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Glacier/permafrost relationships in forefields of small glaciers (Swiss Alps)

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ABSTRACT: Thermal and geoelectrical measurements were carried out in three recently deglaciated forefields of small glaciers situated within the belt of discontinuous permafrost in the Penninic Alps, Western Switzerland. Results show that many parts of the investigated surfaces are currently not underlain by permafrost and that the Little Ice Age (LIA) glacier advance modified both the geometry and the thermal regime of pre-existing permafrost bodies. Occurrence of neo-permafrost could be observed only very locally, on the basis of the methods used.

1 INTRODUCTION

Since the end of the Little Ice Age (LIA), glaciated surfaces in the Alps have considerably decreased, exposing large areas of unconsolidated sediments. The LIA proglacial forefields of most of the small glaciers (<1 km^2) are situated within the belt of discontinuous permafrost (>2200 m a.s.l.). Few attempts have been made to map the ground ice distribution in such recently deglaciated terrains (e.g. Evin & Assier 1983, Evin 1992, Kneisel 1999, Kneisel et al. 2000a, Delaloye & Devaud 2000). There is however current interest for a clarification of knowledge of the ice distribution and characterization in these forefields, because of potential instabilities due to ice degradation (e.g. Lugon et al. 2000).

The objectives of the current study were therefore to map and characterize the ice distribution in the forefield of three small glaciers (<1 km^2) of the Penninic Alps of Valais (Western Switzerland): the Aget Glacier in the Grand Combin area, and both Becca d'Agè and La Chaux Glaciers in the Mont Fort area (Fig. 1).

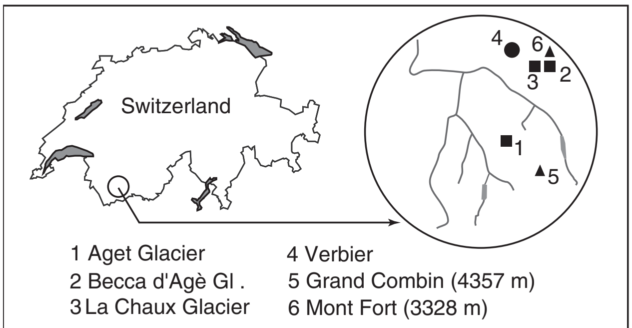

Figure 1. Map situation.

2 METHODS

2.1 *Introduction*

Three direct current (DC) resistivity methods were used: vertical soundings, lateral mapping and 2D resistivity profiling. BTS (Basis Temperature of the Snow cover) measurements and continuous logging of the subsurface temperature were also performed. These methods were complemented by geomorphological observations and mapping.

2.2 *Geoelectrical methods*

DC resistivity methods in the periglacial areas have proved to be successful at detecting the presence of ground ice. The various types of ground ice that can be found are described by Haeberli & Vonder Mühll (1996).

Vertical sounding is well suited for characterizing both the stratification of frozen grounds and the width of permafrost bodies (e.g. Vonder Mühll 1993). Several soundings were carried out in the three investigated forefields (Aget: 9 soundings, Becca d'Agè: 12 shallow soundings, La Chaux: 9 soundings).

Lateral mapping (parallel iteration of 1D resistivity lines using a fixed Wenner configuration) is not a widely used method. The results are complementary with DC resistivity soundings as they allow the cartography of lateral variations of the ground apparent resistivity (for permafrost bodies, usually 2–5 times lower than the calculated resistivity) at a fixed pseudo-depth (Reynard et al. 1999, Delaloye & Devaud 2000). In the present research, the method was used only in the Aget Glacier forefield (9 lines).

The third geoelectrical method used is the 2D resistivity profiling (DC resistivity tomography). The method is recent and is being increasingly used in mountain permafrost studies (e.g. Kneisel et al. 2000b, Hauck 2001, Vonder Mühll et al. 2001, Marescot et al. in press). Methodological problems of data interpretation are discussed by Marescot et al. (in press). Three transverse 2D resistivity profiles were obtained in the Becca d'Agè Glacier forefield and one longitudinal profile was recorded in the La Chaux Glacier forefield.

