British Geological Survey

REGIONAL GEOPHYSICS RESEARCH GROUP

Technical Report WK/88/10

Regional Geophysics Series

BASEMENT AQUIFER PROJECT

Geophysical studies to evaluate groundwater resources in crystalline bedrock terrains in Malawi, Sri Lanka and Zimbabwe, 1986 – 1988

R M Carruthers

Research and Development Project funded by the Overseas Development Administration

Natural
Environment
Research
Council

British Geological Survey
Natural Environment Research Council

Technical Report WK/88/10
Regional Geophysics Series

BASEMENT AQUIFER PROJECT

Geophysical studies to evaluate groundwater resources in crystalline bedrock terrains in Malawi, Sri Lanka and Zimbabwe, 1986 – 1988

R M Carruthers

Regional Geophysics Research Group

Keyworth, Nottingham British Geological Survey 1988

TECHNICAL REPORT WK/88/10

BASEMENT AQUIFER PROJECT

Geophysical studies to evaluate groundwater resources in crystalline bedrock terrains in Malawi, Sri Lanka and Zimbabwe, 1986 – 1988

R M Carruthers

British Geological Survey

Natural Environment Research Council

Technical Report WK/88/10

Regional Geophysics Series

BASEMENT AQUIFER PROJECT

Geophysical studies to evaluate groundwater resources in crystalline bedrock terrains in Malawi, Sri Lanka and Zimbabwe, 1986 – 1988

R M Carruthers

Regional Geophysics Research Group

Research and Development Project funded by the Overseas Development Administration

Bibliographic reference

Carruthers, R M. 1988. Basement Aquifer Project: Geophysical studies to evaluate groundwater resources in crystalline bedrock terrains in Malawi, Sri Lanka and Zimbabwe, 1986 – 1988. *British Geological Survey Technical Report* WK/88/10.

Keyworth, Nottingham British Geological Survey 1988

BRITISH GEOLOGICAL SURVEY

The full range of Survey publications is available through the Sales Desks at Keyworth and Murchison House, Edinburgh. Selected items can be bought at the BGS London Information Office, and orders are accepted here for all publications. The adjacent Geological Museum bookshop stocks the more popular books for sale over the counter. Most BGS books and reports are listed in HMSO's Sectional List 45, and can be bought from HMSO and through HMSO agents and retailers. Maps are listed in the BGS Map Catalogue and the Ordnance Survey's Trade Catalogue, and can be bought from Ordnance Survey agents as well as from BGS.

The British Geological Survey carries out the geological survey of Great Britain and Northern Ireland (the latter as an agency service for the government of Northern Ireland), and of the surrounding continental shelf, as well as its basic research projects. It also undertakes programmes of British technical aid in geology in developing countries as arranged by the Overseas Development Administration.

The British Geological Survey is a component body of the Natural Environment Research Council.

Keyworth, Nottinghamshire 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
☎ 01-589 4090 — Fax ☎ 01-584 8270
☎ 01-938 9056/57

64 Gray's Inn Road, London WC1X 8NG
☎ 01-242 4531

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

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

Bryn Eithyn Hall, Llanfarian, Aberystwyth, Dyfed SY23 4BY
☎ Aberystwyth (0970) 611038

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 HYDRO G — Fax ☎ 0491-32256

Parent Body

Natural Environment Research Council

Polaris House, North Star Avenue, Swindon, Wiltshire SN2 1EU
☎ Swindon (0793) 40101 — Telex 444293 ENVRE G — Fax ☎ 0793-641652

ABSTRACT

Geophysical surveys were undertaken over shallow crystalline bedrock in Malawi, Sri Lanka and Zimbabwe for siting exploratory boreholes and to assist with specfic hydrogeological studies. Resistivity, electromagnetic (EM), seismic and magnetic methods were employed with two main objectives: first, to check their reliability both in defining the depth to hard rock and in identifying local variations on the overburden/bedrock interface; second, to locate zones of weathering or of enhanced fracturing within the bedrock. These aims relate respectively to the siting of dug wells and higher yielding boreholes.

Results from detailed surveys around Chimimbe dambo, Malawi were consistent with borehole data although it was only by combining different techniques that a reliable overall interpretation was achieved. The analysis of single data sets in isolation can be subject to large errors. EM traversing characterized the dambo and interfluve deposits and also identified a zone of enhanced weathering on the southeast margin of the dambo. Resistivity soundings could not be analysed unambiguously but a sequence comprising three main units was usually modelled. Seismic data also failed to resolve the weathering profile in detail but a similar type of depth section was identified, showing highly weathered material succeeded by more compact weathered rock above a partially fractured bedrock. The depth to hard rock was shallowest beneath the ground occupied by the dambo itself though significant zones of weathering did occur below this; on the interfluve the transition from more weathered rock to fresh rock with occasional fractures was much sharper. Colluvium was distinguished from dambo deposits within the upper part of the sequence and there were indications of marked variations both in the nature of the bedrock and in the derived weathering profile over different parts of the interfluve.

