Part II

Case studies

5

Typology of vertical electrical soundings for permafrost/ground ice investigation in the forefields of small alpine glaciers

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5.1 Introduction

During the Little Ice Age (LIA), many small glaciers – usually less than 1 km wide and some having completely vanished since that time – overlaid permafrost areas in the Alps above approximately 2500 m a.s.l. Strong mechanical (e.g. push moraines) and thermal disturbances (e.g. permafrost degradation) of the former frozen sediments occurred. LIA glacier forefields located in the discontinuous belt of permafrost are thus complex geomorphic features (Figure 5.1) including various types of ground ice and coalescent frozen and unfrozen ground conditions (Evin and Assier 1983). Since the 1980s, several studies have been carried out to map the ground ice distribution in such recently deglaciated terrains (e.g. Evin 1992, Kneisel 1999, 2003a). From the same perspective, we performed about 100 vertical electrical soundings (VES) on thirteen sites in the western Swiss Alps and the Pyrenees between 1997 and 2003 (Delaloye and Devaud 2000, Delaloye *et al.* 2003a,b, Reynard *et al.* 2003, Delaloye 2004, Lambiel *et al.* 2004, Lugon *et al.* 2004, Lambiel 2006). The following case study proposes an interpretative typology of VES measured in this kind of glacial/periglacial environment. The typology is complemented by additional indications on the ground surface thermal regime.

5.2 Method

The VES technique (see Chapter 1) is logistically adapted to permafrost investigations in difficult terrain and remote areas. The power supply requirement is limited and, in contrast to the ERT method, the basic equipment remains lightweight (and not expensive!). In spite of the blocky nature of the ground surface (replacing metallic electrodes with sponges soaked in salt water ensures, when

Applied Geophysics in Periglacial Environments, eds. C. Hauck and C. Kneisel. Published by Cambridge University Press.

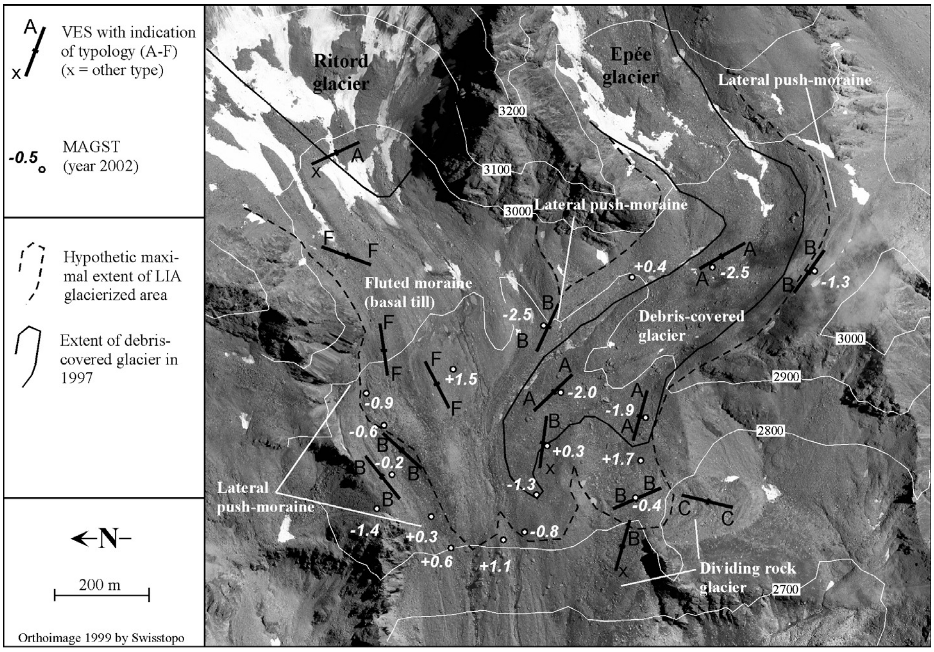

Figure 5.1. ~~Typology of VES performed in the forefield of small alpine and pyrenean glaciers (after Delaloye and Devaud 2000). Ag: Aget (Delaloye and Devaud 2000), LC: La Chaux (Reynard *et al.* 2003), LP: La Paùl (Lugon *et al.* 2004), Re: Réchy (Delaloye 2004), Ri: Ritord (Delaloye 2004), Ts: Tsarmine (Lambiel *et al.* 2004).~~‸

