Pergamon

Journal of African Earth Sciences, Vol. 24, No. 4, pp. 635-647. 1997

0899-5362/97 $17.00 + 0.00

PII:S0899-5362(97)00085-7

Error in depth determination from resistivity soundings due to non-identification of suppressed layers

A. I. OLAYINKA
Department of Geology, University of Ibadan, Ibadan, Nigeria

Abstract—The magnitude of errors in the determination of depth to bedrock from Wenner and Schlumberger resistivity sounding curves, caused by the non-identification of a suppressed layer, has been investigated. The principal objective is to evaluate how the layer thicknesses and resistivities affect the accuracy of depth estimates. In the computations, the intermediate layer in a 3-layer model, in which the resistivity increases with depth, is removed and the 2-layer sounding curve that is electrically equivalent to the 3-layer curve is generated. The results indicate that there is a possibility for large depth underestimations when the resistivity contrast between layers 1 and 2 is very large. This is manifested in a steeply rising terminal branch on the sounding curve. There is a slight decrease in the depth underestimation as the resistivity contrast between layers 2 and 3 increases. Conversely, if the intermediate layer is fairly thick and the resistivity contrasts are not too large, the best-fit 2-layer curve shows large deviations from the 3-layer curve. In such cases, the intermediate layer can be identified, resulting in reliable depth estimates. A field example from Nigeria is presented in which the sounding data has been interpreted so as to account for a prebasement layer of intermediate resistivity, indicative of a fractured granite. © *1997 Elsevier Science Limited.*

Résumé—On a étudié la magnitude des erreurs dans la détermination de la profondeur du socle à partir des courbes de sondages de résistivité de Wenner et Schlumberger, causée par la non-identification d'un niveau disparu. Le principal objectif est d'évaluer comment l'épaisseur et la résistivité des niveaux affectent la précision des estimations de profondeurs. Dans les calculs, le niveau intermédiaire d'un modèle à trois couches, où la résistivité augmente avec la profondeur, est enlevé et la courbe de sondage à deux couches équivalente électriquement de la courbe à trois couches est calculée. Les résultats indiquent qu'il est possible de sous-estimer grandement les profondeurs quand le contraste de résistivité entre les niveaux 1 et 2 est très grand. Ceci se manifeste dans une branche terminale très redressée de la courbe de sondage. La sous-estimation diminue quand le contraste de resistivité entre les niveaux 2 et 3 augmente. Inversement, si le niveau intermédiaire est assez épais et le contraste de résistivité pas trop fort, la meilleure courbe à deux couches montre de grandes variations par rapport à la courbe à trois couches. Dans de tels cas, le niveau intermédiaire peut être identifié et l'estimation des profondeurs est correcte. On présente un exemple de terrain au Nigeria où les données de sondage ont été interprétées pour tenir compte d'un niveau de résistivité intermédiaire au-dessus du socle, indiquant un zone de fracturation du granite. © *1997 Elsevier Science Limited.*

(Received 26 January 1994: revised version received 8 February 1997)

