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A geoelectrical survey above an Antarctic ice shelf

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Abstract
A geoelectrical survey was performed on the Hells Gate ice shelf (Victoria Land-Antarctic) within the framework of an integrated geophysical and glaciological research program. The resistivity profiles show a similar trend, with resistivity values ranging from about 25 000 Ω · m to 500 000 Ω · m These results have been interpreted as the effect of a sharp transition from «marine ice» to «continental ice», an interpretation that is consistent with the results of surface mapping. Interpreting the Vertical Electrical Soundings (VES) is a complex process. In fact, the alternating layers of ice with different compositions and salt content generate great uncertainty relative to the corresponding electric stratigraphies. To solve these problems of equivalency, all the available constraints were used including the drilling thickness, seismic reflection profiles as well as radar profiles. The results were used to provide what is mainly a qualitative overview that is coherent with the glaciological hypotheses relative to the evolution and structure proposed by some researchers for this ice shelf.

Key words *applied geophysics – ice shelf – electrical prospecting*

1. Introduction

The possibility of using geoelectrical exploration on the Antarctic ice shelves is suggested by the presence of strong contrasts in resistivity between the glacial body and the confining medium, such as sea water and rocky formations. Resistivity values for continental ice vary between 5.10^5 and 7.10^6 Ω · m (Glen and Paren, 1975; Morey and Kovacs, 1982) while for rocky formations and sea water the values are about 10^3 Ω · m and 0.1-10 Ω · m respectively. However, resistivity within the ice shelf may be lowered to values around 10^4 Ω · m by the presence of marine ice containing significant and variable quantities of residual salt. Another element supporting the use of this geophysical technique is the vertical stratigraphy proposed for this type of structure by some authors (Jenkins and Doake, 1991; Bondesan *et al.*, 1997).

Generally, an ice shelf is the outlet to the sea of an ablator glacier of the plateau. The existence of an ice shelf is controlled by the balance (fig. 1a) between ablation factors (sublimation, fusion, drop out of icebergs) and additive factors (contributions from the plateau, snowfall, basal freezing, surface regelation). The ice shelf section thus consists of a series of different types of ice. Roughly speaking, continental ice is replaced from the bottom by marine ice originating from basal freezing. In greater detail, the standard stratigraphy can be structured as follows (fig. 1b): in the innermost part of the shelf (I) from the top to the bottom the series consists of snow being compressed and continental ice in direct contact with the bedrock; moving toward the external part of the ice shelf there is (II) first a series that includes a level of sea water between the ice and the bedrock and then, more externally (III) ma-

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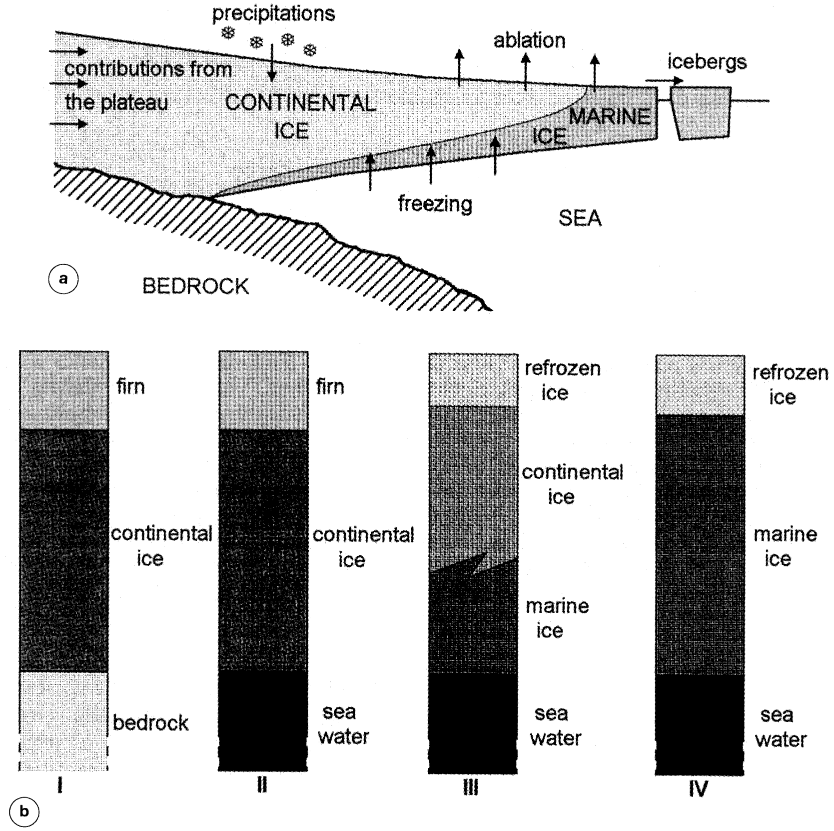

Fig. 1a,b. a) Simplified diagram of the evolution of an ice shelf; b) stratigraphy in different positions of the shelf.

rine ice separates the continental ice from sea water and, at the same time, at the surface, reworked ice which originated from local fusion and regelation phenomena; in the outermost part of the shelf (IV), if the ablation phenomena are intense, the continental ice may be completely replaced by the marine ice.

These stratigraphies and the decreasing thickness of the continental ice toward the external part should make it possible to identify the various levels forming the shelf with geoelectrical prospections.

The electrical measurements presented in this paper were carried out during the IX ItaliAntartide Expedition of the PNRA in the Antarctic summer 1993-1994. Seismic reflection and radar measurements were also performed during the same experiment. The area selected for the study was the Hells Gate ice shelf (fig. 2). This ice shelf has a surface area of about 70 km^2 (Baroni, 1988) located approximately 25 km to the south of the Italian scientific base of Terra Nova Bay. The ice shelf is bordered on the NW by the Priestley

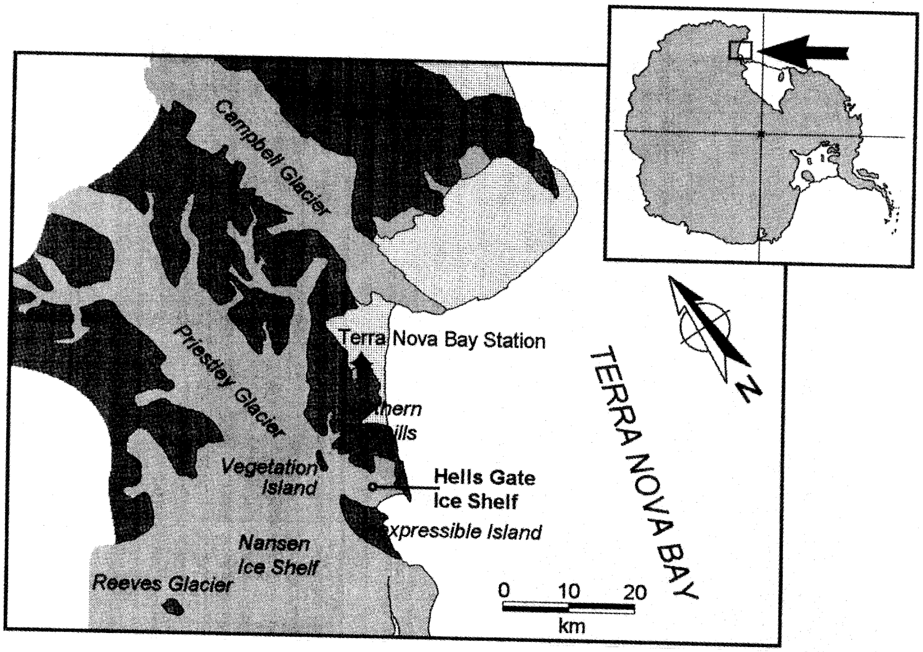

Fig. 2. Location of the Hells Gate ice shelf, in the area of Victoria Land – Antarctica (black: periodically exposed rocky surface; gray: permanent glacied surface).

