British Geological Survey

REGIONAL GEOPHYSICS RESEARCH GROUP

Technical Report WK/88/23

Regional Geophysics Series

BASEMENT AQUIFER PROJECT 1984 – 1988

Summary report on surface geophysical studies

R M Carruthers and I F Smith

Research and Development Project funded by the Overseas Development Administration

Natural Environment Research Council

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Cover photo

Rural water supply from the basement aquifer near Maramba School, Masvingo Province, Zimbabwe

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Keyworth, Nottingham NG12 5GG
☎ Plumtree (060 77) 6111 Telex 378173 BGSKEY G
Fax ☎ 060 77-6602

Murchison House, West Mains Road, Edinburgh EH9 3LA
☎ 031-667 1000 Telex 727343 SEISED G
Fax ☎ 031-668 2683

London Information Office at the Geological Museum, Exhibition Road, South Kensington, London SW7 2DE
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☎ 01-938 9056/57

64 Gray's Inn Road, London WC1X 8NG
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Fax ☎ 01-242 0835

19 Grange Terrace, Edinburgh EH9 2LF
☎ 031-667 1000 Telex 727343 SEISED G

St Just, 30 Pennsylvania Road, Exeter EX4 6BX
☎ Exeter (0392) 78312

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Windsor Court, Windsor Terrace, Newcastle upon Tyne NE2 4HB
☎ 091-281 7088 Fax ☎ 091-281 9016

Geological Survey of Northern Ireland, 20 College Gardens, Belfast BT9 6BS
☎ Belfast (0232) 666595 and 666752

Maclean Building, Crowmarsh Gifford, Wallingford, Oxfordshire OX10 8BB
☎ Wallingford (0491) 38800 Telex 849365 HYDROL G
Fax ☎ (0491) 25338

Parent Body

Natural Environment Research Council

Polaris House, North Star Avenue, Swindon, Wiltshire SN2 1EU
☎ Swindon (0793) 411500 Telex 444293 ENVRE G
Fax ☎ 0793-411501

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SUMMARY

The application of geophysical methods to a multidisciplinary investigation of groundwater resources in crystalline basement rocks in Sri Lanka, Malawi and Zimbabwe is described. On the basis of a number of experiments and a study of previous rural water supply projects, assessments are made of the validity of the interpretation of resistivity depth soundings in relation to problems resulting from lateral variation and equivalent layers, of the benefit to be gained from using 'slingram' type electromagnetic equipment in identifying fracture systems and of the use of seismic refraction for siting boreholes. Recommendations on the use of geophysical methods in this environment are made and some possible future developments are discussed.

1. INTRODUCTION

1.1 Background

The Overseas Development Administration (ODA) of the British Foreign Office agreed to support a multi-disciplinary Research and Development project relating to the hydrogeology of crystalline basement terrain. The objectives were to establish the mode of occurrence of the aquifers and the most effective ways of locating and exploiting the groundwater resource.

This type of terrain is found over large areas, notably in tropical Africa, which are subject to water shortage and periodic droughts. The combination of population growth and a desire to improve standards of living means that there is increasing demand for domestic water supply in scattered rural communities as well as in the expanding urban centres. The requirements of the former have been met traditionally by use of the limited amount of surface water and by hand-dug wells, both of which tend to be unreliable and susceptible to pollution.

In recent years, the local practice has been to provide a water supply based on boreholes equipped with hand-pumps and most externally funded aid projects have adopted the same strategy. Boreholes may be drilled and the pumps fitted within a period of two days on a routine basis, while a dug well may take several weeks to construct. The borehole supply is safer due to the depth from which the water is drawn and because the pump installation is completed so that the groundwater is not contaminated by fouled water at the well-head.

The crystalline basement typically consists of granites and gneisses, and it is overlain by a thin cover resulting from chemical weathering processes largely controlled by the circulation of groundwater (Jones, 1985). In a geophysical context the terms overburden, saprolite and weathered material tend to be used synonymously, rather than in a rigorous sense, to describe this cover. As Palacky, Ritsema and de Jong (1981) describe for Burkina Faso, the aquifer can be a three-component system: a perched water table which is likely to disappear during a prolonged dry period; a zone of relatively high porosity within the clay- and quartz-rich residual products of advanced weathering which is called saprolite; a deeper zone of weathered and jointed rock containing a number of fractures with high transmissivity but limited storage, sometimes called saprock. The interconnection between these two lower zones, either at the transition zone or by fractures which intersect both, may be critical in siting productive wells. All three components will not necessarily be represented at a given locality and their relative contribution is an important factor in determining the best exploration and development strategies.

Because the weathered layer is generally discontinuous and variable, siting boreholes simply on the basis of the proximity to the intended users' community results in a significant number of unproductive sites. Geophysical methods offer one means of identifying the more favourable locations. Low yields (0.15-1.0 litres/s at most sites) are acceptable for domestic supply but in some areas it may be possible to find sites capable of providing for a larger population or for supplementary irrigation. Such sites are often associated with major fracture systems which may be picked out from satellite imagery or aerial photographs; geophysical surveys are appropriate to fixing the precise location of these narrow features on the ground, so as to ensure that boreholes intersect them.

1.2 Programme of work

1.2.1 General points

The project began with hydrogeologists, a geochemist and a geophysicist who established the framework for detailed investigations and set up collaborative field studies with local government agencies in countries in East-Central Africa and in Asia. Reviews of the application of remote sensing and studies of the weathering profile were also initiated. Following these initial phases the project grew both in manpower and in the range of activities being pursued. There is considerable overlap in terms of the geophysical studies with a separate R&D project, funded by ODA, concerned with the use of 'collector' wells (large diameter dug wells, from the base of which holes are drilled radially to improve their performance) in this type of terrain.

In this report we present an outline of the geophysical work carried out, together with some broad conclusions and recommendations. Detailed results of the work is contained in the following reports: Carruthers (1985, 1986, 1988), Griffiths (1987), Herbert and others (1984), Smith and Raines (1987, 1988). The results of other disciplines are documented separately.

1.2.2 Preliminary review

A desk study (Carruthers, 1985) was undertaken to consider the geophysical procedures currently adopted for borehole siting and to assess other techniques which might be applicable within the context of the project.

Resistivity surveys had been used almost exclusively for routine siting work because of the relative simplicity of the equipment and the availability of interpretation techniques to supplement qualitative assessment of the results.

The method could be used to provide evidence of lateral variations (by profiling) or to indicate the depth to favourable zones within a layered sequence (by VES - vertical electrical sounding).

There was increasing evidence of the value of the electromagnetic (EM) methods in preference to resistivity for profiling to pick up narrow conductive zones associated with fractures. The very low frequency (VLF)EM and horizontal loop EM systems had been available for some time but it was the advent of more sensitive instruments in the early 1980s which led to their more widespread use. The relative merits of such techniques are discussed further in Section 2.

Magnetic traversing was also an established procedure for mapping dykes where these were known to occur. Dykes may act as barriers to groundwater movement, to give a ponding effect, or they can be associated with zones of enhanced porosity.

Seismic refraction methods can provide valuable information on both the sub-horizontal layering and the location of fractures; however, the lack of appropriate equipment and the more cumbersome field procedure had restricted its use to a few specific case studies.

Other techniques such as induced polarization and use of a shear wave source for seismic refraction also had potential for generating additional information in more specialized studies, although only the developments in Time-Domain EM (TEM) equipment offered good prospects for direct application in borehole siting for the future.

Various claims had been made regarding the improvement in success rates attributable to the use of geophysical surveying but these were poorly defined. While it seemed clear that there was a benefit in many cases, the cost effectiveness of the geophysical procedures adopted was open to question. With the availability of useful but expensive equipment it is important to be aware of the costs of surveying in relation to both drilling and the objectives of the survey.

1.2.3 Reconnaissance visits overseas

The results obtained from the project were intended to be of general relevance but it was clearly going to be possible to obtain and analyse data from only a limited number of areas. Two regions, East-Central Africa and Sri Lanka, were selected for detailed studies because they represented somewhat different environments in terms of geological history and present climate, and because previous cooperative projects involving BGS had established good contacts with government departments in these countries.

In 1984 short visits were made to Sri Lanka and Malaysia (Herbert and others, 1984) and subsequently to Kenya, Malawi and Zimbabwe for discussions with potential counterpart organisations. These meetings established a strong local interest in the aims of the project and a willingness to participate in the investigations. Proposals were drawn up for exchanging information and to initiate a programme of fieldwork to look at specific problems based mainly in Sri Lanka, Malawi and Zimbabwe. Less formal relations were established with a much wider range of countries by means of a questionnaire which was designed to provide background information on the occurrence and use of the basement aquifer.

A large amount of data from resistivity surveys and drilling was already available in these countries and it was hoped that characteristics of the aquifer and correlations with the geophysical results could be derived from this source. An attempt was therefore made to transfer information on to a data-base using microcomputers. A second short visit to Sri Lanka in 1985 was used in part to establish this capability and to devise an appropriate format in which to store data. Similar systems were introduced in Malawi and Zimbabwe but with less effort to include geophysical data.

Discussions indicated that resistivity surveys were a prerequisite of drilling in most cases although existing procedures for interpreting the results were qualitative and based on previous experience rather than on any understanding of the relation between the aquifer system and the geophysical signature. In some districts it seemed that the criteria being adopted were inappropriate to the target, while in others there was little evidence that the surveys were contributing significantly to successful borehole siting. Although a variety of geophysical equipment was becoming available from donor agencies, the local survey departments relied almost entirely on traditional resistivity methods carried out by technicians and hydrogeologists with little geophysics training.

1.2.4 Field studies

Consideration of existing geophysical data indicated that they were rarely adequate for correlating with specific aspects of the aquifer, either because the data themselves were unreliable or insufficient at any one site, or because the drilling control was not good enough. Specific geophysical surveys were therefore undertaken in conjunction with other project studies covering activities such as the identification of fractures from remote sensing data, the nature of weathering processes, geochemistry etc.

MALAWI

Work undertaken in 1985 and 1986 was concerned with:

1. mapping the depth to hard rock and providing some indication of the nature of the overlying saprolite (more particularly the likely clay content, as a possible guide to permeability); this was directly related to the siting of dug wells for subsequent radial drilling as part of the collector well project;

2. investigating the structure of dambos (valleys which may flood in the wet season and may be occupied by seasonal streams) and their relation to the interfluves in terms of groundwater movement and recharge/discharge relationships;

3. checking for a characteristic response related to the occurrence of sulphate-rich groundwaters.

The results from this work were discussed in project reports (Carruthers, 1986, 1988). The limitations of resistivity VES data (see also Section 2) were clearly brought out in relation to well siting: some general guide to ground conditions could be given for locating exploratory boreholes but the data did not in themselves resolve the sequence in the required detail. This was attributed in part to the heterogeneous nature and complex geometry of the subsurface, and also to the limited resolution and ambiguities inherent to the method. Identification of relatively favourable ground using profiling techniques proved equally if not more effective.

Interesting results related to dambos (Chimimbe and Chikobwe) were provided by a variety of methods. Resistivity and EM data showed the marked contrast in the nature of the near-surface material with some evidence of hard, but more fractured rock at shallower depth beneath the dambos themselves. Seismic refraction data also gave additional information, although there was insufficient energy provided by the falling weight source to ensure good arrivals over the full distance required. Correlation with core drilling was reasonable in general terms but the boreholes were too shallow to prove the deeper interfaces.

Conductive zones detected in the vicinity of wells with high sulphate levels were indicative of either graphite or pyrite within the sequence. While direct interaction between pyrite bands and the groundwater system was not proved there was enough evidence to recommend further studies along these lines. The electrical responses from graphite and pyrite are similar and the finding of highly conductive beds only serves as a warning of possible water quality problems; high chloride content within the subsoil and the groundwater may also be detected this way.

SRI LANKA

A limited amount of fieldwork was undertaken during the preliminary visits in 1984-85 with more intensive studies in 1986 (Carruthers, 1988). The two aspects of particular interest were:

1. the reliability with which relative changes in the depth to hard rock could be determined, with reference to the optimum siting of dug wells;

2. the relation between discontinuities observed in VES curves and the occurrence of water-bearing fracture zones within the underlying bedrock.

The thickness of saprolite is often limited here but the resistivity and seismic velocity of the harder rock are usually less than shown in results from Zimbabwe. This may be due to greater structural disturbance having produced a higher incidence of fracturing and to the more gneissic rather than granitic nature of the rocks in Sri Lanka.

In most cases the geophysical data provided a useful qualitative guide to site selection, but none of the techniques were entirely satisfactory in yielding interpretations that correlated in detail with borehole control. This is attributed mainly to the limited resolution of the geophysical methods and their tendency to measure properties as averages over relatively large volumes of ground: better results were obtained where the subsurface layering was simplest, either in terms of more uniform sub-horizontal layering or of sharp lateral discontinuities, and where a combination of methods was used.