Surveys in Sri Lanka failed to confirm that 'breaks' in resistivity sounding curves relate directly to underlying fractures but the overall shape of the curves and the total conductance implied for the regolith are relevant to site selection. Curves generated by computer from 2D resistivity models imply that the main cause of irregularity must lie within the saprolite; fracture zones may be a contolling factor. The lack of EM signatures attributable to steeply-dipping fracture zones (as found in Zimbabwe) may reflect higher conductance in the regolith or a more complex system of fracturing here. Core drilling showed that numerous fractures occur, albeit with decreasing frequency, to depths of more than 40m; such fractures do not necessarily carry water.

Differences between interpreted depth to hard rock and drilling data were typically 10-30%, with the geophysical data implying a deeper bedrock in most cases. For dug well construction it is important to distinguish those values typical of weathered rock from the lower resistivities and velocities which relate only to the softer, looser material above. Direct comparisons with borehole logs are difficult because the geophysical methods sample a much larger volume of ground which may not be fully represented by a narrow diameter hole. Geophysical surveys proved most successful in marginal areas as a means of rejecting large tracts of ground as unsuitable for exploratory drilling and for detecting lateral variations within the weathering profile; resistivity soundings are best suited to proving more extensive areas of deeper weathering.

Seismic methods are not recommended for routine surveys and an emphasis on EM traversing supported by resistivity sounding is usually more appropriate. Geophysical methods can improve borehole success rates but they are far from being infallible; surveys must be set within a hydrogeological context for the best results to be obtained.

CONTENTS

FIGURES

Front cover: photograph illustrating geophysical logging in progress at a typical rural water supply borehole site in the south of Sri Lanka.

NOTE: all Figures are to be found at the back of the report, following the text.

1. INTRODUCTION

1.1 Background

This technical report covers geophysical investigations related to the Basement Aquifer Project in the period 1986-87; previous reports (Carruthers,1985 and Carruthers,1986) describe the ideas underlying the approach to the studies, and the results of the fieldwork from which the programme described here developed. The geophysical results are discussed in some detail and a summary of the main findings is provided at the end of each section. The Research and Development project, which is funded by the Overseas Development Administration (ODA) of the British Government, is based on a multidisciplinary approach which includes remote sensing, geochemistry, geomorphology, core drilling and sample analysis, database compilation and analysis of information from regional borehole records, as well as borehole and surface geophysics. These other aspects of the project are covered in separate reports.

The primary objectives of the studies are to get a better understanding of the occurrence of groundwater, and of the most efficient means of locating and developing this resource in terrains where crystalline bedrock lies at shallow depths, often within 20m of the surface. The aquifer is typically both low-yielding and patchy which makes it suitable for development only as a protected source of water for a rural population; in some areas the supply is adequate for supplementary irrigation purposes or small town schemes but the conditions for this are usually site specific and related to major fractures or zones of deeper weathering.

Field investigations have been concentrated in East-Central Africa and in Sri Lanka to provide data from a variety of environments without spreading the effort too thinly. The combination of unreliable rainfall and a shortage of surface reservoirs, together with the pressures of increasing population, the need to develop less favourable districts and a desire not only to maintain but to improve the basic standard of living in such countries, ensures a growing demand for supplies of potable water.

A borehole yield of about 0.1l/s is usually considered sufficient to justify installation of a handpump for village supplies but, despite such a low threshold level, there are many areas where the selection of drilling sites on the basis of local preference and convenience leads to a high failure rate - of perhaps 50% or more. The application of basic hydrogeological criteria in conjunction with an assessment of aerial photographs will usually reduce the number of dry holes but better results are often achieved when geophysical surveys are undertaken also.

Most development programmes rely on boreholes drilled to intersect either the permeable zone which may occur at the base of thick saprolite, or fractures within the bedrock. This is partly because the potential of the upper aquifer itself has not been fully recognised but other important factors are the speed of drilling in comparison with manual construction of a dug/collector well, the added protection from pollution provided by boreholes, and the complete absence of a shallow aquifer in some districts. Surface geophysical techniques can assist site selection by mapping variations in the depth to bedrock and by giving information on the nature of the overburden; they are not usually capable of defining the depth to the individual fractures (typically only a few millimetres in width) which yield water and their application is to locating the broader zones of weakness within which fractures are more frequent. Where these zones are steeply dipping they can be associated with a thickening of the overburden and it is this combination which gives the clearest geophysical response; if the upper bedrock/weathered rock is highly fractured over a wider area it may be distinguishable as a discrete sub-horizontal layer. The extent to which this type of anomaly can be related to structural features identified on aerial photographs and to the more successful borehole sites was the subject of studies undertaken in Zimbabwe (Smith and Raines, 1987 and 1988).

1.2 Geophysical techniques

Electrical resistivity techniques respond directly, though not unambiguously, to the presence of subsurface water and they have been used as an aid to borehole siting in this type of terrain for many years. Their advantages are that the equipment can be relatively simple, cheap and easy to use, and that the results can be assessed qualitatively in the field without the need for sophisticated or time-consuming interpretation procedures: the empirical relations established by experienced operators may prove as successful in practice as results based a more rigorous analysis of the data but without the advantage of local knowledge.