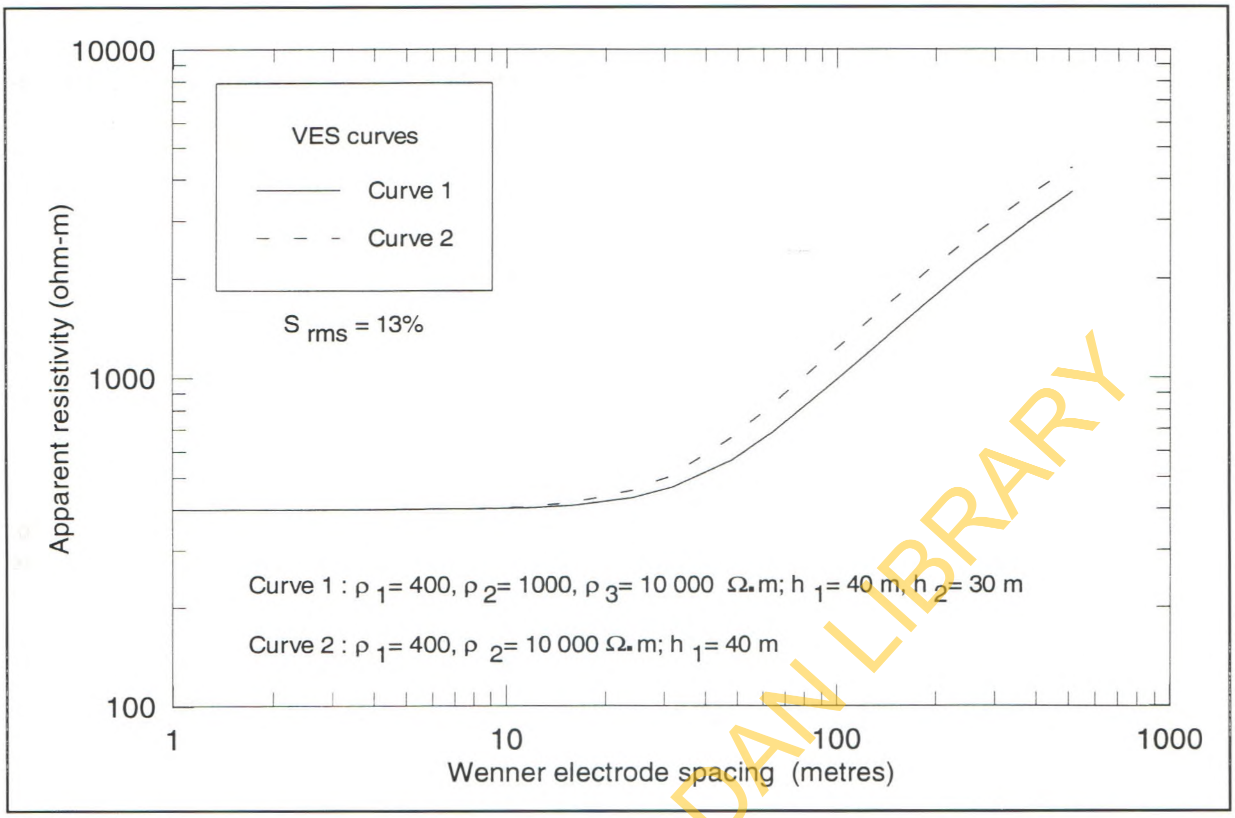

Figure 1. *Example showing the similarity between a 3-layer model (Curve 1) and a 2-layer model (Curve 2).*

INTRODUCTION

Vertical electrical sounding (VES) curves (Wenner and Schlumberger) for a 3-layer model, in which the resistivity increases with depth, are often very difficult to interpret unambiguously because they resemble those for two layers. In particular, if the intermediate layer in the 3-layer model is removed, the curve retains practically the same shape, save for a slight horizontal shift. An example is presented in Fig. 1 for a 3-layer case in which the resistivities are 400, 1000 and 10,000 ohm-m, respectively. The thickness of the first layer is 40 m and that of the second 30 m. The Wenner theoretical sounding curve computed for this model (curve 1) has the same shape as that for a 2-layer model in which a 40 m thick layer, having a resistivity of 400 ohm-m, overlies a substratum with a resistivity of 10,000 ohm-m (curve 2). It is obvious that the apparent resistivities for curve 1, just like those for curve 2, can be inverted to give a 2-layer model.

It is generally assumed that suppression occurs when a thin layer is present or when the resistivity of a layer has a value between that of the surrounding layers (Simms and Morgan, 1992). This problem of "suppression" may cause either the non-detection or partial detection of the intermediate layer in a 3-layer model, with grave implications on the inversion of field data on account of contributing to the non-uniqueness of the interpretation. In practical terms, it could, as in the example of Fig. 1, lead to the erroneous determination of the depth to the fresh bedrock (Carruthers and Smith, 1992). The phenomenon is of special significance in the use of resistivity soundings for selecting sites for the drilling of water-supply boreholes in areas underlain by crystalline basement rocks. In such terrains there is often a difficulty in identifying the fractured/ weathered bedrock (or saprock) from the sounding interpretation (Hazell *et al.*, 1992) because its resistivity is intermediate between those of the adjacent beds, namely the regolith (i.e. residual overburden) on top and the fresh bedrock below. The non-identification of the saprock on a VES curve may be partly responsible for differences between the depth to bedrock predicted by sounding interpretation and that confirmed by borehole drilling (Olorunfemi and Olorunniwo, 1985).