Computer modelling of two-dimensional resistivity distributions showed that breaks in VES curves could only be explained realistically in terms of variations within the near-surface layers and saprolite, with any expression of fracturing being a secondary phenomenon transferred through into the overlying material.

ZIMBABWE

Initial visits were associated with the siting of collector wells in areas of shallow hard rock (Carruthers, 1986). The saprolite was generally significantly thinner than in Malawi and resistivity VES tended to overestimate its thickness due to the range of equivalent solutions and the need to attribute surprisingly low resistivities to it; a suppressed layer of intermediate resistivity which correlated with hard rock had also to be invoked in some cases to reconcile the data.

Despite the large number of exploration boreholes, some of the discrepencies between predicted and proved depths to rockhead were unexplained (Carruthers, 1988): it seems possible that widely spaced, weathered fractures or joints surrounding blocks of unaltered granite led to a reduction in the observed bulk resistivities. The range of ground conductivity values given for different coil configurations of the EM34 provided some limits on the range of equivalent VES models and favoured the presence of thinner, more conductive saprolite.

The main value of the geophysical surveys lay in their use for rejecting large tracts of ground as being unprospective, on the basis of high resistivities. In marginal areas, a significant amount of exploratory drilling may still be required to discriminate between the more favourable geophysical indications; otherwise, the use of additional geophysical techniques, such as seismic refraction and TEM, must be considered.

Subsequent visits concentrated in the Masvingo Province of Zimbabwe which has ranges of different geological provinces and of climatic zones, making it a suitable region for the investigation of varying hydrogeological conditions. Thirteen separate areas were identified, each with characteristic geology and climate, and with both successful and unsuccessful boreholes. In these areas a multidisciplinary study was initiated with the overall objective of improving the efficiency with which boreholes found viable rural groundwater supplies.

The components of the project sought to collate all the known groundwater exploration data, to study the structural geology and geomorphology, to investigate the reasons that caused certain boreholes to be unsuccessful, to identify suitable strategies for siting rural water supply wells, to run a geophysical log suite in accessible wells, and finally to recommend sites, to drill and to log a small number of boreholes to test these strategies.

In 1986 geophysical investigations were carried out at 18 sites at which previous projects had drilled boreholes, and which had proved a limited or inadequate supply. The objectives of this work were:

1. to evaluate various geophysical methods for siting wells in the crystalline basement;

2. to study the geophysical parameters which might have a bearing on the yield of a well;

3. to assess the methods used at each site and to ascertain whether more geophysical work or a different approach might have improved the outcome;

4. to suggest methodologies which might improve the overall success rate of well-siting methods.

On the basis of the strategies developed from the initial field study, further work was done in 1987 in the same region in order to suggest boreholes sites which might intersect water-bearing structures. Sixteen sites were visited and suitable targets were identified at most of them. Prof D.H. Griffiths of Birmingham University visited several sites in order to apply a prototype microprocessor-controlled resistivity traversing system.

These studies have been reported in Smith and Raines (1987, 1988) and Griffiths (1987). They demonstrated that lineations observed on aerial photographs could be related to conductive zones identified using EM traversing methods, which allowed the siting of successful boreholes in areas which had previously been non-productive, although the relationship between the anomalies and the aquifer is not as yet fully understood. Further limitations to VES and seismic refraction methods in this scale of exploration were also identified.

2. GEOPHYSICAL TECHNIQUES

2.1 Resistivity

Resistivity surveys are the traditional means by which geophysics has been applied to borehole siting in basement terrains, although their limitations - as made apparent during this project - have not always been appreciated. The most common use of the method is in the vertical electric sounding (VES) mode for estimating thicknesses and resistivities in a sub-horizontally layered sequence.

Several countries, such as Zimbabwe and Malawi, have produced 'Master Plans' which include criteria for successful borehole siting based mainly on VES interpretations, which recognise that there is a correlation between depth to bedrock and borehole yield. In crude terms the low resistivity middle layer of the typical sounding curve represents the target zone, and the properties of this layer are used to define suitable sites for a hand-pumped rural water supply. In the 'Zimbabwe Master Plan', Martinelli (1984) specifies that for

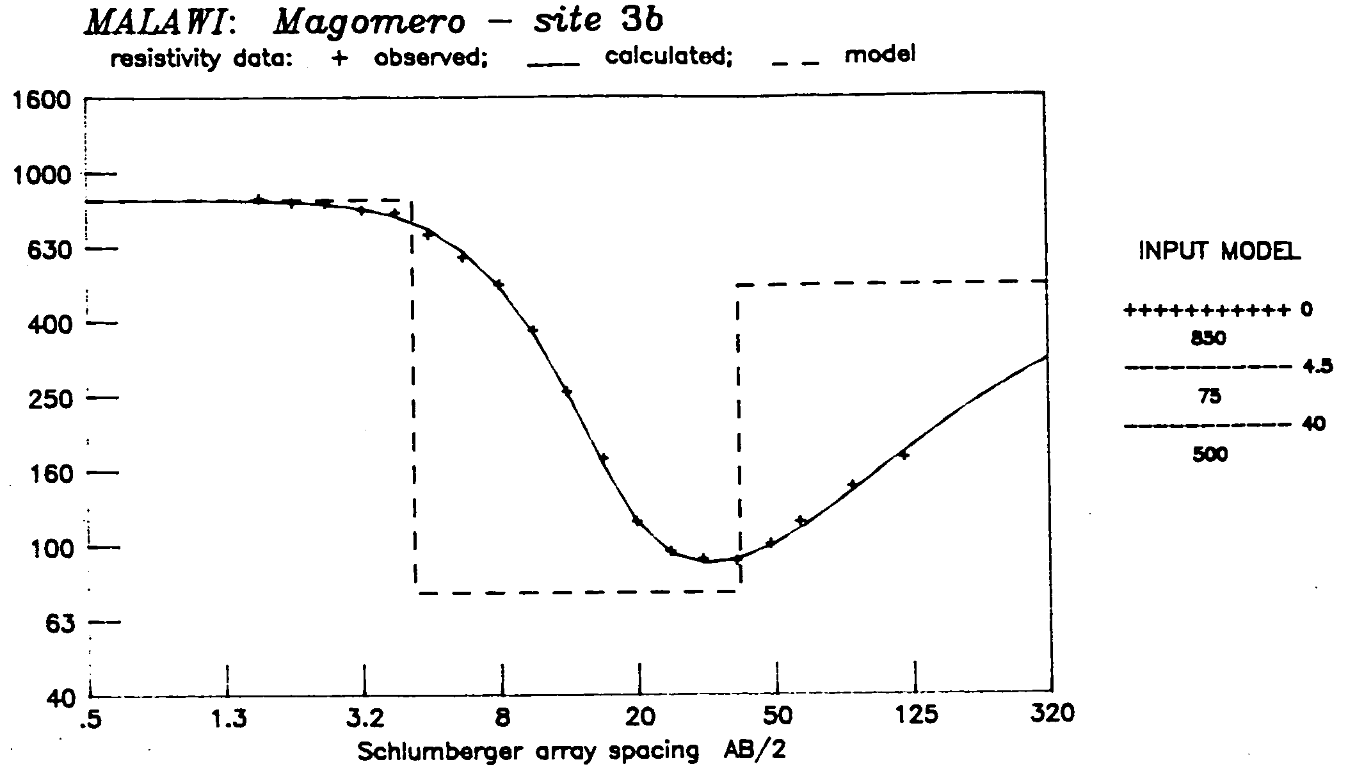


Figure 1a

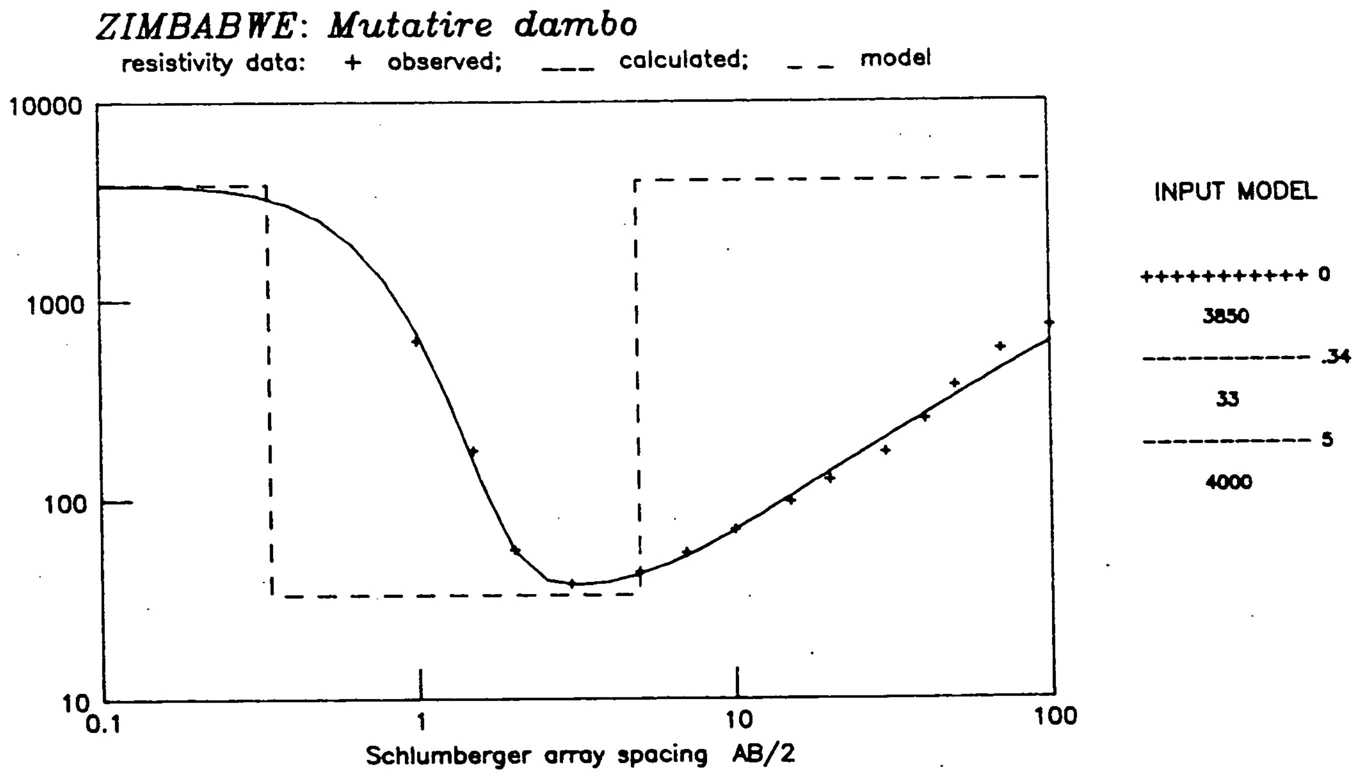


Figure 1b

Figure 1. Two vertical electric soundings illustrating 'Master Plan' criteris for use of resistivity in borehole siting.

a. Thickness and resistivity of saprolite which would fulfil criteris for a successful borehole site.

b. A sounding measured alongside a successful borehole which exploits a narrow zone of deep weathering; this demonstrates a site which would have been rejected (note unequal axis scales).

a successful well the thickness of saturated overburden must exceed 25m and have a resistivity between 30 ohm m and 150 ohm m, thus recognising the relationship between resistivity, rock type and borehole yield. The lower limit of 30 ohm m represents an estimate of the greatest content of clay which will allow adequate permeability; 150 ohm m is the upper limit indicating that the rock is sufficiently weathered or fractured. Figure 1a shows the type of curve and interpretation which would meet these criteria for a borehole site, allowing for the uncertainty in the depth to water table. Other workers have suggested that 400 ohm m is the preferred upper limit, (I. Clifford, oral communication). The recommendations are considered valid in order to provide a high success rate in areas of thick overburden, but may be unduly restrictive in the more difficult districts where the use of a different approach, aimed specifically at - for example - fracture zones, may locate adequate reserves to improve conditions for the resident population. Figure 1b is an example of a sounding curve obtained beside a successful well which clearly would not have been drilled if the above standards had been observed.

Quantitative interpretation of VES data has often proved to be unreliable in this type of environment when compared with borehole control. The reasons for this are not always clear but it is important to be aware of a number of limitations to the method if the models are to be taken seriously. The most obvious sources of ambiguity are equivalence and suppression, reflecting the lack of discrimination inherent to the method even under ideal working conditions.

