Reprinted from

APPLIED
GEOPHYSICS

Journal of Applied Geophysics 37 (1997) 103–115

The inversion of geoelectrical data for hydrogeological applications in crystalline basement areas of Nigeria

A.I. Olayinka [a], A. Weller [b,*]

[a] *Department of Geology, University of Ibadan, Ibadan, Nigeria*
[b] *Institut für Geophysik, Technische Universität Clausthal, Arnold-Sommerfeld-Str. 1, 38678 Clausthal-Zellerfeld, Germany*

Received 15 August 1996; revised 29 January 1997; accepted 29 January 1997

ELSEVIER

JOURNAL OF APPLIED GEOPHYSICS

Editors-in-Chief
T.E. Owen, San Antonio, TX
H. Rüter, Bochum

Founding Members
D.S. Parasnis, Luleå
M. Puranen, Helsinki
S. Saxov, Aarhus
T. Siikarla, Helsinki
E. Tengström, Uppsala

Editorial Board
M. Bernabini, Rome
D. Chapellier, Lausanne
N.B. Christensen, Aarhus
S. Crampin, Edinburgh
C.A. Dias, Belém
T.L. Dobecki, Houston, TX
R.K. Frohlich, Kingston, RI
M. Goldman, Holon
J.P. Greenhouse, Waterloo, Ont.
P.G. Killeen, Ottawa, Ont.
J.-Y. Kim, Taejou
T. Lee, Canberra, A.C.T.
O. Olsson, Uppsala
D.S. Parasnis, Luleå
D. Patella, Rome
C.H. Stoyer, Golden, CO
K.-M. Strack, Houston, TX
T. Ulrych, Vancouver, B.C.
P. Valla, Orléans
K. Vozoff, North Sydney, N.S.W.

UNIVERSITY OF IBADAN LIBRARY

Scope of the journal
The *Journal of Applied Geophysics* is the continuation of *Geoexploration* founded in 1965 by the Geoexploration Publishing Group in Stockholm, originally for mining geophysics. The new title is designed to reflect the widening scope of the applications of geophysics. To meet modern needs the *Journal of Applied Geophysics* places particular emphasis on environmental, geotechnical, engineering and hydrological aspects, at the same time welcoming papers in traditional subjects like mining and petroleum geophysics. Petrophysics in its widest sense including soil and rock-mechanical properties is another aspect that is covered by the *Journal of Applied Geophysics*.

Publication Information
Journal of Applied Geophysics (ISSN 0926-9851). For 1997 Volumes 37 and 38 are scheduled for publication. Subscription prices are available upon request from the publisher. Subscriptions are accepted on a prepaid basis only and are entered on a calendar year basis. Isasues are sent by surface mail except to the following countries where air delivery via SAL mail is ensured: Argentina, Australia, Brazil, Canada, Hong Kong, India, Israel, Japan, Malaysia, Mexico, New Zealand, Pakistan, PR China, Singapore, South Africa, South Korea, Taiwan, Thailand, USA. For all other countries airmail rates are available upon request. Claims for missing issues must be made within six months of our publication (mailing) date. For orders, claims, product enquiries (no manuscript enquiries) please contact the Customer Support Department at the Regional Sales Office nearest to you:

New York, Elsevier Science, P.O. Box 945, New York, NY 10159-0945, USA. Tel: (+1) 212-633-3730, [Toll Free number for North American Customers: 1-888-4ES-INFO (437-4636)], Fax: (+1) 212-633-3680, E-mail: usinfo-f@elsevier.com
Amsterdam, Elsevier Science, P.O. Box 211, 1000 AE Amsterdam, The Netherlands. Tel: (+31) 20-485-3757, Fax: (+31) 20-485-3432, E-mail: nlinfo-f@elsevier.nl
Tokyo, Elsevier Science, 9-15, Higashi-Azabu 1-chome, Minato-ku, Tokyo 106, Japan. Tel: (+81) 3-5561-5033, Fax: (+81) 3-5561-5047, E-mail: kyf04035@niftyserve.or.jp
Singapore, Elsevier Science, No. 1 Temasek Avenue, #17-01 Millenia Tower, Singapore 039192. Tel: (+65) 434-3727, Fax: (+65) 337-2230, E-mail: asiainfo@elsevier.com.sg

Advertising information
Advertising orders and enquiries may be sent to: Elsevier Science, Advertising Department, The Boulevard, Langford Lane, Kidlington, Oxford, OX5 1GB, UK, tel.: (+44) (0) 1865 843565, fax: (+44) (0) 1865 843976. *In the USA and Canada*: Weston Media Associates, attn. Dan Lipner, P.O. Box 1110, Greens Farms, CT 06436-1110, USA, tel: (203) 261 2500, fax: (203) 261 0101. *In Japan*: Elsevier Science Japan, Marketing Services, 9-15 Higashi-Azabu 1-chome, Minato-ku, Tokyo 106, Japan, tel.: (+81) 3 5561 5031; fax: (+81) 3 5561 5045.

© 1997, ELSEVIER SCIENCE B.V. ALL RIGHTS RESERVED.

0926-9851/97/$17.00

This journal and the individual contributions contained in it are protected by the copyright of Elsevier Science B.V., and the following terms and conditions apply to their use:

Photocopying: Single photocopies of single articles may be made for personal use as allowed by national copyright laws. Permission of the Publisher and payment of a fee is required for all other photocopying, including multiple or systematic copying, copying for advertising or promotional purposes, resale, and all forms of document delivery. Special rates are available for educational institutions that wish to make photocopies for non-profit educational classroom use.
In the USA, users may clear permissions and make payment through the Copyright Clearance Center Inc., 222 Rosewood Drive, Danvers, MA 01923, USA. In the UK, users may clear permissions and make payment through the Copyright Licensing Agency Rapid Clearance Service (CLARCS), 90 Tottenham Court Road, London W1P 0LP, UK. In other countries where a local copyright clearance centre exists, please contact it for information on required permissions and payments.
Derivative Works: Subscribers may reproduce tables of contents or prepare lists of articles including abstracts for internal circulation within their institutions. Permission of the Publisher is required for resale or distribution outside the institution.
Permission of the Publisher is required for all other derivative works, including compilations and translations.
Electronic Storage: Permission of the Publisher is required to store electronically any material contained in this journal, including any article or part of an article. Contact the Publisher at the address indicated.
Except as outlined above, no part of this publication may be reproduced, stored in a retrieval system or transmitted in any form or by any means, electronic, mechanical, photocopying, recording or otherwise, without prior written permission of the Publisher.

Notice: *No responsibility is assumed by the Publisher for any injury and/or damage to persons or property as a matter of products liability, negligence or otherwise, or from any use or operation of any methods, products, instructions or ideas contained in the material herein.*

∞ The paper used in this publication meets the requirements of ANSI/NISO Z39.48-1992 (Permanence of Paper).

