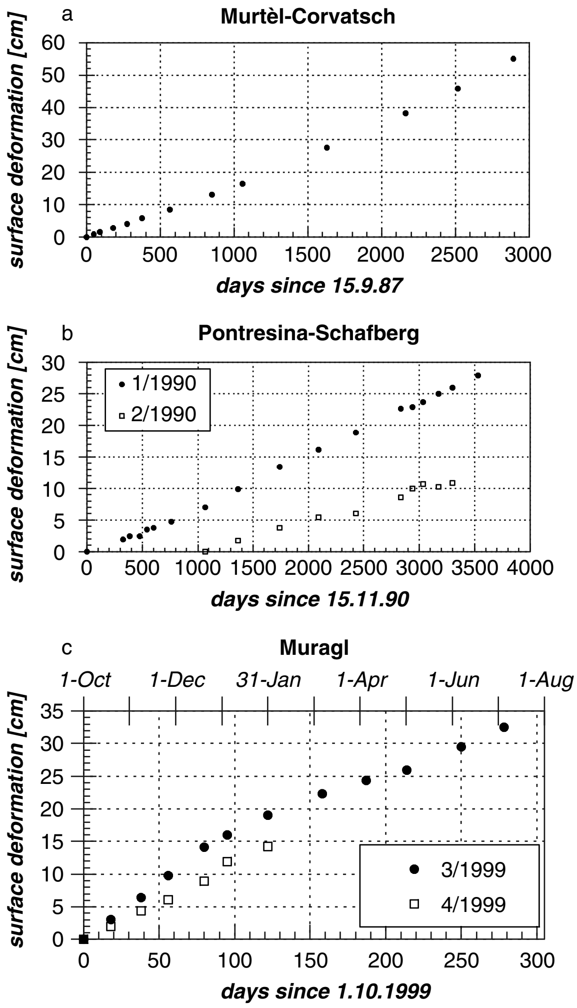


Figure 10 Surface deformation with time. a) Murtèl-Corvatsch, borehole 2/1987: 1987–1995; b) Pontresina-Schafberg, boreholes 1/1990 and 2/1990: 1990–2000 ; c) Muragl, boreholes 3/1999 and 4/1999: 1999–2000.

(1996) and Haeberli *et al.* (1998) for the Murtèl-Corvatsch rock glacier. If large boulders were present, such as those seen at Murtèl-Corvatsch (Figure 5b), the interlocking forces at that depth would override the tendency for creep under the present stress and temperature conditions and the shear zone would be at a shallower depth. Due to the convex-shaped ridge of the bedrock (VAW, 1991), no large boulders would have been able to remain on the ground before the rock glacier passed over them. When the ice content increases so that particle interlocking is reduced or eliminated, as found at the base of borehole 1/1990, creep becomes prevalent. Some further effects, such as a 4 m thick basal shear zone in combination with the presence of water just above the bedrock might explain why the creep velocity within the shear zone was three times higher than for borehole 2/1990. Another differentiation between the two boreholes is that borehole 1/1990 shows nearly all its deformation within the shear zone while about half of the deformation within the second borehole is spread over the layer above the shear zone. The material above 24 m in borehole 2/1990 seems to be more creep-susceptible.

The most interesting measurements come from the Muragl rock glacier (Figure 10c), where seasonal changes in deformation rate were observed. Surprisingly, the velocity is up to three times higher during the winter months than during the summer months (Figure 11). These differences can be explained by considering the temperature-penetration down to the shear zone. The annual variation in temperature over the entire permafrost body can be described with a sinusoidal law. With depth, amplitude decreases and the maximum and the minimum shifts depending on the thermal diffusivity of the subsurface. According to the deformation measurements for Muragl 3/1999, a shift of four months can be observed (Figure 11). Unfortunately the temperature data from this period are not continuous, so that no direct comparison with the deformations is possible. These four months are, however, shorter than the phase lag Vonder Mühll *et al.* (1998) measured within the rock glacier Murtèl-Corvatsch, where the phase lag at a depth of 11.6 m was about six months. The larger amount of rock within the Muragl rock glacier, which has a slightly higher thermal diffusivity than ice, may explain the difference in thermal conditions and, hence, the observed variation in creep velocity.

