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Analysis and application of a non-conventional underwater geoelectrical method in Lake Geneva, Switzerland[1]

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Abstract

The electrical method presented is used for determining the resistivity of lake-bottom sediments and is based on the d.c. electrical sounding principles. The electrode array, called the fishing rod (FR), is of pole-pole type and is orientated vertically on a line perpendicular to the surface of the water. The technique is used for mapping resistivity anomalies located deep underwater. This paper presents an analysis of the resolution capabilities of the FR method and the results of a case study carried out in Lake Geneva, where measurements were interpreted using a one-dimensional (1D) multilayer earth model. The analysis of the uncertainty in the model parameters of a 1D multilayer earth model is carried out using the covariance matrix of the linearized inversion problem. The results of the analyses show that when the thickness and resistivity of the water layer is known, the resistivity of the sediment layer is well determined under most circumstances. The thickness of the sediment layer is well determined when resistivity contrasts are not too low. In Lake Geneva the FR method has been used to study an old depression with a resistive channel. This application shows the efficiency of the method compared with conventional electrical methods, where water depth becomes a limiting factor. The use of an automated iterative inversion scheme in this particular case is advantageous, as a joint interpretation of the three different data sets measured with the FR method can be carried out. Finally, the result of the inversion is compared with the trial-and-error interpretations of a previous study.

Introduction

Mapping of lake-bottom geology is important in many different contexts such as environmental geophysics and structural studies (Meyer de Stadelhofen and Favini 1968; Lagabrielle and Theilhaud 1981; Baumgartner 1996a,b). When dealing with lakes with a water depth exceeding 100 m, conventional geophysical methods become

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either very expensive or inadequate. For these reasons a novel geoelectrical method called the fishing rod (FR) is used. The principle of this method is to measure the potential at the electrode M from a current electrode A at different vertical positions of the moving pair of electrodes A and M. The stationary current electrode B and potential electrode N are placed at infinity (in practice, more than 10 times the water depth) on each side of the boat (Fig. 1). Basically three types of measurement are made in order to obtain a data set. When the measurement location has been chosen, electrodes B and N are placed far away from each other and from the boat. Measurements are performed in three steps. Firstly, the current electrode A is lowered from the surface to the bottom while keeping the potential electrode M at the surface (EC1). Secondly, the potential electrode M is lowered through the water while keeping the current electrode A at the bottom (EC2). Finally, both electrodes are drawn to the surface, keeping the distance between the electrodes constant, typically equal to 10% of the water depth (EC3). Note that the nomenclature for the electrode configurations has been changed from that in the previously published paper (Baumgartner 1996b). The EC3 configuration corresponds to a normal log. In all three configurations measurements are made with a vertical interval of 5–10% of the water depth. The measuring procedure is repeated at each field location. Usually data from four locations can be collected in one day in this way.

The aim of this study is to analyse the resolving capabilities of the FR method and not to perform an extensive comparative analysis of different electrode arrays. The problem of assessing the efficiency of various electrode configurations in resolving the electrical properties of a 1D layered earth has been theoretically and thoroughly addressed by Straub (1995). For arrays in water, he concluded that the best way to resolve the first underwater layers is to lay the electrodes on the water bottom, a

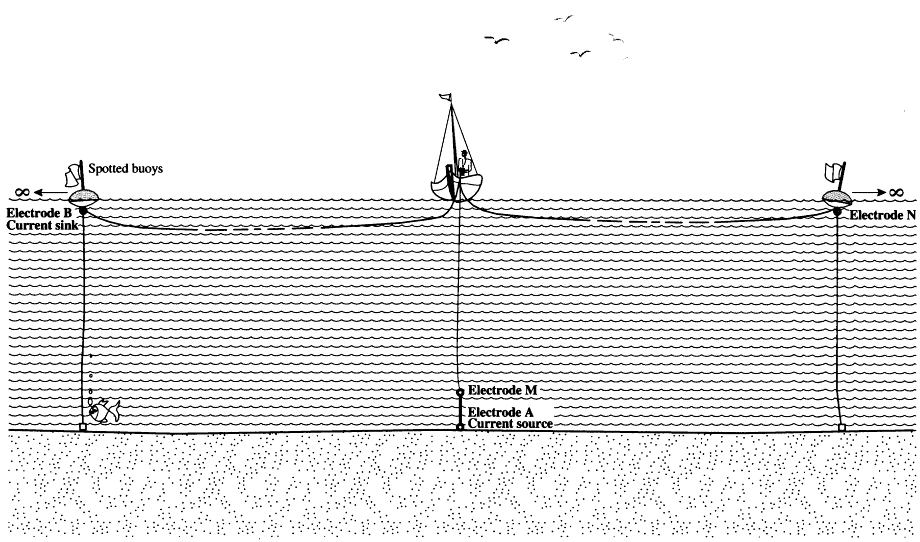

Figure 1. The fishing rod (FR) device.

conclusion which confirms the results of Lagabrielle (1983). However, as stated above, in the case of water depths exceeding 100 m, the application of water-bottom electrode arrays becomes expensive and cumbersome and the FR method offers an attractive alternative with good resolution capability. Furthermore, the lateral resolution of the FR method is certainly better than that of extended lake-bottom electrode arrays.

The FR method has been presented earlier (Baumgartner 1996b), and forward modelling was used to interpret the data through a trial-and-error procedure. In order to investigate the resolving capabilities of the FR method and the interpretation results obtained previously, a more complete study is presented here. An analysis of the uncertainty in the model parameters of a 1D layered earth using the covariance matrix of the linearized inversion problem will be shown. The program used for these analyses is SELMA (simultaneous electromagnetic layered modelling and analysis), which has been developed by Christensen (Christensen and Auken 1992). The program permits an automated iterative inversion and an analysis of the uncertainty in all model parameters and certain model parameters combinations, i.e. the resistivities, the thicknesses, the depth to the layer boundaries, the vertical resistance and the horizontal conductance of each layer. Finally an automated inversion and analyses have been applied to an FR study of an old depression in Lake Geneva where basically a five-layer earth model has been used. Although the 1D inversion program includes all model parameters and many model parameters combinations, only a restricted analysis for three-layer models can be presented within the space of this paper.