Glacier and by Vegetation Island, on the W by Inexpressible Island, on the S by the Ross Sea and on the NE by the Northern Foothills. The glacial body consists of three tongues of ice, bordered by longitudinal morainic structures, originating from contributions from the Nansen Ice Shelf (western sector), from the Priestley Glacier (central sector) and from local accumulation areas (eastern sector). The limited extension and the vicinity of the logistic base make this ice shelf an excellent test site for various types of explorations.

2. Field procedures

The survey was carried out mainly in the southern part of the central sector of the ice shelf (fig. 3) and include twelve Vertical Electrical Soundings (VES), oriented along the parallel (N-S) and orthogonal (W-E) directions with respect to the sliding direction of the ice, and two resistivity profiles, carried out in the N-S and E-W directions. The position and the dimensions of the arrays are reported in table I.

Performing geoelectrical measurements in an environment like the Antarctic requires special procedures for adapting the instrumentation and for interfacing the electrodes with the studied medium (Lozej *et al.*, 1997a). The measurements performed still provide a great amount of data regarding VES and profiles carried out on marine ice as well as continental ice.

The resistivity profiles were carried out using an electrode spacing of 50 m with a Wenner spread. This type of array and its dimensions were selected because of the greater sensitivity of the Wenner electrode configuration with regard to the lateral contrasts of resistivity (Barker, 1979) and the possibility of operating

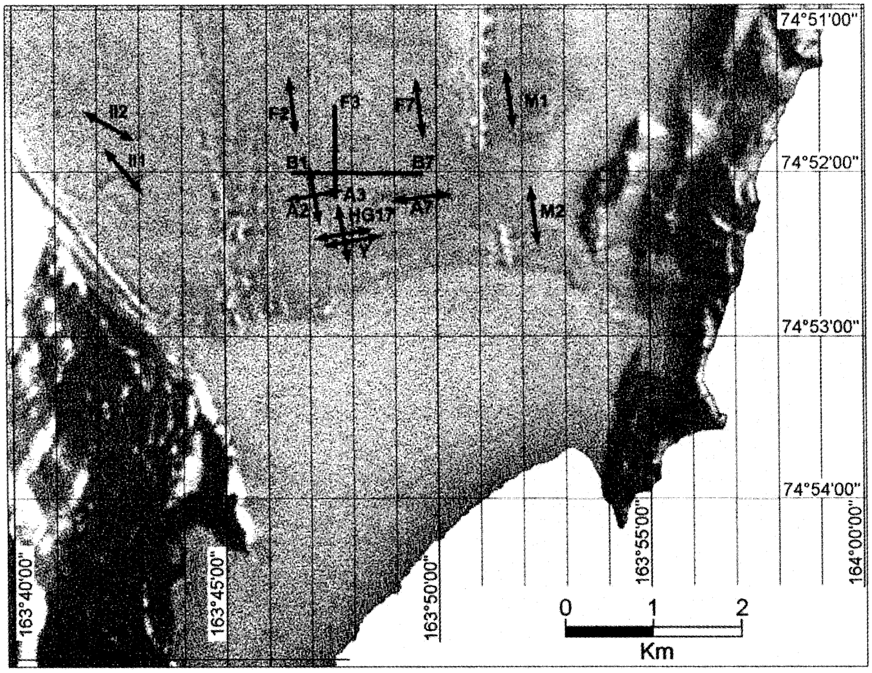

Fig. 3. Positioning and orientation of the geoelectric profiles and the VES performed above the ice shelf.

Table I. Coordinates of the VES station centres and of the extremes of the geoelectrical profiles, dimension and direction of the arrays.

Station	Latitude	Longitude	(AB/2) max.	Direction
A2	74° 52′.180 S	163° 47′.088 E	200 m; 80 m	Long., transv.
A7	74° 52′.110 S	163° 49′.656 E	50 m	Transv.
F2	74° 51′.620 S	163° 47′.092 E	200 m	Long.
F7	74° 51′.606 S	163° 49′.619 E	200 m	Long.
HG17	74° 52′.371 S	163° 47′.852 E	100 m; 100 m	Long., transv.
II1	74° 51′.995 S	163° 42′.648 E	50 m	Long.
II2	74° 51′.718 S	163° 42′.296 E	200 m	Long.
M1	74° 51′.557 S	163° 51′.749 E	130 m	Long.
M2	74° 52′.267 S	163° 52′.299 E	150 m	Long.
Y	74° 52′.379 S	163° 47′.859 E	130 m	Transv.
A3	74° 52′.174 S	163° 47′.612 E	Length m 1250	Long.
F3	74° 51′.613 S	163° 47′.614 E		
B1	74° 52′.006 S	163° 49′.050 E	Length m 1500	Transv.
B7	74° 52′.110 S	163° 49′.632 E		

with electrodes equally spaced along the profile, thus reducing the number of movements necessary between measurements.

The VES were distributed on the frontal part of the ice shelf to obtain information on the three sectors forming Hells Gate. The Schlumberger array was used. The greatest values of AB/2 are 200 m. This limitation is due to the power systems, the instrument sensitivity, and the high resistivity of the ice, that prevent efficient generation of power at greater lengths.

Some soundings were carried out with the same station centre but perpendicular directions: one parallel to the ice flow (hereinafter indicated as longitudinal) and one orthogonal (hereinafter indicated as transversal); this made it possible to verify any electric directional anisotropies in the glacial mass.

3. Resistivity profiles

The two profiles marked as B7B1 and A3F3 (fig. 3), extend, respectively, 1500 and 1250 m and were carried out in the front area of the shelf where, as already mentioned, there is a sharper transition between continental ice and marine ice (Souchez *et al.*, 1991).

The resistivity profiles provided interesting results since it was possible to measure apparent resistivity less than 40 000 Ω · m in the sector consisting of marine ice and greater than 350 000 Ω · m where the thickness of the marine ice is reduced.