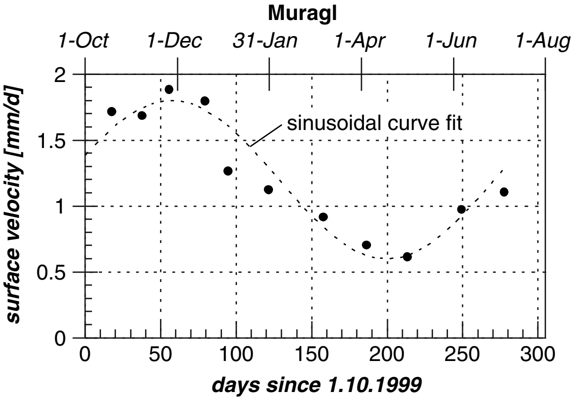


Figure 11 Surface velocities with time of the Muragl rock glacier, borehole 3/1999.

The more elevated borehole 3/1999 shows larger deformation rates with time than borehole 4. The flow is compressive in this region. This has been described by Kääb and Vollmer (2000) as having a negative deformation gradient.

Vertical Deformations

Magnet rings were used for the nominally vertical deformation measurements within the Murtèl-Corvatsch (1987) and the Pontresina-Schafberg rock glaciers. These are fixed with adhesive tape outside the inclinometer casing, which has no telescoping couplings, and are separated by intervals of between 3 and 5 m. Their position is then measured with the help of a magnetic sounding lead. The magnet rings can be located with an accuracy of ±1 mm. The main problem is, however, that the inclinometer plastic casing might not follow the vertical movements of the soil mass and, therefore, the magnetic rings do not represent absolute values. For the Muragl rock glacier, vertical deformations were measured with the SINCO settlement USBR-type probe, which uses telescoping coupling between the inclinometer casings (Figure 12). The USBR-type probe has two spring-loaded arms that catch on the bottom edge of the distinct casing section near the coupling when the operator pulls the probe up on the survey tape. A special mount guarantees that the tensile stress within the tape is always the same. In contrast to the magnetic rings, the casing, which is well grouted into the ground, moves with it.

However, some of the telescoping couplings were filled with grout during the installation of the inclinometer casings, resulting in unsatisfactory data. In order to measure the vertical displacements more accurately, different systems, such as increx or rod extensometers, are recommended. Due to the horizontal deformations of the inclinometer tubes, the data do not represent the vertical deformation of the rock glaciers but merely the extension or

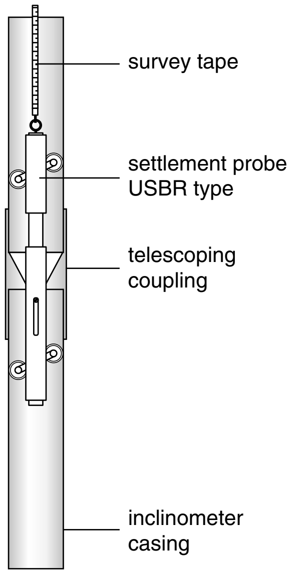


Figure 12 Vertical deformation measurements with the SINCO settlement USBR-type probe.

compression of the tubes. The distributions of these deformations are, nevertheless, helpful in revealing the flow mechanisms.

Measurements are available on the Murtèl-Corvatsch site for over a decade. Three main phenomena can be observed. First, the main settlement occurs around the shear zone (Figure 13a). Additional settlement occurs in the uppermost metre, possibly an artefact due to the installation of the magnetic rings. Second, the upper part of the rock glacier above approximately 22 m shows an increase in thickness. Third, the measurements between August 1995 and August 1996 indicate a net extension of the tube of around 5 cm; since then, the thickness has continued to decrease (Figure 14). It is unlikely that there was heave of the rock glacier. Because this event coincides with the period in which it became impossible to obtain inclinometer readings (Figure 9a), it is thought that the stresses on the plastic tube caused the tube to break and a sudden extension of the casing occurred.