Analysis of the resolution power of the FR method

Before discussing the results, we describe the inversion program SELMA. SELMA is a computer-based program for the calculation of 1D model responses and joint least-squares iterative inversion and analysis. The model is a 1D plane-parallel earth model consisting of homogeneous and transversely isotropic layers. The model parameter space consists of the horizontal layer resistivities, the coefficient of anisotropy for each layer (the square root of the quotient between vertical and horizontal resistivities), and the layer thicknesses. Several array types are implemented in the program but we only use the type which allows electrodes to be placed anywhere in a layered half-space. With the SELMA program the actual positions of the far electrodes are modelled, so no error is introduced from the fact that they are not infinitely far away.

In the analyses of the FR method, we limit ourselves to the case where the parameters of the first layer are completely determined. This is in accordance with the FR method of measurement, where the depth of the water is determined jointly by an echo sounder and by the cable length of electrode A, and the water resistivity is measured continuously with a small fluid conductivity cell. We restrict ourselves to the case of a model with three layers and we assume all layers to be isotropic. We consider two cases: one where the resistivity of the third layer is fixed while the parameters of the second layer vary. In the second case the thickness of the second layer is fixed and the resistivities of the second and third layers vary. For each case, we have determined the

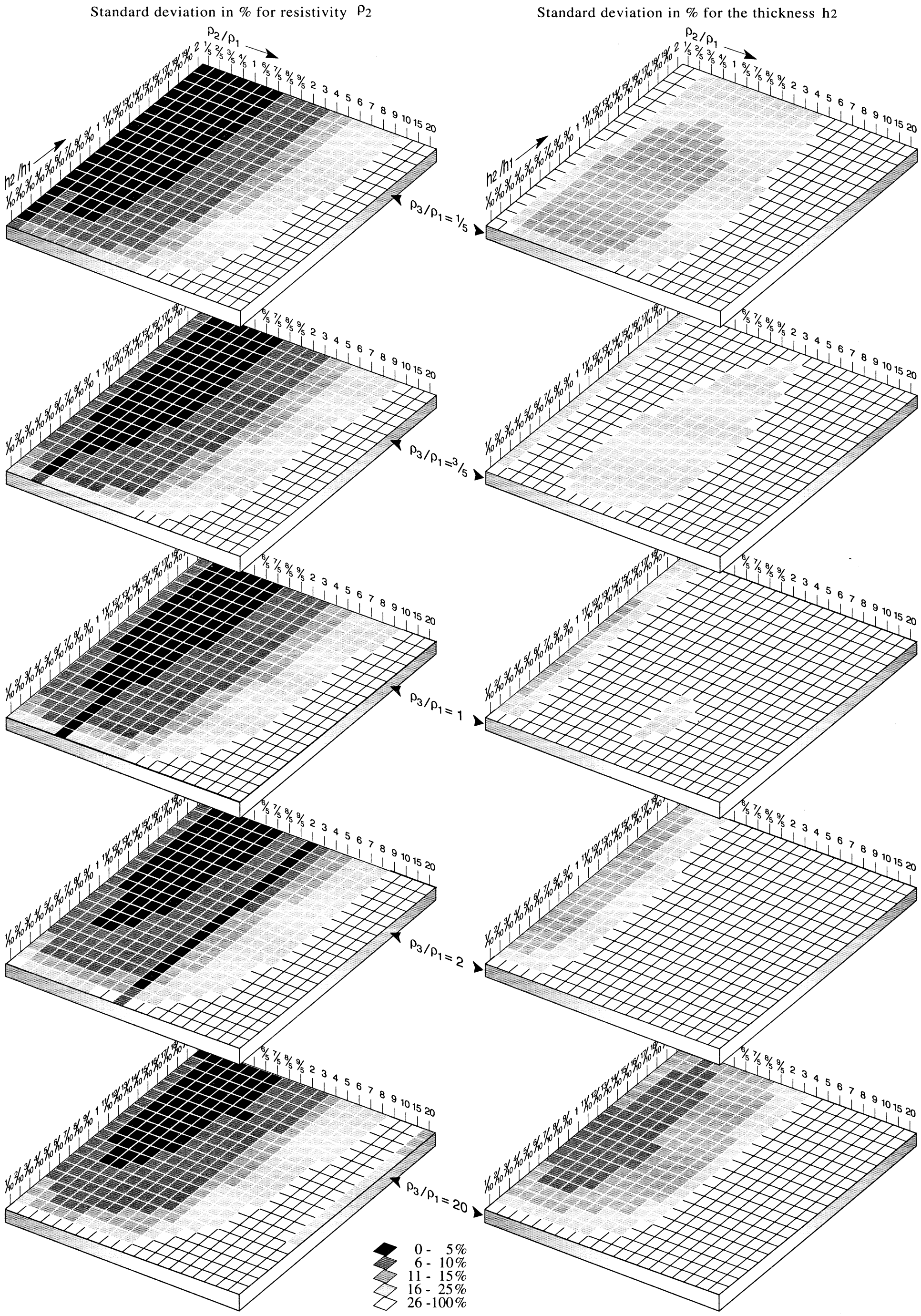

Figure 2. Analysis of FR soundings. ρ_2 and H_2 are the free parameters.