Additional resistivity results were obtained for these studies using the ABEM Terrameter SAS300 system which belongs to the latest generation of micro-processor controlled instruments. Such equipment has been provided by aid programmes to many developing countries in recent years for this type of work. 'Sounding' data were collected with an expanding Schlumberger array (ESA) type of electrode configuration; this is generally to be preferred over the Wenner array from both practical and theoretical considerations. Interpretations of these results were based on forward modelling procedures such that a curve computed for a specified set of layered earth parameters is compared with the field data; adjustments to the model needed to obtain a good match are deduced by the operator and a new curve computed accordingly.

Routine resistivity surveys undertaken for borehole siting tend to be the minimum necessary to obtain a response which is considered favourable in the local context; they are not designed to identify the best locations or to gain any information on details of the geological setting. This is understandable given the need to select sites quickly and cheaply but as a result, and notwithstanding the large amount of resistivity data that has been collected in numerous countries, it is difficult to reach any general conclusions on their effectiveness, a difficulty compounded by the absence of both formal interpretations and subsequent assessment of the data in relation to drilling results. Computer database systems have been introduced in Malawi, Zimbabwe and Sri Lanka as part of the project, to see if statistically significant trends can be inferred from existing data. Setting up the framework for such systems provides an opportunity for the local survey departments to assess how they collect and review data so that they can implement better procedures in future even if the historical records prove unsuitable for analysis.

Electromagnetic (EM) equipment also provides information on the variations in resistivity within the ground although its response is usually considered in terms of conductivity, numerically equal to the reciprocal of the resistivity. EM methods have some inherent advantages and with advances in instrumentation they are now being applied routinely to groundwater surveys, more especially as an efficient means of traversing to delineate localized features which may be related to deeper weathering or underlying fracture zones. One of the problems with resistivity data is their poor resolution of lateral changes: the length of the array is relatively large in comparison with the effective depth of investigation and any variations in layer thickness or resistivity over this distance tend to be averaged out.

EM methods respond preferentially to conductive zones within a resistive environment and characteristic anomalies are produced in profiles crossing narrow, steeply dipping conductors. Thus, instruments utilizing VLF (very low frequency) transmissions or the moving-source (Slingram) systems can provide information on both the layering down to bedrock, which is related to the upper aquifer, and on the presence of potentially water-bearing fracture systems within the bedrock itself.

The Geonics EM34-3 conductivity meter is essentially a development of the type of moving-source equipment familiar from mineral exploration and also used to a limited extent in groundwater surveys. It operates at fixed frequencies and gives information to a depth similar to the separation between transmitter and receiver coils; this spacing can be 10m, 20m or 40m, covering the range of primary interest for mapping variations within the regolith. Apparent conductivity values read directly from the meter are a reasonable guide to ground resistivities in the range 10-200ohm.m. Six measurements can be obtained by taking readings with the coils both horizontal and vertical at each coil spacing for a fixed central point. While such data are inadequete for interpreting the thickness of different layers in any but the simplest of conditions they help qualitatively in discriminating between near-surface and deeper effects. An equivalent resistivity sounding taken with an expanding Schlumberger array (ESA) would comprise perhaps twenty data points with a maximum current electrode separation of 200m. Standard moving-source EM systems provide a greater range of coil spacings and operating frequencies; these may be of advantage in fracture zone detection but such instruments are not calibrated for conductivity mapping and they may be less sensitive than the EM34 in the low conductivity range.

The latest generation of time-domain EM equipment provides the means to obtain a complete set of 'sounding' data within the required depth range of 5-60m whilst operating in a traversing mode. This technique has yet to be tried in the field but it represents potentially a more significant step forward than the introduction of the EM34. EM soundings are intrinsically less susceptible to equivalence problems with the high-low-high (H-type) resistivity sequence commonly found in basement terrain but they would ideally be combined with standard resistivity data. These EM techniques will not be effective where apparent resistivities remain above about 200ohm.m.

Seismic methods give information on formation velocity which is strongly influenced by porosity and the degree of compaction; thus they can be used to distinguish between for example sands, clays and bedrock. As the physical properties being measured are different, the results from seimic and electrical surveys are complementary and the additional information will usually enable a better overall interpretation to be made. Changes in velocity can often be mapped in some detail and the interpretation procedures lead naturally to a two-dimensional model in terms of layer thickness and velocity which will give the depth to bedrock and show the location of fracture zones. In general, seismic surveys are capable of giving better definition of the bedrock configuration in comparison with electrical methods but there can be problems in interpretation if the layer velocities are not clearly defined.