Confirmation that the bottom of the inclinometer casing in borehole 1/1990 is not fixed into the bedrock can be shown by the data from Pontresina-Schafberg (Figure 13b). No significant changes can be observed down to a depth of 11 m. All the settlements take place below this level, down to the bottom of the casing at 18.4 m. The most recent measurement shows dramatic changes at depths below 12.5 m, which indicates a large increase in deformation within the shear zone during the last year, which resulted in the casing shearing-off. As a consequence, the inclinometer probe cannot be lowered anymore. The second borehole at Pontresina-Schafberg and both Muragl boreholes show that major vertical movements occur within the shear zone (Figure 13c-e), as was the tendency at Murtèl-Corvatsch. Very minor changes can be observed above and below the shear zones. However, two details at the Pontresina-Schafberg borehole 2/1990 are (Figure 14c): i) because the top marker seems to settle with time, and since this marker is placed within the active layer, it seems as if the top layer of this rock glacier becomes thinner with time; and ii) an unexplained slight heave is observed at the bottom of the casing. It is possible that boulders induce these local effects.

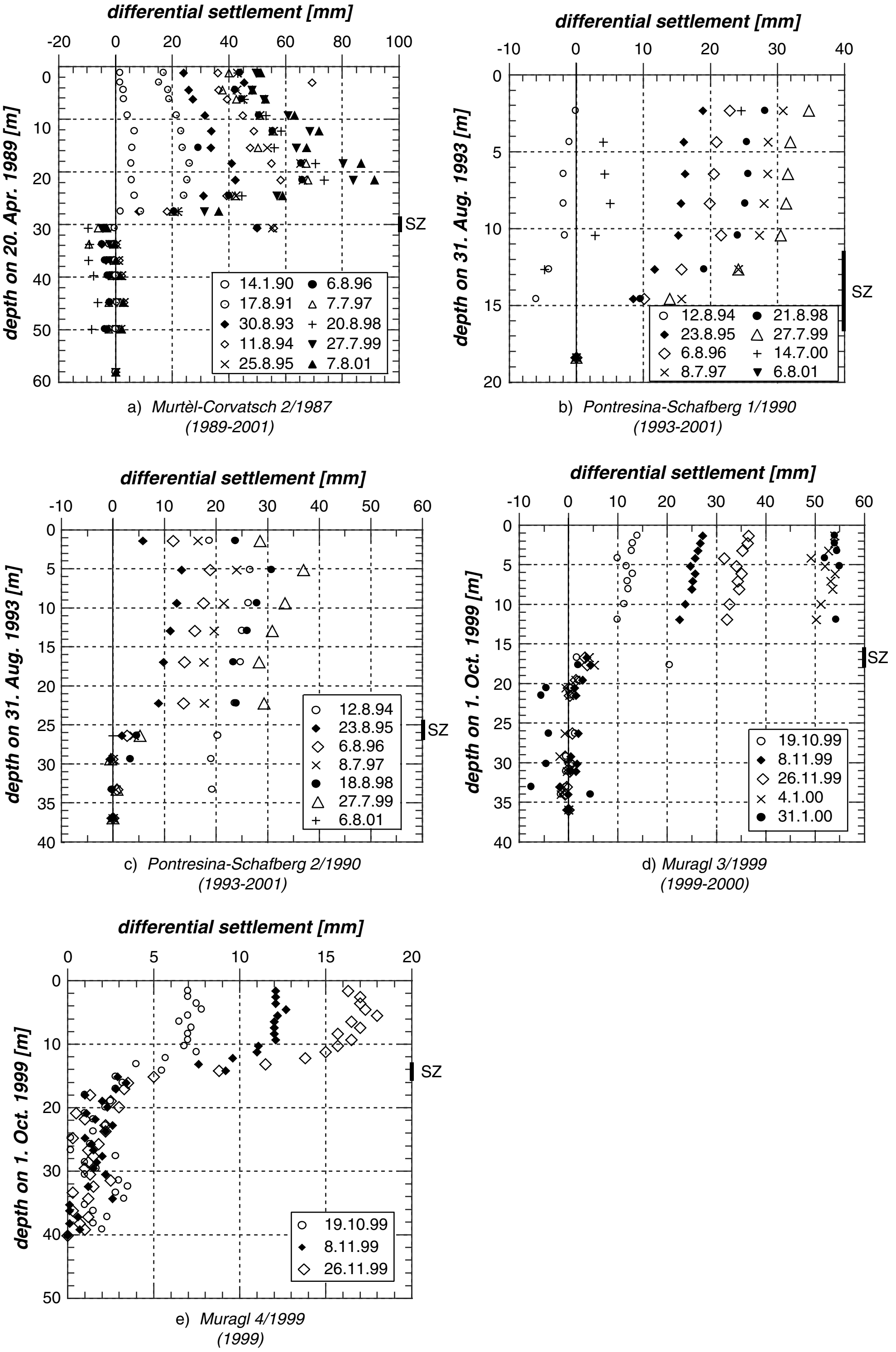
DISCUSSION

The objective of this research is to achieve a better understanding of the deformation behaviour of rock glaciers. This helps with the characterisation of their past and prediction of their ongoing evolution. In order to reach this goal, deformation measurements within active Alpine rock glaciers are necessary, in combination with a profound knowledge of the internal structure.

Drilling and Measuring Devices