2.3 *Temperature measurements*

The BTS method (Haeberli 1973) allows the mapping of zones of probable absence/presence of permafrost or ground ice with relatively good accuracy. Nevertheless, the threshold at $-2/-3$°C usually used for distinguishing probable and improbable presence of permafrost is arguable as it depends on ground type and snow conditions. We therefore consider that in some cases, temperatures warmer than -2°C could indicate the presence of permafrost. Several BTS measurement campaigns were carried out in the three areas (Aget Glacier: 1997 and 1999, Becca d'Agè Glacier: 1995, 1999 and 2000, La Chaux Glacier: 2001). These measurements are not presented in the current paper; however, they are used for interpreting and corroborating some other results.

Continuous logging of the subsurface temperature using miniature loggers (Hoelzle et al. 1999) was also carried out. Temperatures were recorded every two hours at a few centimetres under the surface. Mean subsurface temperature (MST) for the period 15th February–15th March was systematically calculated in the three forefields: Aget Glacier, 7 loggers, winters 1998–1999 to 2000–2001; Becca d'Agè Glacier, 8 loggers, winter 1999–2000; La Chaux Glacier, 8 loggers, winter 2000–2001. Results presented in Fig. 3, 4, and 5 are complemented with standard deviation in order to substantiate the stability and therefore the validity of the mean temperature. The MST appears to be usually higher (from a few tenths to more than one degree) than the BTS measurements performed at the same place (Delaloye et al. 2001). Recorded values are changing from one year to another: MST in the investigated terrains were relatively warm in 1998–1999, cold in 1999–2000 and warm in 2000–2001 (Tab. 1).

3 SITES

The three proglacial margins are situated in the Penninic Alps of Valais, Western Switzerland. Geology is dominated by highly fractured metamorphic rocks (gneiss, prasinites, micaschists, amphibolites, quartzite shales). Current mean annual precipitation is about 2000–2400 mm and mean annual air temperature (MAAT) is about -2.5°C at 2800 m a.s.l. All three sites are situated within the belt of discontinuous permafrost as described by Delaloye & Morand (1998) and Lambiel & Reynard (2001).

During the LIA, the Aget Glacier occupied a small, north-east oriented valley with frontal moraines at 2760 m a.s.l. Since that time, the glacier has lost 70–80% of its surface and the deglaciated area now lies from 2760 to 2900 m a.s.l. Only the orographic left side of the forefield was investigated because large sediments deposits are restricted to this area. A small remnant white glacieret still occupies the upper north-oriented slope of the cirque.

The Becca d'Agè Glacier forefield is situated in a small, east-oriented valley (2750–2900 m a.s.l.), south of Mont Fort (3328 m a.s.l.). During the LIA, the glacier partially covered an active rock glacier (Fig. 2). Almost 70% of the surface glaciated during the LIA is now free of ice. But a small, north-east-oriented

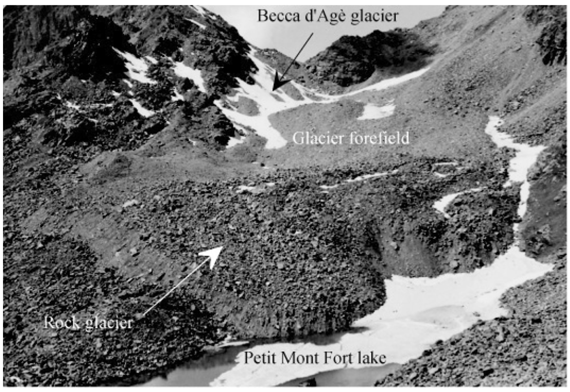

Figure 2. A view of the Becca d'Agè glacier forefield.

Table 1. Mean subsurface temperature (MST) during the period 15th February–15th March in the Aget Glacier forefield.

	Mini-loggers (location on fig. 3)						
Year	1	2	3	4	5	6	7
1998–1999	−0.44	−0.64	−0.79	−1.29	−0.58	−0.89	−1.59
1999–2000	−0.96	−1.43	−2.25	−1.60	−0.91	−1.14	−2.47
2001	−0.44	−0.41	−0.59	−0.89	0.00	−0.49	−1.12

Standard deviation is less than 0.22 for every series.

glacieret, highly covered with debris, still occupies the upper part of the small valley.

The La Chaux Glacier is bigger than the two others and is situated in an adjacent valley to the Becca d'Aget Glacier. It is oriented north-west and the LIA frontal moraines are situated at 2520 m a.s.l. About 60–70% of the LIA glacier has disappeared and the ablation area is highly covered with debris. The glacier forefield lies from 2520 to 2850 m a.s.l.