Seismic refraction surveys have been undertaken successfully on a small scale despite the reservations of additional complexity and cost which are usually associated with them. Omorinbola (1983) and Ovaskainen (1984) describe the application of seismic refraction techniques to groundwater studies in areas of crystalline basement terrain. The former gives an example of a time-distance plot of the first refracted arrivals from Nigeria: this is a 'classic' three-layer case with straight line segments defining a superficial zone, 6-8m thick at 0.9m/ms, the base of which is set at the water table; the saprolite with a velocity of 1.65m/ms to a depth of 20-25m; a refractor of 3m/ms representing weathered bedrock. Both sources show a good statistical correlation between their interpretations and drilling results for bedrock depths in the range 15-50m.

Seismic refraction data were collected on this project using signal enhancement systems (a 24 channel ABEM Terraloc seismograph was used in Malawi; a 12 channel OYO instrument was used in Sri Lanka). Geophone spacings were 3-6m and the separation between 'shot points' was restricted to 30-50m in order to monitor lateral variations within the upper layers. There is usually some conflict between maintaining adequete controls on the data and the time available to cover the ground: for this survey the emphasis was on evaluating the resolution of the technique rather than on undertaking a large-scale survey.

The two energy sources employed for the main survey were a 14lb sledgehammer and a locally constructed weight-drop device. The latter proved to be very cumbersome and little more effective than the hammer because the 40lb weight fell from a height of no more than 2m. There was insufficient time to organise a better system or to arrange for the use of explosives and so most of the data were collected with the hammer. While this was adequete over shallow bedrock, a more powerful source was needed to improve the signal strength where the overburden was thicker and less consolidated. An inertia switch on the hammer generated the shot-instant time reference signal but with the weight-drop, and after the switch had failed, a geophone planted next to the shot point had to be used to trigger the seismograph. As the geophone was sited 0.5-1m from the source, this method introduced a variable time delay of several milliseconds for which a correction had to be made.

A common problem in shallow seismic surveys is that of defining the velocities within the upper layers when the interfaces are irregular: of the various techniques that have been developed for interpreting such data some form of delay time analysis is usually preferred (Sjogren, 1984). The deep refractor can be defined over the full spread length by offsetting the shot point sufficiently but the range over which first arrivals are recorded from layers above this tends to be much more restricted.

If the refractors can be approximated by uniform layers their velocities and depths may be defined beneath shot points by a standard intercept time analysis and interpolated to the intervening geophone positions; otherwise variations must be monitored by reducing the distance between shot points. Most of the interpretations described in this report were derived from intercept times on the assumption that the refractors could be approximated by plane, dipping interfaces between adjacent shot points, a distance of about 35m. Some values were also obtained using delay time analysis for comparison.

Tests were made using shear waves rather than compression waves for collecting the seismic data as a means of providing additional information on the lithology of the saprolite and the occurrence of fractures in the bedrock. Shear waves invariably have a lower velocity within any given type of material and so they will not usually be recorded as first arrivals but the compression waves can be suppressed by preferentially generating horizontally polarized shear waves and using special geophones.

Variations in magnetic anomaly are usually associated with the presence of one of a small number of minerals, of which magnetite is the most common. While the magnetic response does not usually relate directly to aquifer properties it can be used to map specific rocks and structural features, such as dykes and fractures, which control groundwater occurrence and the anomalies can also be interpreted to provide an indication of depths to bedrock. The proton magnetometer provides a direct read-out of the earth's total magnetic field (more correctly referred to as flux density) and the only correction required is to allow for the diurnal variation in the external component of the field.

1.3 Programme of work

Previous geophysical surveys had shown that large areas were unfavourable for either wells or boreholes due to the high resistivity of the ground; however, they were less successful in confirming usable sites, especially in the more marginal environments where unexpectedly low overburden resistivities were related to clays or where hard rocks of relatively low resistivity occurred at shallow depths. The reasons for the discrepencies between exploratory drilling and resistivity results were not fully understood and there was clearly a need to have reliable borehole control against which to assess more intensive geophysical surveys. Detailed studies of the nature of the uppermost part of the aquifer and its interaction with dambos had been started in 1985 at a site in Malawi and geophysical surveys were written into the continuing programme of work here, for correlation with drilling information in particular.

Surveys in Sri Lanka were to encompass both the mapping of variations in the depth to bedrock and an assessment of the amount of information on fracturing that was contained in depth sounding data. These studies were undertaken in collaboration with staff of the Water Resources Board in Sri Lanka and made use of their existing equipment, following on from the contacts established during the short appraisal visits of previous years. Two topics had been chosen as being of particular relevence to the local situation. The first concerned the siting of dug wells and the ability of geophysical surveys to map bedrock relief with sufficient accuracy either to check that the soft saprolite is thick enough to justify construction of a well or, more specifically, for locating the bedrock depressions which will ensure that the maximum amount of water is available in periods of drought. The second related to the cause of the discontinuities observed in resistivity sounding curves, which have been used locally with some success as an indication that the bedrock is fractured. Apart from more detailed surveys to define the extent of these anomalies in the field, the influence of fracture zones was to be modelled theoretically by means of a two-dimensional computer programme.