Drilling in such a heterogeneous environment is an enormous technical challenge. A triple-tube system with cold-air flushing is necessary to obtain nominally undisturbed samples. However, if there are too many solid particles of gravel-size or larger, not even such a system delivers good cores. In this case, information from the drilling progress, as well as the drill chips, helps in the interpretation of the stratigraphy. Additional geophysical loggings may deliver the spatial distribution of some features. However, they have to be calibrated with the borehole logs.

Not only is the drilling in Alpine permafrost a challenge, the installation of measuring devices is often complex. Data loss can occur due to the exposure to rough weather conditions. Rearrangements and bedding-in effects have to be allowed for during the first readings of the deformation measurements. In addition, strange and sudden changes in a data series, such as the heave in Murtèl-Corvatsch borehole 2/1987 within an ongoing settling trend, have to be analysed and interpreted carefully. As a consequence, the actual numbers are sometimes less important than the observed trends.



a) *Murtèl-Corvatsch 2/1987 (1989-2001)*

b) *Pontresina-Schafberg 1/1990 (1993-2001)*

c) *Pontresina-Schafberg 2/1990 (1993-2001)*

d) *Muragl 3/1999 (1999-2000)*

e) *Muragl 4/1999 (1999)*

Figure 13 Vertical deformations with time. Net settlement measured from the top of the borehole means compression, which results in a decrease of the rock glacier thickness (SZ: shear zone). a) Murtèl-Corvatsch, borehole 2/1987; b) Pontresina-Schafberg, borehole 1/1990; c) Pontresina-Schafberg, borehole 2/1990; d) Muragl, borehole 3/1999; e) Muragl, borehole 4/1999.