4 RESULTS

4.1 *Aget Glacier forefield*

Vertical soundings and BTS measurements show that the lower left side of the recently deglaciated forefield is currently unfrozen (Delaloye & Devaud 2000). The upward part is quite different as most of the terrain is creeping towards the bottom of the valley (Fig. 3, black arrows). Vertical soundings *Ag-06* and *Ag-08*, performed within this area, indicate the presence of a 20 m thick layer with specific resistivity of 50 kΩm *(Ag-08)* to 200 kΩm *(Ag-06)* below a 6–8 m deep unfrozen active layer (specific resistivities: 3–10 kΩm). These soundings indicate the presence of profound permafrost bodies partly thawed on their top (Delaloye & Devaud 2000). MST (−0.6 to −1.6°C in 1998/99) corroborate this interpretation. Two reasons allow us to think that permafrost bodies were removed by the glacier advance: (1) there is no source of sediments directly above the permafrost area and (2) the majority of the frozen terrain is currently creeping towards the valley floor, which is assumed to be a re-equilibrating movement now that the glacier has disappeared.

Sounding *Ag-09*, performed outside the lateral LIA moraine on sediments with a blocky surface, indicates a frozen body (specific resistivities: 8–15 kΩm, width: 6–15 m) under an active layer 4–6 m thickness (2–3 kΩm). MST was −0.9°C in 1998/99. The zone is interpreted as permafrost which could be inactive (Delaloye & Devaud 2000).

4.2 *Becca d'Agè Glacier forefield*

Most of the proglacial margin is covered with lodgement till (rounded blocks and fine sediments). Both frontal and lateral left side parts are quite different with large angular blocks. Four different areas are evidenced (Fig. 4). The central depressed part of the margin has a MST very close to 0°C (−0.3°C), indicating the absence of permafrost. Several BTS measurements of both the 1999 and 2000 campaigns corroborate this mean value. DC resistivity vertical sounding Lo-02 is interpreted as 3–4 m of unfrozen sediment (moraine) immediately covering the bedrock. This part, which is situated in the continuation of the current glacial front, is interpreted as a sector where the glacier advance thawed and disturbed the pre-LIA permafrost body. The former material was certainly largely removed by the glacier and partially replaced by lodgement till.

Around this central sector, the MST are colder (−0.6 to −0.9°C), but still relatively close to 0°C, indicating