PRINTED IN THE NETHERLANDS

ELSEVIER
Journal of Applied Geophysics 37 (1997) 103–115
JOURNAL OF APPLIED GEOPHYSICS

The inversion of geoelectrical data for hydrogeological applications in crystalline basement areas of Nigeria

A.I. Olayinka [a], A. Weller [b,*]

[a] Department of Geology, University of Ibadan, Ibadan, Nigeria
[b] Institut für Geophysik, Technische Universität Clausthal, Arnold-Sommerfeld-Str. 1, 38678 Clausthal-Zellerfeld, Germany

Received 15 August 1996; revised 29 January 1997; accepted 29 January 1997

Abstract

A methodology is presented for the inversion of two-dimensional (2-D) geoelectrical data for solving hydrogeological problems in crystalline basement areas. The initial step entails compiling an earth model using all available geological, borehole and geophysical information. This model then served as the input to a 2-D inversion algorithm based on the Simultaneous Iterative Reconstruction Technique (SIRT). The algorithm tries to find a model that is as close as possible to the starting model. To demonstrate the usefulness of this procedure, two field examples from Nigeria, conducted as part of a borehole siting programme, are described. In the first example, borehole information regarding the thickness of the weathered zone overlying a gneissic bedrock was used to constrain the 1-D inversion of sounding data and the model thus compiled was used as the starting model for 2-D inversion. In the second example, only sounding information was used to determine the starting model. If the starting model has incorporated all the available information as constraints, it is generally possible to compute a model that not only fits the measured data but is also a good approximation of the subsurface geology, more so when several 2-D models can fit the same set of field measurements on account of the limitations posed by equivalence.

Keywords: crystalline basement; electrical resistivity; geoelectrical prospection; inversion algorithm; Nigeria; non-uniqueness

1. Introduction

Although the solution to a geophysical inverse problem is seldom unique, the conventional approach to the inversion of direct current resistivity data requires no prior information on the distribution of resistivity in the subsurface (Smith and Vozoff, 1984; Tripp et al., 1984; Shima, 1990; Loke and Barker, 1995, 1996). However, the resulting image, being just one out of several probable models, is not necessarily free from the interpreter's bias. Simms and Morgan (1990) have shown that in the 1-D inversion of sounding data the indirect method, in which the geophysicist prescribes the initial model parameters, gives better results than an automatic inversion which requires no initial model. It has been suggested (Ellis and Oldenburg, 1994) that all a priori information should

---

[*] Corresponding author. Tel.: +49-5323-722233; fax: +49-5323-722320; e-mail: andreas.weller@tu-clausthal.de.

PII S0926-9851(97)00005-0

be used in generating a base model which would serve as a constraint for an inversion algorithm.

The application of electrical imaging or electrical tomography in geology normally involves the deployment of an array of colinear, equidistant electrodes. A series of constant separation traverses is measured, using a computer-controlled system (Griffiths and Turnbull, 1985; Griffiths et al., 1990; Griffiths and Barker, 1993), the electrode separation being increased with each successive traverse. The data are classically presented in the form of pseudosections (Edwards, 1977). The unit electrode spacing affects the length of the profile, depth of investigation and resolution. In field surveys cost considerations dictate that a large area be covered in minimal time; hence the unit spacing could be very large. This inevitably leads to a loss of geoelectrical information about the near-surface materials.

In the 2-D interpretation of resistivity pseudosection data from crystalline basement areas it is often possible to calculate a rather simplistic equivalent 2-D model that fits the measured data in which the entire overburden is lumped together as having a single resistivity (Olayinka, 1988). This resistivity can be visualized as a weighted average of the resistivity of the various geoelectrical units that make up the overburden. In the absence of any supplementary information this is possibly the best that could be done. However, significant lateral and vertical variations have been reported in the lithologic characteristics of the weathered profile developed upon the crystalline basement in several parts of Africa (Chilton and Foster, 1995). In these areas, the depth to the fresh bedrock varies from 0 to 70 m and the vertical profile can be subdivided into three main parts, namely the topsoil, the saprolite (saturated regolith), and saprock (weathered bedrock). The resistivity of the topsoil varies from less than 50 to over 1000 Ω m; that of the saprolite from 10 to 600 Ω m, the saprock 300 to 3000 Ω m and the fresh bedrock over 3000 Ω m (Aina et al., 1996). The highly heterogeneous nature of the overburden implies that situations could arise in which the images on pseudosections do not emulate the geologic structure.

In this paper, we have examined how the inclusion of borehole control and the results obtained from the 1-D inversion of vertical electrical sounding (VES) data can be used in compiling a 2-D geoelectrical model which could subsequently serve as the starting model for an inversion algorithm. The field measurements were acquired as part of hydrogeological investigations in crystalline basement areas of Nigeria. It is demonstrated that this approach to the inversion of 2-D pseudosection data leads to an improvement in the resolution of subsurface structures than is hitherto possible, especially when the unit electrode spacing in the survey is very large. Moreover, the solution is achieved after a fewer number of iterations than in automatic inversion, with a considerable saving in computer time.

Since electrical resistivity imaging is aimed at a more accurate delineation of subsurface structures any technique that could aid in the attainment of a realistic earth model is definitely welcome. The utilization of all a priori information including borehole control and sounding interpretation in the inversion of pseudosection data as described here is one such approach.

2. Inversion procedures

Geoelectrical measurements are performed in order to gather information on the subsurface resistivity distribution. Since each measured apparent resistivity is influenced by both the resistivity distribution in a large volume of earth and the electrode configuration the pseudosections cannot in most cases reflect the real subsurface structures. The reconstruction of a possible resistivity distribution can only be performed by inversion techniques, and the non-uniqueness in 2-D and 3-D interpretation can be reduced by including all available information into the inversion process.

The objective of inversion consists in finding a resistivity model which can approximate the measured data within the limits of data errors and which is in agreement with all a priori information. The inversion can be done manually by forward modelling in which changes in the model parameters are made by trial and error until a sufficient agreement between measured and synthetic data is achieved (Olayinka, 1988).

For more complicated geological structures where the number of parameters increases automatic inversion procedures are applied. Most of them work iteratively. The steps involved are as follows:

(1) The subsurface is subdivided into blocks of constant resistivity. The number of blocks N is equal to the number of model parameters. All parameters may be described by a parameter vector $\mathbf{x} = (x_1, \ldots, x_N)^T$. The parameter x_j is defined as the logarithm of the resistivity of the jth block.

(2) The measured data are compiled in a data vector $\hat{\mathbf{y}} = (\hat{y}_1, \ldots, \hat{y}_M)^T$ where M corresponds to the number of measurements. The element $\hat{y}_i$ of the data vector $\hat{\mathbf{y}}$ is the logarithm of the apparent resistivity of the ith measurement in the survey.

(3) A starting model is chosen. The parameter vector is initialized $\mathbf{x} = \mathbf{x}^{(0)}$.

(4) The forward modelling for the model $\mathbf{x}^{(k)}$ is performed where k denotes the number of the model. The apparent resistivity is calculated for all M configurations of electrodes used in the field survey. The calculated data are compiled in a data vector $\mathbf{y}^{(k)}$. The forward modelling is described by an operator S which is applied to the parameter vector $\mathbf{x}^{(k)}$:

$$\mathbf{y}^{(k)} = S(\mathbf{x}^{(k)}). \tag{1}$$

(5) The residual $\mathbf{r}^{(k)}$ between measured and computed data is determined:

$$\mathbf{r}^{(k)} = \hat{\mathbf{y}} - \mathbf{y}^{(k)}. \tag{2}$$

If a norm of the residual $\|\mathbf{r}^{(k)}\|$ is less than a predetermined value ε the iteration process can be stopped. The last model is accepted as a solution of the inversion.