The effect of equivalence is that equally good fits between model and field data can usually be obtained with a variety of layer parameters; that of suppression is equally good fits can be obtained by adding layers. Lateral variations due to the inhomogeneous nature of the weathered profile significantly increases the uncertainty; the averaging of resistivity effects due to the large volume of ground sampled by the VES is strongly weighted by changes in the near-surface layers and the interpretations cannot be scaled simply to adjust for these effects. The resultant errors produce sounding curves which may be noisy so that curve matching needs judgement to choose a best fit: this adds significantly to the range of resistivity-depth options. The full significance of this becomes clear when computer-based methods of curve-matching are used. Interpreted models may be a gross simplification of the actual distribution of resistivities within the ground, especially where there are no other data by which to control the model.

Where there is little or no control on the type of model which should be applied within a given area it may be useful to consider the total longitudinal conductance of the sequence overlying resistive bedrock. A value for this can be derived directly from the steeply-rising limb of a sounding curve and if necessary checked against the value obtained by summing the contributions (of thickness divided by resistivity) of the individual layers in an interpreted model. The total conductance is defined within much closer limits than any layer interpretation and so it may give a more reliable comparison of conditions between different sites. Clearly, being an aggregated quantity, the total conductance contains less information on the nature of the sequence and it needs to be considered in relation to observed apparent resistivities and likely limits on layer thicknesses.

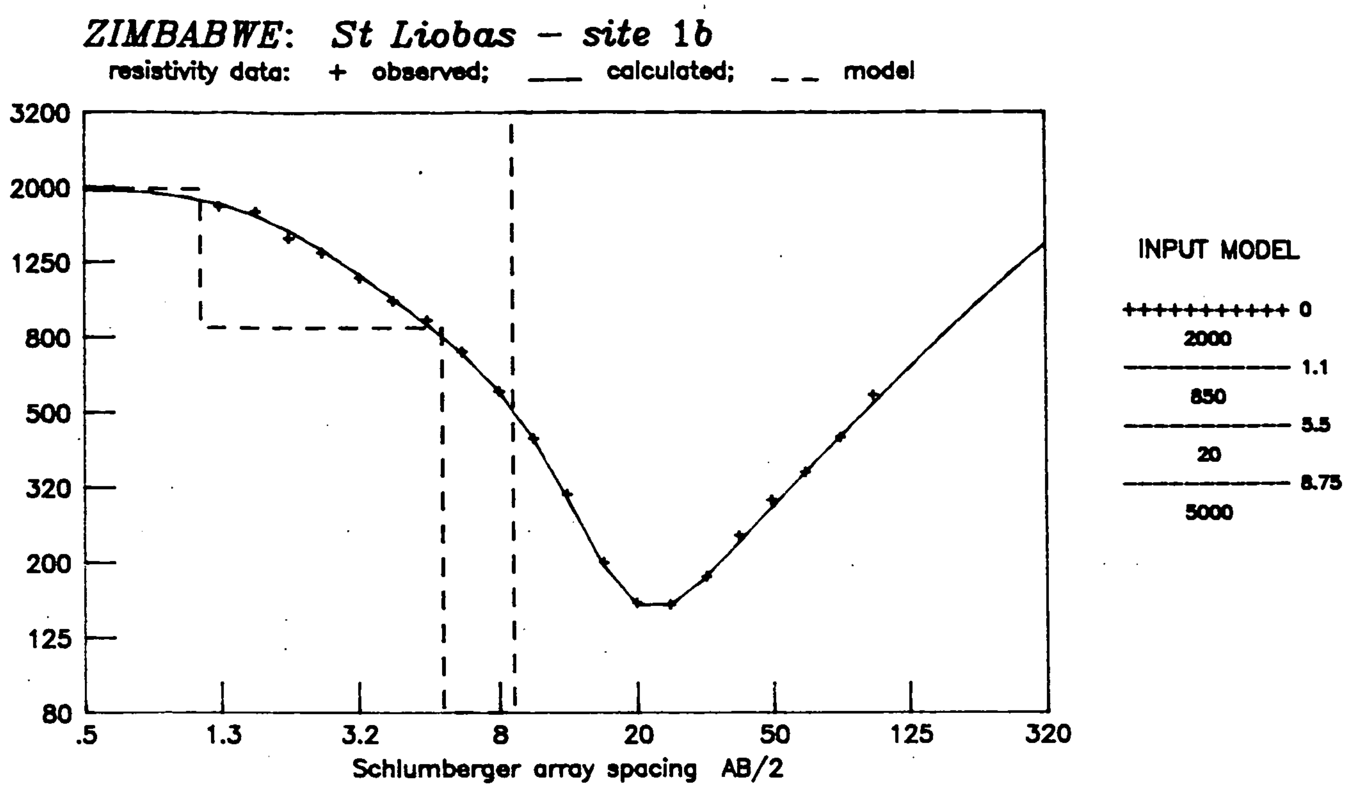


Figure 2a

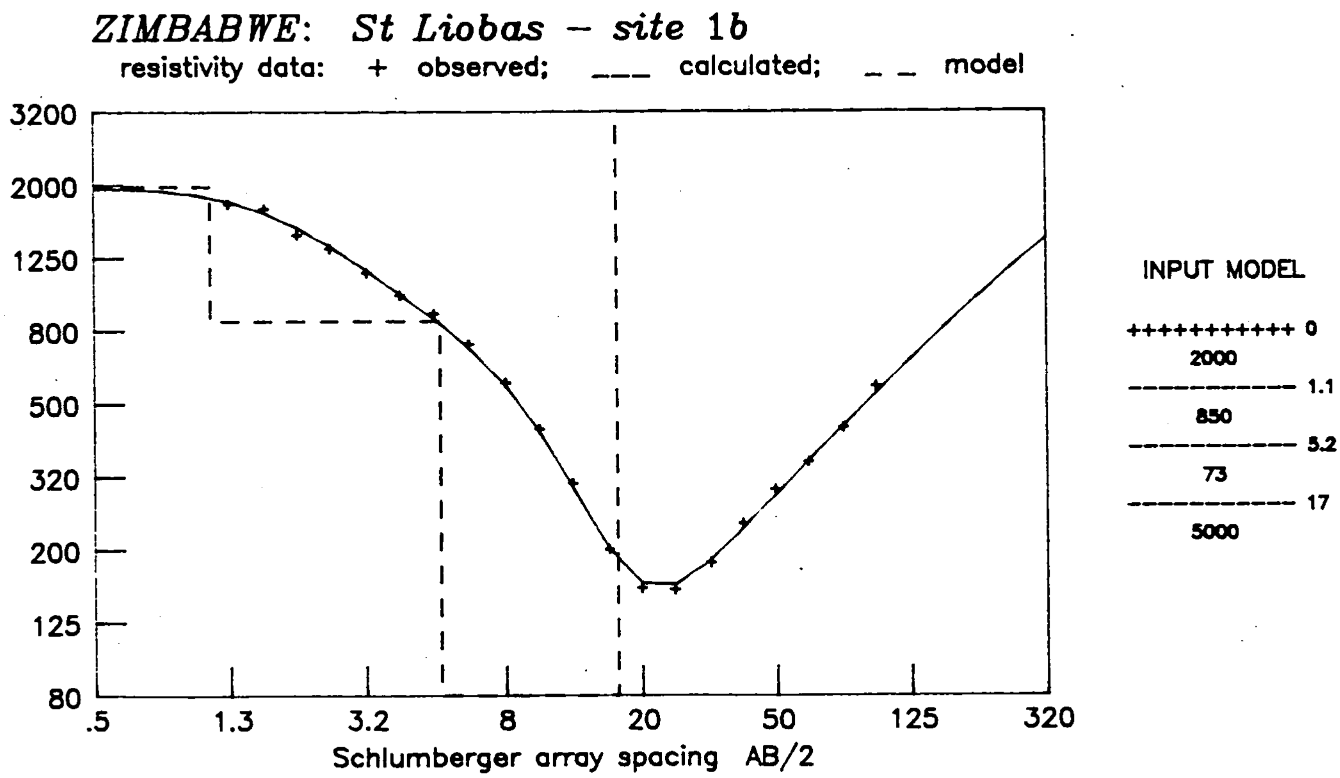


Figure 2b

Figure 2. Two interpretations of a single vertical electric sounding showing the wide range of equivalence.

a. The layer representing saprolite has a thickness of 3.25m, and a resistivity of 20 ohm m.

b. Here the layer has a thickness of 11.8m and a resistivity of 73 ohm m.