necessary, a good connection with the ground surface), apparently coherent VES results are quite easy to obtain in glacier forefields and surrounding areas. Data interpretation may be conversely more hazardous. A source of misinterpretation is the potentially strong lateral subsurface heterogeneity of the ground properties. It can be prevented by systematically applying an asymmetrical Hummel configuration, which permits one to detect the changes in resistivity towards both sides of the profile (Vonder Mühll 1993). Delaloye (2004) described in detail the strengths and limits of the interpretation of dissymmetrical VES in heterogeneous mountain periglacial terrain.

VES (as any other electrical resistivity data) interpretation gains in reliability when it is supported by additional geophysical data or ground surface temperature measurements. Apart from ground temperatures measured in boreholes, two further parameters of the ground thermal condition are often determined: the winter equilibrium temperature (WEqT) (close to the classical BTS – bottom temperature of the winter snow cover – value measured by probing) and the mean annual ground surface temperature (MAGST). Such parameters are however subject to significant annual changes depending particularly on both the timing and the development of the snow cover (e.g. Delaloye and Monbaron 2003, Delaloye 2004). Recently, 2D electrical resistivity tomography (ERT) has tended to replace 1D VES for permafrost investigation, e.g. in glacier forefield environments (Kneisel 2003b, 2004, Marescot *et al.* 2003, Reynard *et al.* 2003). ERT provides high-quality data that are nevertheless limited by the depth to which the inversion model provides reliable data, the so-called DOI (depth of investigation index, Marescot *et al.* 2003) and the difficulty of inverting highly contrasted resistivity values (see Chapter 1). Glacier forefields are often quite large areas and there is consequently a tendency to install long ERT profiles with large electrode spacings, which do not resolve the active layer zone (Reynard *et al.* 2003). In these cases additional shallow VES may be performed along the ERT profile for complementing and improving the ERT data (and/or additional ERT surveys with shorter spacing).

5.3 Typology

Most of the VES that were carried out in glacier forefields and their immediate surroundings can be grouped in six main types, according to the shape of the VES curve (Figure 5.2), the characteristics of the active layer, the resistive subjacent layer (as indicated by the apparent resistivity maximum, ρ_a max, and the resistivity ρ) and the ground surface thermal parameters. They are described hereafter and summarised in Table 5.1. Ranges given for the resistivity values are indicative; in particular they may differ depending on the ground lithology. The thermal parameters mentioned in the typology are based on mean values observed between 1997 and 2003.

5.3.1 Type A

The sounding curve of a VES belonging to this group comprises an initial oversteepening and a maximum value ranging between 100 and more than 1000 kΩ m. It indicates the occurrence of massive ice (often of glacial origin) very close to the surface. WEqT has been measured between −1 °C and −8 °C. MAGST is generally negative and tends to be colder than in the surroundings. Summer temperatures can remain colder than +5 °C. Type A was mainly obtained on debris-covered glaciers, on buried ice patches and on the internal side of lateral push moraines.

5.3.2 Type B

Type B is a decreasing continuum of type A without oversteepening: the mantle of unfrozen sediments probably exceeds 2 m in thickness. The specific resistivity