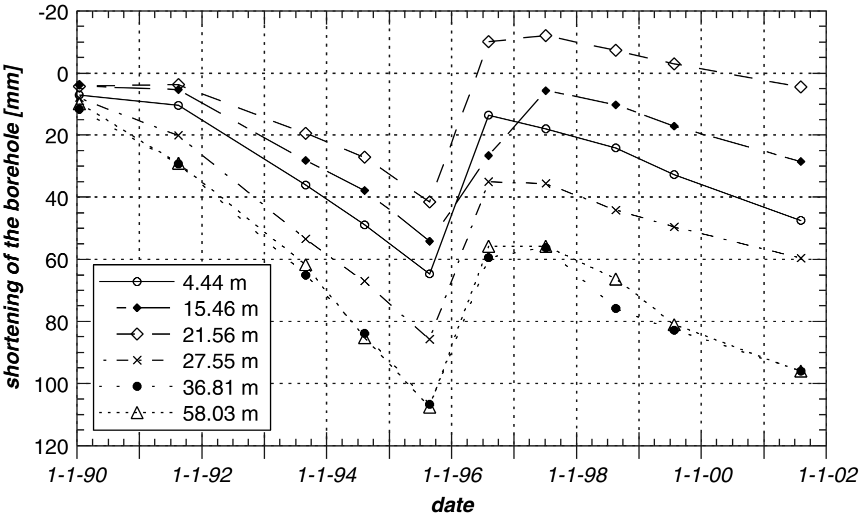


Figure 14 Vertical deformations with time for selected depths for Murtèl-Corvatsch 2/1987.

The soil deformation profile measured in a zone of extreme shear using a slope inclinometer system may not represent the actual soil deformations. The plastic casing has a specific stiffness and might act like a rigid dowel (similar to a laterally loaded pile) in the deforming soil whereby there could be differential lateral movement between casing and soil. The soil may deform more than the rigid tube immediately above the shear zone and less below (Figure 15). For a more accurate representation of the lateral deformation in zones of high shear, the tube should have a high flexibility ratio, which is a function of the tube geometry and material, and the skin friction between the soil and the tube (e.g. analogous to a pile; Fleming *et al.*, 1994). In such a case, the tube moves with the soil since the stresses acting on the tube bend it rather than causing the soil to shear around it.

A second problem is that fine shear bands cannot be identified since the vertical deformation is an average over a depth of 2 ft (0.61 m) along the borehole. Figure 16 shows a close up of a sample of the rock glacier Murtèl-Corvatsch at a depth of 20.25 m. Such fine layers might be important for deformation processes since shearing is likely to be concentrated in such thin layers. These are nearly parallel to the surface, and contain relatively fine-grained particles, each with a thickness of just millimetres. Additional resistance can be mobilized due to interlocking of grains (when these are relatively densely packed) and this is inevitably a function of particle size and ice content.

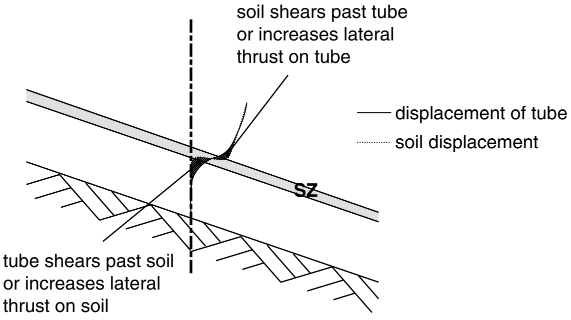


Figure 15 Sketch of a deformed stiff tube in a shear zone (SZ).

Time domain reflectometry (TDR) might prove to be a useful tool for deformation measurement in rock glaciers in the future, since the relatively flexible cable is grouted directly into the ground (O'Connor and Dowding, 1999). The flexibility ratio of a TDR cable is about six times larger than that of a standard inclinometer tube. In this case the cable should follow the soil deformation more closely. In addition, continuous monitoring is possible without having to make manual measurements. Such a system was installed in the new boreholes at the Murtèl-Corvatsch rock glacier. In the future it should be possible to identify i) fine shear bands, ii) change in depth of the shear zones and eventually iii) seasonal changes. The latter will only be measurable if the creep velocity increases, and the shear zone is above the zero annual

