# Ground characteristics and deformation of a frozen moraine affected by tourist infrastructures (Col des Gentianes, Valais)

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## Abstract

Since 2002, various measurements have been carried out on the Col des Gentianes frozen moraine (Tortin glacier) in order to determine its internal structure and dynamics. Thermal data recorded in a borehole reveals temperatures of -0.5 to -1°C between 5 and 20 m depth in the moraine. Observations and analyses of ice outcrops in an excavation show that the moraine contains congelation and sedimentary ice layers close to the surface. According to the electrical resistivity tomography, massive ice may also be present at depth. Finally, GPS survey highlights different types of movements, such as settlement due to ice melt close to the surface and rapid movements in the steep flank of the moraine in the direction of the glacier.

## Introduction

Recent moraines (Little Ice Age) of small glaciers located within the alpine permafrost belt, at about 2700-3000 m a.s.l., may be the result of the deformation of pre-existing frozen sediments (former moraines, rock glaciers) by the glacier advance. These landforms are called *push moraines* (e.g. Haeberli 1979, Reynard et al. 2003, Delaloye 2004, Kneisel 2004). Because of the relatively few studies, the ice content, the distribution and origin of the ice and the deformation mechanism having affected and still affecting the frozen sediments are still little known. This paper presents and discusses the results of preliminary studies aiming to characterize the ground characteristics and the dynamics of the Col des Gentianes moraine (Valais), a landform on which tourist infrastructures have been built and whose initial surface topography has been modified (Lambiel 2006, Schütz 2007). This study comes within the double problematic of the glacier-permafrost interaction study and that of the sustainability of tourist infrastructures built in alpine permafrost.

## Site description and measurements

The studied moraine is located in the vicinity of the Col des Gentianes (2880 m a.s.l., 589'450/103'500) (Fig. 1). It was built by the Tortin glacier, on the north-western side of the Mont Fort (3328 m a.s.l.) during the Little Ice Age and probably earlier cold phases of the Holocene. At the end of the 1970s, the moraine was landscaped for ski activities (building of a cable car station, ground surface grading). During the excavation works, large ice lenses were observed (P. Glassey, pers. comm.).

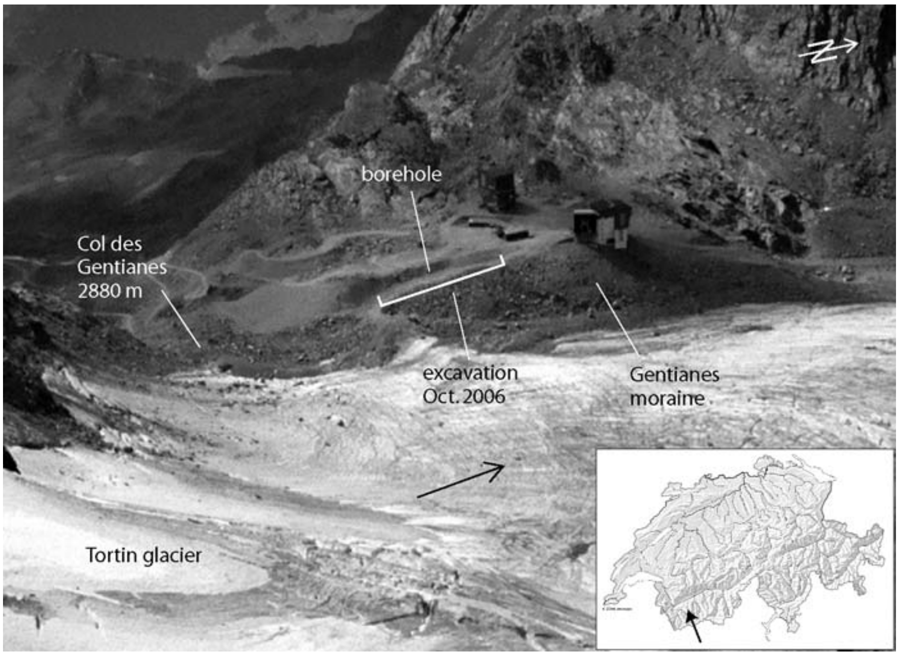



Fig. 1. The Col des Gentianes area viewed from the Mont Fort (July 2003).