It is to be expected that the detectability of a buried bed is directly proportional to its relative thickness, this being the ratio of the bed

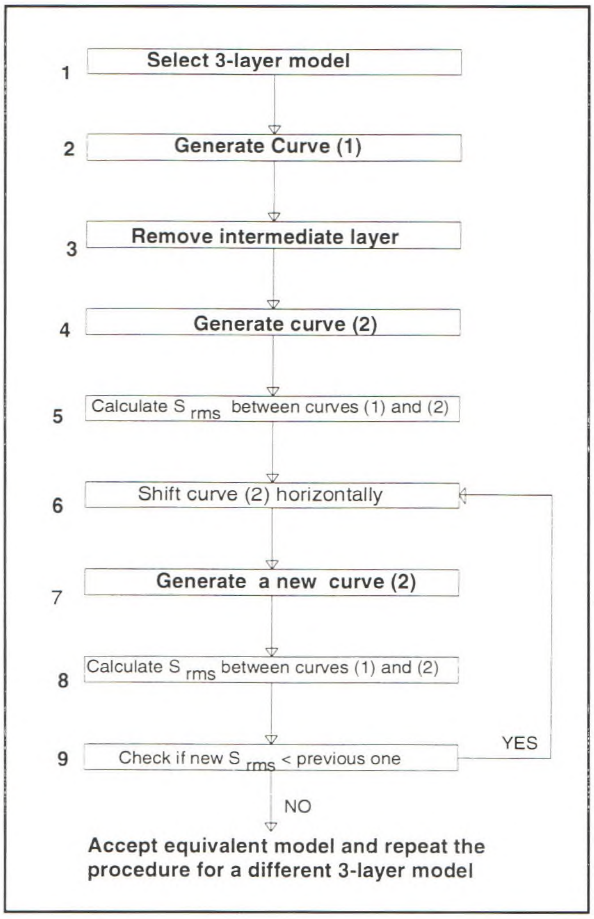

Figure 2. *Flow chart for the computation of a 2-layer VES curve that is equivalent to a 3-layer model.*

thickness to its depth of burial (Flathe, 1963). In this respect, it has been suggested (Verma *et al.*, 1980) that for a buried bed to be identifiable from sounding data its relative thickness should be more than 1. Nonetheless, the role of resistivity contrasts in the identification, or non-identification, of the suppressed layer and their effects on the accuracy of depth estimations has not received much attention. An appreciation of the limitation posed by the non-identification of the supposedly suppressed layer in the inversion of resistivity sounding data, coupled with the recognition of the limited attention hitherto given to it in the literature, have led to the present work. The specific objective is to examine how the model parameters (thickness and resistivity) of the suppressed layer affect depth estimates from sounding interpretations.

The procedure adopted entailed calculation of a 2-layer sounding curve which fits the curve generated for the 3-layer model, to within 1 or 2 percent; in other words, the latter can be interpreted as the former due to the non-recognition of the effect of the intermediate layer. As pointed out by Zohdy (1989), any such two models are equivalent and it is not possible to know with certainty which of them represents the actual subsurface layering. The results indicate large errors in depth estimates when the resistivity contrast between layers 1 and 2 is very large, even for a relatively thick intermediate layer.

COMPUTATION OF EQUIVALENT MODELS

In this study, the effect of the non-detection of the intermediate layer in a 3-layer curve interpretation has been studied in terms of the difference in the estimated depth to bedrock in a 3-layer model compared to that computed for an equivalent 2-layer model. The steps involved in the curve fitting are outlined in the flow chart of Fig. 2.

1. A 3-layer model, in which the resistivity increases with depth (Fig. 3a) is selected. The depth to bedrock in this model, which is equal to the combined thickness of layers 1 and 2, is denoted H.

2. The theoretical sounding curve for this model is computed by convolution (Ghosh, 1971), using the computer programs by Xu and Barker (1994) for a Wenner array and Koefoed (1979; pp98-99) for a Schlumberger array. This is curve (1).