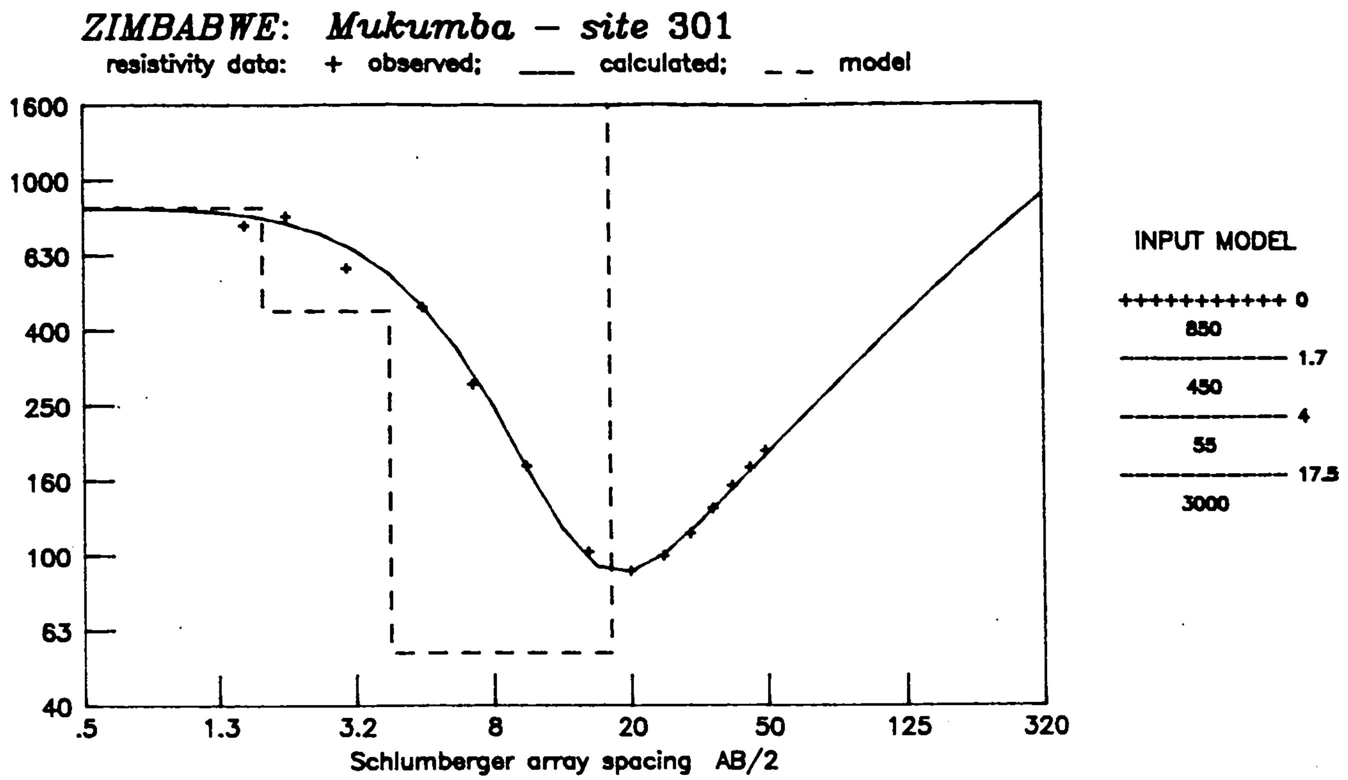


Figure 3a

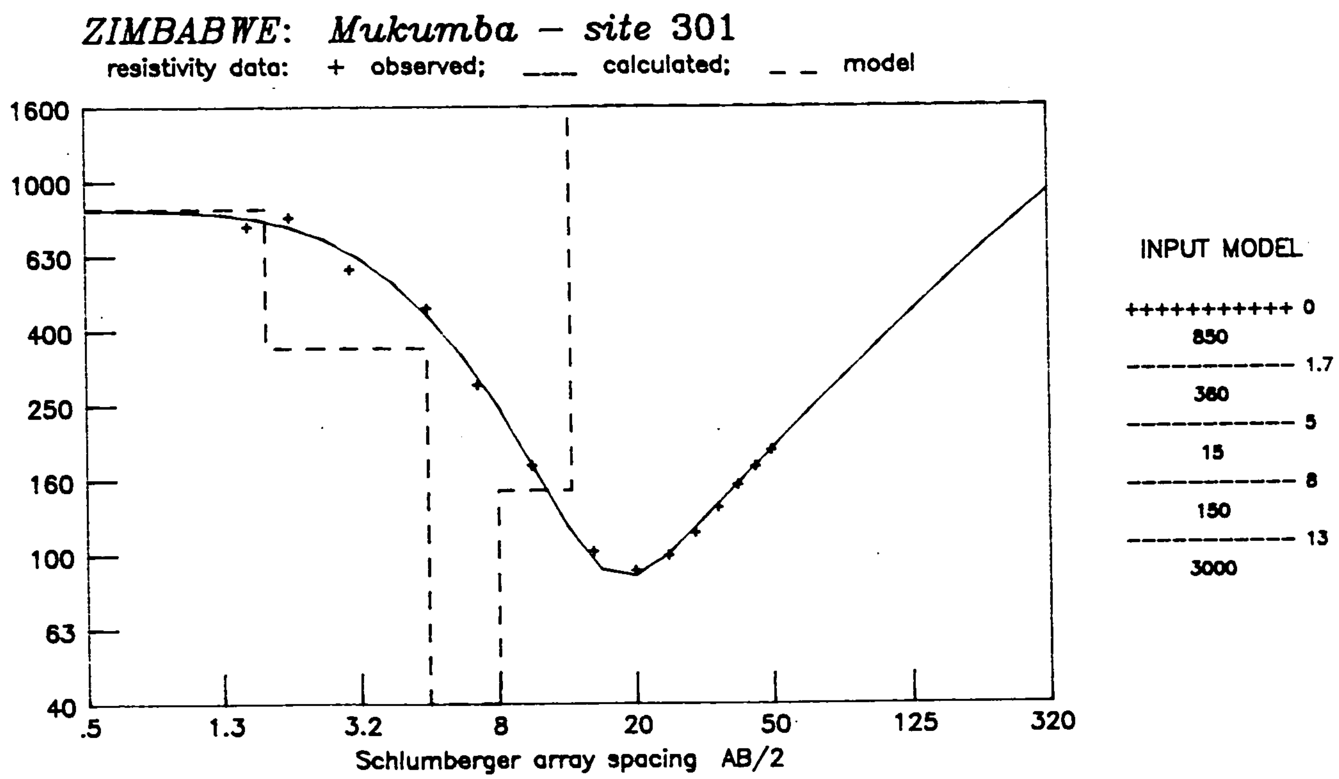
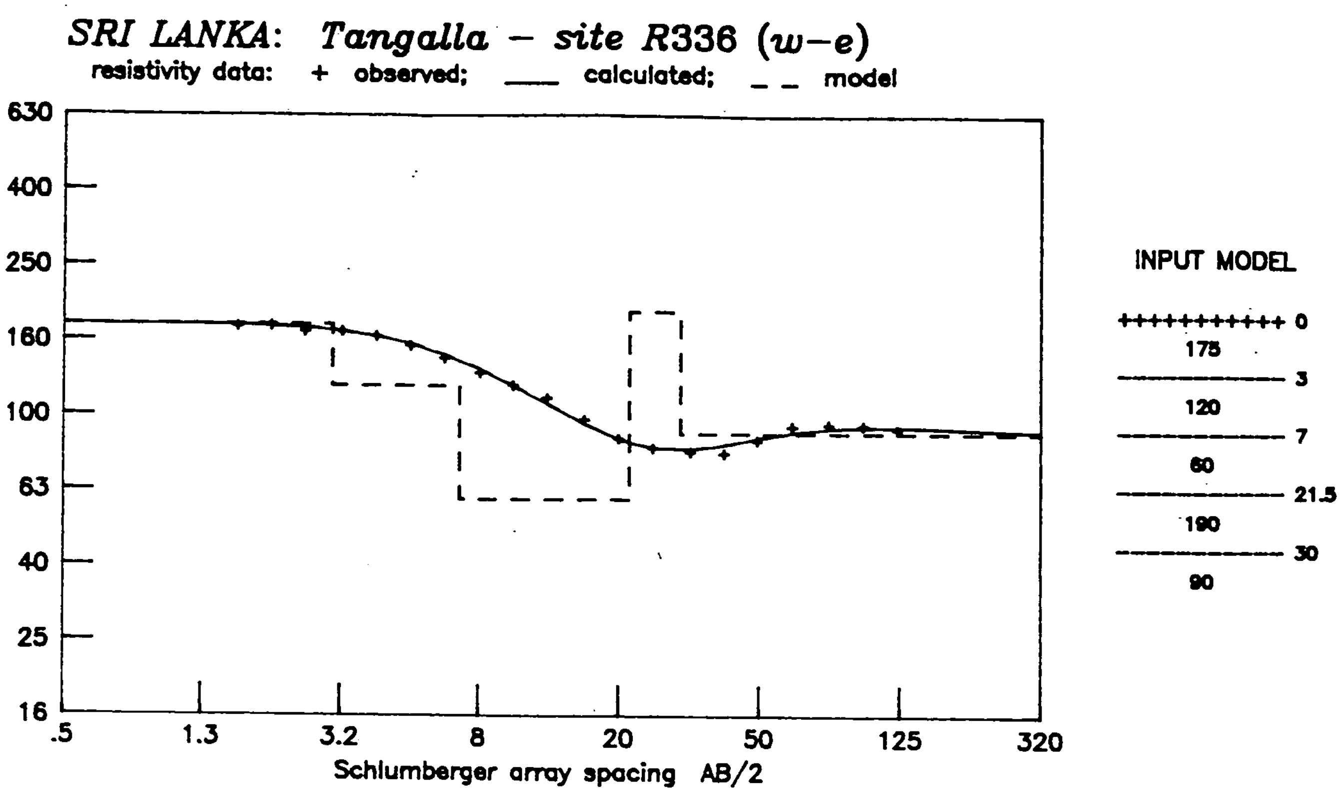


Figure 3b

Figure 3. A vertical electric sounding interpreted before and after drilling, showing suppression of thin layers.

a. A satisfactory fit achieved before drilling.

b. The results of drilling forced an alternative interpretation, showing an equally satisfactory fit.



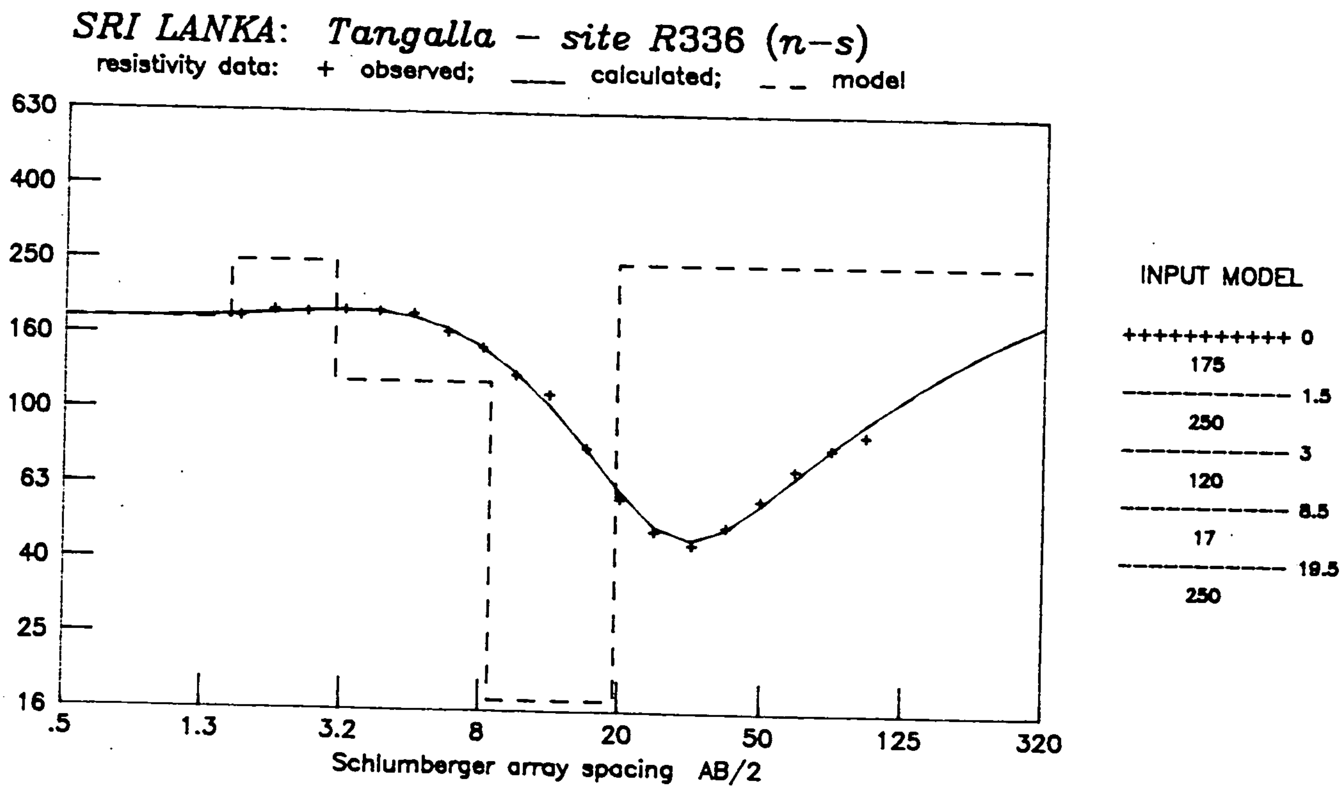


Figure 4. Orthogonal electric soundings measured from the same origin and their interpretations. There are significant differences reflecting lateral variations in geology.

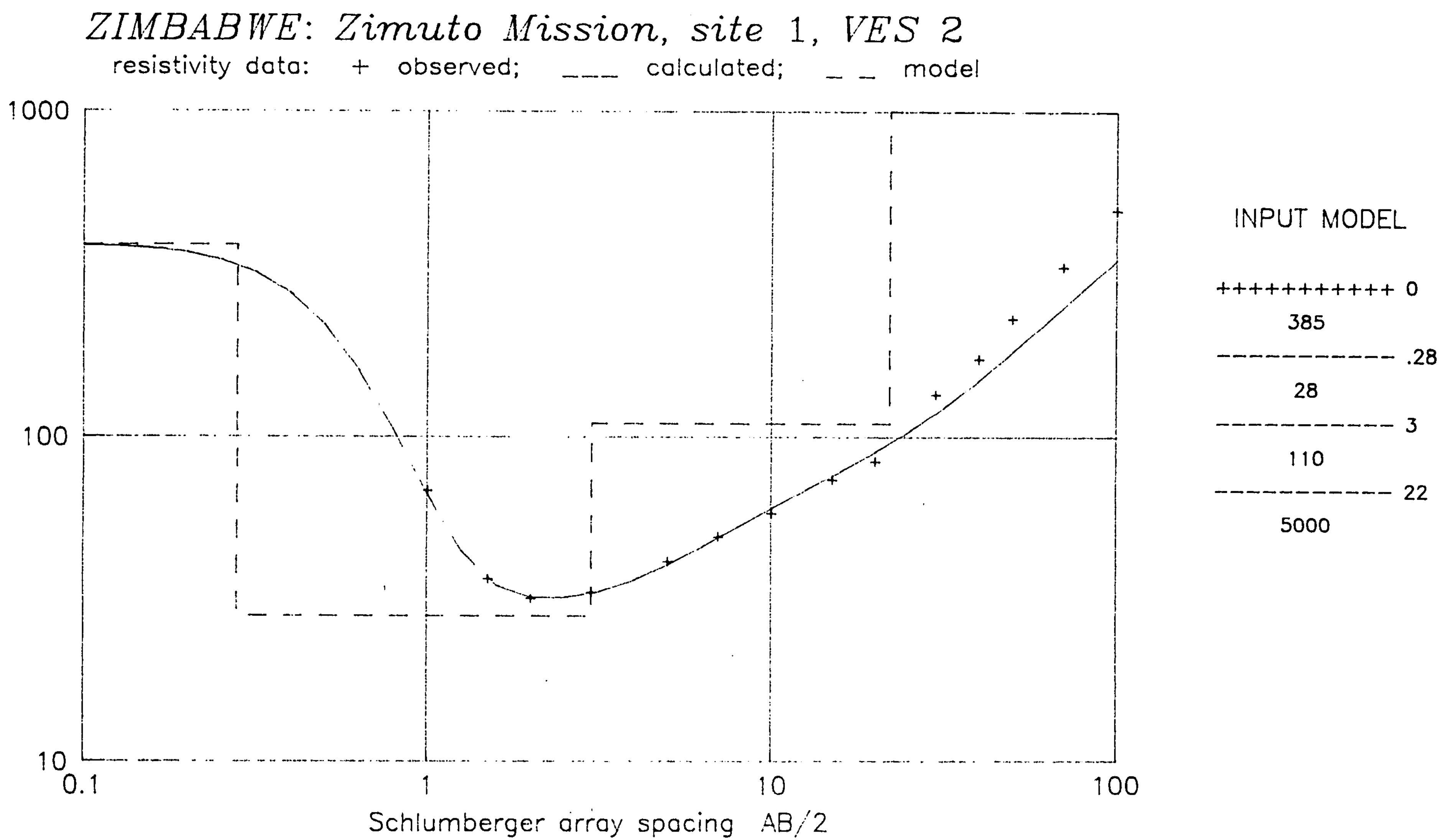


Figure 5. Vertical electric sounding with an ascending limb with slope greater than the theoretical maximum of 45°:

In the majority of soundings measured during this project a three layer analysis provided an adequate match to the main features of the field curve, which was typically 'H-type', that is with a distinct minimum (as in Figure 1). These layers are associated with a resistive cover, an intermediate layer of lower resistivity representing the saprolite and a resistive bedrock. This is not to argue that more layers may not exist, but that in a simple interpretation of a resistivity depth sounding produced in the field - which is required practice in most production surveys - inclusion of more layers to satisfy the sounding curve may not be justified; more complex models depend on borehole control, comparison with a number of adjacent soundings, or the experience of the interpreter in that area. Figure 2 illustrates the ambiguity due to equivalence when interpreting sounding data: in this case the thickness attributed to the saprolite can be varied by a factor of four without the quality of the curve match being adversely affected.