In order to determine the internal structure and deformation of the moraine, different types of measurements have been carried out (Lambiel 2006). In November 2002, a 20 m deep borehole was drilled in the upper internal part of the moraine, on the upslope part of a track built for skiers to leave the glacier in winter (Fig. 1 and 2). Integrated in the PERMOS network (Vonder Muehll et al. 2007), the borehole was equipped with ten temperature sensors. Several vertical electrical soundings and mapping lines were carried out on the moraine and in the glacier forefield (Schütz 2007). A permanent electrical tomography profile (24 electrodes, 4 m spacing) was installed on the upslope part of the track in summer 2007 for geoelectrical monitoring. Finally, the movements of about 70 blocks are measured twice a year since summer 2004.

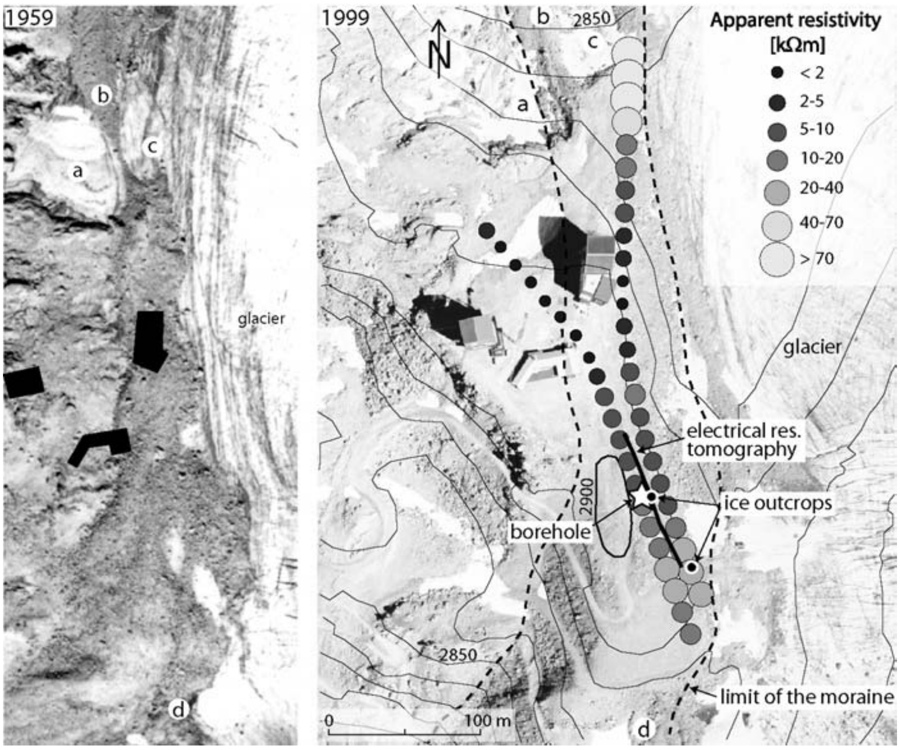



Fig. 2. On the left, 1959 aerial photography with location of the future buildings (non rectified). On the right, 1999 orthophoto; location of the borehole, the geoelectrical mapping (interval inter-electrodes 15 m), the 2D geoelectrical survey line and the ice outcrops observed in excavations in 2006. The letters provide landmarks for comparing the two images. Reproduced by permission of swisstopo (BA081197).

## Observations and results

### *Ice outcrops*

In mid-October 2006, excavation works were carried out on the internal flank of the moraine, on the road connecting the buildings to the glacier (Fig. 1 and 3). In numerous places, the excavation depth was limited by the presence of ground ice. Close to the borehole, ice appeared at about 2 m depth (Fig. 4), whereas it was already visible at about 50 cm depth in the southern part of the moraine (Fig. 5).