3. The intermediate layer is removed from the 3-layer model. As shown in Fig. 3b, what is left is a 2-layer model in which the depth to bedrock, represented as H', is the thickness of the first layer in the initial 3-layer case.

4. The theoretical sounding curve for this model is also calculated. This is curve (2).

5. Curves (1) and (2) are compared by taking the root-mean-square (rms) percentage difference (S_{rms}) between the two curves using the equation:

$$S_{rms} = [1/N.\sum_{j=1}^{N}(P_{1j} - P_{2j})^2]^{1/2}.100\% \, , \quad (1)$$

where P_{1j} = apparent resistivity at the jth spacing for curve (1); P_{2j} = apparent resistivity at the jth spacing for curve (2); and N = number of electrode spacings at which the resistivity sounding curve is sampled.

The calculated value of S_{rms} would depend on both the shape and the phase relationship between the two curves being compared. If the two curves have substantially different

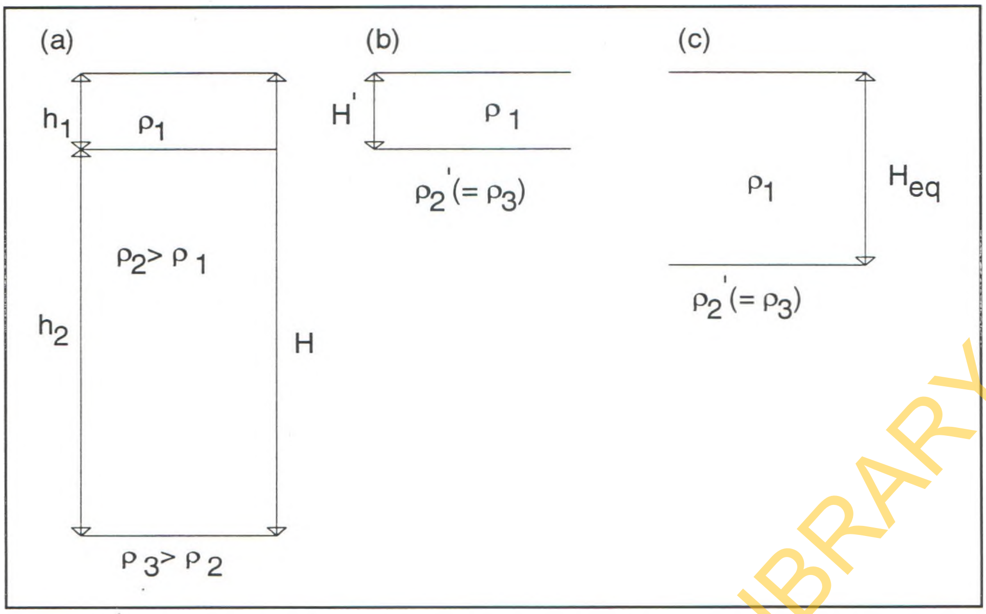

Figure 3. *Comparison between a 3-layer model and the equivalent 2-layer model. See text for explanation.*

shapes, this will be indicated by a high value of S_{rms}. Similarly, the two curves could have the same shape but be offset horizontally on the spacing scale, i.e. they are out of phase, in which case the S_{rms} will also take a high value. On the other hand, if the two curves have the same shape and are in phase, S_{rms} will be close to zero, and the two curves being compared can be regarded as equivalent to each other.

The subsequent stages in the analysis, therefore, consist of an attempt to minimise the S_{rms} percentage between the 3- and 2-layer models by bringing curves 1 and 2 into phase. The expected end product is a 2-layer VES curve which is electrically equivalent to the starting 3-layer curve; the S_{rms} should be less than 2% for synthethic data.

6. In order to bring the two curves into phase before calculating the rms error, a small horizontal shift is applied to the 2-layer model with respect to the 3-layer model. This could take the form of a small increment in the depth to interface in the 2-layer model. Similar approaches have also been described by Zohdy (1989) and Barker (1992).