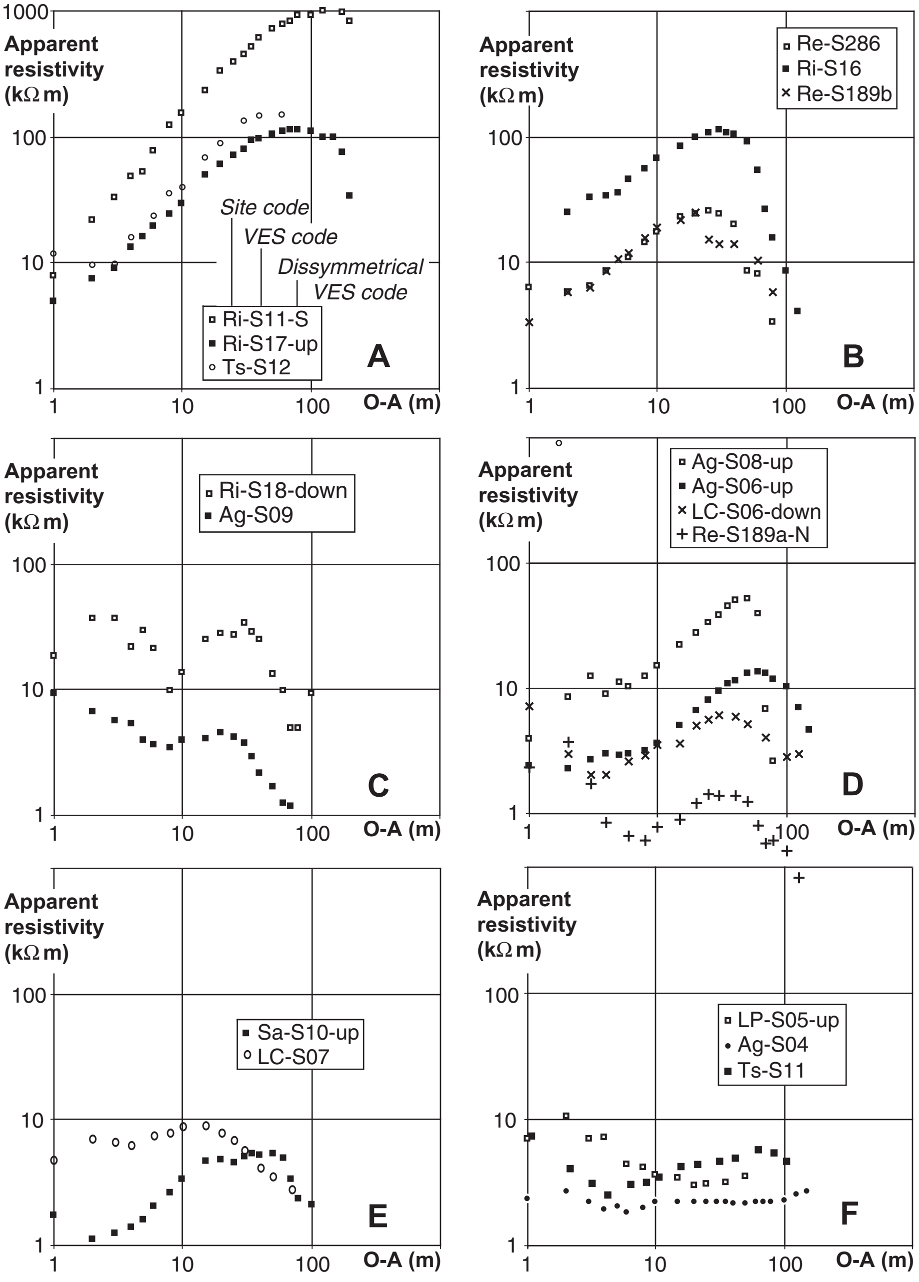

Figure 5.2. ~~The Ritord glacier forefield, with some typical landforms, the interpretation of VES and MAGST observed in 2002. At Ritord, MAGST in 2002 is close to the mean of the period 1997–2006.~~

Table 5.1. *VES typology and thermal characteristics*

Type	Active layer	ρ_a max	ρ max	WEqT	MAGST
A	shallow, often < 2 m	100–>1000	>1000	various, rather cold	<0 °C, colder than surroundings
B	>2 m	50–300	100–500	cold (<−3 °C)	slightly negative, approx. 1 °C warmer than type A
C	>3 m	10–>100	50–500	between −1 and −5 °C	various, depending on ground nature
D	>5 m	2–100	20–200	between 0 and −2 °C	close to 0 °C or slightly warmer
E	2–3 m	5–20	10–50	between −0.5 and −2 °C	close to 0 °C
F	no active layer	1–5		close to 0 °C	> +1 °C

ρ_a max is the maximal apparent resistivity for a VES, ρ max is the maximal specific resistivity of the frozen subjacent layer.

of the resistive subjacent layer most often ranges between 100 and 500 kΩ m. WEqT is cold (<3 °C) and MAGST is often warmer (by approximately 1 °C) than for type A, remaining nevertheless very slightly negative (−0.5/−1 °C). Type B is interpreted as a cold and thick layer of frozen sediment, in which the occurrence of massive ice of glacial origin cannot be excluded. Such VES were primarily obtained in the external part of push moraines and, sometimes, in the upper part of rock glaciers directly connected to a proglacial margin.