standard deviation of the two free parameters. We have illustrated the values of the standard deviations in the form of templates, each of them showing the standard deviation of a parameter as a function of the free parameters. By reiterating the technique for different values of the fixed non-aquatic parameters and by stacking the templates showing the analyses, we obtain an insight into the determination of a model parameter as a function of the varying parameters. Note that all parameters are expressed in units of the first layer. The analyses are carried out on the log (parameter) space and the value of the standard deviation is expressed as a percentage. The standard deviation is the square root of the diagonal elements of the posterior covariance matrix and the analysis is thus linear and therefore only approximate. When parameter uncertainties are small, they can be considered as quantitatively correct. When the value is large (e.g. in excess of 60%), it is only indicative that the parameter is poorly determined or undetermined. When looking at Figs 2 and 3, the black/dark grey colours indicate a good determination of the parameter and the light grey/white colours indicate a poorly determined parameter. In all analyses, the configurations EC1, EC2 and EC3 are used jointly. It is assumed that measurements are performed every 10 m for all three configurations and that the data error is 5%. For the EC3 configuration the distance between the electrodes A and M is 10 m.

Analysis of ρ_2 and H_2 for ρ_1, H_1 and ρ_3 fixed

Let us first examine the uncertainty in the determination of ρ_2 for ρ_1, H_1 and ρ_3 fixed (Fig. 2). ρ_1, H_1 and ρ_3 are all fixed with an uncertainty of 5%. ρ_2 is better determined for $\rho_2 < \rho_1$ than for $\rho_2 > \rho_1$ and, not surprisingly, the thicker the second layer the better. However, even for small thicknesses of the second layer ($H_2/H_1 = 1/5$), the determination of ρ_2 is good. This is due to (i) the minimum distance between the electrodes A and M, which in this analysis has been set to 0.1 times the water depth, being of the order of the thickness of the second layer, and (ii) the proximity of the electrodes A and M to the sediment layer. The uncertainty in ρ_2 is weakly dependent on ρ_3. For $\rho_2 = \rho_3$ there is a minimum in the standard deviation of ρ_2. Generally, ρ_2 must be said to be well determined. This analysis shows the excellent capacity of the method to determine the resistivity of the second layer, even if its thickness is small compared with the water layer $H_2 = H_1/10$. On the other hand, if the second layer has a resistivity 10–20 times greater than that of the water, the determination of ρ_2 is obviously strongly compromised. Let us turn to the determination of the thickness of the second layer, H_2 (Fig. 3). ρ_1, H_1 and ρ_3 are all fixed in the same manner as for the previous example. Obviously, when $\rho_2 = \rho_3$, H_2 is not determinable. This is indicated in the templates by a line of infinite uncertainty. For $\rho_2 < \rho_1$ and $\rho_3 < \rho_1$ there is an extended minimum in the standard deviation centred around $H_2 = H_1$ which shrinks away for increasing ρ_3. However, for $\rho_3 > \rho_1$ another minimum appears for $\rho_2 < \rho_1$. Thus we may conclude that H_2 can be determined if $\rho_2 < \rho_1$ and if there is a sufficient contrast between ρ_2 and ρ_3, but the determination is inferior to that of ρ_2.