The comparison of the apparent resistivity with the morphology of the shelf is reported in the three-dimensional representation of fig 4. The A3F3 profile exhibits a sudden change of

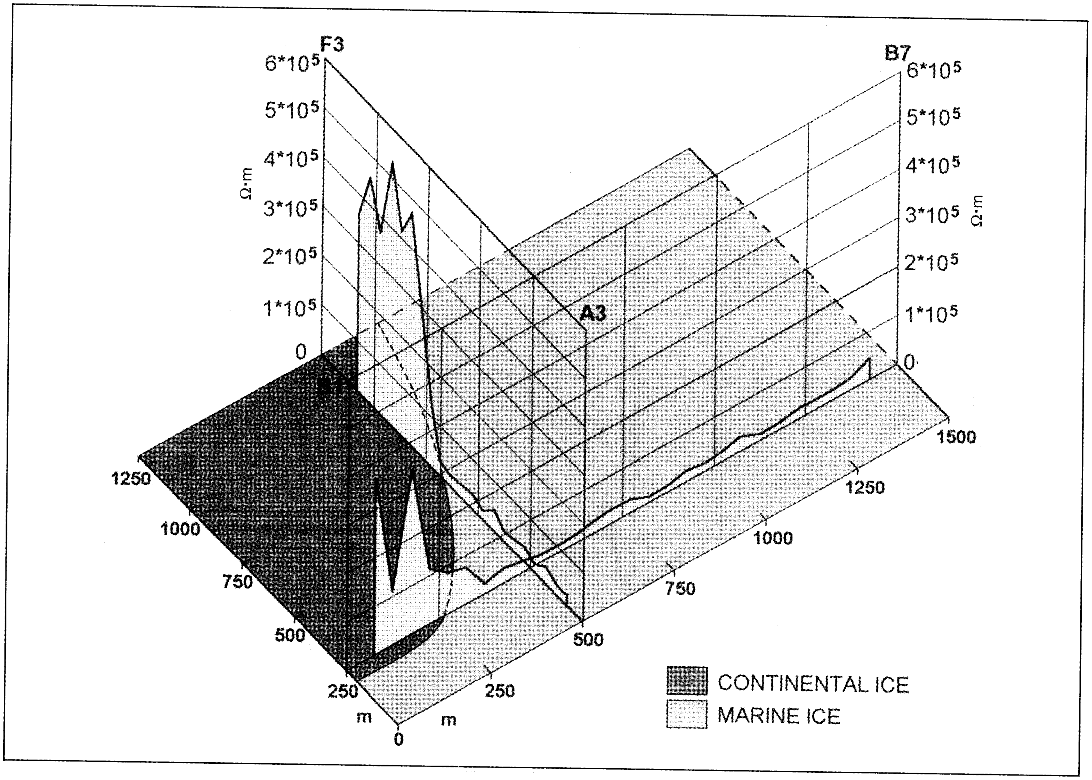

Fig. 4. Three-dimensional representation of the apparent resistivity along profiles A3F3 and B7B1 and comparation with distribution of different types of ice as stated by Souchez *et al.* (1991).

apparent resistivity near the progressive 700 m, a limit beyond which this parameter stabilises on values which are greater by one order of magnitude.

In the B7B1 profile the change of apparent resistivity is not as sharp as in the previous case. There are oscillations of the measured values up to the progressive 250 m and after this position the apparent resistivity stabilises on lower values. This behaviour may be justified by the position of the measurement line with respect to the transition between the two types of ice. In fact, the electric profile is located in proximity of a very superficial contact between the two types of ice, *i.e.* in an area where the thickness of the continental ice is very small and not constant.

4. Vertical Electrical Soundings

The Vertical Electrical Soundings (VES) were very difficult to interpret only on the basis of semi-automatic inversion with 1D models. We have utilised the applicative program RESIX (Interpex, 1993) to obtain a series of solutions. For this reason, all the independent available information was used, consisting basically of the thickness of the shelf obtained from drilling stratigraphies, seismic reflection profiles and radar profiles (Bondesan *et al.*, 1996; Pavan, 1996; Lorrain *et al.*, 1997; Lozej *et al.*, 1997a,b,c).

4.1. *VES Y*

This VES was performed in proximity of a drilling site with a depth of more than 40 m which provided information (Lorrain *et al.*, 1997) relative to the saline content of the ice (fig. 5), while the maximum thickness of the ice shelf was obtained from the seismic reflection profiles (Pavan, 1996; Lozej *et al.*, 1997b) and was set at 70 m.

The experimental data (fig. 6a) were smoothed to limit oscillatory trend in the resistivity values generated by the presence of sur-

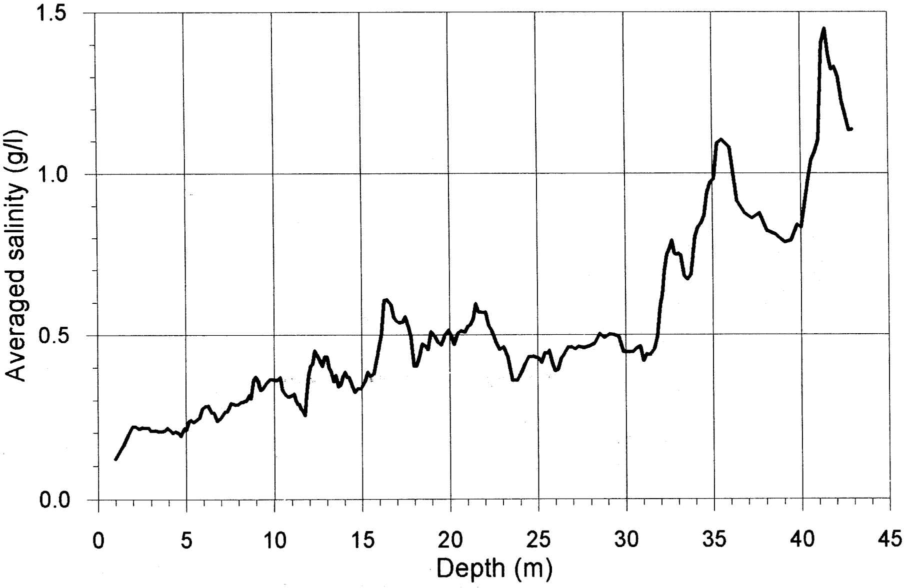

Fig. 5. Distribution of salinity determined on the core resulting from the drilling carried out at VES Y.