5.3.3 Type C

In most cases, the apparent resistivity ρ_a is relatively high for small electrode spacings due to the presence of a superficial blocky layer without fine matrix. For increasing spacings, ρ_a decreases at first indicating a thick active layer (approximately 5 m), before drawing a ‘bell’-shaped curve. The layer causing the rise in ρ_a has a specific resistivity of about 10 to more than 100 kΩ m and is often not very thick (10–20 m). WEqT (between −1 °C and approximately −5 °C) as well as MAGST can vary depending on both the surface composition and the thermal state of subjacent permafrost. Type C is typically measured on blocky rock glaciers. It indicates the occurrence of frozen sediment, without any layer of massive ice close to the surface, which was not covered by a glacier during the LIA. Elsewhere, the blocky surface layer would be absent or filled with fine moraine matrix.

5.3.4 Type D

The superficial blocky layer is lacking and a significant increase in ρ_a first starts beyond AB/2 distances of 8–10 m (A and B being the two outer (current) electrodes). The specific resistivities of the deep-lying (frozen) materials range from 20 to more than 200 kΩ m and their thickness can be larger than 20 m. WEqT often ranges between 0 and $-2\,^\circ$C; MAGST is approximately $0\,^\circ$C or slightly positive. VES of type D, such as those shown in Figure 5.2, were systematically measured in zones covered by LIA glaciers that were not heavily charged with debris, as confirmed by the generalised occurrence of subglacial till. The VES curves often show that the thickness of the unfrozen surface layer exceeds 5 m. The complete freezing of the active layer in winter is uncertain. In our sites, type D appears to indicate either the degradation of former permafrost by a warm-based LIA glacier, or the current thermal degradation of permafrost pushed by a LIA glacier towards a location unfavourable to its preservation.

5.3.5 Type E

Such VES were measured in areas that have not been glacier covered for a few years or decades. ρ_a rises beyond AB/2 = 3–4 m, indicating the occurrence of a resistive layer around 2–3 m below the surface. Its specific resistivity is about 10 to 50 kΩ m; WEqT is generally warm, between -0.5 and $-2\,^\circ$C. MAGST is close to $0\,^\circ$C. Because of the shallow depth of the resistive layer, type E may be interpreted as either neo-permafrost – still in formation – or as subglacial permafrost originating when the glacier was only a few metres thick. However, according to the relatively warm surface conditions, such VES could also reflect coarse debris covered with fine material.

5.3.6 Type F

VES of type F were measured in areas covered by a LIA glacier. ρ_a is relatively constant at a low value. WEqT is usually close to $0\,^\circ$C. MAGST is generally warmer than $+1\,^\circ$C. Type F, associated with such warm ground surface conditions, indicates the absence of permafrost.

Except VES of type E that appear to be relatively rare, the other types of VES are potentially common in the proglacial margins of small alpine glaciers (Table 5.2). They do not however occur in every glacier forefield. As an example Figure 5.1 shows a glacier forefield where types D and E are lacking. Only 14% of the VES carried out on our different sites cannot be attributed to one of the main types. Their

Table 5.2. *Absolute and relative number of VES by type*

	Total	*Type A*	*Type B*	*Type C*	*Type D*	*Type E*	*Type F*	*Other*
Number	105	17	15	13	15	3.5	26.5	15
Percentage	100	16	14	12	14	3	25	14

A value of 0.5 is attributed to each part of the dissymmetrical VES.

interpretation, even complemented by thermal and geomorphological data, sometimes remains difficult.

5.4 Conclusion

Numerous field investigations have shown that the pattern of the spatial distribution of permafrost and ground ice is somewhat similar in the forefield of every small LIA alpine glacier located in the discontinous permafrost belt: (a) permafrost and ground ice are often restricted to the margins of the former glacierised area; (b) the central part of LIA glacier forefields may be still occupied by a degrading debris-covered glacier; (c) when not, this central area is mostly not underlain by permafrost. The proposed VES typology implies that some kinds of similar permafrost and ground ice characteristics are recurrent. In many cases, they can be identified by electrical resistivity measurements, VES in particular, corroborated by ground surface temperature measurements.

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