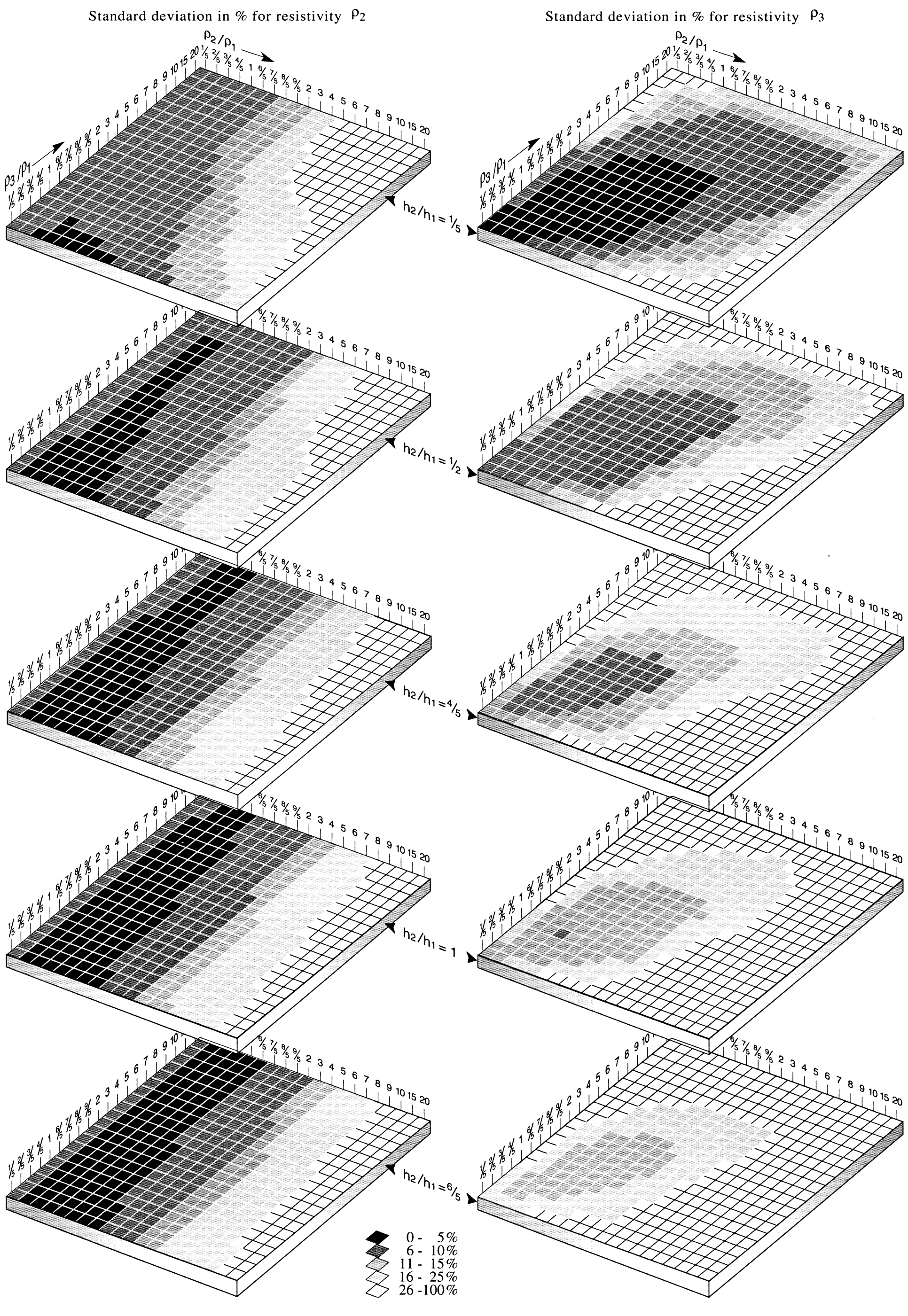

Figure 3. Analysis of FR soundings. ρ_2 and ρ_3 are the free parameters.

Analysis of ρ_2 and ρ_3 for ρ_1, H_1 and H_2 fixed

We now turn to an analysis of the uncertainty in the determination of ρ_2 for ρ_1, H_1 and H_2 fixed (Fig. 3). ρ_1, H_1 and H_2 are all fixed with an uncertainty of 5%. This analysis confirms the results obtained in the previous section. ρ_2 is better determined for $\rho_2 < \rho_1$ than for $\rho_2 > \rho_1$ and the thicker the second layer the better, even though the determination is also good for small thicknesses of the second layer ($H_2/H_1 = 1/5$). The uncertainty in ρ_2 is weakly dependent on ρ_3. Generally, ρ_2 must be said to be well determined if $\rho_2 < \rho_1$. As for the determination of ρ_3, it is clear that ρ_3 is better determined as the thickness of the second layer becomes less with a minimum centred around $\rho_3 = \rho_2$ and $\rho_3 = \rho_1$. For all values of H_2, the determination of ρ_3 is poor for $\rho_3 << \rho_1$ and $\rho_2 >> \rho_1$ (maximum model) and for $\rho_3 >> \rho_1$ and $\rho_2 << \rho_1$ (minimum model).

Summary of the analyses

The main results of the analyses can be summarized as follows: the resistivity of the second layer is well determined for a wide range of parameters of that layer. The thickness of the second layer is determinable when the resistivity contrast to the surrounding layers is not too small. This is due to the verticality of the FR array and the fact that three different electrode configurations are used jointly. Finally, we note that the previous results and remarks deduced in the forward modelling are confirmed and that the depth of investigation of the FR method is approximately twice the water depth.

Interpretation of the data

In the north-west part of Lake Geneva, where the city of Rolle is located, the general geology of the area can be described as follows: the substratum consists of Tertiary sandstone (molasse) and is covered by Quaternary deposits. Under the lake, a typical cross-section, from bottom to top, is: molasse, moraines, glacio-lacustrine and lacustrine sediments. In order to consider all these formations, a five-layer model has been used, the water column being split into two layers as there is some water stratification during the summer season. As some of the model parameters were almost completely determined from other information, these have been included as *a priori* information with realistic uncertainties. The resistivity of the upper water layer is fixed with an uncertainty of 5% and its thickness with an uncertainty of 20%, as these latter values vary for different measurement points. The resistivity of the bottom water layer has been fixed at 50 Ωm with an uncertainty of 5%. The thickness of this layer has been given an uncertainty of 20% but the depth from the surface to the bottom of this layer is known within 5%. The resistivities and thicknesses of the third and fourth layers are unbounded. The same applies to the depth from the surface to the bottom of the third layer. The depth to the lower boundary of the fourth layer is known from seismic information and it is fixed with an uncertainty of 10%. The resistivity value of the substratum is known approximately and is bounded within 20%. Figure 4 indicates the location of the FR measurements. Typical results of the interpretation process are illustrated in Figs 5, 6 and 7. They show the field data, the model result and the interpretation.

Based on the interpretation of all FR measurements, a contoured map can be drawn showing the top of the substratum, the isopach of the moraines, and an iso-resistivity map of the area (Figs 8, 9 and 10, respectively). The latter clearly delineates the full extension of the resistive channel into Lake Geneva. Finally, according to these results, a cross-section is presented in Fig. 11, where the gravel channel has been inserted as a layer into the moraines layer (rather than substitute it) for cosmetic reasons only. The location of the cross-section is shown in Fig. 4.

Comparison with previous results obtained with forward modelling

The interpretation using trial-and-error forward modelling presented in an earlier study (Baumgartner 1996b) was based on a three-layer earth model without any splitting of the water layer. It is interesting to compare the results of this earlier work with the results from the present iterative least-squares inversion. First we notice that both interpretations provide the same answer to the fundamental question: is there a resistive or a conductive anomaly? At a second closer look, we see that the different