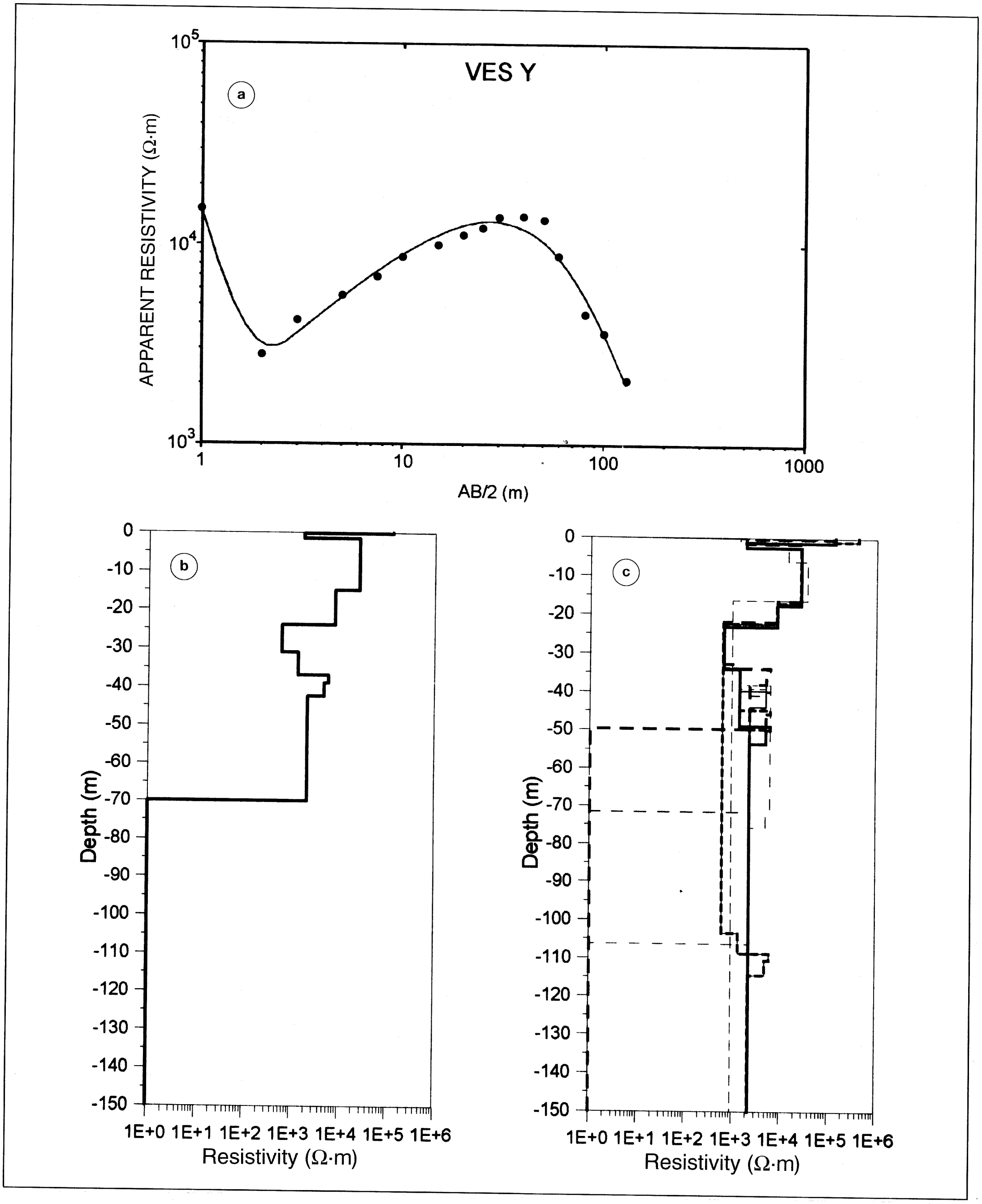

Fig. 6a-c. a) Smoothed experimental resistivity curve of VES Y; b) electric stratigraphy obtained with thickness constraint (h = 70 m); c) equivalent models without any restriction in the model.

face ice, resulting from melting and regelation phenomena, for which the resistivity values are quite variable. The experimental curve was interpreted by constraining the value of the shelf thickness and some characteristic depths, derived from the salinity curve in fig. 5, in which there are significant changes in the ice saline content. The model derived (fig. 6b) shows that the resistivity is not linearly correlated to the ice salinity. This behaviour can be explained on the basis of different ways of segregating the salts inside the glacial mass (Bondesan *et al.*, 1996, 1997), or by the presence of fractures which deeply modify the apparent resistivity without it being visible from the trend of the salinity in the cores. If the depth values used for the previous model are not constrained, there is a strong dispersion in the thickness values of layers (fig. 6c).

4.2. *VES HG17*

Two orthogonal VES were carried out in marine ice in proximity to position HG17. Though being close to Y, the site has experimental curves with slightly different trend and variations in the values measured along the two directions (fig. 7). The stratigraphy which best satisfies the experimental curves can be represented with a series of two groups of three layers with decreasing resistivity which can be identified as regelation ice (at the surface) and more recent marine ice at a deeper level.

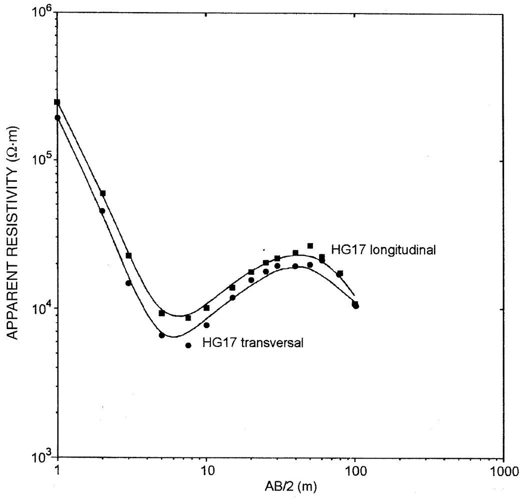

Fig. 7. Experimental resistivity curve at VES HG17 with longitudinal and transverse spreads with respect to the shelf.

To interpret the VES pair, only the value of the thickness of the ice shelf was set at 73 m based on the seismic reflection profiles. The models obtained, as well as the experimental curves, highlight the presence of an anisotropy of the shelf ice with greater electric conductivity in the E-W direction (fig. 8a). This phenomenon might be interpreted as a consequence of the presence of fractures aligned in this direction, for example preferential iceberg detachment lines. If the maximum depth value is not constrained and the modelling operations are repeated, electric stratigraphies are obtained which also satisfy the experimental measurements, but with a shelf thickness less than that is determined with other geophysical methods (fig. 8b).

4.3. *VES A2*

Another pair of VES, relative to site A2, was carried out in an area with known shelf thickness (88 m). These VES are located in proximity to the transition area between marine and continental ice, and thus in a situation involving significant variations in the lateral electric characteristics. The effect is very evident in the experimental curves which have a similar development but much higher resistivity values for the sounding with N-S orientation. This last spread is the most sensitive to the presence of continental ice in the northern side of the spread (fig. 9a). The interpretation of these two experimental curves led to the electric stratigraphies represented in figs. 9b and 9c, which leave many doubts about their validity, especially as concerns the distribution of the resistivity values. In conclusion we can confirm that 1D modelling is not appropiate to interpret that kind of data.