7. The theoretical sounding (curve 2) for this model is generated.

8. The S_{rms} difference between curves (1) and (2) is calculated using equation (1).

9. The new S_{rms} difference is compared with the previous one. If the new value is less than the old one, steps 6 to 8 are repeated. Otherwise, the preceding model, for which the rms is the minimum, is the equivalent model where there is a perfect or near-perfect match between curves (1) and (2). The depth to the interface in the equivalent 2-layer model is represented as H_{eq} (Fig. 3c).

The error in depth estimation E is expressed as:

$$E = (H - H_{eq})/H.100\%. \qquad (2)$$

The first layer is normally well resolved on the sounding curve and its thickness is the minimum depth to the interface in any 2-layer model that is equivalent to the 3-layer model. The largest depth underestimation is expected when $H_{eq} = h_1$ for which:

$$E = E_{max} = (H - h_1)/H.100\% = (h_2/H).100\%. \qquad (3)$$

On the other hand, the minimum value is E = 0%, which is recorded when $H_{eq} = H$, under which situation the entire thickness of the intermediate layer is resolved.

Several 3-layer models for a variety of layer thicknesses and resistivity contrasts have been considered. Theoretical sounding curves were computed for the Wenner array, using values of a = 1.0, 1.5, 2.10, 3.0, 4.0,..., 512 m, to give 19 data points on each sounding curve (i.e. N = 19 in equation [1]). In the Schlumberger array, N = 23, with the theoretical sounding data generated at 8 points per decade, for the values AB/2 = 1.0, 1.33, 1.78,..., 562.34. The results obtained are presented in the following section.

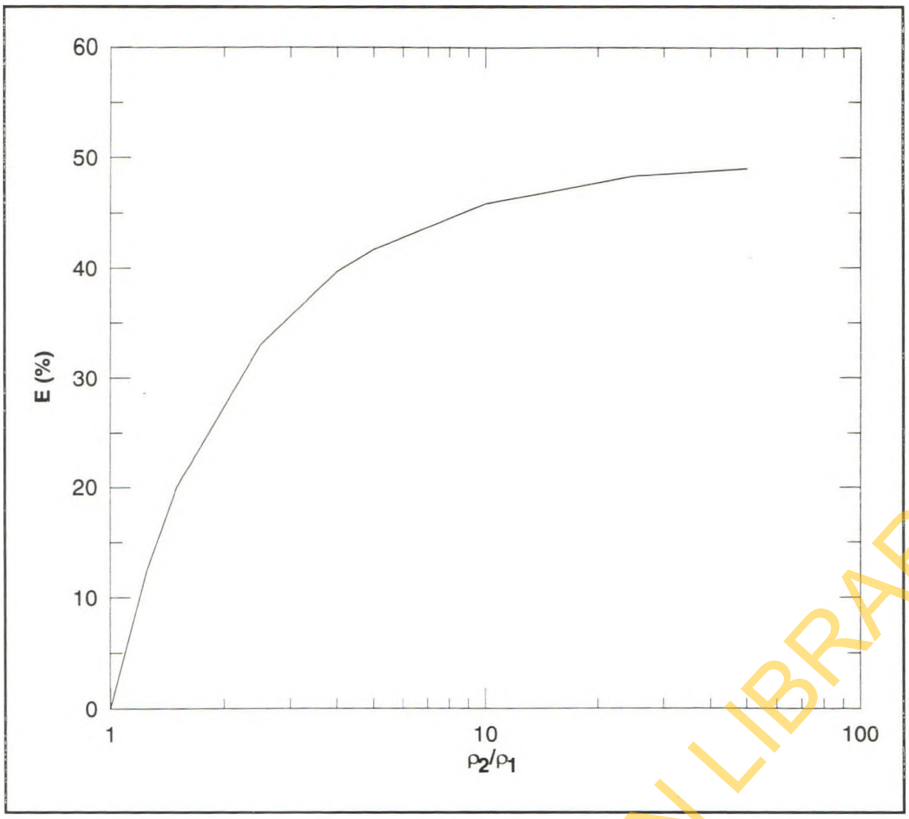

Figure 4. *Variation of error in depth estimates with the resistivity contrast between layers 1 and 2 (Schlumberger array). $\rho_2 = 750$, $\rho_3 = 10{,}000$ ohm-m; $h_1 = 30$ m, $h_2 = 30$ m.*

RESULTS

Equivalence between 3- and 2-layer curves

It was possible to generate a 2-layer curve that fits the starting 3-layer curve along the lines described above in many cases. In the example shown in Fig. 1, a 2-layer Wenner curve that fits the 3-layer curve (1) to within 1% was calculated in which the depth to the bedrock interface is 51.6 m; this represents an error E of 26% in the depth estimation. Identical results were also obtained for the Schlumberger array.