2. MALAWI

2.1 Previous work

The limited amount of fieldwork carried out in the earlier phases of the project had been confined mainly to resistivity soundings and traverses with the EM34-3 conductivity meter to locate sites suitable for collector wells - the name given to dug wells from the bottom of which holes are drilled radially to a distance of perhaps 30m in order to provide higher yields. These wells were to be new constructions rather than drilling within existing dug wells to improve their performance. Information was required mainly on the depth to hard rock, to determine if a well could be sunk deep enough to give adequete storage and saturated thickness; indications of more or less permeable zones within the overlying material would also have been useful.

Similar work in Zimbabwe had been especially concerned with ensuring that the wells could be taken to a sufficient depth before encountering hard rock. It was expected that the overburden thickness in Malawi would be more than enough for wells to be dug but that yields could be impaired by the presence of clays within the well section. Shallow bedrock did occur at several sites though as these localities had been selected for investigation because of unsatisfactory drilling results in the past they may not have been representative of the basement terrain.

No exploratory drilling was done during the course of the survey work and the resistivity/EM data had to be assessed in isolation when recommending potential sites for further investigation. While the geophysical results did provide a good indication of changes in local conditions they could not in themselves be relied on for accurate predictions of layer thicknesses or lithologies and they needed to form part of an integrated exploration approach (see also Section 4).

Proposals were put forward at this time for core drilling through the regolith along a section including dambo and interfluve settings. Preliminary data were therefore collected from resistivity soundings and traversing with an EM34-3 and a magnetometer in the chosen area near the head of Chimimbe dambo. Some additional work was done after the borehole site locations had been revised and ESA were available for most of the points drilled subsequently by coring and/or percussion techniques. Several interesting points emerged from this survey - as described in section 2.2.1 - including the discovery of a thick conductive zone between the active dambo and typical interfluve regolith to the southeast. Given the opportunity to integrate the data with the further studies, such as core drilling, borehole logging and piezometer installation, planned for 1986 it was decided that surveys to evaluate the effectiveness of the seismic refraction technique should be undertaken in the same area.

2.2 Chimimbe dambo

Chimimbe dambo lies about 60km south of Lilongwe in a region of low, undulating relief within the Linthipe plains. The main area of investigation was towards the head of the dambo with the location of the geophysical surveys and boreholes as shown on the site plan in Figure 2.1.

Precise description of the various components of the weathering profile lies outside the scope of this report as they cannot be resolved in detail using surface geophysical techniques; the terminology adopted here may conflict in points of detail with the more definitive texts resulting from other aspects of the project. Regolith is taken to cover the entire weathered section; both saprolite and overburden refer to highly weathered material, essentially residual sands and clays which may include dambo clays and colluvium; weathered and fractured bedrock encompasses a range of conditions characterized by varying degrees of competence but retaining hard rock as a major constituent.

2.2.1 Results from traverse T1a/T1b

The initial EM traverse (ET1a) started on the northwest flank of Chimimbe dambo and extended for a distance of 2000m to the southeast, onto the higher ground of the interfluve. Readings were obtained using the six standard combinations of coil spacing and orientation and, as shown in Figure 2.2, they produced characteristic responses over the dambo, palaeodambo and interfluve deposits. Although the most diagnostic variations were given with the 20m coil spacing it is necessary to have the values at 10m and 40m separations also in order to confirm the way that conductivities vary with depth.

All the conductivity values tend to converge to a level of 5-10mS/m over the interfluve to the southeast; higher readings at the northwest end of the traverse are attributed to their still being in the transition zone near the margin of the dambo. The resolution of the EM34-3 is relatively poor at these lower conductivities but the fact that horizontal coil readings at 10m and 20m spacings were slightly greater than their vertical coil equivalents is evidence of a less resistive zone (?with higher porosity, clay or moisture content) in the depth range 5-15m, sandwiched between a resistive upper layer (?with drier, quartzitic or indurated material) and bedrock.

On reaching the lower-lying, open ground of the existing dambo conductivity values measured with the 10m coil spacing increased rapidly to reach a maximum of more than 50mS/m in the vertical configuration; vertical coil readings also increased at 20m and 40m spacings, but to a lesser extent. These results show the presence of a superficial layer with high conductivity; this correlates with the cover of grey dambo clays in which smectites predominate. The overall thickness of saprolite appears to be less here than outside the active dambo as the values obtained with the coils horizontal are if anything slightly reduced despite the influence of the conductive cover.

Resistivity sounding RS1 near the centre of the dambo confirmed these findings and the interpreted model (see Figure 2.3b), showing conductive clays to nearly 3m and saprolite of low-intermediate resistivity to 10-13m above resistive bedrock, was in good agreement with the subsequent drilling data from the same site (C1). The resistivity curve does not show a clear change distinguishing saprolite from the substrait and its gradational form is consistent with there being relatively fresh, shallow bedrock within which zones of weathering are developed locally along fractures or micaceous bands. The core samples between 3.7m and 15.5m depth taken from the nearby site A1 have been described in terms of hard saprolite and rock with four separate bands of more weathered material, 0.3-0.7m in thickness; very hard, nearly fresh rock with fractures predominated below about 10.5m. The more complex model shown in Figure 2.3 was derived from an automatic curve-matching programme; this detail can only really be justified if additional soundings give the same result, undisturbed by lateral effects or local inhomogeneity, although it is consistent with the borehole logs.