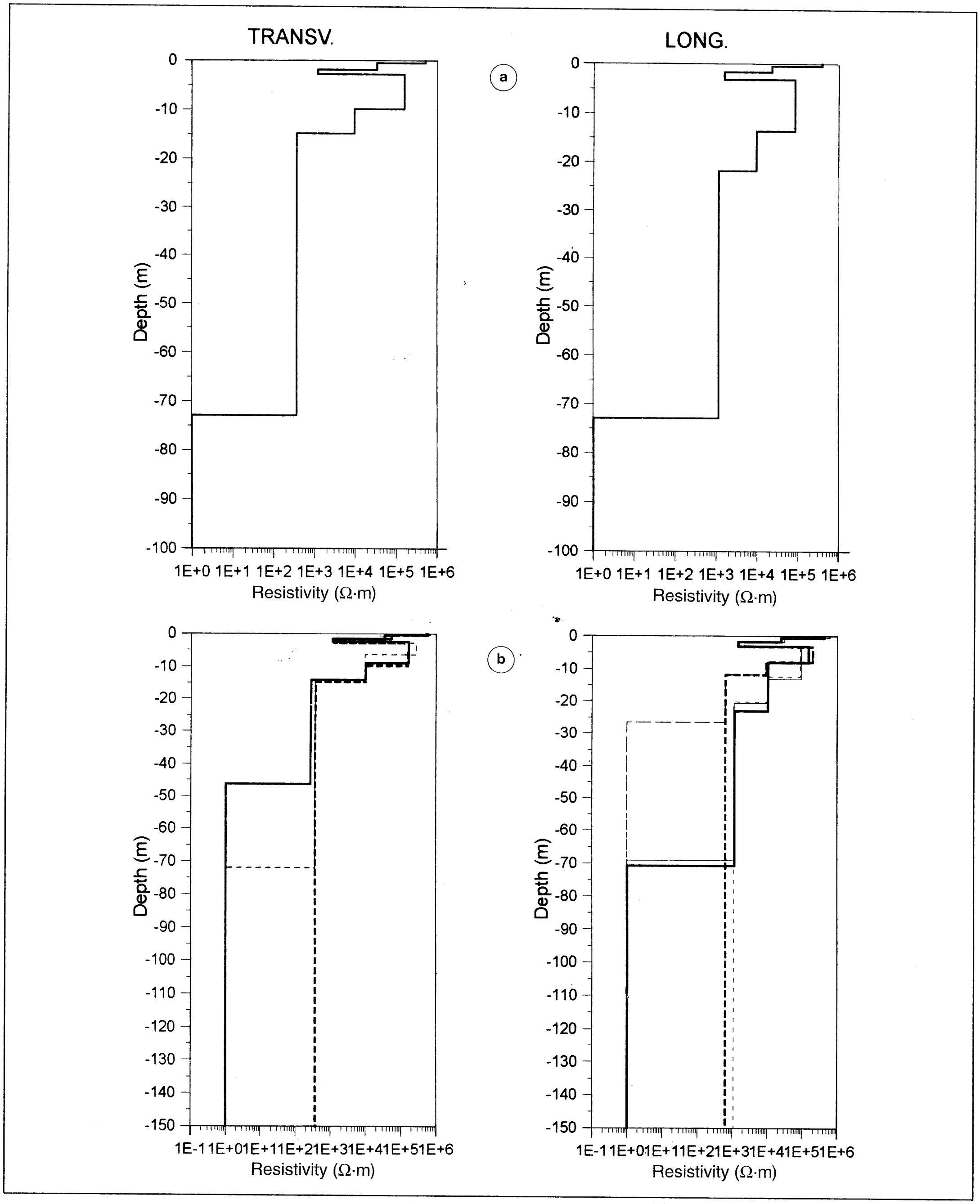

Fig. 8a,b. Electric stratigraphies relative to VES HG17 LONG and HG17 TRANS: a) obtained assuming the maximum shelf thickness (h = 73 m); b) equivalent stratigraphies without depth constraints.

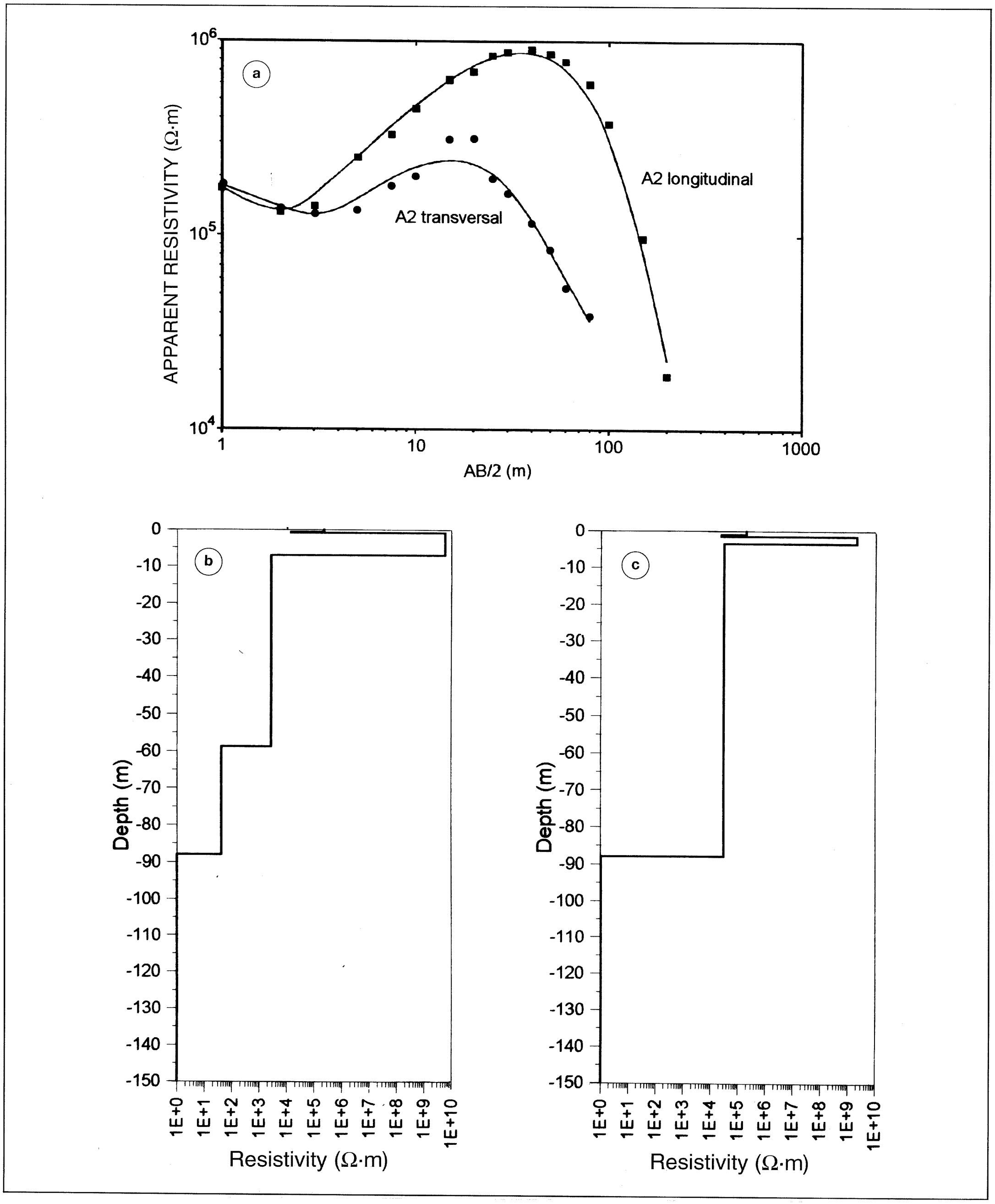

Fig. 9a-c. a) Experimental resistivity curves of VES A2 in the longitudinal and transverse directions; b) electric stratigraphy relative to transverse VES A2 with thickness constraint (h = 88 m); c) electric stratigraphy relative to longitudinal VES A2 with thickness constraint (h = 88 m).

4.4. *VES F1*

Site F1 is the last one for which there are reliable values for the shelf thickness (about 105 m). The corresponding experimental curves are reported in fig. 10a. The significant dispersion of the values can be easily observed: this can be partially attributed to lateral heterogeneities and to some extent to the low signal/noise ratio determined by the high resistivity of the ice which does not permit adequate energization power.