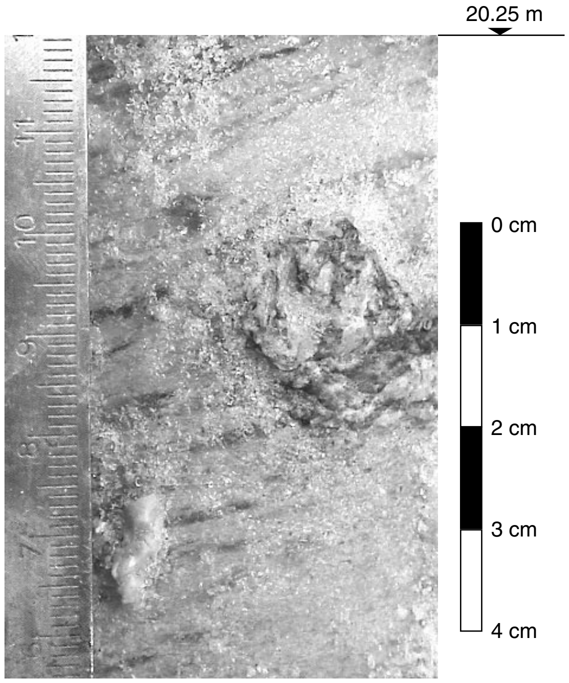


Figure 16 Sample from rock glacier Murtèl-Corvatsch borehole 2/2000, depth: 20.25m. The scale on the left is in millimetres.

amplitude, so that seasonal temperature changes can affect the creep.

Deformation Processes

Different deformation processes, influenced mainly by the internal structure of the rock glaciers, were observed using the investigation and monitoring programme presented herein.

- Within mountain areas where the temperatures inside the permafrost lies between 0 and about −2 °C (e.g. Murtèl-Corvatsch), the rate of shearing and the shear resistance is influenced by the ice content, the size and distribution of the soil particles, the confining pressure and the temperature. Low ice content and larger particles strengthen the frozen material due to interlocking of the soil particles. The permafrost body is cold enough in order to refreeze water within the ground.
- As soon as the topography plays an important role (e.g. shallow bedrock, change in slope, length of the slope, ridges and furrows in the bedrock), additional mechanisms (e.g. possible basal gliding) have to be considered when analysing the deformation processes.
- In degrading permafrost, with temperatures very close to the melting point (e.g. the lower reaches of Muragl), the ice only exists because it has been carried downslope with the rock glacier. The shearing movements take place in the lowest part of the frozen zone in which the material tends to be ice-rich (>50 vol.-% ice). Since the ice will melt from the bottom, the shear zone might also move slowly towards the surface, accompanied by a loss of volume.

The horizontal deformation measurements show that the layers within a rock glacier have different creep susceptibilities. Extrusion beneath the active layer was observed for all sites (Figure 9). Figure 17 shows a simplified sketch of this gravity-driven effect, which is induced by the different equivalent shear stiffnesses of these layers, including the rate effects from creep. The shear moduli G_1 and G_4 are higher than those in the main body of the permafrost G_2 and in the shear zone G_3. Within the shear zone, the conditions are slightly different (temperature, amount of soil particles, unfrozen water content, grain size distribution, etc.) than in the layer above and therefore, this layer is more creep-susceptible.

Similar to the horizontal movements, the majority of the vertical deformation was measured within the shear zone. Even though compressive flow occurs downslope in the areas under investigation, only settlements, i.e. a decrease in thickness of the rock glacier, were observed. The common assumption that the material within a rock glacier is incompressible (e.g. Haeberli and Vonder Mühll, 1996; Wagner, 1996; Konrad *et al.*, 1999; Kääb and Vollmer, 2000) is now proven to be incorrect. This is largely owing to the high percentage of air voids (Almasi, 2001) within the frozen body. The assumption of incompressibility might be true for glaciers, if limited

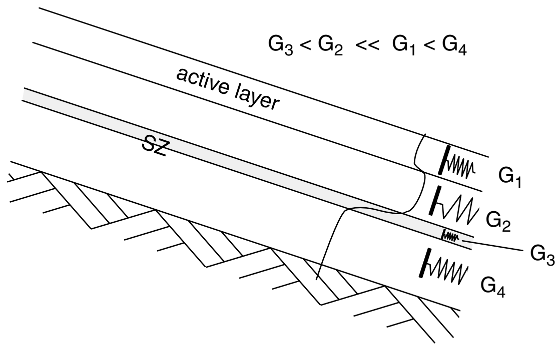


Figure 17 Schematic model of rock glacier stiffness distribution. G_1–G_4 are shear moduli.