The EM34 profiles were unusually noisy over the dambo, more especially with the horizontal coil configuration. Orientation or sensitivity errors were not a problem here and it seems that the response reflects the nature of the bedrock profile: that is, a shallow, irregular depth to rock associated with fractures and clay infill. The horizontal coils may be responding to steeply dipping multiple fractures extending to depth within the bedrock, but coupled with a local increase in the thickness of overburden.

Another general feature of the EM34 data is the asymmetry in the conductivity profile, with a more rapid change over the northwest margin of the dambo. This may be due in part to a correlation with topography but it also suggests a lateral migration of the 'active' dambo from southeast to northwest with the possibility of a more permeable zone on the northwestern side. Results from Chikobwe dambo, north of Mponela, were very similar except that the bedrock underlying the dambo showed a lower resistivity: the same asymmetry was observed and, on the above hypothesis, any palaeodambo deposits should be developed preferentially to the northeast. Conductivity values recorded over the centre of the dambo were also higher, suggesting that the grey clays are thicker here than at Chimimbe dambo; this was confirmed by both resistivity ESA and drilling data.

The most unexpected results from the EM traverse were observed to the southeast of the dambo where the values were higher for all the coil configurations over a distance of about 600m. Readings obtained with the 40m horizontal coils showed only a modest change but other values exceeded 25mS/m and there was no marked difference according to coil orientation or separation. This type of response can only arise from a relatively thick conductive sequence which correlates here with the zone of palaeodambo and its underlying soft saprolite. It proved very difficult to obtain good resistivity sounding data within this area as the indurated nature of the upper layer greatly restricted the input current. Its high resistivity also tended to suppress the response from the saprolite, increasing the range of equivalent solutions. The interpretations for RS2 suggested that a clay-rich zone extends to a depth of 15-20m here with somewhat lower conductivities reflecting a difference in the mineralogy between active dambo and palaeodambo clays near the top of the sequence.

Borehole C2 lay beyond a slight topographic rise marking the edge of the zone of thick clay/soft saprolite, where conductivity values were decreasing again quite rapidly to levels more typical of a regolith response. The change in conditions was confirmed by RS3 beside C2 and only 70m southeast from RS2. The surface layers were less resistive, but thicker, and the conductance (evaluated as the layer conductivity multiplied by its thickness) of the saprolite was reduced by about 50% compared with values from RS2. While lateral variations may have distorted the sounding curve obtained here, it was not clear that the depth to bedrock had changed. The interpreted depth to bedrock as defined by the resistive substrate could be varied over a relatively wide range: by splitting the intermediate layer into two components (see Figure 2.4) a thinner clay-rich zone to about 10m depth would be expected to overlie either weathered rock or bedrock with a conductive matrix extending to more than 30m; the simpler model implies a sharp transition from saprolite to bedrock at a depth of about 15m. EM34 data are more consistent with the latter model though the discrimation is not great.

A magnetic profile, MT1a, for the same line indicated anomalies at the margins of the dambo, over the centre of the thick clays and at the transition to more resistive regolith (see Figure 2.7). The anomalies may not originate entirely from near the surface and variations deeper within the bedrock may be a factor. Susceptibility measurements on core samples gave the highest response, of more than 0.003 SI units in the top 6m of colluvium over the interfluve, with the dambo clays being only weakly magnetized. The absence of any systematic increase in susceptibility through the saprolite may simply reflect a limited change in volume prior to the formation of colluvium but the concentration of the magnetic minerals in the uppermost layer may be a secondary effect. Susceptibility data from the core of A6, closer to the dambo, showed a tendency for values to reduce upwards through the saprolite but again they increased in the sands and lateritic sandy clays above the water table. Zones of higher susceptibility were observed in the deeper part of the saprolite and also locally within the hard rock.

The original traverse crossed the dambo more obliquely than the second, T1b, which followed the line of shallow drilling from its north-northwest side as far as the site for borehole C2. There is little difference in the general shape of the profiles although the measured values were generally higher and the transitions more sharply defined on T1b (see Figure 2.2c).

Seismic data were obtained from orthogonal spreads ST1b-1 by boreholes C1/A1, within the active dambo. The thin dambo clays are not resolved with a geophone spacing of 3m although the models can accommodate 1-3m of material with a velocity of about 1m/ms below the 1m thick superficial layer. Beneath this, the average velocity increases to 2m/ms, corresponding to the softer saprolite and the low-intermediate values of the resistivity sounding. Variations of velocity within this layer are taken to represent travel paths following discontinuous bands of less weathered material.