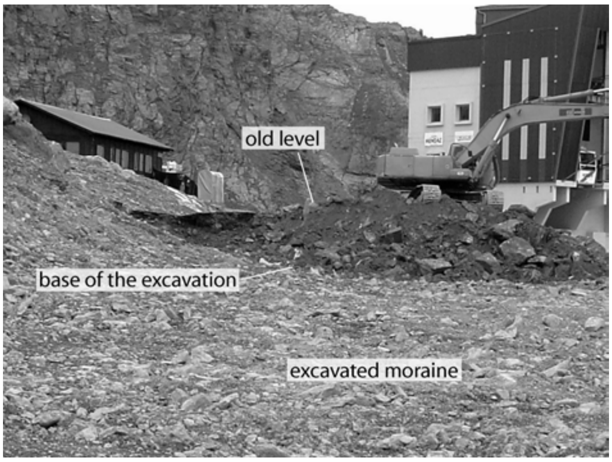



Fig. 3. Excavation works carried out in October 2006 to the south of the cable car station, on the road leading to the glacier.

To better understand the origin of the sedimentary deposit, initial analyses of ice samples have been carried out in collaboration with the Laboratory of Glaciology of Grenoble University. In the northern outcrop (Fig. 4), the ice contained very few rock fragments. We can observe a succession of layers of pure ice, rich in spherical air bubbles, and layers of dirty ice, which draw local micro folds. The presence of the air bubbles indicates that the origin of the ice is probably sedimentary (cf. Shumskii 1964, Haeberli & Vonder Muehll 1996). It would correspond to glacier ice incorporated in the moraine. As for the micro folds, they indicate that the ice affected by local deformation. In the southern outcrop (Fig. 5), the origin of the ice is completely different. Indeed, the ice is translucent and extremely pure. Air bubbles are absent. These characteristics are those of congelation ice. Lastly, we can also notice the presence of ice-cemented gravels and refrozen soaked-snow ice in the same excavation. These different observations show the diversity of the ice present in the moraine.

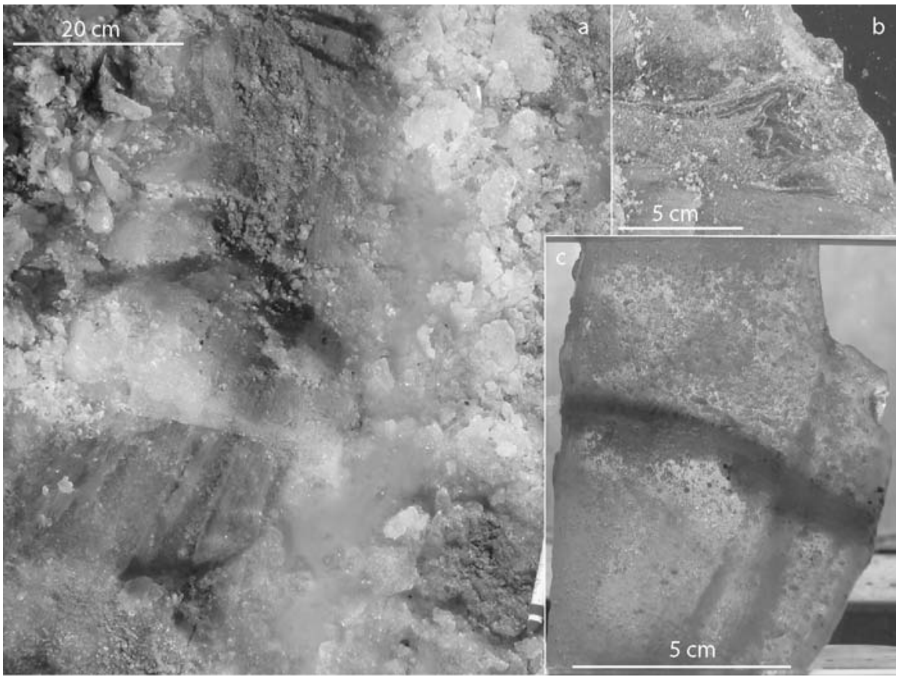



Fig. 4. Sedimentary ice found in the vicinity of the borehole. The ice presents a foliation (a), local micro folds (b) and high air bubble content, clearly visible on the thin section (c). For location, see Fig. 2.

As the excavation was carried out by the end of the hydrologic year, the depth of the unfrozen surface layer may be considered as representative of the active layer thickness. However, the heat amount accumulated in the ground in summer 2006 was the least since the beginning of the measurements (Fig. 6). In addition, the ground froze regularly during the night since the beginning of October. Thus, it is possible that a part of the congelation ice observed in the southern part of the excavation was formed in spring 2006 or even in the few days preceding the excavation. Anyway, compared to the usual data available for alpine rock glaciers and talus slopes (e. g. Vonder Muehll et al. 2007), the thickness of the superficial layer of unfrozen material is relatively thin.