(6) If the residual fails the stopping criterium the differences are applied to correct the resistivity model according to the inversion scheme and the next iteration is started with the forward modelling in step (4).

The use of the logarithms of resistivities instead of resistivities has proved to be more appropriate in resistivity inversion because negative resistivities are avoided and relative changes are emphasized.

We used two different inversion techniques which can be described by the above mentioned iteration scheme. The first one is based on the Zohdy–Barker algorithm (Barker, 1992), which is only applicable to Wenner measurements. The discretization grid is designed such that each resistivity block is representative for one data point in the pseudosection. Thus, the number of data corresponds to the number of resistivity blocks $M = N$. The depth to the centre of each block is one-half of the spacing between adjacent electrodes. The measured apparent resistivity data are used as starting model for a 2-D inversion ($\mathbf{x}^{(0)} = \hat{\mathbf{y}}$). The forward modelling is performed by a finite difference algorithm

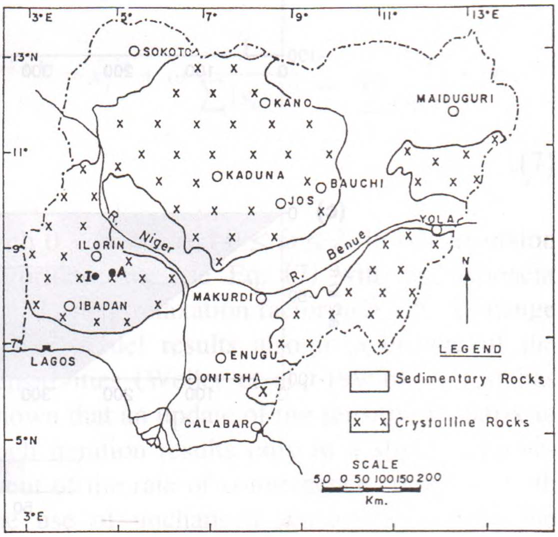

Fig. 1. Simplified geological map of Nigeria showing the study area (A = Agbamu; I = Ira).

(Dey and Morrison, 1979; Weller, 1986). The ratio between measured and computed apparent resistivity is used to correct only the resistivity in the corresponding block. In logarithmic notation the correction is written as:

$$x_j^{(k+1)} = x_j^{(k)} + \omega r_j^{(k)}, \qquad (3)$$

where j is the number of measurement or the corresponding resistivity block, and ω is a relaxation factor which was set to unity in the original version. From our experience a relaxation factor of $\omega = 1.2$ accelerates the convergence. In our modified version we use also a weighting between adjacent resistivity blocks in the horizontal direction to ensure a better convergence.

The second technique is a more general inversion algorithm which is applicable to variable electrode configurations including buried electrodes. It can be applied to both 2-D and 3-D inversion. In the 2-D case, the subsurface is subdivided in a rectangular grid. The resistivity of each grid element is a parameter which should be determined during the reconstruction algorithm. Since the number of grid elements is generally much higher than the number of data, a strongly underdetermined system has to be solved. The forward modelling uses a finite

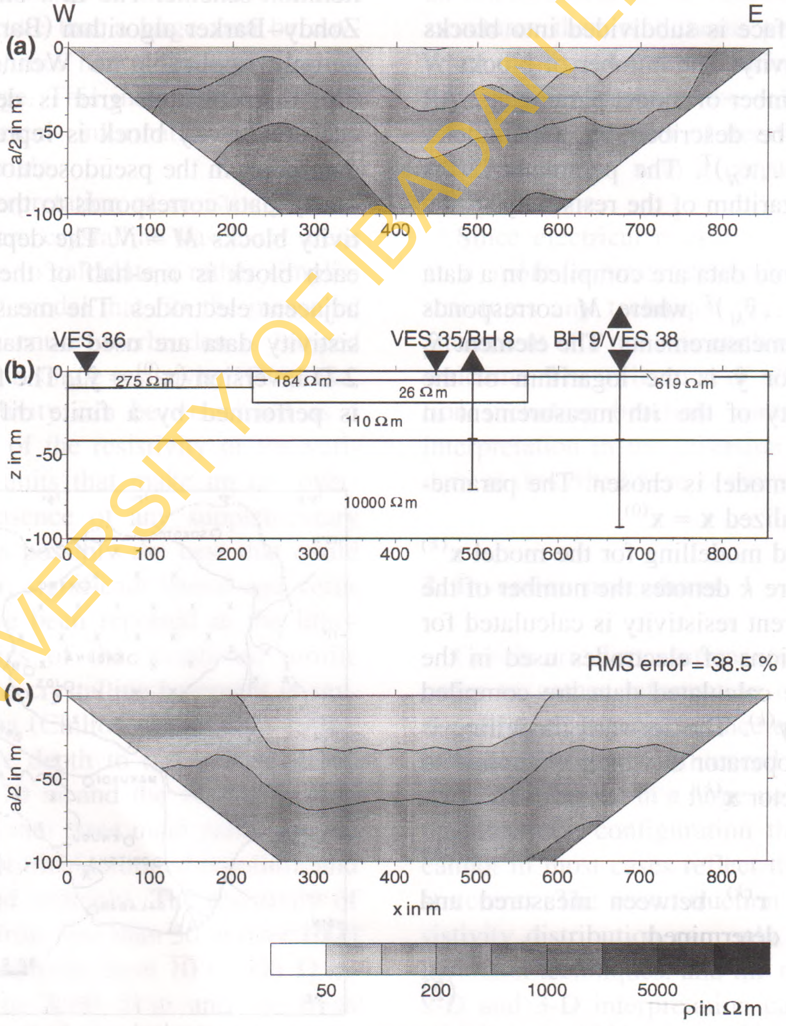

Fig. 2. Interpretation of Agbamu Line 4. (a) Measured apparent resistivity pseudosection. (b) Model derived from *VES* interpretation. (c) Pseudosection calculated from the model in (b).

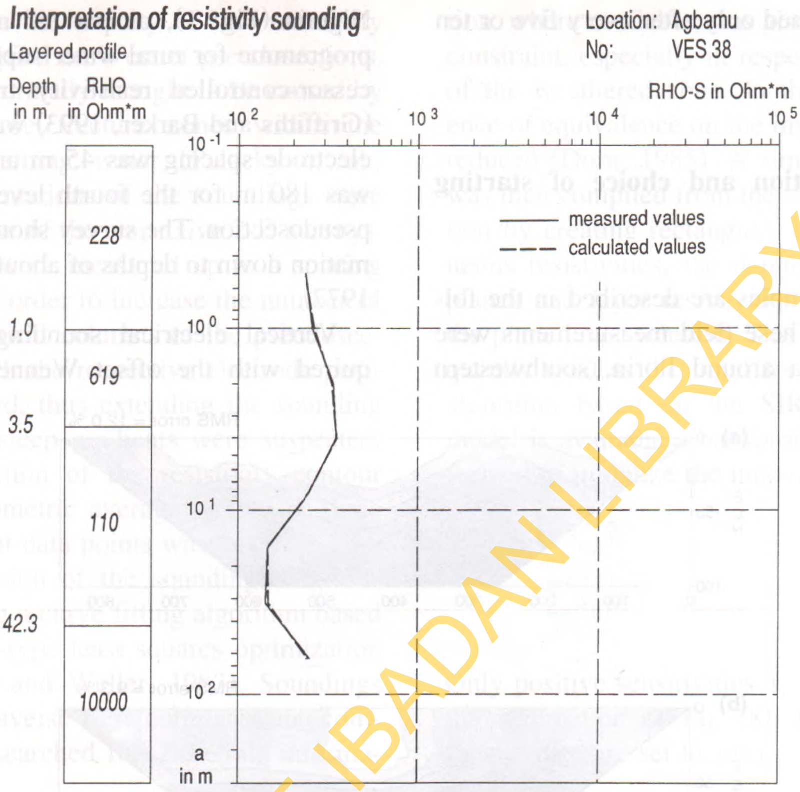

Fig. 3. Inversion of Agbamu VES 38, constrained by borehole information.