In some examples from Zimbabwe it was necessary to subdivide the second (low resistivity) layer to differentiate a zone of partially weathered or fractured rock from the saprolite in order to match borehole data. Figure 3a shows the initial, more optimistic interpretation, while Figure 3b gives the revised model needed to match the shallower depth to rock encountered in the drilling. Suppressed layers of this sort are thought to be a factor in many cases. A conceptual model should be developed, based on all the information available at any given time, to provide overall consistency and to avoid the interpretation of VES on an individual basis. A comparison of a number of soundings, and especially orthogonally oriented pairs of soundings, provides evidence of the degree of lateral variation. Figure 4, taken from a site in Sri Lanka lying about 20m within a localized zone of thicker weathering, illustrates how the presence of lateral effects can be detected in this way. If the subtle differences in curve shape which may indicate additional layering are to interpreted reliably it is important to show that data can be represented as a horizontally layered sequence.

Identification of the various layers in terms of formation-type is especially important, because in much of the literature it appears to be tacitly assumed that the top of the low resistivity layer represents the water table. Closer examination of case histories often show this not to be the case. In Zimbabwe our experience re-inforces this conclusion. The upper (high resistivity) layer may represent dessicated soil, leached saprolite, or laterite (Palacky and others, 1981) and is typically about 1m thick in Masvingo. A moist zone, which can be seen in shallow dug wells, probably represents the top of the low resistivity intermediate layer. The moisture may represent pendular, infiltrating water closely associated with clay particles and retained by surface tension. However it does not bear an obvious relationship to the water table, or to a capillary fringe, even though the latter may be over a metre thick. Smith and Raines (1988) showed that at Chinembire, Zimbabwe for example, there is about 25m between the top of the low resistivity layer and the water table as intersected in a borehole.

A very large number of soundings in Zimbabwe showed an ascending limb steeper than 45°, which is the theoretical maximum which would result from a basement of infinite resistivity beneath a horizontal layer with negligible resistivity. Fig. 5 shows an example from Mhativa, Zimbabwe. The cause of the effect is not clear, although it is particularily common in areas of high contact impedance and may result from systematic errors in measuring low voltage signals. Alternatively it might result from a basement surface which was not horizontal, although 2-dimensional model studies could not reproduce the effect, and estimates of the magnitude of the uniform dip required (Koefoed, 1979) are not compatible with the thicknesses of the layers and outcrop distribution.

The significance of this phenomenon lies in the effect on the interpretation: can values of resistivity derived for the basement be relied on, or will they be artificially high; should the data on the ascending limb be relied on at all, and to what extent will they distort the interpreted thickness of the intermediate layer. These factors should be borne in mind during an interpretation in arid areas as the possible limitations to the solution.

As described above, the standard interpretation of VES curves assumes a sequence of uniform layers but a two- or three-dimensional earth can be modelled if required. These techniques are useful in evaluating the effect that specific features might have on a VES curve. While the data do not usually justify such a sophisticated approach, a technique known as Micro-processor controlled Resistivity Traversing (MRT) has been developed to provide coverage which is a compromise between profiling and full VES: these data are then interpreted in the form of a cross-section through the ground (Griffiths and Turnbull, 1985). This method was tested with some success in Zimbabwe (Griffiths,1987), indicating that quite detailed information can be obtained, as shown in Fig. 6 from a traverse across a lineament at Mhativa, Zimbabwe. However, the method is relatively slow and cumbersome and may have no advantage over EM traversing in identifying fracture systems.

The traversing mode of operation is used to identify and trace localized anomalous zones, almost invariably those showing a lower resistivity. The depth of investigation is related to the electrode separation being used. Whilst the chosen separation must be small enough to maintain lateral resolution, it must be large enough to be sensitive to changes over the depth range of interest. It is possible to quantify changes in the depth to bedrock for a simple two-layer situation using only a pair of separations, selected on the evidence of resistivity soundings.

The type of anomaly attributable to a localized water-bearing fracture will not usually be detectable but the effect of a broader zone of fracturing within the bedrock may give a resolvable anomaly. A large anomaly can only be expected where the deeper fracturing is reflected in a local thickening of the overlying saprolite due to enhanced weathering, or where the fractures are associated with saline waters or conductive minerals such as clay minerals, ore minerals or graphite.

The role of resistivity methods in traversing has been largely superseded by EM instruments which are faster and require fewer people for the fieldwork. The latter also have two technical advantages for this type of terrain: resistive surface conditions are not a problem because inductive coupling between the transmitter and the ground avoids the need for direct electrical contact; the spacial resolution of anomalies is significantly better, which improves the identification of the narrow conductive bodies which are important targets here. However, this type of EM equipment is not always available and so the use of resistivity traversing will continue in developing countries.

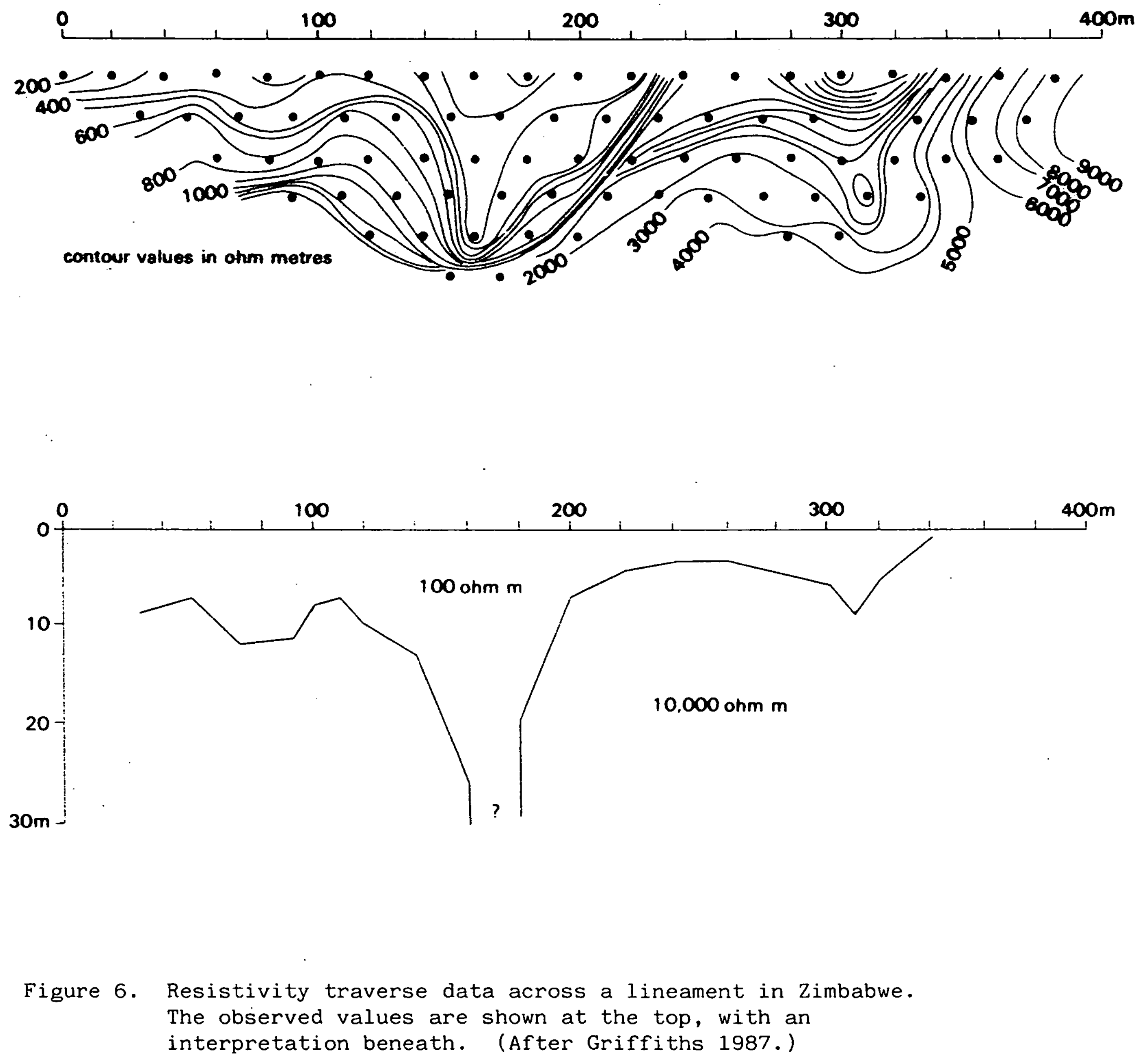


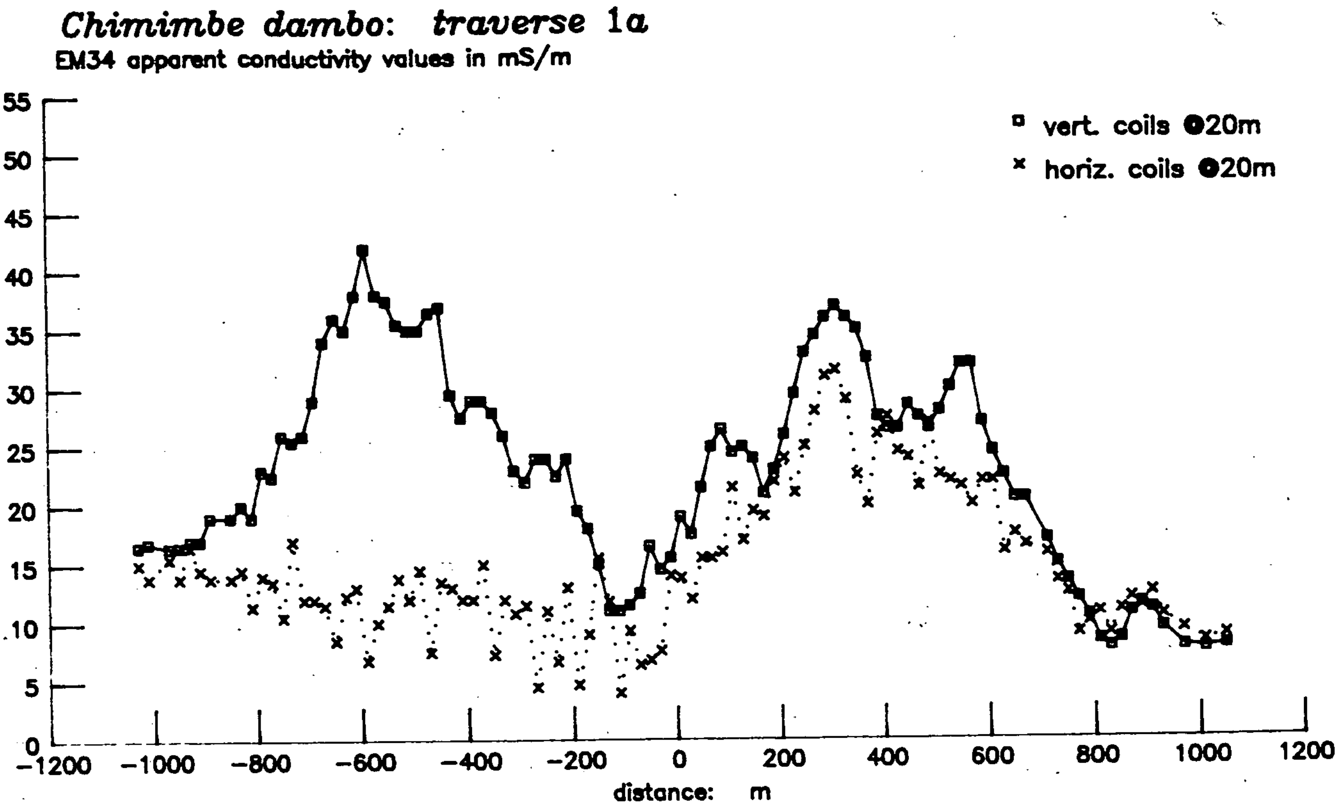
Figure 6. Resistivity traverse data across a lineament in Zimbabwe. The observed values are shown at the top, with an interpretation beneath. (After Griffiths 1987.)