Fig. 5. Congelation ice in the southern part of the moraine. The unfrozen surface layer thickness is about 50 cm (photo: 20 Oct. 2006). For location, see Fig. 2.

### *Thermal regime*

The temperatures measured in the borehole since 2002 indicate that permafrost is present at least in the first 20 meters of the moraine (Fig. 6). Near-surface temperatures are in agreement with the observations made during the excavation works of October 2006. Indeed, the temperature at 1.5 m depth has never exceeded 0°C, which indicates a relatively thin active layer. The data illustrates also the strong interannual variations, with greatly contrasted winters. For instance, early snow fall in autumn 2002 prevented the ground from significant cooling, which explained the quite warm near-surface temperatures of winter 2002-2003, whereas the ground cooling was strong in winter 2005-2006, due to a thin snow cover during the first part of the winter and cold air temperatures. At 9.57 m depth, a slight warming (+0.2°C) occurred until February 2006, after which a cooling down occurred. At 20 m depth, the evolution was the same, but the variations were smaller. Temperatures at that depth are about -0.5°C.

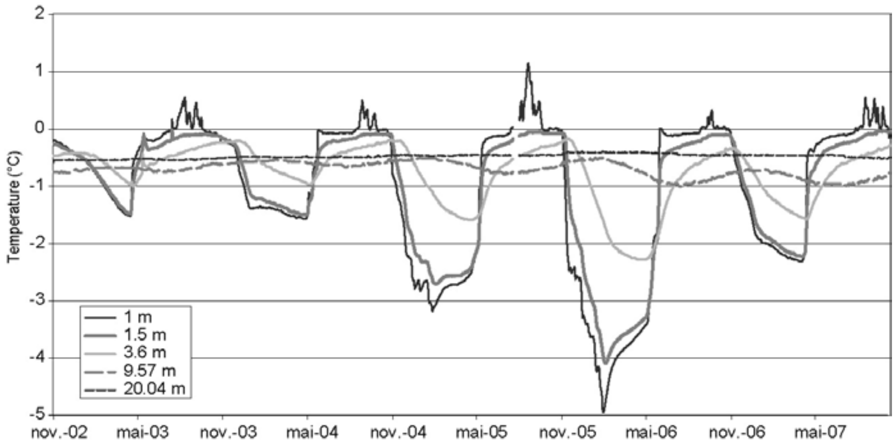



Fig. 6. Temperatures recorded in the Gentianes borehole, between November 2002 and October 2007.

### *Electric properties*

The 2D geoelectrical monitoring is carried out with the Wenner-Schlumberger configuration and inversed with the RES2DINV software. The measurements of August 2007 show resistivities everywhere higher than 5 kΩm, with a general increase of the values towards the southern part of the profile (100-150 kΩm) (Fig. 7). Two zones of higher resistivities are clearly visible in the southern and middle parts of the profile. They probably correspond to relatively pure ice bodies, like those which were observed in the excavation in October 2006. In the middle part, resistivities are relatively low (< 6 kΩm) below 10 m depth. However, the borehole, which is located near the centre of the survey line (Fig. 2), indicates negative temperatures throughout the first 20 m of the moraine. Thus, we can conclude that the frozen material is very little resistant in places. An increase of the specific surface due to a high proportion of fine-grained sediments may explain such low resistivities (Lambiel & Baron, 2008).
The two presented mapping lines show the apparent resistivity variation at about 7-10 m depth (15 m inter-electrode) over the length of the moraine (Fig. 2). In the northern part of the landform, the maximal values were measured (>70 kΩm). As we can see in

Fig. 2, this area was occupied by the glacier in 1959. In addition, sedimentary ice outcrops could be observed in the internal flank of the moraine, downstream the mapping line (Lambiel 2006). Thus, the high measured resistivities are very probably explained by the presence of buried glacier ice in the ground. The values decrease close to the buildings, where they are lower than 2 kΩm, which corresponds either to the bedrock (between the buildings) or to the presence of unfrozen sediments (permafrost degradation due to anthropogenic causes). To the south of the buildings, the resistivities increase again. They are comprised of between 5 and 20 kΩm for about 150 m, before reaching values of 20-40 kΩm in the southern part of the moraine. The increase of the resistivities in this area is conform to the 2D electrical imagery and probably corresponds to an increase of the ice content at depth.