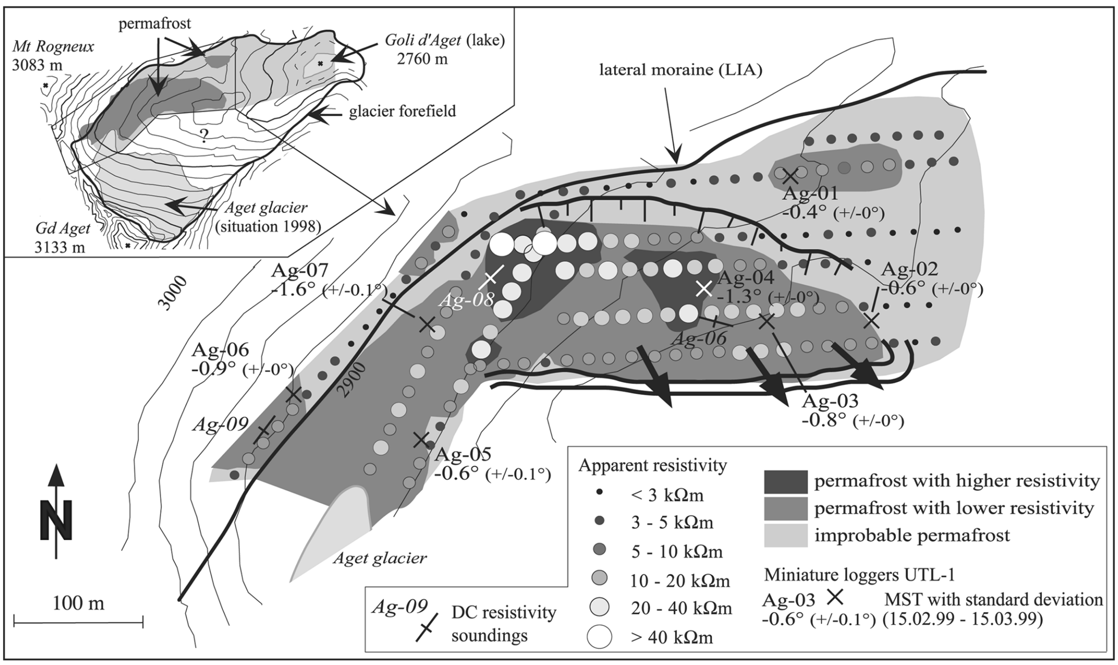

Figure 3. Aget proglacial margin: electrical apparent resistivity at 10–15 m deep, mean subsurface temperatures (MST) and result interpretation. Black arrows indicate creeping terrain.

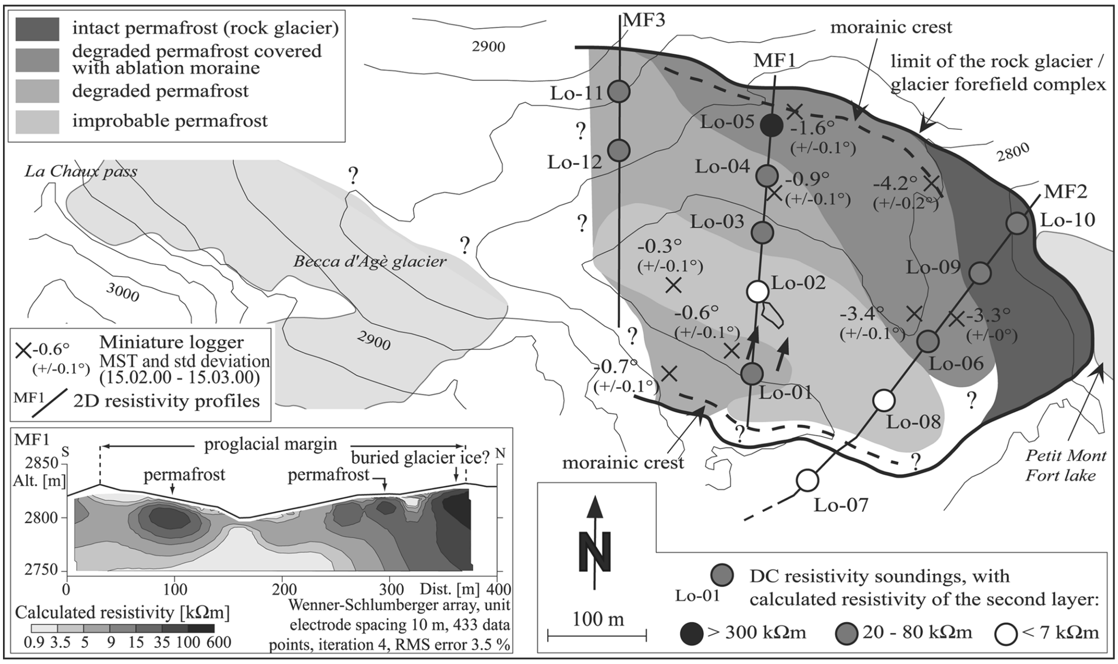

Figure 4. Becca d'Agè proglacial margin: DC resistivity shallow soundings at 10 m deep, 2D resistivity profiles, mean subsurface temperatures (MST) and result interpretation. Black arrows indicate creeping terrain.

the possible presence of permafrost. Several shallow DC resistivity soundings and the 2D resistivity profiles (Fig. 4 and Marescot et al. in press) indicate the same configuration as in the Aget forefield, that is the presence of a resistive layer (width: 6–10 m, specific resistivity: 20–80 kΩm) below a 3–5 m deep subsurface layer with low resistivity. The southern side of the margin shows evidence of active creeping towards the central depression (black arrows, Fig. 4) and most of the surface is characterized by longitudinal organization of the debris cover (fluted moraines). All these observations allow us to interpret this sector as composed of deep permafrost bodies partially melted by subglacial water circulation and covered by unfrozen moraine deposed during the LIA glacier advance.