difference algorithm which allows the modelling of both resistivity and induced polarization data (Weller et al., 1996a). The inversion is based on a Simultaneous Iterative Reconstruction Technique (SIRT), which has been applied to several tomographic algorithms to solve linear equation systems (e.g., Dines and Lytle, 1979; Van der Sluis and Van der Vorst, 1987). Although the forward modelling operator S is nonlinear, we tried to use the SIRT for a linearization of Eq. (1) in the vicinity of the model $\mathbf{x}^{(k)}$

$$\mathbf{y} = \mathbf{y}^{(k)} + \mathbf{S}(\mathbf{x} - \mathbf{x}^{(k)}). \tag{4}$$

The matrix $\mathbf{S}$ is the Jacobian or sensitivity matrix

$$\mathbf{S} = \{s_{i,j}\}_{\substack{i=1,\dots M \\ j=1,\dots N}} \tag{5}$$

with the elements

$$s_{i,j} = \frac{\partial y_i}{\partial x_j}. \tag{6}$$

SIRT determines in each iteration step a correction of all model parameters using the residual and the sensitivities according to the following general equation

$$x_j^{(k+1)} = x_j^{(k)} + \omega \frac{1}{\sum_n |s_{n,j}|^{\alpha}} \sum_i \frac{s_{i,j}}{\sum_l |s_{i,l}|^{2-\alpha}} r_i, \tag{7}$$

with $0 \leq \alpha \leq 2$ and $0 \leq \omega \leq 2$. In our inversion algorithm, we use Eq. (7) with an exponent $\alpha = 1$ and a relaxation factor $\omega > 1.5$. A change in the model results also in a change of the sensitivities (Weller et al., 1996b). A test has shown that an update of the sensitivity matrix in each iteration results only in a slight improvement of the rate of convergence compared with the use of unchanged sensitivities. Since the computational effort of a sensitivity update is considerable, our experience suggests that it should be performed only after every five or ten iterations.

3. Data acquisition and choice of starting model

Two field examples are described in the following section. These field measurements were made in the area around Ilorin, southwestern Nigeria (Fig. 1), as part of a borehole siting programme for rural water supply. A microprocessor-controlled resistivity traversing system (Griffiths and Barker, 1993) was used. The unit electrode spacing was 45 m and the maximum was 180 m for the fourth level of the Wenner pseudosection. The survey should provide information down to depths of about 90 m (Edwards, 1977).

Vertical electrical sounding data were acquired with the offset Wenner array (Barker,

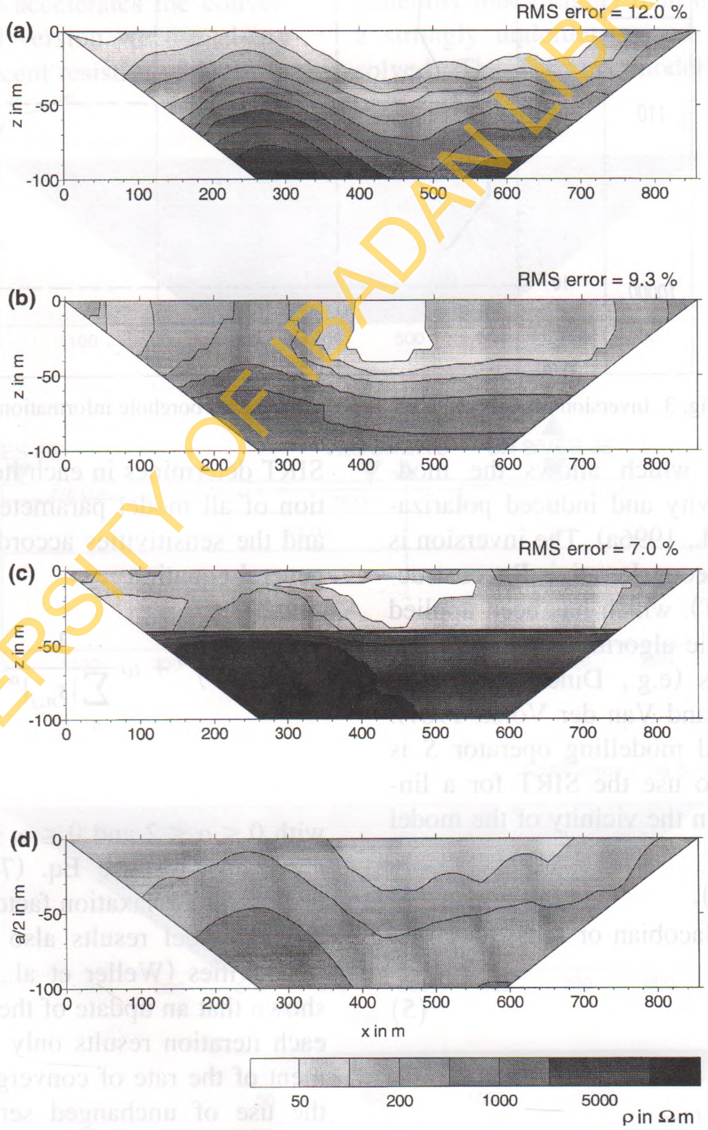

Fig. 4. Inversion results of Agbamu Line 4. (a) Zohdy–Barker method, 5 iterations. (b) SIRT, 10 iterations, starting with backprojection. (c) SIRT, 10 iterations, starting with model from VES. (d) Pseudosection calculated from (c).

1981) mainly in the vicinity of low resistivity anomalies identified on Wenner pseudosections. Such lows are normally thought to be caused by conductive fissure/fracture zones within the basement, containing water (Palacky et al., 1981). The orientations of the soundings were the same as those of the respective 2-D surveys. The soundings were measured up to a spacing of $a = 64$ m. In order to increase the number of data points, vertical columns of the pseudosection data beneath the respective electrode positions were added, thus extending the sounding curves. Where steep gradients were suspected, from an inspection of the resistivity contour pattern, the geometric average of two or three laterally adjacent data points was taken.

A 1-D inversion of the sounding data was carried out using a curve fitting algorithm based on a Marquardt-type least squares optimization method (Rösler and Weller, 1983). Soundings along a given traverse were correlated and common attributes searched for. Borehole information, where available, was also incorporated as a constraint, especially in respect of the thickness of the weathered zone. In this way, the influence of equivalence on the inversion results was reduced (Dorn, 1985). A simplified 2-D model was then compiled from the sounding interpretation by creating rectangular blocks of homogeneous resistivities, the depths to the boundary planes and layer resistivities being those from the plane layer solution. This model was subsequently used as the input for the 2-D inversion algorithm based on the SIRT. If no starting model is available a backprojection can be performed to initialize the model parameters:

$$x_j^{(0)} = \frac{\sum_i s_{i,j}\hat{y}_i}{\sum_i s_{i,j}} . \qquad (8)$$

Only positive sensitivities $s_{i,j}$ are considered in the summation of Eq. (8) while the negative sensitivities are set to zero.