air is trapped in the ice, and can therefore be used for studying mass balance and for deformation modelling (e.g. Gudmundsson and Bauder, 1999; Kääb, 2000). However, air voids and cavities were observed within the permafrost body during the drilling operations and subsequently determined to be about 5% from core samples. These voids may allow the soil mass to deform horizontally in regions of compressive flow within the rock glacier, without any effect in the orthogonal direction, due to volume reduction of the soil-ice-air matrix.

Seasonal changes in the velocity may be observed, depending on the depth of the shear zone. For shallow shear horizons at depths above the zero annual amplitude (16–20 m), seasonal differences have to be expected, with a phase shift depending on thermal properties, and hence, heat propagation within the ground. At greater depths, changes in velocity can be induced by long-term variations of climatic conditions, which influence the permafrost temperature through changes in the mean annual air temperature, snow cover or solar radiation. However, these influences can be strongly retarded.

Origin of Shear Strength and Slope Stability

Shear strength may be thought to derive from friction and cohesion (Coulomb, 1776). For permafrost containing particles in contact with each other, the shear strength is based on the former mechanism and is a function of the angle of friction and the effective normal stress (effective stress = total stress − pore pressure) mobilised between these particles, where pore pressure is positive if it acts to push the soil particles apart from each other. The angle of friction of the soil matrix may be judged approximately by the angle of repose of a dry body of this soil. Additional components of shear strength may be mobilised due to interlocking and the accompanying dilatancy (e.g. Bolton, 1986) in densely packed soil matrixes.

Within the ice-rich zones, the shear strength is mainly due to cohesion, which will vary principally due to structure and temperature. Changes to either of these may be one of the triggers leading to transition from secondary to tertiary creep and 'failure'.

Stability analyses depend on determination of the driving forces as well as the resisting forces within the failure plane. The latter are usually quantified based on mobilised shear resistance, which can be affected by influences at the micro-scale. At this scale, unfrozen water, which is attracted to the particle surfaces and requires more energy to freeze than normal porewater (e.g. Williams, 1967), might play an important role in adding to or detracting from the stability of the rock glacier in terms of slip failure, since it is likely to influence the effective stresses at temperatures close to 0 °C. With decreasing temperature, the unfrozen water content is reduced and suction is generated between the particles. This increases the effective stresses and hence the frictional component of the shearing resistance. However, the thickness of the unfrozen water film around the particles will increase as the permafrost approaches 0 °C. When the water-filled voids increase further in extent, positive porewater pressures will develop, reducing the effective stresses to the detriment of the frictional shearing resistance. Not only does the temperature influence the unfrozen water content, the particle size does as well: fine particles have larger specific surfaces in relation to their weight and can therefore bind more water with higher Gibbs energy. Furthermore, the temperature must be lower to eliminate the unfrozen layer and hence the suctions and freeze all of the porewater (e.g. Williams, 1967; Anderson and Morgenstern, 1973) at which time the particles are 'cemented' to each other by the ice and the shear resistance will derive from 'cohesion' as well as some friction.

Based on the observations presented herein, it is possible to consider the stability of a rock glacier. It is clear that creep processes dominate within the potential shear zone. The main question to be asked is whether the creep mode will develop towards the tertiary stage—which implies an acceleration of the velocity until this local element 'fails'. For slope failure to occur, a sufficient number of elements must lose shearing resistance along a potential failure zone. Laboratory tests on specimens under triaxial conditions as well as in-situ pressuremeter testing have demonstrated tertiary creep, but only at shear stress levels significantly higher than relevant for these rock glaciers (Arenson, 2001).

Even though the ice matrix is almost impermeable, the whole system can have large system permeability due to interlinked air voids and cavities. Significant bodies of unfrozen water can also be 'locked' into cavities within the frozen body for some time, and can influence the deformation behaviour due to local reduction in effective stress.