The northern side of the proglacial margin has a surface quite different from the rest of the forefield. The surface is covered with large angular blocks, interpreted as ablation till (with blocks fallen on the glacier surface from the Mont Fort walls). Because of circulation of cold air between the blocks, the MST are much colder (−1.6 to −4.2°C) than in the center of the margin. They could indicate the probable presence of near-surface permafrost. Measured resistivity at sounding Lo-06 is similar to most of the rest of the margin, but sounding Lo-05, situated near a 5 m deep thermokarstic depression, shows a layer with 300 kΩm specific resistivity. It is interpreted as a possible dead ice body covered with ablation till.

The frontal part of the investigated area is situated outside the morainic crests. Specific resistivity of the frozen layer is 170 kΩm and the area is interpreted as an active rock glacier uncovered by the LIA glacier advance.

4.3 *La Chaux Glacier forefield*

Two DC resistivity soundings (Ch-05 and Ch-09, specific resistivities: >600 kΩm) and the 2D resistivity profile confirm geomorphological evidence of the presence of a debris-covered glacier in the southern part of the margin and near the current visible glacier front (Fig. 5). The MST is about −1.6°C.

Downstream, in a recently deglaciated area, sounding and miniature logger Ch-07 show the presence of a frozen body (18 kΩm, width: about 20 m) under a 3 m deep active layer, with a MST of −1.4°C. Because of its situation in a longitudinal depression, where the activity of the LIA glacier certainly completely degraded the former permafrost, the frozen body found here is assumed to be neo-permafrost. It could have formed either just after the melting of the glacier, or just before its disappearance, when it was already very thin. This case is very similar to the one reported by Kneisel et al. (2000) (sounding Muragl_3).

Directly downslope, a patch of preserved permafrost (10 kΩm, width: 8 m) situated under a thin layer, that is interpreted as dead ice (200 kΩm), is attested by sounding Ch-08. Creeping features (Fig. 5, black arrows) are clearly visible. On the other side of the valley, preserved permafrost can also be found at sounding Ch-04, with a MST of −1.2°C.

All the methods used show that large surfaces of the prospected part of the margin are unfrozen. MST are

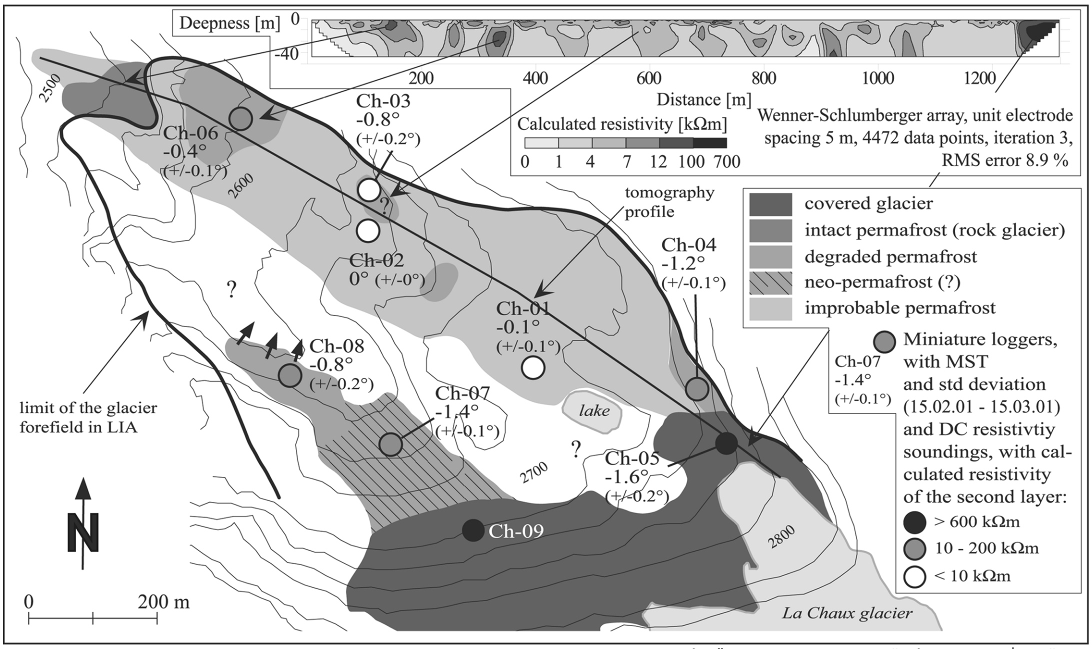

Figure 5. La Chaux proglacial margin: DC resistivity soundings interpretation, 2D resistivity profiles, mean subsurface temperatures (MST) and result interpretation. Black arrows indicate creeping terrain.

close to 0°C. Field BTS measurements carried out during winter 2001 confirm these values. DC resistivity sounding Ch-01, Ch-02 and Ch-03 show no evidence of ice in the ground. These results are confirmed by the 2D resistivity profile (Fig. 5).