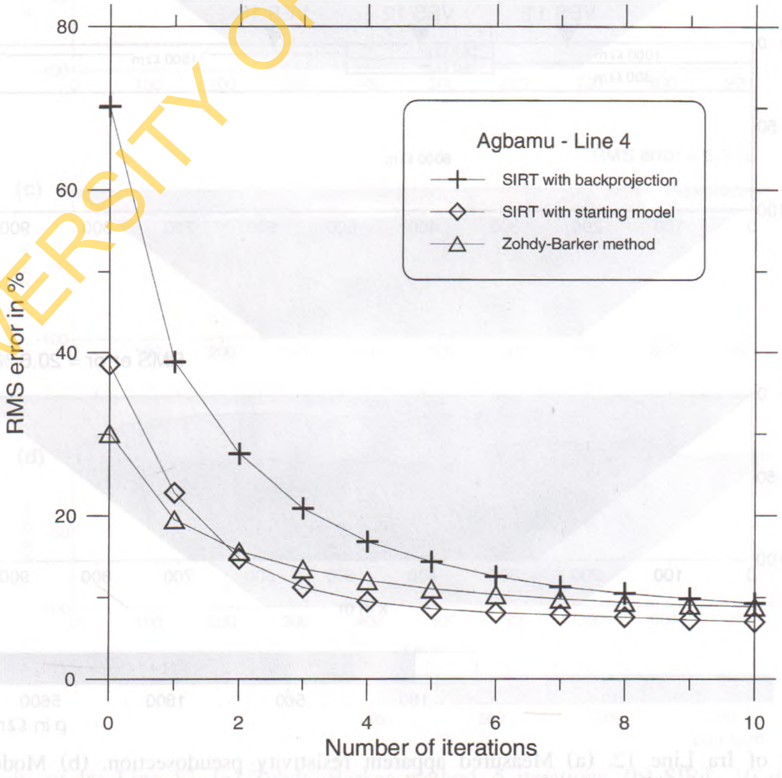

Fig. 5. RMS error curves for the 2-D inversion of Agbamu Line 4.

The results obtained from SIRT with different initializations (starting model or backprojection) have been compared with those from the Zohdy–Barker algorithm.

4. Examples

4.1. Agbamu case history

Agbamu village is situated about 53 km southeast of Ilorin (see Fig. 1). The area is underlain by Precambrian to Upper Cambrian crystalline basement complex rocks, with the dominant rock type being gneiss. There is a pervasive presence of weathered materials. Fig. 2a shows the apparent resistivity pseudosection from one of the survey lines at this village. There is a fairly broad low resistivity anomaly which is about 350 m wide. Towards the deeper part of the pseudosection, there are two high resistivity structures centered at about the 260-m and 580-m marks along the profile.

Soundings were made at three points along

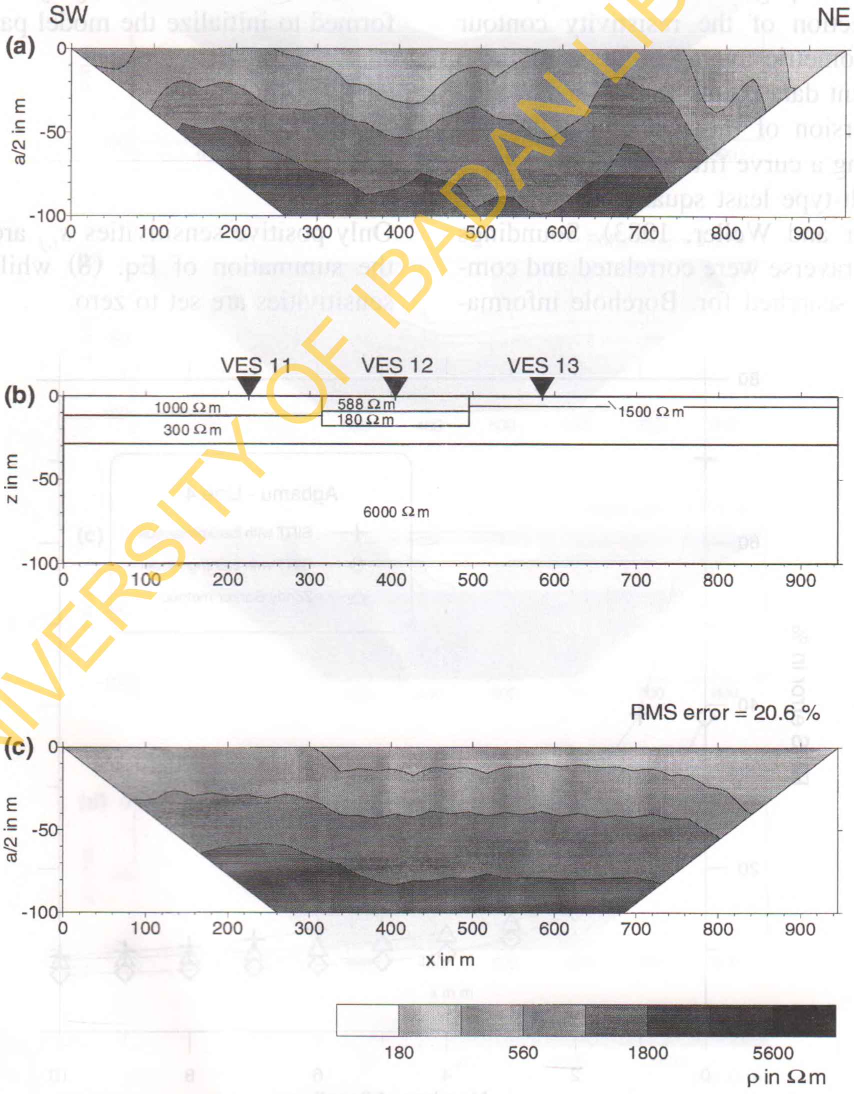

Fig. 6. Interpretation of Ira Line 12. (a) Measured apparent resistivity pseudosection. (b) Model derived from *VES* interpretation. (c) Pseudosection calculated from the model in (b).

the line; two of these were within the resistivity low. A borehole (BH 9) drilled at the position of VES 38 penetrated a very thick (42 m) weathered profile, comprising low permeability silty material, underlain by partially weathered and fractured gneiss (saprock) down to the total drilled depth of 93.4 m. With this information, a 1-D inversion of the sounding measurement was carried out (Fig. 3) in terms of a four-layer model. The layer resistivities are 228, 619, 110 and 10,000 Ω m, respectively. The thickness of the first layer (topsoil) is 1.0 m, that of the second (laterite) 2.5 m and the third (saprolite) 38.8 m. Similarly, at the position of borehole BH 8 the depth to basement is 40 m. This suggested that the bedrock topography along this traverse is probably fairly flat and the depth to bedrock at the three sounding locations was,