2.2 Electromagnetics (EM)

The principle of electromagnetic (EM) induction has been widely applied in geophysical surveying for minerals using a range of transmitter and receiver configurations. Systems based on the 'Slingram' principle, which utilises two portable coils linked by a reference cable, have become important tools in groundwater exploration especially since their modification to provide a direct read-out of apparent ground conductivity at high sensitivities. One such system, the Geonics EM34-3, was used at many sites during this project. EM methods (including VLF where received signal strengths are adequate) are most appropriate in regions with relatively shallow depths to bedrock (<20m), where fracture zones or local pockets of thicker saprolite form the target, as deeper conductors may be masked by the presence of the sub-horizontal conductive cover.

The EM34 equipment provides a variable depth of investigation by changing either the coil separation (10-40m) or coil orientation (McNeill 1980). When the coils are vertical and co-planar this depth is significantly less than in the horizontal mode and the instrument is sensitive to the upper (relatively conductive) overburden material. It can therefore be used for mapping the thickness of regolith overlying crystalline basement rocks and determining suitable sites, in particular for hand-dug wells. Higher values of apparent conductivity measured using a single coil configuration indicate either an increased thickness of the conductive overburden, or an increased conductivity within the layer: this ambiguity cannot be resolved without additional information. If two different coil spacing are utilised concurrently, then the greater depth of penetration of the larger coil spacing would allow some discrimination between the alternatives. When the coils are used in the horizontal coplanar mode, then the depth penetration is relatively greater; in this way a maximum of 6 apparent conductivities values for different depths can be measured for the same point.

An example of EM34 traverse data across a dambo in Malawi is given in Figure 7. Highest conductivities (near station -600) measured with 10m vertical coils originate from a thin cover of smectite-rich clays while the low response from the 20m horizontal data show that the saprolite is relatively thin. Near station 400 the higher values are reflected in all coil configurations and spacings, indicating that the saprolite is thicker here though the superficial cover is less conductive.



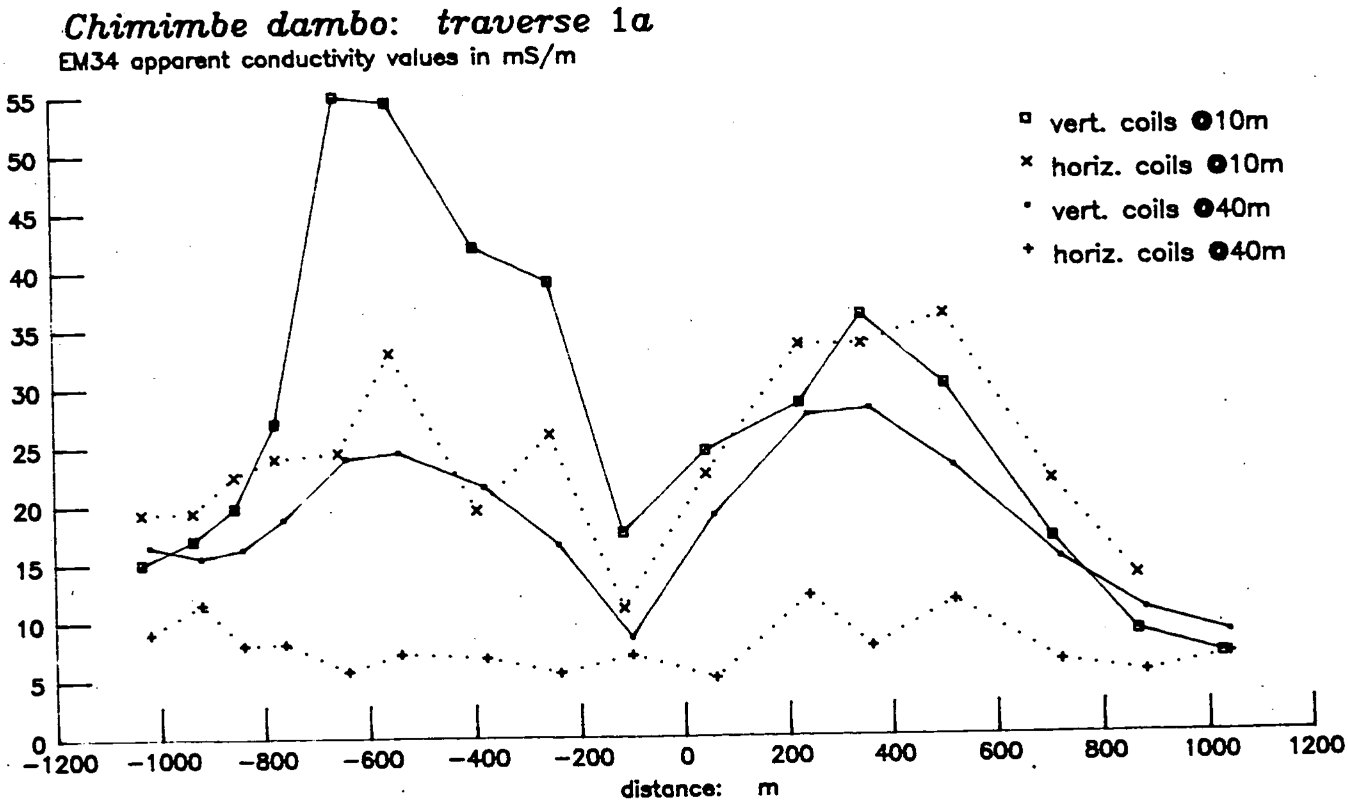


Figure 7. Ground conductivity traverse data, illustrating the different responses of the various coil configurations to shallow, highly conductive clays (to the left of the profile) and thicker, moderately conductive saprolite (to the right).

An approximate depth interpretation can be made, either using an inversion technique for a two-layer case or by computing the EM34 values expected from a given resistivity model. The latter technique can be useful for reducing the ambiguity when modelling resistivity soundings as EM equivalence operates within a different range. An example of this is given by the predicted EM34 values for the models illustrated in Figures 2 and 3:

	coil spacing	apparent conductivity (from EM34) vertical coils (mmhos/m)	horizontal coils
St Liobas 1b (upper model) -			
	10m	6.2	9.3
	20m	7.1	6.6
	40m	5.7	2.7
St Liobas 1b (lower model) -			
	10m	3.9	6.0
	20m	4.8	5.5
	40m	4.5	3.1
Mukumba site 301 (upper model) -			
	10m	6.5	9.6
	20m	7.8	8.2
	40m	7.0	4.6
Mukumba site 301 (lower model) -			
	10m	9.5	13.6
	20m	10.5	9.2
	40m	8.3	3.9

While the numerical values of the readings themselves are probably not a reliable guide for quantitative assessments, the ratios between different coil spacings and orientations provide good control for distinguishing between different models under field conditions. Additional case studies are needed to establish how effective this approach can be.

McNeill (1980) also described the response of the EM34 to thin steep-sided conductive bodies, which is well-known in the mineral prospecting literature. The effect is more common in *horizontal* co-planar coil data because of the greater coupling of the EM field with this type of conductor, and the greater depth of penetration. A characteristic anomaly pattern is produced in which two apparent conductivity maxima occur on either side of a conductivity minimum, centred approximately over the conductor. Negative values may be obtained where background conductivities are low, as shown in Figure 8, from Chikore, Zimbabwe (Smith and Raines, 1988). It should be noted that the apparent conductivity maxima occur over resistive ground and anomalies of this type have to be distinguished from real lateral variations in bulk conductivity. Although McNeill describes the bodies which produce these anomalies as 'dyke-like', there is no implication that they are indeed dykes: any steep-sided conductive body, such as a fracture zone, will produce this

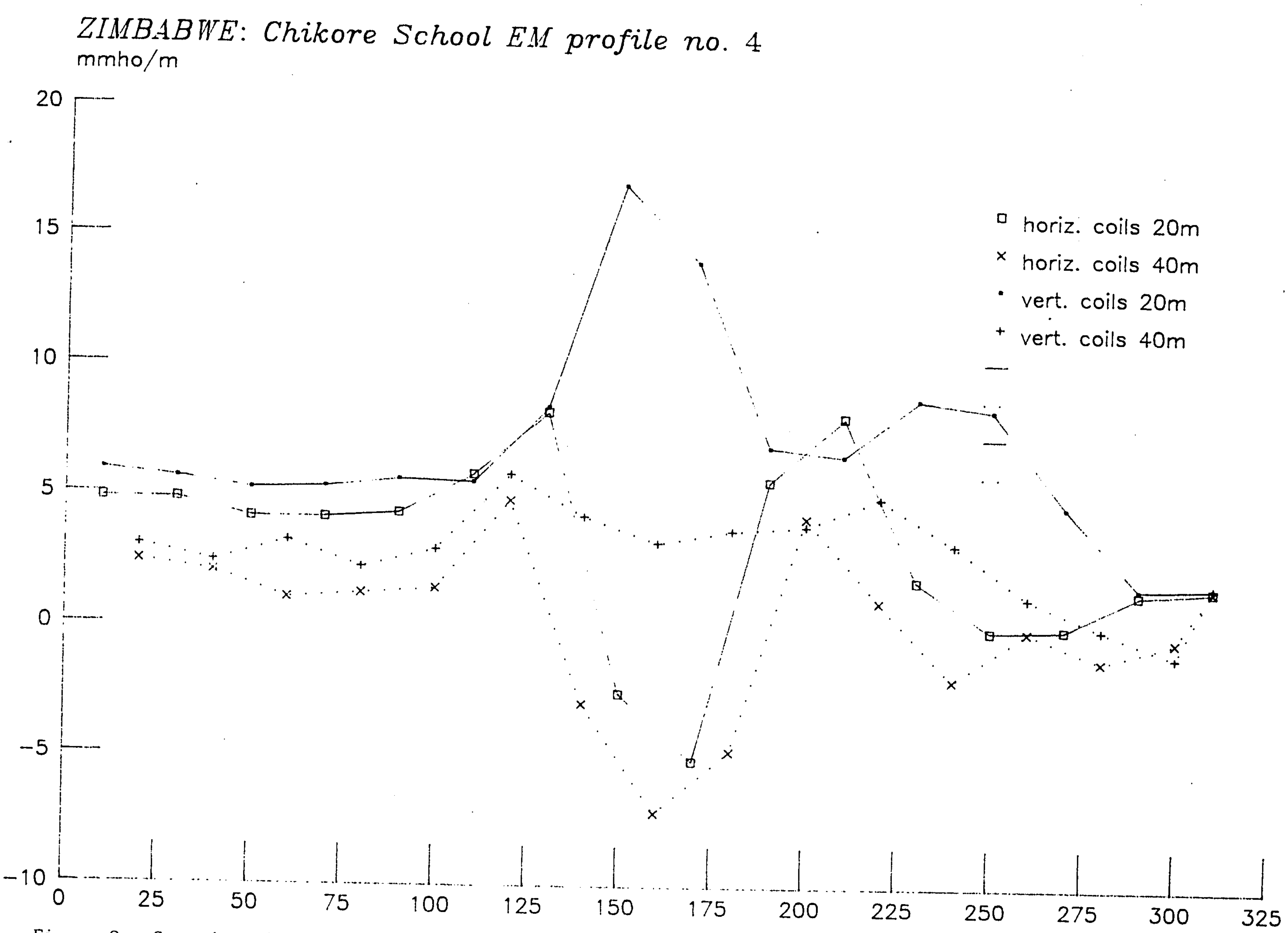


Figure 8. Ground conductivity traverse data across a narrow steep-sided conductive body, indicated by the apparent conductivity minimum in the horizontal coil mode.

type of anomaly. The anomaly can provide some limited diagnostic data on the conductivity, thickness and attitude of the conductive body as described in standard textbooks (for example Telford and others, 1976), although, as discussed below, care must be taken in the application of these methods.