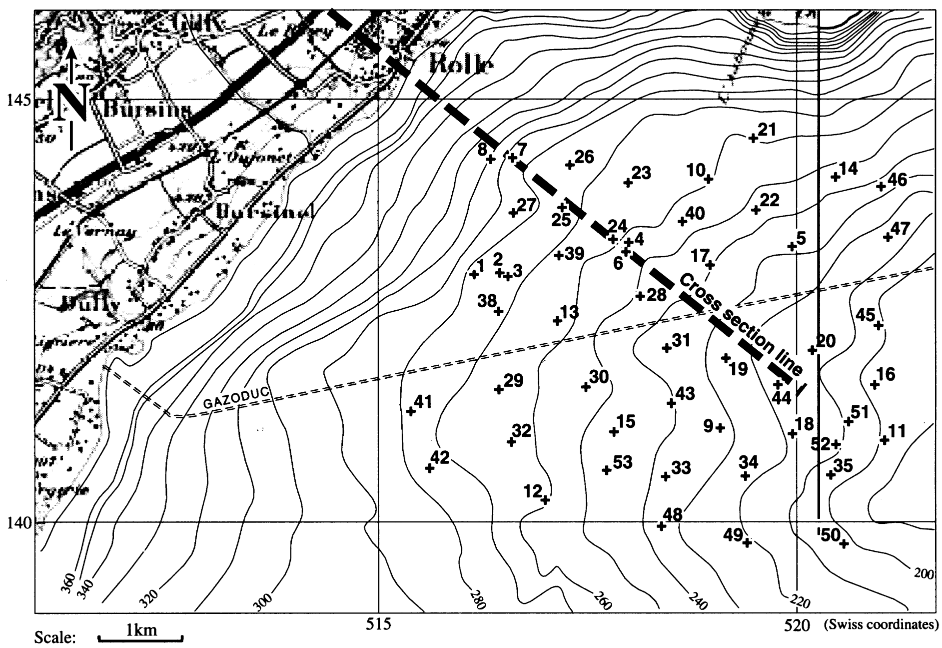

Figure 4. Positions points of the FR measurements.

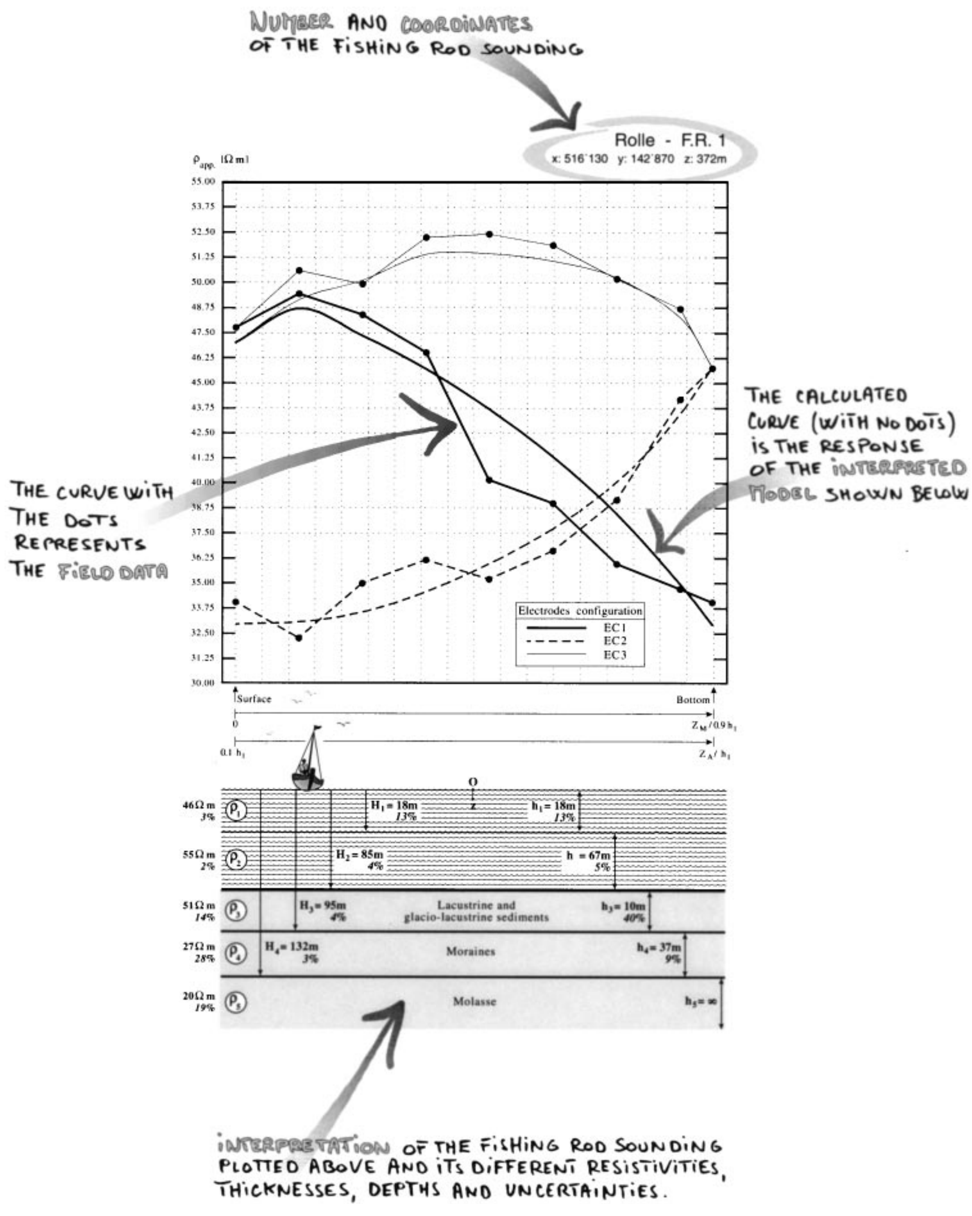

Figure 5. Typical interpretation process result.

values of the model parameters (except for the water, which is not modelled in the same way here) are very similar. For instance, if we compare the interpreted resistivities at measuring point 19 (conductive layer), there is a perfect match between them. When comparing the results at point 8, a change in the substratum resistivity value is noticed as well as a change in the resistivity of the sand-gravel deposits. On the other hand,