Another interface, interpreted at a depth of 10-15m, relates to the fresher rock recorded in the borehole logs: its velocity of 3.5m/ms is too low for massive bedrock and indicates that the material beneath is weathered or highly fractured. The depth range arises from the apparent easterly dip on this interface though the refractor may well not follow a lithological boundary. Spreads located further northeast (S-6 and beyond), 'downstream' within the dambo, produced similar layer thicknesses but with a systematic increase in velocity suggesting more massive rock at higher levels in the sequence: 2km from C1/A1 the refractor velocity of over 5m/ms at an interpreted depth of 15m shows that the fresh bedrock here has few fractures.

Seismic data collected on ST1b-2, from spreads over the zone of thicker clays deduced from ET1b, covered a distance of 560m to end just beyond borehole C2. They were interpreted in terms of three continuous layers beneath the low velocity superficial zone although the section shown in Figure 2.5 represents a compromise which smooths out inconsistencies within the derived models. The upper layer has a velocity of 1.6-2m/ms which is typical of clay-rich material and attributed here to soft saprolite together with any overlying dambo clays; the decrease in velocity and increase in thickness to 20m or more to the southeast indicates a more advanced state of weathering and corresponds with the onset of higher electrical conductivities. There is good agreement between this layer and the saprolite beside C2, with its lower interface rising to the southeast as would be expected both from the drilling at A3/A6 and the conductivity profile. Of the three boreholes A3, A6 and C2 which were drilled within 20m of each other, C2 gave a shallower depth to hard saprolite/weathered bedrock with the interface at 18m as against 23-25m for A3/A6. This variation may be exaggerated by a local feature within the weathering profile but it is consistent with the observed decrease in conductivity towards C2.

Near the centre of line ST1b-2 there was evidence of an additional layer of low velocity material, attributed to sandier palaeodambo deposits reaching a depth of perhaps 5m; these might be more extensive than shown as the 6m geophone spacing used here is relatively coarse. The layer with velocities of about

3m/ms beneath the saprolite is taken to be a lateral extension of the deepest refractor picked by C1/A1. Its occurrence at shallower depth coincides with lower conductivities near the margin of the dambo where it is again taken to represent weathered, fractured bedrock. The only check on the reality of this layer is provided by C2/A3, though the increase in velocity across an anomalous zone within 100m of these boreholes suggests that there is a rapid lateral change either in its mineralogy or in the degree of weathering: the sequence with distinctive bands of softer material found at A1 is probably replaced by a more compact weathered rock with a sharper transition to fresh bedrock in this area.

At C2, the top of the layer of intermediate velocity correlates closely with the change from saprolite to weathered bedrock (or from soft to hard saprolite as described in the borehole log) at 18m and the deeper interface is consistent with the level of fresher rock. The slightly lower velocities of 4-4.5m/ms found further northwest are usually associated with fractured or partially weathered rock but they may also indicate a change in lithology beyond the lateral discontinuity noted above. Velocities from minus time plots were generally higher but they gave few indications of the values exceeding 5m/ms to be expected from fresh, massive granite.

The depths to the lower interfaces are not reliable as the interpretations are distorted by irregularities over the distance between shot points, giving rise to errors in both velocities and the intercept times needed for the depth calculation; over most of the line the average depth to fresh bedrock appears to be 25-30m along a surface showing undulations with an amplitude of about 5m, and only near the ends of the line does the depth reduce sytematically.

2.2.2 Results along traverse T2

Line T2 crossed the dambo some 500m further northeast from the line of core drilling. The traverse was offset from T1 partly to avoid interference with concurrent drilling activities and also as a check on the continuity of the section down the dambo. Thus, there was less geological control on the geophysical interpretations although shallow, augered boreholes did indicate subsequently the depth to the boundary between dambo clays and saprolite.

The EM results are shown in Figure 2.6 for comparison with lines T1a/T1b. The conductive zone of thick clays and saprolite found to the southeast of the dambo on T1a/T1b is more subdued here and represented by a 300m section with vertical coil conductivities of 15-20mS/m; this may reflect thinner palaeodambo clays in the top 5-7m of the sequence rather than much difference in the underlying saprolite, though the reduced values with 20m horizontal coils imply that bedrock is shallower. Conductivity values are similar over the dambo itself with the addition of a distinct channel of superficial clay inside its southeastern edge on T2. Features of the magnetic profile can also be correlated with MT1 given that the response is more subdued (see Figure 2.7). The anomaly high near the southeast margin of the dambo is still apparent but variations found to the northwest on line T1a have disappeared completely and it seems likely that they are developed locally, at shallow depth.

Seismic measurements were taken as a continuous profile which covered a distance of nearly 1500m, extending from higher ground on the northwest flank of the dambo to the colluvial soils in the southeast. It is possible to pick up the major features which distinguish the dambo from the adjacent regolith but as before the lack of precision in the calculation of velocity and depth makes any detailed assessment of the lithological implications unreliable. The time-distance data obtained from Chimimbe dambo were internally consistent, implying that the first arrivals had been picked correctly, but the points did not obviously define the velocity layering. There was evidence of intermediate layers but the limitations of data quality and coverage meant that a full delay time analysis was unjustified. Bedrock velocities calculated from the 'minus times' of reversed spread data usually exceeded those for the deepest layer of the intercept time models but it is not clear that this distinction is real. A difference might be expected on the basis that the higher velocities refer to data from larger shot-geophone separations and thus potentially from greater depth; however, the high degree of parallelism between arrivals from different offsets to the same spread did not support this idea in general.