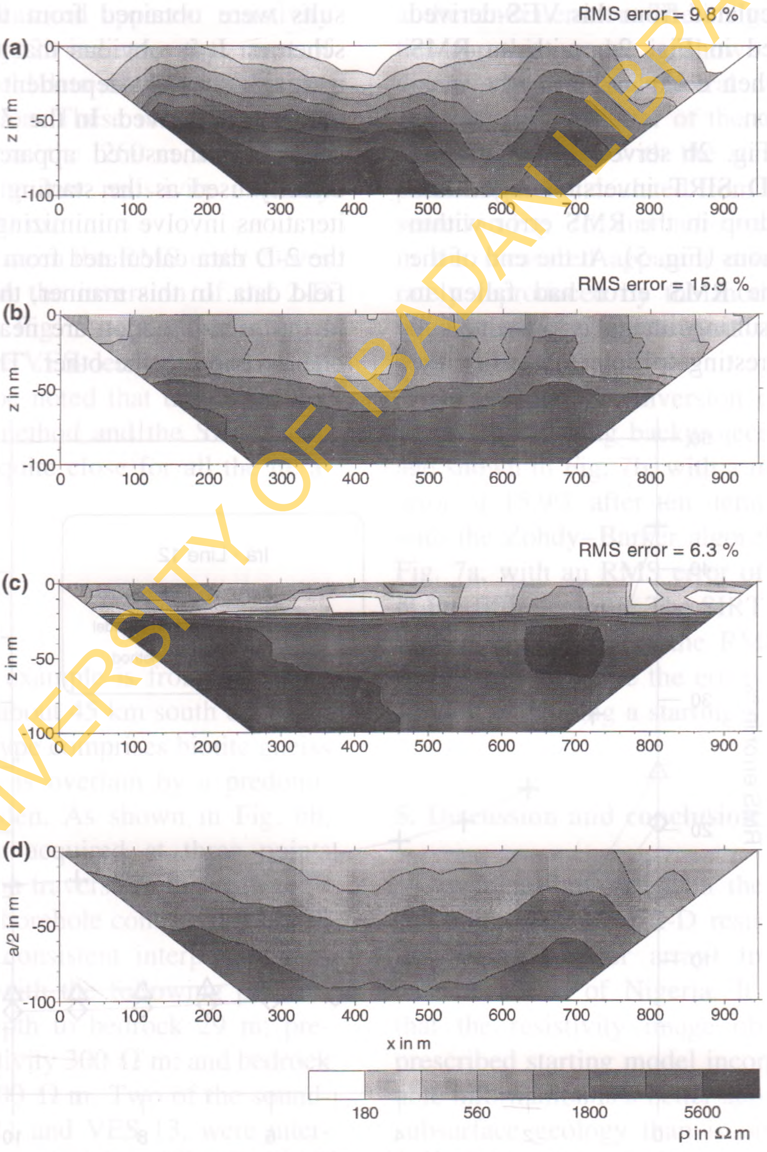

Fig. 7. Inversion results of Ira Line 12. (a) Zohdy–Barker method, 5 iterations. (b) SIRT, 10 iterations, starting with backprojection. (c) SIRT, 10 iterations, starting with model from VES. (d) Pseudosection calculated from (c).

therefore, fixed at 42 m for purpose of the resistivity data interpretation. The resistivity of the prebasement layer in VES 38 (i.e., 110 Ω m) was kept constant in the other two soundings. The interpretations of soundings VES 35 and VES 36 are similar (Fig. 2b), except that there is an intermediate layer with a low resistivity of 26 Ω m for VES 35; it is probably a clayey horizon that gave rise to the low resistivity anomaly on the pseudosection rather than a larger depth to bedrock. The apparent resistivity pseudosection calculated from this VES-derived model is presented in Fig. 2c, with an RMS error of 38.5% when compared with the measured pseudosection.

The model in Fig. 2b served as the starting model for the 2-D SIRT inversion algorithm. There is a large drop in the RMS error within the first few iterations (Fig. 5). At the end of the tenth iteration, the RMS error had fallen to 7.0%, and the resulting image is presented in Fig. 4c. It is interesting to note that when the same field data set was inverted with the SIRT algorithm, but without a starting model being prescribed (rather it was derived from backprojection), the initial RMS error was 70.2%, dropping to 9.3% at the tenth iteration. The resistivity image from the SIRT algorithm, starting with backprojection, at the tenth iteration, is shown in Fig. 4b and that from the Zohdy–Barker algorithm at the fifth iteration is shown in Fig. 4a.

It can be observed that slightly different results were obtained from the three inversion schemes. It is obvious that the final resistivity image is strongly dependent on how the initial model was derived. In the Zohdy–Barker algorithm, the measured apparent resistivities are directly used as the starting model; subsequent iterations involve minimizing the error between the 2-D data calculated from this model and the field data. In this manner, the structures visible in the pseudosection are nearly preserved from one iteration to the other. The SIRT algorithm,

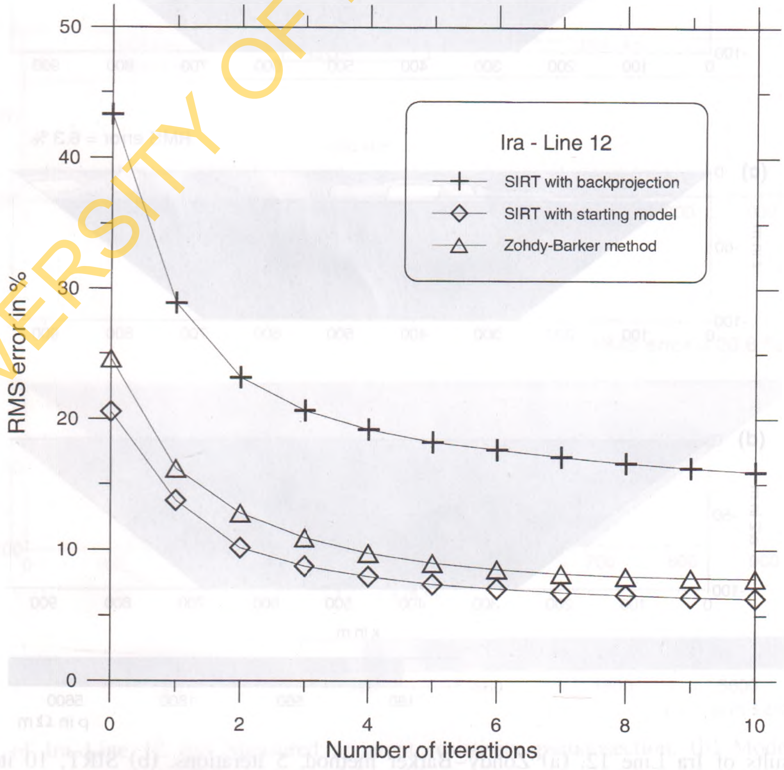

Fig. 8. RMS error curve for the 2-D inversion of Ira Line 12.

on the other hand, allows for near-surface variations in resistivity. Moreover, in the inversion with a starting model there are provisions for lateral variations in the thickness and resistivity of the various geoelectrical units within the overburden and these remain preserved in the final image while there are only minor changes in the resistivity distribution within the bedrock.