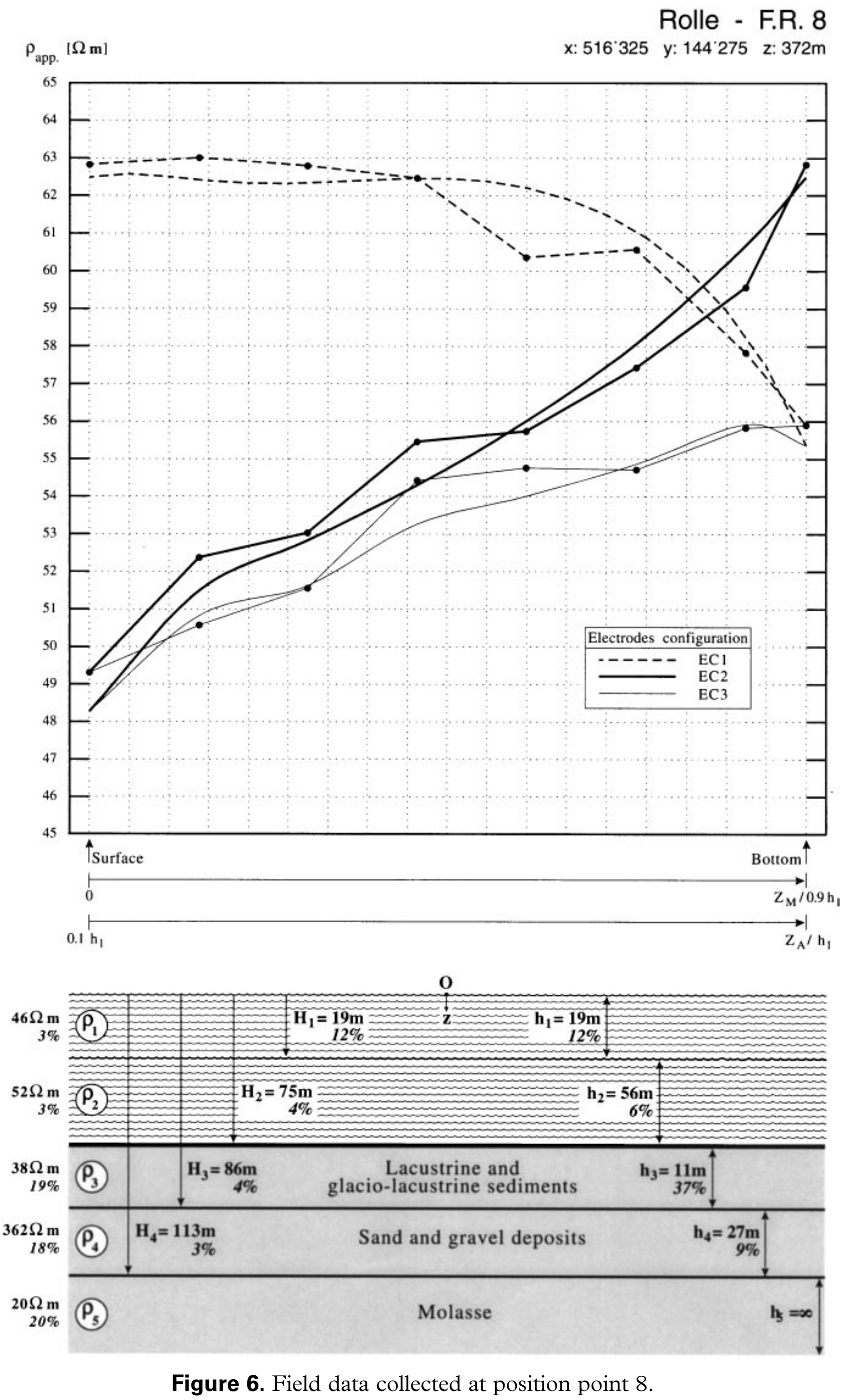

Figure 6. Field data collected at position point 8.