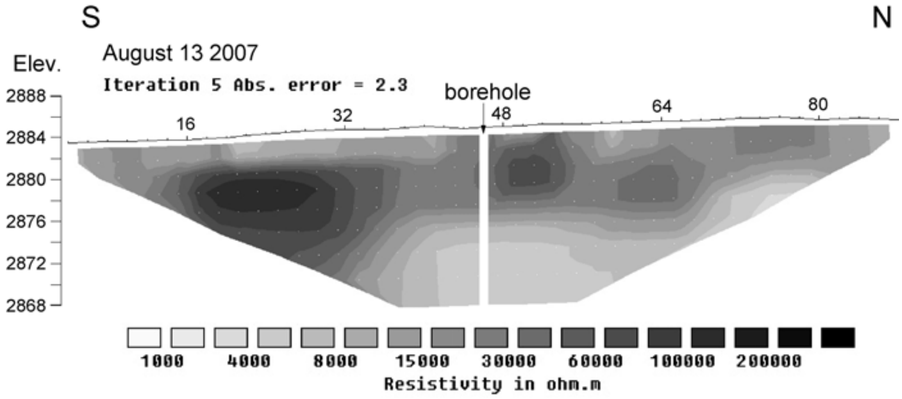
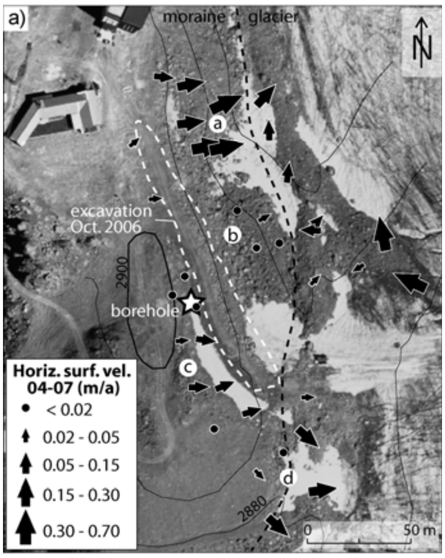



Fig. 7. Two dimensional resistivity profile measured on the Col des Gentianes moraine (13th Aug. 2007).

### *Movement geometry*

Despite the disappearance of numerous measurement points during the excavation works of October 2006, in particular in the area located east of the borehole, the measured blocks give a good image of the movement geometry. The main motion is in the glacier direction (Fig. 8a). Maximal velocities are observed in the internal flank of the moraine, in the vicinity of the buildings, where the slope is the steepest (a). Annual velocities are comprised between 30 and 70 cm $a^{-1}$. On the other hand, the velocities are very low south of this area, where the slope is less steep (b). Despite a low inclined slope, the upper part of the moraine (c) is also affected by deformation, which is, however, quite low (< 15 cm $a^{-1}$) and mostly occurring in summertime.

The repetition of the measurements at the beginning and at the end of the summer (mid July – early October) permits the seasonal variation of the velocities to be determined (periods with and without snow cover). In Fig. 8b, we observe that the velocities are systematically higher in summer than in "winter". In the southern area (d), the winter movements are almost non-existent, whereas the summer velocities can reach 70 cm $a^{-1}$ (summer 2005). In the flank of the moraine (a), the winter movements are also lower than the summer ones, but remain nevertheless significant. Lastly, we can observe in Fig. 8b that the lower velocities of summer 2006 correspond to colder mean annual ground surface temperature and to colder August temperatures.



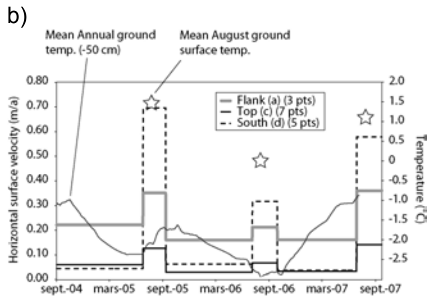




Figure 8. Horizontal surface velocities on the Gentianes moraine. a) Movement geometry. Reproduced by permission of swisstopo (BA081197). b) Seasonal and interannual evolution.