The pseudosection data calculated from the resistivity image of the SIRT algorithm with starting model are shown in Fig. 4d and a comparison with measured apparent resistivity pseudosection in Fig. 2a indicates that most of the features in the field data are preserved in the modeled pseudosection. These include the high resistivity zones near the 260-m and 580-m marks as well as the low resistivity anomaly between 340 and 700 m.

A comparison between the RMS error curves at different stages in the inversion of the 2-D data is presented in Fig. 5. The superiority of the inversion with the VES-derived initial model is obvious. It may be noted that the curves for the Zohdy–Barker method and the SIRT (with starting model) are quite close for all the iteration steps.

4.2. Ira case history

The second field example is from Ira which is a village situated about 45 km south of Ilorin. The basement rock type comprises biotite gneiss and pegmatite. This is overlain by a predominantly silty overburden. As shown in Fig. 6b, sounding data were acquired at three points along a pseudosection traverse in this village.

In the absence of borehole control, it was still possible to have a consistent interpretation of the sounding data, with the following parameters in common: depth to bedrock 29 m; prebasement layer resistivity 300 Ω m; and bedrock model resistivity 6000 Ω m. Two of the soundings, namely VES 11 and VES 13, were interpreted by three-layer models while the third (VES 12) was interpreted with four layers. The sounding interpretation results in the resistivity model shown in Fig. 6b.

The pseudosection data calculated from this model are shown in Fig. 6c, with an RMS error of 20.6% when compared to the measured apparent resistivity pseudosection (Fig. 6a). This is a relatively good fit and this model derived from VES was used as the starting model for the SIRT inversion algorithm; a considerable improvement in the fit to the field data was observed, with the RMS error dropping to 6.3% at the tenth iteration. The image of true resistivities for this model is shown in Fig. 7c, and displays widespread lateral variations in the geoelectrical character of the overburden which are in agreement with the starting model. The pseudosection calculated from this image is presented in Fig. 7d, and indicates that the features in the measured apparent resistivity are accurately reproduced by the model, including the high resistivity structure at about the 680-m mark.

By comparison, inversion of the same data set by SIRT using backprojection gave the image shown in Fig. 7b, with a much higher RMS error of 15.9% after ten iterations. The results with the Zohdy–Barker algorithm are shown in Fig. 7a, with an RMS error of 9.8% at the end of the fifth iteration. The SIRT algorithm shows only a slight drop in the RMS error after the fifth iteration, while the errors are lower in the version employing a starting model (Fig. 8).

5. Discussion and conclusion

An algorithm based on the SIRT was used for the inversion of 2-D resistivity pseudosection data (Wenner array) from a crystalline basement area of Nigeria. It has been shown that the resistivity image obtained when the prescribed starting model incorporated all available information is a better approximation of the subsurface geology than is otherwise the case for a fully automatic inversion, when the starting model is derived from backprojection. While it is desirable to attain a low RMS error between the field and calculated data, a geophysical interpretation along the lines described here which takes into account all available evidences, is a greater priority in view of the non-uniqueness of the interpretation of any given data set due to 2-D equivalence.

It should be noted that the presented algorithm provides no information on the possible existence of other solutions also consistent with both the data and the a priori information. Goldman et al. (1994) suggest in the case of 1-D interpretation of transient electromagnetic soundings to apply first a global inversion algorithm to find all possible solutions and then to use independent information in trying to fix the true solution. If more than one solution is consistent with the information the interpreter is still motivated to resolve non-uniqueness by either obtaining more information or applying other techniques or improving parameters of the method used. In the case of 2-D interpretation this approach would also be advisable. But regarding the large number of resistivity blocks and the computer time needed for a single inversion, a global search for all possible solutions with a lot of statistically distributed starting models is still not practical.

The application of the SIRT algorithm has shown that not much reduction in the RMS error is attained after five iterations. Hence, five iterations should be adequate for the inversion of 2-D data from similar geological settings.

A comparison between the Zohdy–Barker, SIRT with backprojection and SIRT with starting model algorithms suggests that the resistivity model is strongly dependent on how the initial model was found; hence if the starting model is well constrained a more realistic geological picture will likely result.

Acknowledgements

A.I.O. would like to thank the German Academic Exchange Service (DAAD) for the funding provided. The work by A.W. was financially supported by the Deutsche Forschungsgemeinschaft through a Werner-Heisenberg-Stipendium.

References

Aina, A., Olorunfemi, M.O., Ojo, J.S., 1996. An integration of aeromagnetic and electrical resistivity methods in dam site investigation. Geophysics 61, 349–356.

Barker, R.D., 1981. The Offset System of electrical resistivity sounding and its use with a multicore cable. Geophys. Prospect. 29, 128–143.

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

Chilton, P.J., Foster, S.S.D., 1995. Hydrogeological characterisation and water supply potential of basement aquifers in tropical Africa. Hydrogeol. J. 3, 36–49.

Dey, A., Morrison, H.F., 1979. Resistivity modelling for arbitrarily shaped two-dimensional structures. Geophys. Prospect. 27, 106–136.

Dines, K.A., Lytle, R.J., 1979. Computerized geophysical tomography. Proc. IEEE 67, 1065–1073.

Dorn, M., 1985. A special aspect of interpretation of geoelectrical sounding curves and its application for groundwater exploration. Geoexploration 23, 455–469.

Edwards, L.S., 1977. A modified pseudosection for resistivity and induced polarisation. Geophysics 42, 1020–1036.

Ellis, R.G., Oldenburg, D.W., 1994. Applied geophysical inversion. Geophys. J. Int. 116, 5–11.

Goldman, M., du Plooy, A., Eckard, M., 1994. On reducing ambiguity in the interpretation of transient electromagnetic sounding data. Geophys. Prospect. 42, 3–25.

Griffiths, D.H., Barker, R.D., 1993. Two-dimensional resistivity imaging and modelling in areas of complex geology. J. Appl. Geophys. 29, 211–226.

Griffiths, D.H., Turnbull, J., 1985. A multi-electrode array for resistivity surveying. First Break 3 (7), 16–20.

Griffiths, D.H., Turnbull, J., Olayinka, A.I., 1990. Two-dimensional resistivity mapping with a computer controlled array. First Break 8, 121–129.

Loke, M.H., Barker, R.D., 1995. Least-squares deconvolution of apparent resistivity pseudosections. Geophysics 60, 1682–1690.

Loke, M.H., Barker, R.D., 1996. Rapid least-square inversion of apparent resistivity pseudosections by a quasi-Newton method. Geophys. Prospect. 44, 131–152.

Olayinka, A.I., 1988. Microprocessor controlled resistivity traversing and its use in borehole siting in basement areas of Nigeria. Ph.D. Thesis, Univ. Birmingham.

Palacky, G.T., Ritsema, I.L., De Jong, S.J., 1981. Electromagnetic prospecting for groundwater in Precambrian terrains in the Republic of Upper Volta. Geophys. Prospect. 29, 932–955.

Rösler, R., Weller, A., 1983. New results in automatic interpretation of resistivity soundings. Freiberg. Forschungsh. C 387, 61–70.

Shima, H., 1990. Two dimensional automatic resistivity inversion technique using alpha centers. Geophysics 55, 682–694.

Simms, J.E., Morgan, F.D., 1990. Re-evaluation of Pekeris' one-dimensional resistivity interpretation method. First Break 8, 130–136.