A patch of frozen sediment is clearly shown by sounding Ch-06 (resistivity: 18 kΩm) and by the 2D resistivity profile in the lower part of the margin. The warm MST (−0.4°C) confirms that the permafrost table is deep and that we could be in the presence of former permafrost which was not totally degraded by the LIA glacier advance.

Outside the frontal moraine, BTS measurements and 2D resistivity profiling confirm the presence of an intact, dynamically inactive rock glacier.

5 DISCUSSION AND CONCLUSIONS

From the three field surveys, five main conclusions can be drawn.

(1) First of all, large surfaces of the investigated glacier forefields are currently not underlain by permafrost (Aget: 50%, Becca d'Agè: 30%, La Chaux: certainly more than 50%). The fact, that all the margins are situated within the belt of discontinuous permafrost and that relict ice bodies remain both in-depth and on the lateral parts of the margins, indicates that in all three cases, the LIA advance modified the thermal regime of large sectors of the former frozen sediments. Heath fluxes induced by the covering glaciers warmed and sometimes thawed the frozen sediments. The permafrost thermal degradation is however not always identical. In the Becca d'Agè margin for example, the permafrost degradation is relatively reduced, certainly because of the presence of an active rock glacier directly at the front of the advancing glacier. The thermal degradation depends therefore on the pre-existing thermal regime and ice content of the sediments.

(2) The LIA advance also modified the geometry of pre-existing permafrost bodies. In several places, one can see geomorphological evidences of geometrical deformation due to the glacier dynamic. Push-moraines (Haeberli 1979, Evin 1992) are, for example, visible at Aget and Becca d'Agè margins. The frozen sediments, which were deformed and pushed up to the lateral slopes by the glacier advance, are now creeping back down (Fig. 6).

(3) Both electrical and thermal methods also demonstrated the presence of sporadic frozen bodies preserved at great depth (>6–8 m deep) under the surface. The surface layer is composed of glacial sediments such as fluted moraines, ablation till or lodgement till, that cover the frozen sediments. In these situations, the preserved frozen body may be considered as inactive permafrost.

(4) Sediments with high resistivities (more than 300–500 kΩm) are also present in La Chaux and Becca d'Agè forefields. Small sectors of La Chaux margin are in fact a debris-covered glacier. Other sectors may be interpreted as patches of dead ice covered with unfrozen sediments.

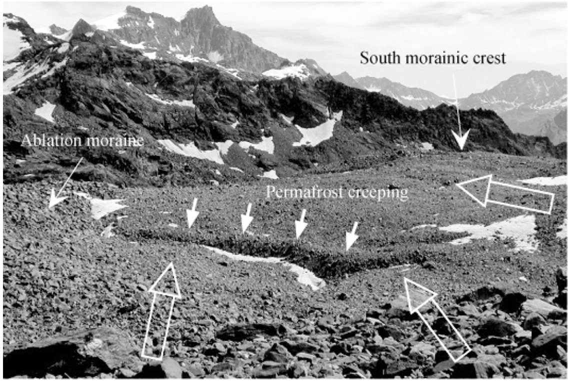

Figure 6. Internal front showing permafrost creeping (small arrows) by geometrical re-equilibration (Becca d'Agè glacier forefield). Large arrows represent the direction of glacier flow during LIA.

(5) Occurrence of neo-permafrost, formed after the glacier retreat, could only be assumed on one limited area.

From a methodological point of view, the combination of various geoelectrical surveys with thermal measurements has proved to be very efficient for mapping and characterizing the ice distribution with good accuracy (Delaloye et al. 2001).

Studies on the cartography and characterization of ice distribution in recently deglaciated glacier forefields are relatively rare. Research should however be encouraged in such environments, especially in morainic situations and on lateral valley bastions, where debris flows hazards are not excluded.

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