Following the excavation of October 2006 (cf. Fig. 8a), the measurement of 30 new blocks located on the road was carried out in order to follow the readjustment speed of the active layer. In one year, the settlement of the moraine reached a mean of 11 cm, with maxima of about 40 cm. Visual observations show that the settlements are locally more important, which indicates the rapid melting of massive ice at the permafrost table. The movements occurred nearly exclusively during the period free of snow.

## Synthesis and discussion

The observations and measurements carried out permit us to better understand the structure and the dynamics of the moraine. The thermal data indicate that the active layer is thin (about 1.5 m). The excavation of October 2006 showed that congelation and sedimentary ice is present close to the surface (0.5 m to 2 m). According to the electrical resistivity imaging, massive ice lenses may be present at depth. Another piece of information provided by the electrical prospecting is the large variations of the resistivities. This indicates that the internal structure of the landform is very heterogeneous. Massive (sedimentary?) ice layers may juxtapose ice-rock mixture sediments of still indeterminate nature and origin. Such characteristics are in agreement with the observations of Keusen and Haeberli (1983) in another alpine frozen moraine.

In the relatively flat areas of the upper part of the moraine, the major part of the movements occurs in summer. The melting of ice present at a few tens of centimetres from the ground surface, which was attested by the excavation, probably explains these strong summer movements. In the steep internal flank of the moraine, the presence of significant winter velocities indicate that the movements are not only explained by ice melting near the surface, but probably also by the deformation of the frozen body (permafrost creep). The sliding of the superficial unfrozen layer on massive ice may also be envisaged, although the apparent resistivities measured in the upper part of the slope show that the ice content in this sector should not be very important. In the south of this sector, the lower velocities measured can probably be explained by the lower slope declivity and by the presence of the debris covered glacier at the base of the slope, which constitutes a support for the moraine.

Where ice is present very close to the surface, the summer velocities are dependant on the mean summer temperatures (in

particular August). Where the unfrozen superficial layer is thicker, the variations of the summer velocities may also be explained by the evolution the mean annual ground surface temperature.
The aerial photography of 1959 permits the shape of the moraine before the anthropogenic interventions to be observed (Fig. 2). At that time, the sedimentary deposit presented a rounded shape, which differences it from a classical angular lateral moraine, like the one present to the north of the buildings (letter b in Fig. 2). This morphology is typical of push moraines. Thus, the Col des Gentianes moraine could be the result of the displacement and of the deformation of frozen sediments by the advance of the Tortin glacier during the Little Ice Age (or even during an older cold period). In the steep flank of the moraine, the geometry of the movements and the existence of significant winter velocities may illustrate the back-creeping of the moraine in the direction of the glacier. Another hypothesis to the rounded shape of the moraine would simply be the creeping of ice-rich sediments containing dead glacier ice and congelation ice formed in situ.

## Conclusions and perspectives

Together with the direct observations of ice outcrops, the measurements carried out show the heterogeneity of the internal structure of the moraine. This complexity is related to the double glacial and periglacial origin of the landform. To the natural movements due ice melting and ice-rich material deformation, rebalancing following the anthropogenic modifications of the superficial layers of the moraine is added. In the future, the moraine deformation may be amplified by the accelerated retreat of the glacier (loss of support), by the melting of massive ground ice and by the permafrost warming.
The thermal, electrical and dynamics monitoring on the Gentianes site will go on in the future. To better understand the spatial and temporal variations of the surface movements, new tomography profiles are needed, in particular in the steep internal flank of the moraine. In addition, the contribution of Terrestrial Laser Scanning for the study of terrain motion in the alpine periglacial belt is currently being evaluated on this site (cf. Riff et al. 2008). Finally,

further analyses of ice samples collected in the recent excavations should be carried out.


## Acknowledgments

We would like to thank Téléverbier SA and Télénendaz SA for their financial and logistic support, to Reynald Delaloye for his critical comments and to Meredith Blake for proofreading the English.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