When layers 1 and 2 have identical resistivities, a 3-layer model reduces to that for a homogeneous overburden on top of the bedrock. In this case the determination of the depth to bedrock would be precise, being equal to the combined thickness of layers 1 and 2.

The error in depth determination resulting from a partial detection of the intermediate layer is relatively small for a small contrast in resistivity between the first and second layers. As the resistivity contrast increases, the possibility for the non-identification of the intermediate layer also increases and the depth to bedrock in the equivalent 2-layer model will approach the thickness of layer 1 in the 3-layer model. A very high resistivity contrast between these two layers implies that the second layer already behaves like a resistive basement compared to the more conducting overburden, in spite of the presence of a substratum with a higher resistivity. Under this condition only the depth to the top of the intermediate layer (i.e. the thickness of layer 1) can be ascertained fairly accurately. This is in agreement with the proposition that once the resistivity contrast in a 2-layer model for either the Wenner or Schlumberger array exceeds 10 the sounding curve stays practically the same (van Nostrand and Cook, 1966, p90).

The increase in the error in depth estimation as the resistivity contrast between layers 1 and 2 increase is shown in Fig. 4 for Schlumberger 3-layer sounding curves, in which the resistivity of the intermediate layer is 750 ohm-m and that of the bedrock is 3000 ohm-m. The thickness of layer 1 is 30 m and that of layer 2 also 30 m. There is a non-linear increase in E as the resistivity contrast increases, approaching its maximum value of 50% asymptotically at a resistivity ratio of about 20. This pattern was also observed when other 3-layer models were considered, in which the resistivity of the bedrock is 1000 ohm-m.

low latitude regions comprises, from top to bottom, the soil layer, the saprolite (product of the *in situ* chemical weathering of the bedrock), the saprock (fractured bedrock) and the fresh bedrock (Fig. 10). It is worth noting that the resistivity of the saprolite can be of the order of 10 ohm-m, especially when the regolith is rich in clay. The theoretical examples considered earlier have amply demonstrated that if such a low resistivity layer is underlain by a horizon whose resistivity is at least 10 times more, then the unit below that layer may not be discernible on the sounding curve. Hence, the interpretation of a VES curve is often simply in terms of a 3-layer model, indicative of the soil cover, saprolite and fresh rock, respectively, resulting in an underestimation of the depth to the fresh bedrock interface, if the saprock is present. Since noise is invariably present in field measurements, the S_{rms} between field and calculated data has to be larger than for synthethic data. The minimum S_{rms} for good quality field data should be of the order of 5%.

The field example shown in Fig. 11a was measured at Ogboro, southwestern Nigeria, as part of a borehole siting investigation, involving a total of 20 Schlumberger soundings. There are granite outcrops, giving rise to an inselberg landscape in parts of the village. In several places the bedrock is also masked by weathered regolith material. There are several shallow wells, less than 10 m deep, which terminate on reaching the weathered bedrock. The measured apparent resistivities were first inverted as a 3-layer model in which the depth to bedrock is 10.6 m. The S_{rms} between the theoretical sounding curve calculated from this model and the field data is 10%. There is a fairly large underestimation of apparent resistivities for electrode spacings between 6 m and 40 m and a slight overestimation for spacings exceeding 50 m. It was consequently decided to introduce a new layer directly on top of the bedrock. In this manner, it became possible to model the field data more accurately with the S_{rms} reduced to 5%. In the final model (Fig. 11b) there is a 24.6 m thick prebasement horizon with a resistivity of 650 ohm-m. This most probably represents a fractured bedrock sequence. It may be pointed out that the 4-layer interpretation is in good agreement with that for another sounding conducted 100 m west of this location. Moreover, borehole drilling in the village has indicated the presence of a weathered/fractured granite, underlying the sandy regolith.