Factors affecting the shearing resistance within a rock glacier can therefore be condensed as follows.

- When ice is present, slopes can be stable at angles steeper than the angle of repose of the dry granular mass, representing the friction angle of the soil mass. However, the possibility of tertiary creep should be considered.

- Infiltrating water generates positive increments of porewater pressure, which then reduce the effective stress and hence the shearing resistance of the soil. The angle of the stable slope is reduced to less than the friction angle of the soil. This is a more dangerous scenario and is much more likely to lead to slip failure or debris flows, particularly within the active layer.
- If the density of the packing (solid particles per volume) increases above a critical ratio, interlocking and dilatancy occur, increasing the shearing resistance. The melting of the ice matrix within a frozen soil can increase the relative density of the soil matrix which would then mobilise greater shear resistance.

CONCLUSION

Borehole deformation measurements, in combination with high-resolution photogrammetric surface deformation measurements and geophysical investigations to establish spatial distribution of permafrost, help understand the deformation processes within creeping permafrost. Not only can long-term monitoring devices, such as deformation or temperature measuring tools, be installed in boreholes, detailed insight into the ground can be delivered when undisturbed cores are taken as well. This information is extremely important for the interpretation and future numerical modelling of rock glacier behaviour.

The following phenomena were either measured or observed.

- The three rock glaciers under observation possess distinct shear zones, where 50–97% of the horizontal strain takes place.
- Despite lateral deformation, only settlements and no heave were recorded in the vertical plane.
- The depth of the shear zones varies. Seasonal changes in strain rates were measured in the shallowest shear zone.
- Water was encountered within the permafrost body during drilling.

From these observations, the following conclusions concerning processes within an active rock glacier can be drawn.

1. The percentage of volume occupied by the soil particles influences the shearing response since interlocking will develop when the ice content is small enough. This might lead to additional strength and stiffness and hence lower creep velocities and a tendency to dilate locally when the soil matrix is dense, but in most cases the matrix was ice-rich and settlement or volume loss accompanied creep.
2. Temperature and quantity of sand- and silt-size particles influence the unfrozen water content. The unfrozen water content decreases with decreasing temperature, which reduces the creep strain.
3. Despite similar external appearance of many rock glaciers, the internal composition can vary significantly. This can affect the potential for slope instabilities to develop.
4. Frozen soil bodies within a rock glacier can be carried downslope to elevations below the lower boundary of permafrost.
5. The shear horizon moves slowly towards a shallower depth as temperatures approach 0 °C due to ice melting at the base, e.g. in degrading permafrost areas.
6. Since a rock glacier can have a large system permeability, meltwater flow through the pores can effect the internal stresses and hence the stability.

These conclusions demonstrate that rock glaciers are heterogeneous and anisotropic. They creep sluggishly, and if changes occur, they happen over decades or even centuries. The three rock glaciers presented herein symbolise different stages during their evolution. The lowest lobes of the rock glacier Muragl, for example, are in a degrading state. This is represented by fast movements in a relatively shallow shear zone. In addition, the temperatures were almost at 0 °C throughout the entire permafrost body. Deformations within the Murtèl-Corvatsch rock glacier, where the shear zone is in the middle of the permafrost body, show a slight acceleration due to an ongoing warming trend at greater depths. Virtually no temperature influences upon the creep velocity have been detected in the Pontresina-Schafberg rock glacier.

ACKNOWLEDGEMENTS

The ETH Research Commission, the Swiss National Science Foundation and the Swiss Academies of Science supported this research financially as part of three projects. The authors wish to express their special thanks to the anonymous reviewers who commented on the manuscript so carefully and constructively, as well as to Wilfried Haeberli, Daniel Vonder Mühll and Michael Davies who reviewed initial drafts of this paper critically. In addition, we acknowledge gratefully all technicians (especially Marco Sperl), students, colleagues (especially Hansruedi Maurer) and friends who helped during all the fieldwork, sometimes under extremely difficult conditions.

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