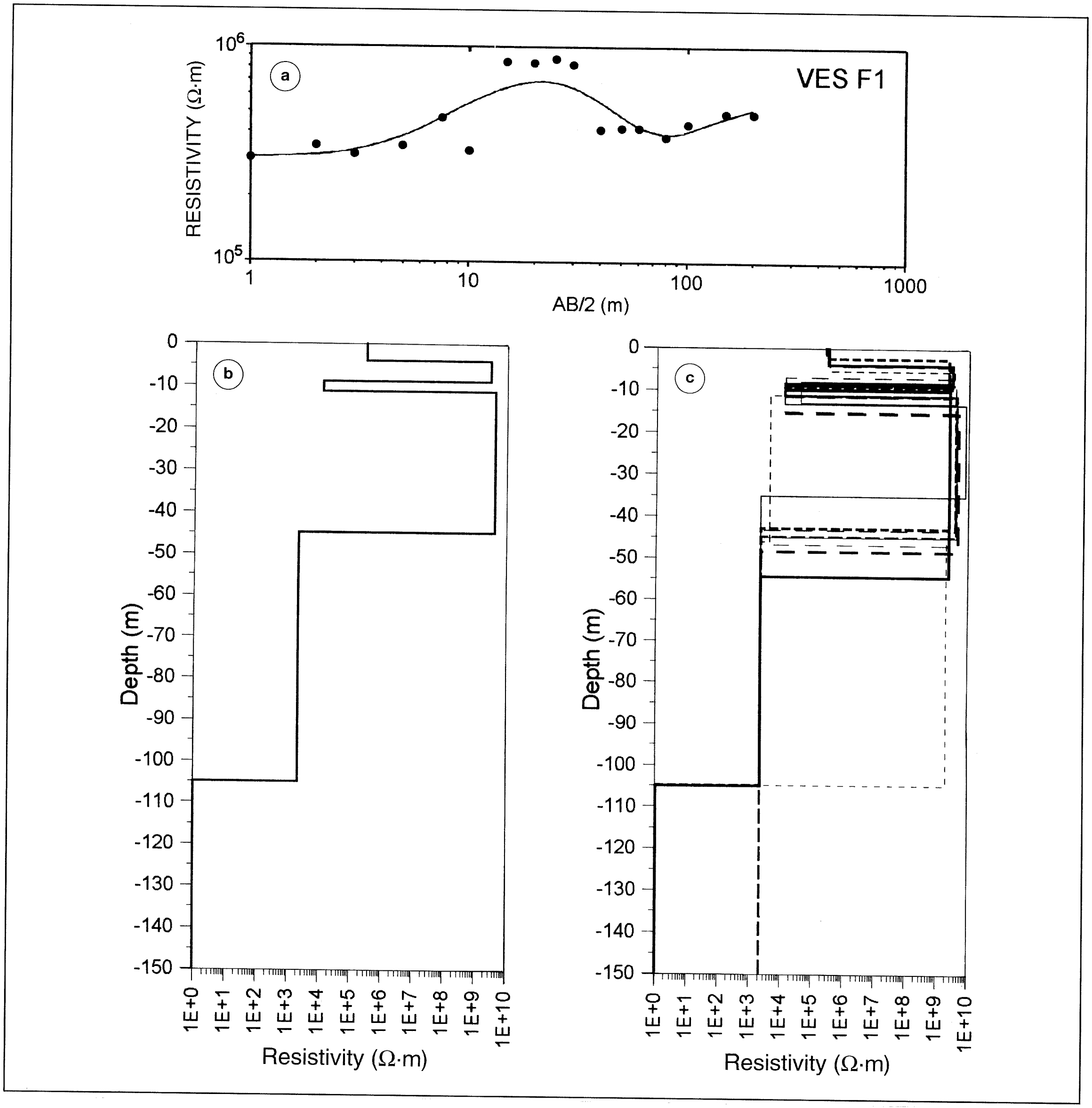

Fig. 10a-c. a) Experimental resistivity curve relative to VES F1; b) electric stratigraphy obtained with maximum thickness constraint (h = 105 m); c) equivalent models without thickness constraints.

Comparing the maximum dimensions of AB/2 with the ice thickness, it can be seen how the descending section of the apparent resistivity curve is not reached. The overall interpretation of this sounding is very ambiguous. The irregularity of the experimental values leads to equivalent models which are very different from each other but analytically correct (fig. 10c). The most plausible electric stratigraphy is shown in fig. 10b. There is a large thickness of continental ice above the marine ice. The continental ice should not be considered homogeneous since during the deformation processes in the valley flanks, it is subjected to stress and marine ice type subvertical intrusions in tension gash type structures. These intrusions are responsible for the noise superimposed on the measurements.

The following soundings were performed in areas of the shelf where the thickness can be defined by means of a very approximate extrapolation from the seismic reflection and radar profiles (Pavan, 1996). Therefore, the depth values are only useful for orienting the interpretations of the soundings toward more likely models.

4.5. *VES A7*

For site A7, an approximate thickness of the ice was hypothesised to be about 100 m. The experimental curve (fig. 11a) was not completely used for the inversion since if we also consider the values relative to the greater dimensions of the spread we obtain what are unacceptable thickness values and resistivity stratification. The most plausible stratigraphy for this site is represented in fig. 11b. In any case, it should be emphasised that this solution is very contrived and permitted by imposing the maximum thickness of the shelf. In fact, the data that can be used are not sufficient to define a reliable electric stratigraphy reaching the bottom of shelf.

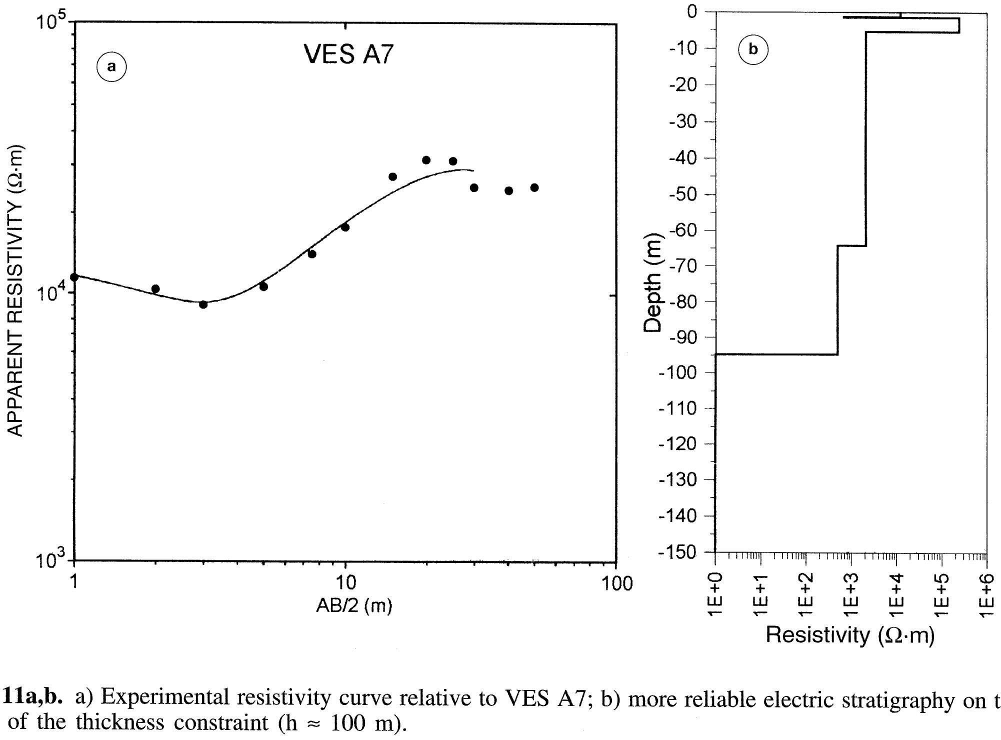

Fig. 11a,b. a) Experimental resistivity curve relative to VES A7; b) more reliable electric stratigraphy on the basis of the thickness constraint (h ≈ 100 m).