DISCUSSION AND CONCLUSION

The sounding curves presented in this paper have shown that when a 3-layer case in which the resistivity increases with depth, is inadvertently interpreted as a 2-layer model, on account of the suppression of the intermediate layer, the depth to bedrock is underestimated. This is often the case when there is a very large resistivity contrast between layers 1 and 2 and/or the thickness of the intermediate layer is not much larger than its depth of burial. Quite often, the interpreted depth to bedrock in the equivalent 2-layer model lies somewhere between the thickness of layer 1 and the combined thickness of layers 1 and 2 in the 3-layer model. There is, therefore, a partial suppression of the intermediate layer. There is invariably a limit of suppression, depending on the resistivity contrasts and thickness of the intermediate layer, beyond which the layer is clearly identified on the sounding curve; if the curve is interpreted without accounting for the intermediate layer there would be a large rms error. This is a guide in the recognition of the intermediate layer as seen in the field example presented.

In the interpretation of field data, the geophysicist needs to be aware of the presence of suppressed layers as a source of error in depth estimates, especially when the terminal segment of the sounding curve rises very steeply. The identification of probable fissured and fractured zones for hydrogeological applications in crystalline basement areas can, however, benefit from supplementary information provided by other geophysical techniques, notably seismic refraction, electromagnetic profiling and electrical well logging.

ACKNOWLEDGEMENTS

The author would like to thank Dr R. D. Barker (School of Earth Sciences, University of Birmingham) and Dr A. Weller (Institute for Geophysics and Meteorology, Technical University, Braunschweig) for comments and suggestions which have helped to improve the clarity of the work. Funding was provided by the German Academic Exchange Service (DAAD).

REFERENCES

Barker, R. D. 1992. A simple algorithm for electrical imaging of the subsurface. *First Break* **10**, 53-62.

Carruthers, R. M. and Smith, I. F. 1992. The use of ground electrical survery methods for siting water-supply boreholes in shallow crystalline basement terrains. In: *Hydrogeology of Crystalline Basement Aquifers in Africa* (Edited by Wright, E. P. and Burgess, W. G.) *Geological Society Special Publication* **66**, 203-220.

Flathe, H. 1963. Five-layer master curves for the hydrogeological interpretation of geoelectric resistivity measurements above a two-storey aquifer. *Geophysical Prospecting* **11**, 471-508.

Ghosh, E. P. 1971. Inverse linear filter coefficients for the computation of apparent resistivity standard curves over horizontally stratified earth. *Geophysical Prospecting* **19**, 192-217.

Hazell, J. R. T., Cratchley, C. R. and Jones, C. R. C. 1992. The hydrogeology of crystalline aquifers in northern Nigeria and geophysical techniques used in their exploration. In: *Hydrogeology of Crystalline Basement Aquifers in Africa* (Edited by Wright, E. P. and Burgess, W. G.) *Geological Society Special Publication* **66**, 155-182.

Koefoed, O. 1979. *Geosounding principles 1: resisivity sounding measurements*. Elsevier, Amsterdam. **276p.**

Olorunfemi, M. O. and Olorunniwo, M. A. 1985. Geoelectric parameters and aquifer characteristics of some parts of southwest Nigeria. *Geologia Applicata Idrogeologia* **20**, 99-109.

Simms, J. E. and Morgan, F. D. 1992. Comparison of four least-squares inversion schemes for studying equivalence in one-dimensional resistivity interpretation. *Geophysics* **57**, 1282-1293.

Van Nostrand, R. G. and Cook, K. L. 1966. Interpretation of resistivity data. *United States Geological Survey Professional Paper* **499.Washington D.C., 310p.**

Verma, R. K., Rao, M. K. and Rao, C. V. 1980. Resistivity investigations for ground water in metamorphic areas near Dhanbad, India. *Ground Water* **18**, 46-55.

Xu, B. and Barker, R. D. 1994. Filter coefficients for offset Wenner and Wenner resistivity sounding interpretation. *Computer Geosciences* **20**, 671-679.

Zohdy, A. A. R. 1989. A new method for the automatic interpretation of Schlumberger and Wenner sounding curves. *Geophysics* **54**, 245-253.