This particular response proved to be of considerable interest in Masvingo, where extensive lineaments had been identified from aerial photographs (Greenbaum, 1986 and 1987). Greenbaum correlates lineaments with the surface expression of fracture systems beneath thin saprolite and this thesis is well corroborated in the literature. In general a lineament has a relatively diffuse effect on the aerial photographs and its trace cannot be defined to the degree of precision needed for siting a borehole to test the concept. EM traverses using the EM34 with coils spaced at 20m and 40m and in both horizontal and vertical modes, in many cases produced a set of characteristic profiles across vleis (the equivalent in Zimbabwe of dambos elsewhere) through which the lineaments ran; there is frequently good correlation between the trace of the lineament and the minimum in the EM anomaly, indicating a fundamental connection between the two. In most cases the vertical coil configuration produced maxima which corresponded to the more complex anomaly from the horizontal coils; in no cases were mimima with flanking maxima produced. However, in the deeper penetration afforded by the 40m vertical coils there may be a suggestion that the pattern is developing, superimposed on the relative high values, as may be seen in Figure 8.

Although there is clearly a relationship between the lineaments and EM anomalies, and the use of EM provides significantly greater precision than aerial photography for identifying a borehole site, with which to intersect the possible fracture system, there are good reasons to suggest that the EM anomaly does not result from a 'dyke-like' body, but rather from a steep sided, body with limited depth extent.

The conventional interpretation process assumes that the conductive body is parallel sided, and infinite in depth and length extents. On the basis of such an assumption the magnitudes of the anomalies in many cases indicate the presence of bodies with conductances (conductivity-width products) of up to 2 mho (using the methods outlined in McNeill, 1980) and a width of up to 20 m. Two geological models might be proposed in explanation:

1. very conductive material (clay or groundwater) contained in a set of relatively thin fractures separated by solid rock. However the groundwater in the region is usually fresh, with conductivities lying between 10 and 100mmho/m (Shedlock, 1987) and it is unlikely that the necessary conductance could be achieved in this model, as recognised by Lindqvist, 1987;

2. moderately conductive material, resulting from enhanced weathering of the fractured bedrock, composing the full width of the anomalous zone. Saprolite with conductivity greater than 100 mmho/m is widely recognised in resistivity soundings and EM traverses (Smith and Raines 1986, 1987 and references therein), which could provide sufficient conductance, with only a limited depth extent.

The fractures suggested in model no. 1 would allow preferred weathering in the zone in which groundwater can circulate, with the increased development of saprolite along the fracture zone, so that this model probably tends towards model no. 2, as shown in Palacky and others (1981). The depth extent of model no. 2 would probably be limited to the zone within which groundwater can circulate freely.

Analysis of the anomaly can give an indication of the dip of the conductive body, which is an important factor in selecting a borehole site to intersect the zone beneath the water table. Simply, the body dips beneath the greater (in both the amplitude and the area beneath the curve) of the two flanking maxima. However, considerable caution must be exercised in this because it is highly unlikely that the assumptions on which the interpretation is made are wholely valid; in particular the following aspects may invalidate the assumptions:

1. as noted above, the depth extent of the conductor is likely to be limited and this has been demonstrated by several of the boreholes in this programme;

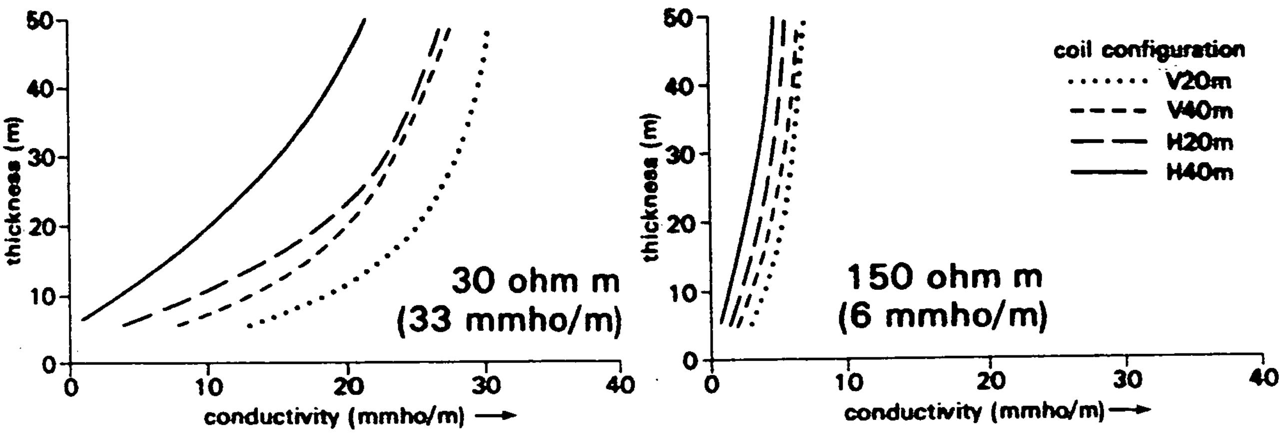
2. it would be expected that the contacts between weathered and unweathered rock at the top of a weathered fracture system would dip towards the fracture, possibly with an unequal dip;

3. the dip analysis depends rather critically on obtaining good definition of the anomaly shape, and station intervals used in routine survey procedures often preclude the reliable determination of maximum value or area under the curve;

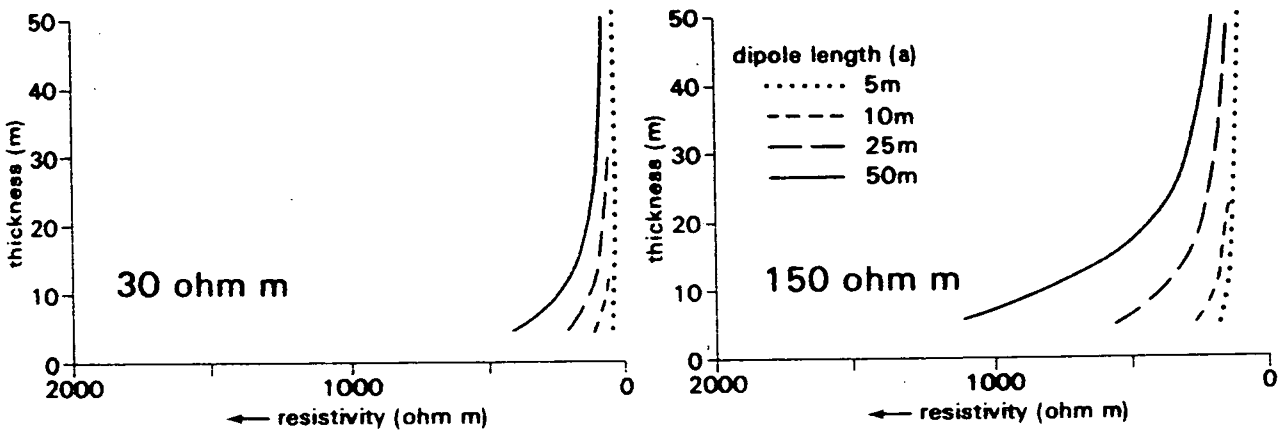
4. the anomaly shape may be modified by the presence of adjacent conductive zones or changes within the overburden: the conductor is not likely to be infinite in length extent.

Modelling, using both numerical and analogue techniques, is required to define the relative importance of changes confined essentially to the weathered material as against the effect of a fracture zone within the bedrock itself.

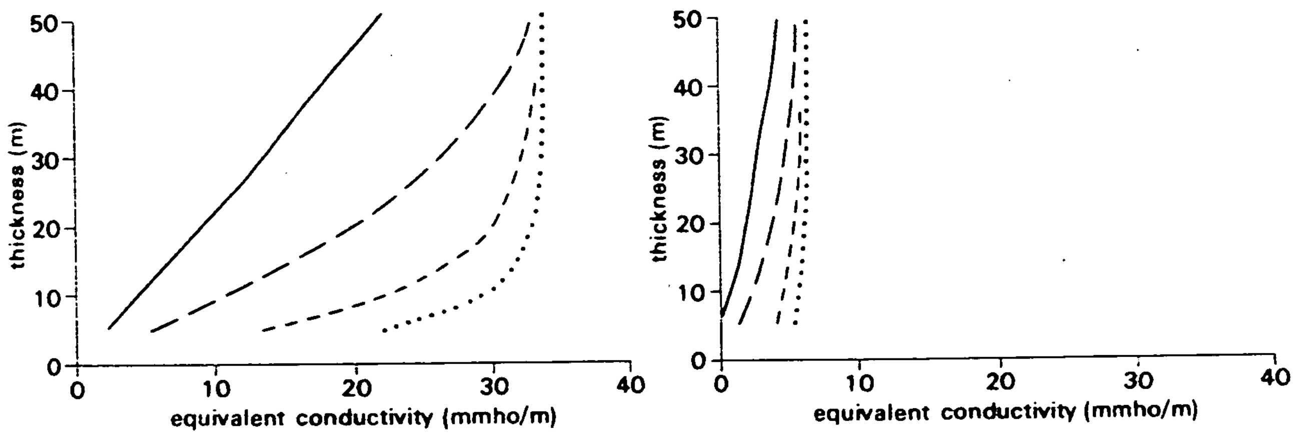
It should be noted that, with the particular frequencies which are utilised by the EM34, the instrument is increasingly less sensitive to bodies with resistivities greater than about 150 ohm m (about 6 mmho/m). If the anomalous body has a greater resistivity than that, then resistivity traversing methods will provide improved discrimination and should be considered, despite their reduced convenience (Smith and Carruthers, in press). This point is made in Figure 9 which compares the responses to a simple layered earth for the various coil configurations of the EM34 and different dipole spacings of a Wenner resistivity array.



a. Theoretical response of various coil configurations of EM34 to a variable thickness of overburden with two different resistivities, overlying a substrate with a resistivity of 2000 ohm m (conductivity of 0.5 mmho/m).



b. Theoretical response of various dipole lengths of a Wenner array to a variable thickness of overburden. Two different values of overburden resistivity are shown, over a substrate with a resistivity of 2000 ohm m.



c. Conversion of theoretical Wenner response in (b) from resistivity to conductivity, for comparison with EM34 response in (a).

Figure 9. Comparisons of theoretical conductivity and resistivity responses to a two-layer earth with various parameters, indicating the range of sensitivity of the techniques.

Tests using VLF methods in both Malawi and Zimbabwe proved unsuccessful, because the received signal strengths from Europe, United States of America and Australia were too low in that part of Africa. More sensitive modern equipment may provide useful data in these areas. The equipment is very portable, reliable in use and simple to interpret and, in appropriate environments, has been used to map fracture zones with great success, as widely described.

The most promising recent developments in EM techniques have been in the pulsed or Time-Domain EM systems (TEM), as compared to the fixed frequency systems such as the EM34. It is now possible to obtain TEM depth soundings which give information from as little as 5m depth, bringing them into the range needed for basement terrain. Their main advantage is expected to lie in the much reduced volume of ground sampled; this makes them less susceptible to the errors caused by the averaging out of lateral variations and means that greater details of bedrock topography can be mapped. The traversing and sounding modes are also more efficiently integrated than for either resistivity or 'slingram' methods. A combined interpretation of resistivity and TEM sounding data will generally lead to a significant reduction in the problems of equivalence which occur when either are used on their own. EM34 data can serve this purpose to an extent but the constraints are less well defined due to the limited number of depth sample points and uncertainty in the zero reference level. However, the effectiveness of TEM equipment has yet to be proved in this field environment and it may suffer from low signal strengths in the more resistive conditions.

2.3 Seismic refraction

Seismic techniques can be used for siting in their own right or as part of more comprehensive investigations. By measuring the elastic rather than the electrical properties of the ground they provide a complementary source of information. It is also possible to measure both shear and compression wave energy which further increases the knowledge of the physical properties of the material.

The main limitations of these methods lie in their practical application as both the fieldwork and data interpretation procedures tend to be more time consuming. The nature of the ground can also give problems in that the boundaries between layers of different acoustic impedence need to be sufficiently distinct and continuous for satisfactory interpretations to be made: occurrences of an irregular bedrock interface and residual blocks within the more weathered material cause difficulties in defining both layer velocities and the true first arrivals used in the analysis.

Energy sources need to be sufficiently powerful without being too cumbersome. Explosives are most effective but their use is often precluded by security or safety considerations; they require augered shot-holes which can be time-consuming and costly and for shallow investigations they are difficult to justify, although air-blast on outcrops can be utilised. Hammer or weight-drop sources can be adequate but energy absorption within the colluvial deposits may cause a loss of true first arrivals, as found during work at Chimimbe dambo, Malawi. In favourable circumstances in Zimbabwe reliable first arrival breaks were obtained at ranges of 200m, and it proved possible to investigate structures to depths of 30m, although for greater depths and larger shot-to-geophone offsets explosives would be essential.

Figure 10 shows an example of an interpreted seismic section from Malawi together with EM34 data for comparison. The seismic traverse indicates that the saprolite tends to be thinner beneath the dambo itself though the underlying saprock is thicker and bedrock refractor velocities tend to be slightly lower here. It is possible to correlate a number of features with anomalies in the EM34 data and, as the seismic layering is not well defined in itself, a more reliable overall interpretation is obtained by combining the two data sets.