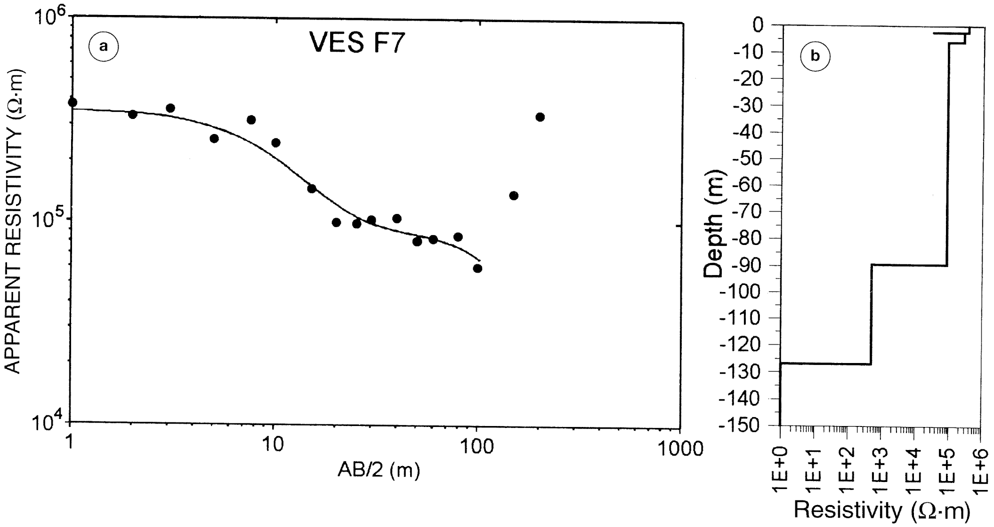

Fig. 12a,b. a) Apparent resistivity curve relative to VES F7; b) resulting electric stratigraphy assuming a constraint on the maximum thickness (h = 127 m).

4.6. *VES F7*

A situation similar to the previous one is shown in VES F7. The improbability of the extreme apparent resistivity values (fig. 12a) can be easily recognised since the experimental curve, in the terminal phase, has an inclination of more than 45° (a situation that cannot be realised even in the presence of an infinite resistive bedrock). Neglecting the resistivity values corresponding to the greater dimensions of the spread, it was possible to define a stratigraphy (fig. 12b) that consists only of a series of marine ice for which conductivity increases with depth.

4.7. *VES M1 and M2*

The two soundings carried out in the eastern sector of the shelf (sites M1 and M2) are not supported by values which have been sufficiently approximated for the thickness of the ice. These soundings (fig. 13a) were carried out in areas close to the snow accumulations, where there is an oblique contact between the ice resulting from the compression of the firn and/or regelation ice and the marine ice. For VES M1, the thickness of the shelf was assumed to be between 50 and 60 m, from which a constrained stratigraphy is obtained as reported in fig. 13b. Figure 13c reports the equivalent solutions without constraints. They demonstrate, once again, that it is impossible to obtain reliable stratigraphies with electrical soundings without auxiliary information. Sounding M2 was not interpreted since the local situations are very complex and difficult to model with plain stratigraphies. In this area, based on glaciological and geomorphological factors, it is assumed that there is ice partially resting on the rocky substrate or on very irregular sedimentary deposits.

4.8. *VES II1 and II2*

Soundings II1 and II2 were performed in the far western sector of the shelf, where the seismic prospection indicated that the thickness was lower than in the central part of that sec-

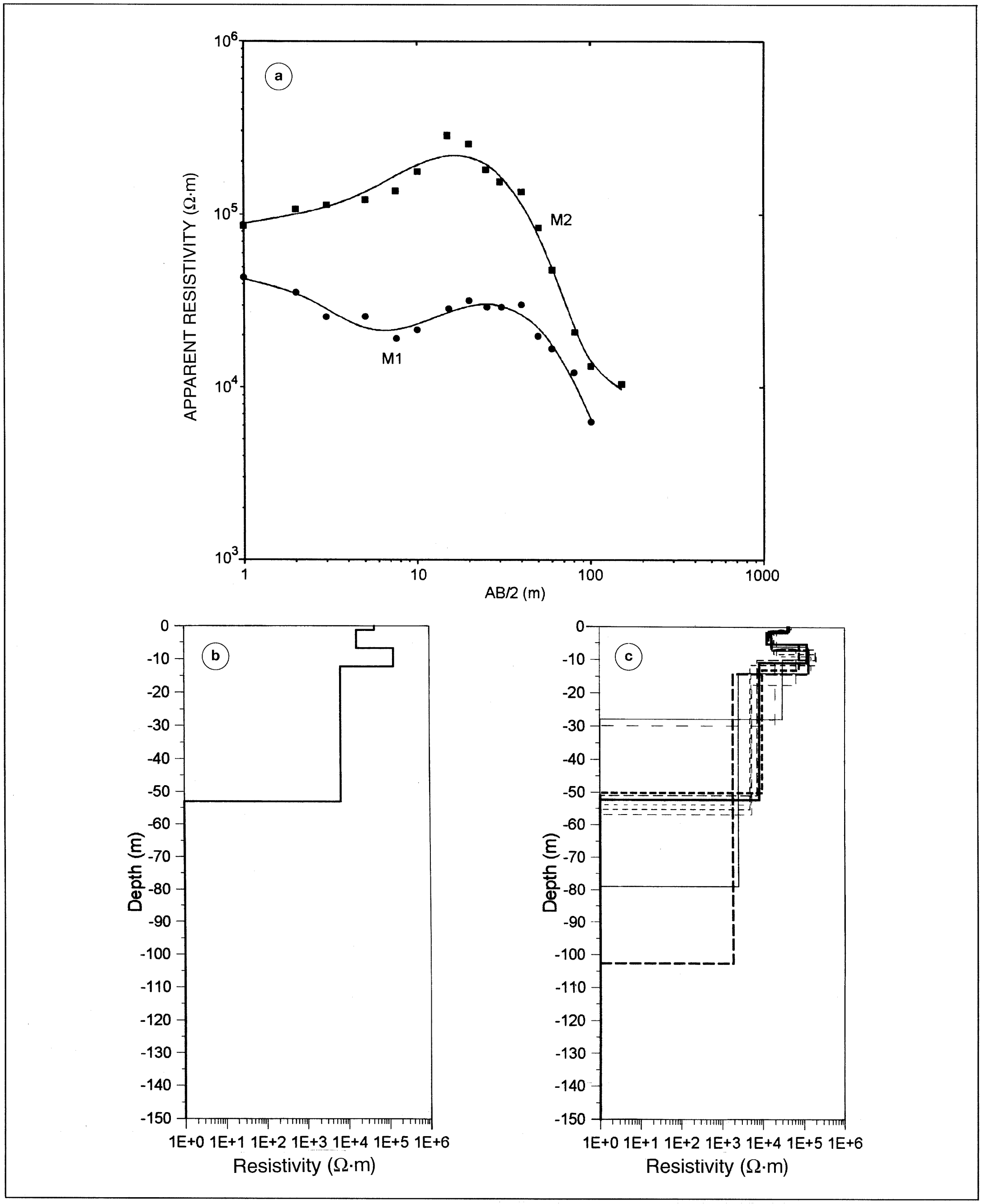

Fig. 13a-c. a) Experimental curves relative to VES M1 and M2; b) electrostratigraphic solution of VES M1 thickness constraint (h = 53 m); c) equivalent models.