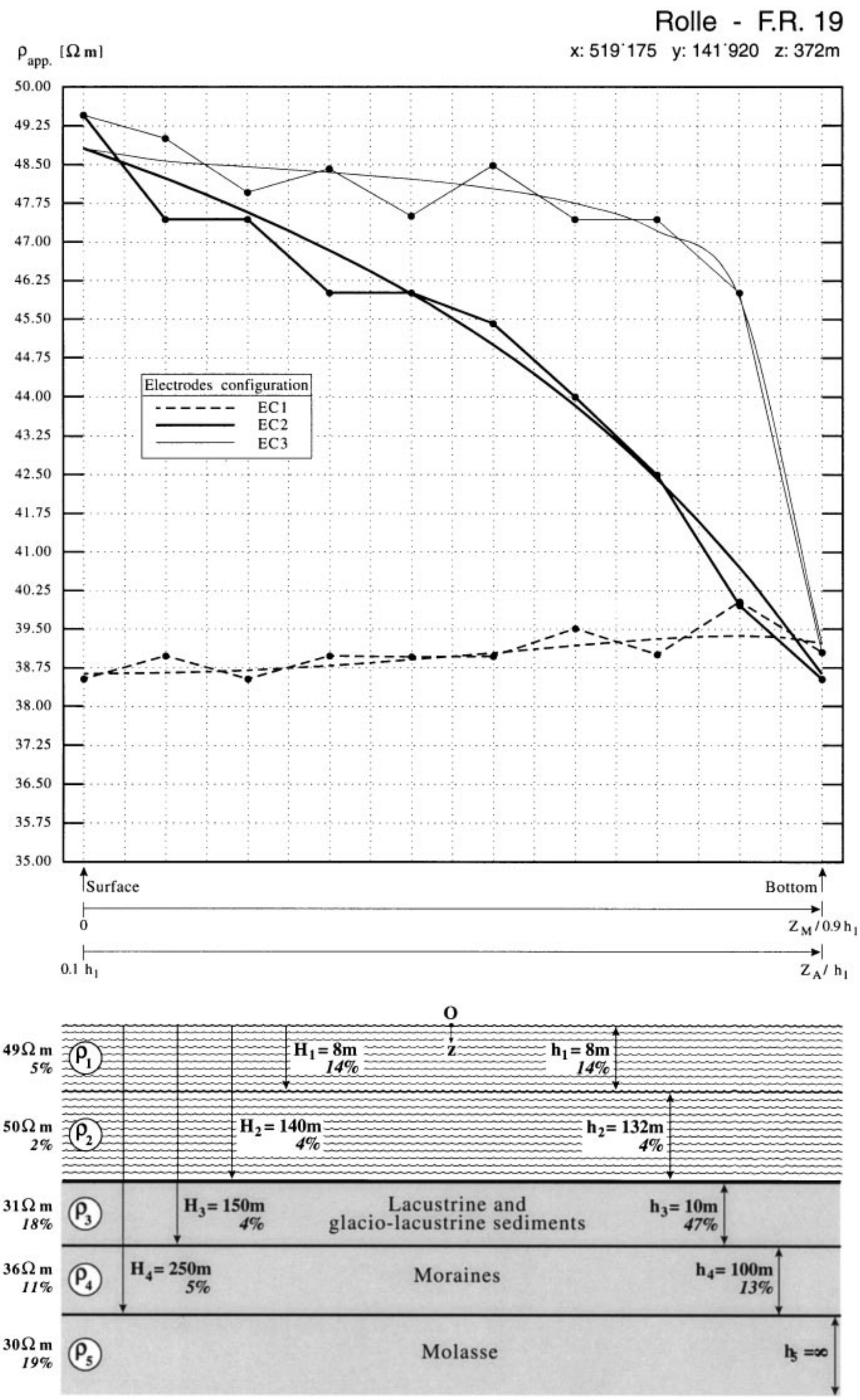

Figure 7. Field data collected at position point 19.

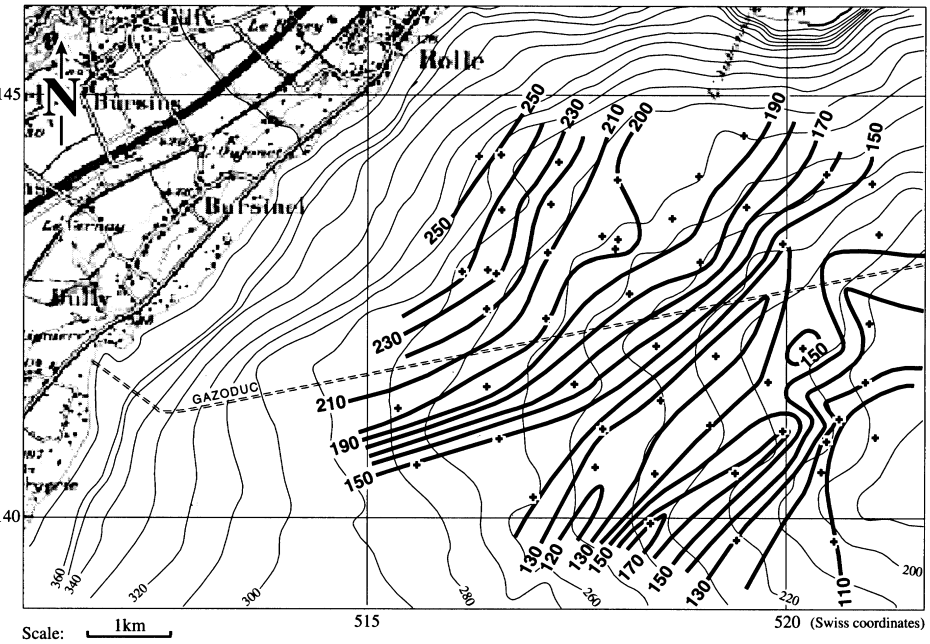

Figure 8. Topographic map of the molasse (in metres).

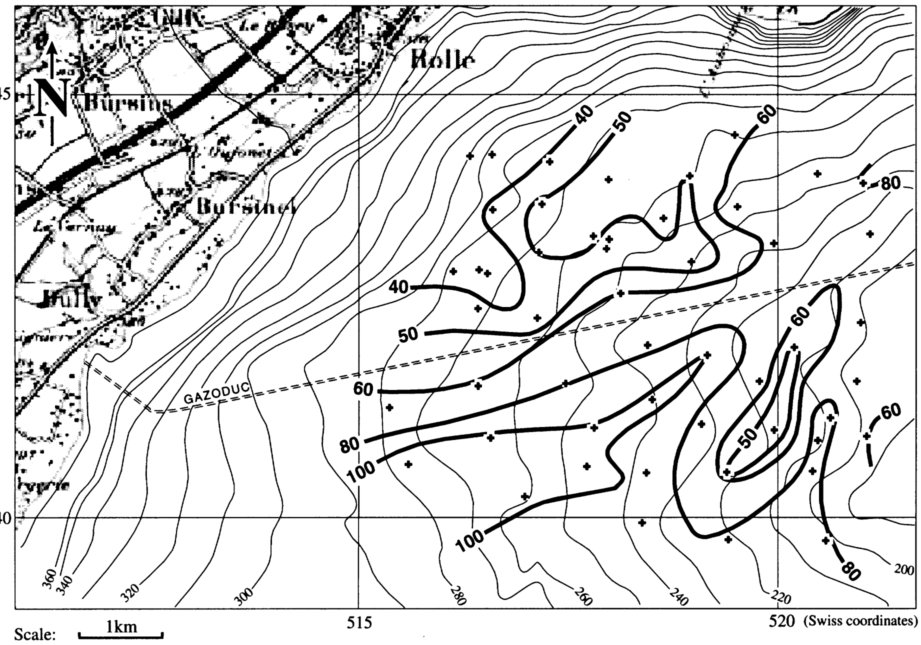

Figure 9. Isopach map of the moraines (in metres).