Smith, N.C., Vozoff, K., 1984. Two-dimensional DC resistivity inversion for dipole–dipole data. IEEE Trans. Geosci. Remote Sensing 22, 21–28.

Tripp, A.C., Hohmann, G.W., Swift, C.M. Jr., 1984. Two-dimensional resistivity inversion. Geophysics 49, 1708–1717.

Van der Sluis, A., Van der Vorst, H.A., 1987. Numerical solution of large, sparse linear algebraic systems arising from tomographic problems. In: Nolet, G. (Ed.), Seismic Tomography. Reidel, Dordrecht, pp. 49–83.

Weller, A., 1986. Berechnung geoelektrischer Potentialfelder mit dem Differenzenverfahren. Freiberg. Forschungsh. C 405, 68–122.

Weller, A., Seichter, M., Kampke, A., 1996b. Induced-polarization modelling using complex electrical conductivities. Geophys. J. Int. 127, 387-398.

Weller, A., Gruhne, M., Seichter, M., Börner, F.D., 1996b. Monitoring hydraulic experiments by complex conductivity tomography. Eur. J. Environ. Eng. Geophys. 1, 209–228.

Note to contributors

A detailed *Guide for Authors* is available upon request. Please pay attention to the following notes:

Language

The official language of the journal is English.

Preparation of the text

(a) The manuscript should be preferable be prepared on a word processor and printed with double spacing and wide margins and include an abstract of not more than 500 words.
(b) Authors should use IUGS terminology. The use of S.I. units is also recommended.
(c) The title page should include: the title, the name(s) of the author(s) and their affiliations, fax and e-mail numbers. In case of more than one author, please indicate to whom the correspondence should be addressed.

References

(a) References in the text consist of the surname of the author(s), followed by the year of publication in parentheses. All references cited in the text should be given in the reference list and vice versa.
(b) The reference list should be in alphabetical order.

Tables

Tables should be compiled on separate sheets and should be numbered according to their sequence in the text.

Illustrations

(a) All illustrations should be numbered consecutively and referred to in the text.
(b) Drawings should be completely lettered throughout, the size of the lettering being proportional to that of the drawings, but taking into account the possible need for reduction in size. The page format of the journal should be considered in designing the drawings.
(c) Photographs must be of good quality, printed on glossy paper.
(d) Figure captions should be supplied on a separate sheet.
(e) If contributors wish to have their original figures returned this should be requested in proof stage at the latest.
(f) Colour figures can be accepted providing the reproduction costs are met by the author. Please consult the publisher for further information.

Page proofs

One set of proofs will be sent to the author, to be checked for typesetting/editing. The author is not expected to make changes or corrections that constitute departures from the article in its accepted form. To avoid postal delay, authors are requested to return corrections to the desk-editor, Mr. Herman E. Engelen, by FAX (+31-20-4852459) or e-mail (h.engelen@elsevier.nl).

Submission of manuscripts

Manuscripts should be submitted (in triplicate) to:
For North and South America: Dr. T.E. Owen, University of Texas at San Antonio, Director Institute for Research in Science & Engineering, San Antonio, TX 78249-0661, USA. Tel: +1 210 691 5590, Fax: +1 210 691 5659, E-mail: towen@lonestar.utsa.edu.
For the rest of the world: Editorial Office Journal of Applied Geophysics, P.O. Box 1930, 1000 BX Amsterdam, The Netherlands. Phone: +31.20.4852701, Fax: +31.20.4852696.
Illustrations: Please note that upon submission of a manuscript that *three sets* of all photographic material printed *sharply* on *glossy paper* or as *high-definition laser prints* must be provided to enable meaningful review. Photocopies and other low-quality prints will not be accepted for review.
The indication of a fax and e-mail number on submission of the manuscript could assist in speeding communications. The fax number for the Amsterdam office is +31-20-4852696.
Submission of an article is understood to imply that the article is original and unpublished and is not being considered for publication elsewhere. Upon acceptance of an article by the journal, the author(s) will be asked to transfer the copyright of the article to the publisher. This transfer will ensure the widest possible dissemination of information.

Submission of electronic text

In order to publish the paper as quickly as possible after acceptance, authors are encouraged to submit the final text also on a 3.5" or 5.25" diskette. Both double density (DD) and high density (HD) diskettes are acceptable. Make sure, however, that the diskettes are formatted according to their capacity (HD or DD) before copying the files onto them. Similar to the requirements for manuscript submission, main text, list of references, tables and figure legends should be stored in separate text files with clearly identifiable file names. The format of these files depends on the wordprocessor used. Texts made with DisplayWrite, MultiMate, Microsoft Word, Samna Word, Sprint, Volkswriter, Wang PC, WordMARC, WordPerfect, Wordstar, or supplied in DCA/RFT, or DEC/DX format can be readily processed. In all other cases the preferred format is DOS text or ASCII. Essential is that the name and version of the wordprocessing program, type of computer on which the text was prepared, and format of the text files are clearly indicated. Authors are requested to ensure that the contents of the diskette correspond exactly to the contents of the hard copy manuscript. Discrepancies can lead to proofs of the wrong version being made. The word processed text should be in single column format. Keep the layout of the text as simple as possible; in particular, do not use the word processor's options to justify or to hyphenate the words. If available, electronic files of the figures should also be included on a separate floppy disk.

The Geoelectrical Methods in Geophysical Exploration

By **M.S. Zhdanov** and **G.V. Keller**

Methods in Geochemistry and Geophysics
Volume 31

This volume deals with electrical methods as used in applied geophysics. There are 14 chapters. The first four chapters comprise a handbook of information needed in applied electrical geophysics. The next three chapters deal with three standard techniques: Direct Current (DC), Magnetotelluric (MT) and Controlled-Source Electromagnetic (EM) methods. Chapters 8 - 11 develop important aspects of the subject which are common to all three standard techniques. These common aspects include ambiguity and insensitivity, data acquisition, modeling and simulation, and interpretation. Chapters 12 and 13 cover experience with electrical methods in the solution of a wide variety of practical problems.

Short Contents:

1. Electrical Methods in Geophysics.
2. General Concepts of Electromagnetic Field Behavior.
3. Properties of Rocks and Minerals.
4. Electromagnetic Environment of Planet Earth.
5. Direct Current and Induced Polarization Methods.
6. Natural-Field Electromagnetic Methods.
7. Controlled Source Electromagnetic Methods.
8. Modeling and Simulation.
9. Insensitivity and Ambiguity.
10. Practical Aspects of Data Acquisition.
11. Interpretation.
12. Other Platforms, Other Methodologies.
13. A Baker's Dozen of Case Histories.
14. The Forest or the Trees?

Appendix A: Mathematical Conventions.
Appendix B: FORTRAN Codes.

ELSEVIER
SCIENCE B.V.

©1994 884 pages
Dfl. 375.00 (US$214.25)
ISBN 0-444-89678-3

ELSEVIER SCIENCE B.V.
P.O. Box 1930
1000 BX Amsterdam
The Netherlands

P.O. Box 945
Madison Square Station
New York, NY 10160-0757

The Dutch Guilder (Dfl.) prices quoted apply worldwide. US $ prices quoted may be subject to exchange rate fluctuations. Customers in the European Community should add the appropriate VAT rate applicable in their country to the price.