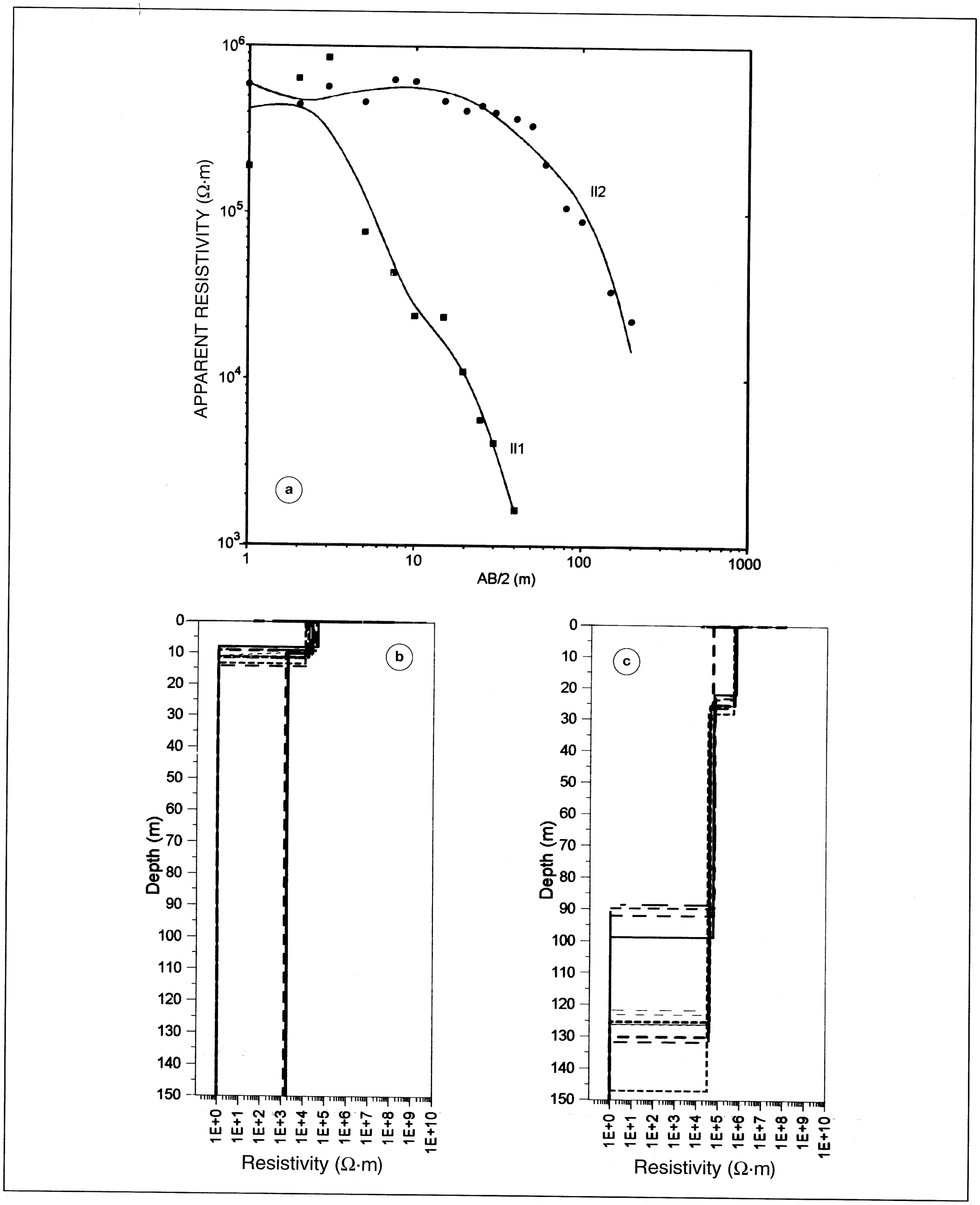

Fig. 14a-c. a) Experimental curves relative to VES II1 and II2; b) electrostratigraphic solution not constrained for VES II1; c) electric stratigraphy not constrained for VES II2.

tor. The maximum thickness limit determined was 60 m. However, it can be considered excessive for calibrating the two VES since they are found in the outermost part of the shelf where the thickness, based on commonly accepted models and through an analogy with the results of the seismic reflection profiles in the central part, should not be so great.

Figure 14a reports the resulting apparent resistivity curves. The two soundings have similar resistivity values for the smallest electrode distances but then develop according to two completely distinct branches. For II1, there is a rapid decrease in the resistivity values and a flexure in its middle part. The latter is probably due to the presence of a thin surface layer of continental ice below which there is some older marine ice which in turn is covered by more recent marine ice that thus has a lower resistivity.

Instead, sounding II2 would seem to be characterised by a surface layer of continental ice with a greater thickness, above of more conductive marine ice. The variation in the thickness of the continental ice agrees perfectly with the shelf models but produces electric stratigraphies which do not correspond to the thickness values supplied by the seismic profile. In fact, for what concerns sounding II2 (fig. 14c), models are obtained which fit the measured data effectively only for shelf thickness values greater than 90 m, while for sounding II1 (fig. 14b) the best results are obtained for a thickness less than 15 m. In both cases, the thickness deviates considerably from an acceptable value that can be compared with that indicated by the seismic reflection profile for this portion of the shelf. Also for this VES's the use of 1D models is not appropriate to interpret experimental data.

5. Conclusions

The overall examination of the data can be used to draw some conclusions on the use of geolectric prospection to define the morphological parameters of ice shelves. The electric profiles provided excellent results which allow us to identify the type of ice even below the screening covers such as layers of snowfall or regelation ice.

As concerns the definition of stratigraphies through VES, we found extreme difficulties in using this technique. There are various limiting factors such as the physical conditions of the investigated bodies. In fact, they do not have stratified homogeneity characteristics for which it is possible to apply the classical interpretation methodologies. In addition, the high resistivity of ice does not lead to efficient power except for small dimensions of the measurement spreads. Finally, our results are affected by uncertainties due to typical equivalency phenomena for resistivity stratifications where the resistivity decreases with depth. These facts emphasise the need to obtain independent information to help interpret the VES in this glacial structures.

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