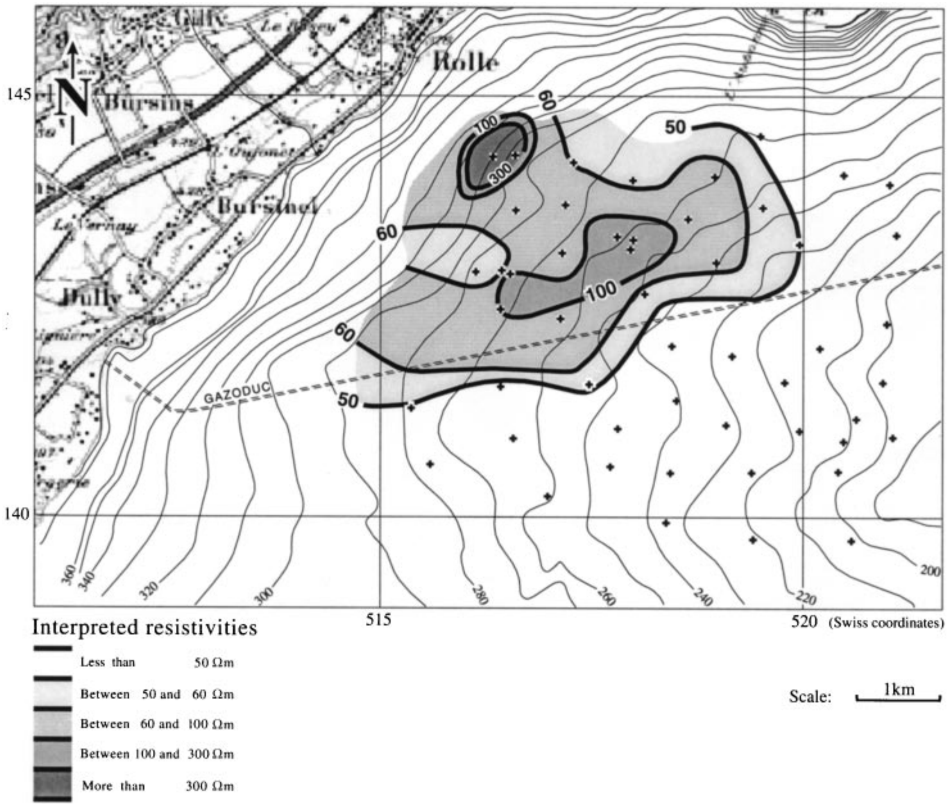

Figure 10. Interpreted iso-resistivity curves (in Ωm).

there is still a perfect match between the depths and thicknesses. In fact, the variations of the resistivities of the molasse and of the channel are complementary. In other words, we have an equivalence between these two models. This can be seen by looking at their responses. The water stratification that has been taken into account in the inversion is essentially the cause of the modifications or, more precisely, the improvements. At point 19, however, there was no water stratification. It thus seems that the trial-and-error approach to inversion is a viable one. However, much more effort is needed to perform the interpretations manually than with an automated inversion program, and the insights provided by the analyses presented in this study would have been difficult to obtain with the same degree of reliability and quantification using forward modelling alone.

Conclusion

The analyses of the FR method justify the use of this method when dealing with deep lakes. It is possible to obtain a good determination of the model parameters in most cases as the parameters of the water layer are known. The automated iterative inversion

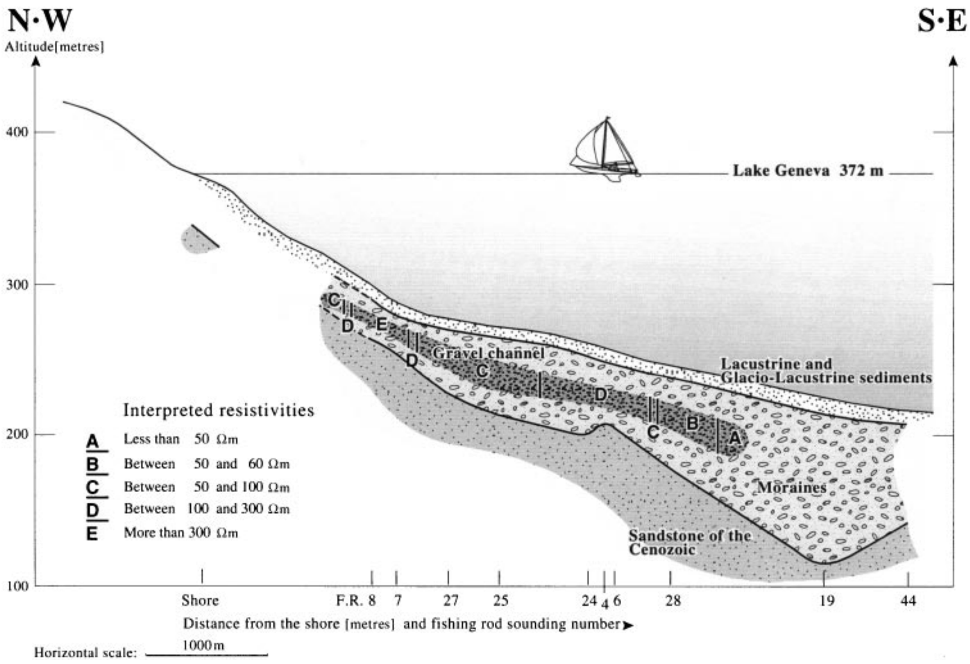

Figure 11. Cross-section offshore Rolle.

of the field data collected in Lake Geneva has permitted a more reliable interpretation with quantitative error analyses, though the results were seen to be similar to those obtained in the trial-and-error case. The analyses have given a clear picture of the resolution capabilities of the FR method.

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