Limited trials using a shear wave source proved to be of limited value, because energy absorption within the overburden proved too great to allow reliable identification of the first arrival times, which is necessary for the analysis.

2.4 Magnetics

Igneous dykes are widely recognised as being suitable targets for groundwater exploration, but the precise relationship to the water-bearing rock requires some definition, so that the correct approach to siting a well is adopted. Two distinct cases are evident:

1. the dyke may form a subsurface barrier to the flow of groundwater in weathered country rock. This may occur because the dyke-rock is more resistant to weathering than the country-rock into which it is intruded, or may intrude the already weathered country-rock. The relatively unweathered dyke may form a partial barrier to water flow, thereby raising the piezometric level behind it and in this case a well should clearly be sited behind the dyke.

2. the dyke may be heavily jointed or fractured, or more deeply weathered than the country-rock, in which case it may be a better aquifer than the country-rock and be a preferable target for a well.

Magnetic surveys are often suitable for identifying and analysing dykes, and there are many case histories of this application. However, it is axiomatic that the dyke must be magnetic. Many basic dykes, composed of dolerite or microdiorite, are rich in magnetite and may be simply traced using magnetic methods. In Masvingo there is a suite of late dolerite dykes, which cross-cut the basement rocks, forming clear features, and which might be suitable targets for wells. At Virimai Kraal (Smith and Raines 1987), a magnetic survey was used demonstrated that the dyke could be easily followed. However the nearby - and similar aged - Great Dyke, which is described as a basic quartz gabbro, had a very low magnetic susceptibility, where tested using a susceptibility meter, and might not have a magnetic signature. This emphasises the value in measuring the susceptibility of possible magnetic rocks, such as dykes or volcanic rocks, proir to any major magnetic survey.

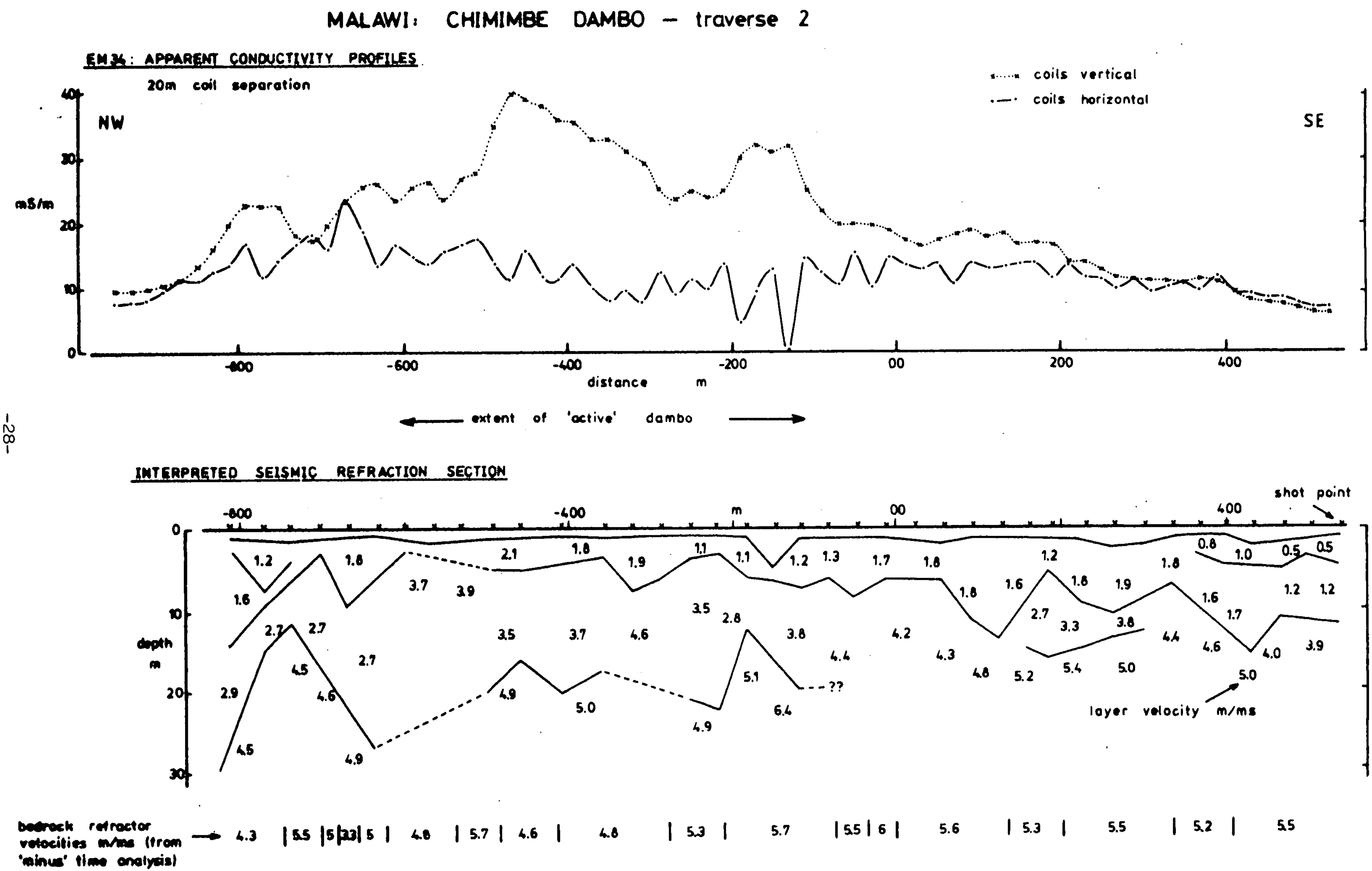


Figure 10. Seismic refraction section across a part of the ground covered by Fig. 7. The improved detail provided by seismic may be seen.

Similarily, rocks described as basic dykes (meta-dolerite) near Chibi and near Mahuto (Zimbabwe), when investigated with a susceptibility meter, showed a low value of susceptibility (rather less than the gneissic country rock), and did not show a systematic magnetic anomaly which would identify them. A visual inspection of these rocks showed them to be coarse-grained, very dark in colour, with a large proportion of dark mineral, probably hornblende, and felspar. Their field relationships with the country rock indicated that they crossed the main gneissosity, but were folded and sheared so that the original structure had disappeared. Although the rocks may have been basic dykes, metamorphism had allowed the iron oxides to be reduced into more stable, non-magnetic mineral phases.

3. DISCUSSION

Geophysical methods have clearly been seen to be successful in semi-quantitative terms for identifying groundwater targets related to thicker overburden and also to zones of fracturing, where the saprolite is generally thin. Traversing methods are particularily efficient for eliminating large areas of unprospective ground. Nevertheless it is our experience that answers to some of the important specific questions raised during exploration for rural water supply cannot be provided by the geophysical field techniques or interpretation methods currently employed. It is equally unlikely that the application of the rule-of-thumb interpretations which are often applied would be able to resolve them with the precision that is often claimed. The limitations of the methods and the interpretations must be recognised both by the geophysicist, and the project manager in drawing up contracts.

In particular to the application of resistivity, the use of graphical or other simplistic analysis to VES results can be grossly misleading in areas of high equivalence; the estimate of depth of water occurrence from VES 'breaks' is contentious and does not appear to be based on rigorous evidence; water-table depth cannot easily be extracted from VES results; the interpretation of VES into rather complex models ignores the major contribution of lateral inhomogeneity in this terrain.

In the case of EM, it is important to recognise that resistivity traversing can be more appropriate, in particular for measured resistivities above about 100 ohm.m, where EM will not provide useful discrimination: other factors to be considered are that: a slower field method utilising horizontal coils in addition to vertical may provide essential information on vertical-sided structures; the apparent conductivity minima which may be derived from the technique must be seen as potentially indicating conductivity highs which might be suitable targets for boreholes; sufficient traverses are needed across a structure to establish its extent because a single profile cannot provide that information; a spacing between readings should be established which is adequate to define the target properly; 10m coil spacings can give useful information by identifying anomalies due to conductive superficial clays, and also for siting dug wells.

Whilst it is clear that in many cases seismic refraction allows a more complex, accurate and reliable model of the geology to be constructed, much relevant information on geology can be obtained using methods which are simpler and cheaper in terms of field operations and interpretational expertise. For example, in areas of thin overburden EM methods can identify sub-vertical fracture systems more reliably, and much more rapidly. In thicker overburden, VES may be used to provide a rapid estimate (within certain limits of accuracy) of the depth to base of the saprolite. It is preferable to reserve seismic as a valuable tool for specific closely defined problems.

The amount and quality of geophysical survey which can be applied to the siting of rural water supply wells is severely restricted by economic factors, such as the pressures on consultants to identify sites at a rate of 2 to 3 each day, and to enter contracts based on maintaining this rate. It may prove difficult to persuade experienced contractors either to acquire new skills, to purchase new equipment or to consider further work on a given site, because in the past they have achieved a creditable success rate using their established techniques. However, it is difficult to escape the impression that such success may be despite the geophysical work, which is often forced on them by contractual arrangements. In other words the experience of particular geological environments and an intelligent inspection of the geology can provide an effective way of siting wells.

It has not proved possible to quantify aspects of interest to the hydrogeologist, in particular depth to water table, clay content, effective porosity or formation permeability. It might be possible using statistical approaches on large data sets to identify correlations between geophysical parameters and borehole data, such as formation type and thickness, depth to water occurrence, yield, specific capacity etc. Whilst the uncertainty associated with individual sites is likely to be relatively high, it may be possible to establish relationships by which to refine siting procedures locally.

The aquifer type determines the geophysical method which is most appropriate in each case, consequently it is necessary to have a clear concept of its type, thickess, depth and permeability. For example, we have distinguished between the sub-horizontal overburden aquifer and the sub-vertical fracture type. But in the former case we must be aware that the major contribution could derive from the highly fractured transition zone (saprock) and seismic refraction might prove to be the only reliable way of determining variations in its thickness. In the case of fracture zones which give rise to lineaments, if we are sure that we are dealing with an aquifer system of great vertical extent, then we could apply the interpretation methods for deducing dips; conversely if the aquifer is of limited depth, created by enhanced weathering along the fracture zone, then these approaches may be invalid. However, it may not be possible to use surface geophysical methods to identify individual fractures, which can make substantial contributions to the yield of a well.

The concept of success rate and its relationship with the amount of geophysics (and other disciplines) is widely discussed but is often very misleading unless the full range of contributory effects are considered. For instance in an 'easy' area, where the aquifer is well known, geophysics may not significantly affect the already high success rate. On the other hand, in unknown aquifers or 'hard' areas, where the success rate may be based on little data or be very low, the application of carefully chosen methods could greatly affect the results. This local gain may be swamped in the consideration of success for a region. It is also the case that the initial yield criteria may be misleading: it is important to consider depth to water, well recovery and drawdown effects and long-term yield (because minor structures might give a high initial yield which might decrease with time). In summary, it is necessary to use geophysics as appropriate rather than by rote, under constraint of overall survey costs and the importance of individual sites.

4. RECOMMENDATIONS AND CONCLUSIONS

Geophysical techniques can offer an invaluable addition to methodologies of siting wells. However, in order to make a significant improvement to the efficiency with which successful sites are identified the methods should be chosen to suite the geological environment, on the basis of availaible information, and economic constraints:

1. The emphasis in areas of shallow bedrock should be on profiling to identify fracture systems noted from aeriel photography.

2. Where the saprolite constitutes the most effectively exploitable resource and is more than 20m thick, then VES should be applied.

3. Where the resources of equipment or expertise are limited, it might be more effective to concentrate geophysical surveys in the more difficult areas, because success rates might be maintained elsewhere using geological approaches and experience.

4. A flexible approach to the application of geophysical surveys is required, and it should not be tied too closely to contractual arrangements.

5. Geophysics should not be undertaken in isolation but fully integrated with the results of geological, hydrogeological and drilling activities.

6. Previous interpretations should be reviewed continuously in the light of drilling results to establish:

   a. areas of greater or less difficulty

   b. areas with specific targets (for example: deep or shallow basement, dykes etc.)

   c. hydrogeophysical models to reduce the ambiguities in interpretations

7. An effective data-base allowing efficient archiving and retrieval would be a considerable help in implementing these reviews.

8. Where high yields are required a range of methods (such as resistivity and seismic refraction) is probably justified to provide complementary data for comparison.

Additional studies which would benefit the appreciation of geophysical methods in this environment include:

a. field trials with Time Domain Electromagnetic equipment

b. model studies using both analogue and mathematical studies of the horizontal loop electromagnetic response

c. compilation of reliable drilling data including geophysical logging with surface geophysical results

d. detection of fracture systems in relation to overburden thickness

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