The depth section shown in Figure 2.5 is derived mainly from intercept time analysis and it smooths over the inconsistencies between the results obtained using different pairs of shot points. The northwest end of the traverse is on rising ground, 200m from the margin of the dambo and nearly 4m above the lowest point of the section. This is within the transition zone between the type of response characteristic of either a dambo or interfluve sequence as indicated by the conductivity profile, and the thickness of the saprolite is still increasing away from the dambo; an underlying velocity of 2.6-2.9m/ms is taken to represent highly weathered rock or hard saprolite. The bedrock high located near 750NW is associated with a conductivity anomaly low and it probably represents a more resistant band which could influence the circulation of any deeper groundwater moving towards the dambo. A pocket of thicker clay occurs at the margin of the dambo with the bedrock surface appearing to dip underneath it to the east, but on reaching the dambo, near 625NW, there is a marked change as the saprolite thins and less weathered or fractured bedrock appears at shallow depth.

The weathering profile across the dambo on this traverse is attenuated in comparison with T1. Beneath the dambo itself the presence of harder bands within 3-8m of the surface does not preclude the possibility of deep weathering but weathered or fractured rock would be expected rather than softer or layered saprolite of the type found at A1/C1. There were also arrivals from relatively fresh bedrock within 20m of the surface. While the seismic velocities do not distinguish soft saprolite from the mineralogically distinct clays referred to as dambo deposits, the values in excess of 3m/ms recorded at shallow depth here must derive from a more consolidated formation. Dambo deposits are apparently restricted to the superficial layer on the northwestern side of the dambo but there may be a hidden zone of low to intermediate velocity to a depth of as much as 5m. Subsequent auger drilling suggested that the clay/saprolite boundary within the dambo was at 3.5-4m though this was not defined fully due to the slow pentration rate.

Minus time velocities tend to be lower beneath the dambo itself and they show lateral variations which might relate either to lithology or to the degree of fracturing or jointing within the bedrock: this extra detail is available as the refractor is closer to the surface here. The occurrence of a bedrock high is expressed in both the seismic and conductivity data near 200NW, mirroring the feature on the opposite margin except that it now lies within the active dambo. The saprolite thickens again southeast of the dambo but the distinctive zone crossed on line ST1b-2 is no longer apparent either in the velocities or the depths calculated for the refractor underlying the clays except in isolated pockets; bedrock velocities are also consistently higher and the values close to 5.5m/ms suggest a less fractured or perhaps a more granitic rock.

There is still a distinction to be made between the nature of the saprolite nearer the dambo and that further southeast. One change occurs close to 100SE where the saprolite starts to thicken; the uppermost layers are becoming more resistive as seen in the 10m vertical coil readings with the EM34 while the horizontal coil values remain relatively high. This zone extends to about 325SE and it is probably related to the palaeodambo environment identified on T1a/T1b. Auger drilling at the point 175SE penetrated a palaeodambo sequence above saprolite to a depth of 6m. Beyond 350SE there is a decrease in velocity in the upper layers to values typical of colluvial cover; velocities within the saprolite are also lower, suggesting a change/reduction in clay content or a looser texture.

Two seismic spreads offset 200-300m either side of the centre of the dambo at a point about 1.5km further northeast from T2 gave quite dissimilar results, confirming the continuation of the asymmetric nature of the weathering profile in relation to the active dambo. To the southeast, 6m of saprolite were underlain by weathered bedrock, with fresh rock at a depth of about 20m. On the northwest flank of the dambo the saprolite was 15m thick; beneath this the relatively low velocity of 2.5m/ms suggests highly weathered rock and fresh bedrock was not detected.

2.2.3 Results from borehole sites

The results obtained near boreholes C1/A1-2 and C2/A3/A6 were generally consistent with the traverse data, as discussed in the previous sections; ESA and seismic data from the interfluve sites (see Figures 2.8-2.12) were notable for their lack of similarity over what appeared superficially to be uniform ground.

Resistivity soundings implied that significant variations occurred in the nature both of the bedrock and the saprolite derived from it. Evidence from the interfluve sites and elsewhere shows that bedrock can have resistivities of less than 100ohm.m and so it is not always possible to distinguish saprolite unequivocally. Thus at B3/C3 (RS4) there was either a conductive bedrock or a further zone of weathering beneath the hard rock encountered in the drilling. At C4 (RS5) the sequence, including the saprolite, was unusually resistive, while at B4/C5 (RS6), further to the southeast, the response was similar to that obtained over the palaeodambo clays of Chimimbe. RS7 was beside the next dambo system (occupied here by a stream); although of the same form as RS1 it showed a somewhat more resistive sequence, without the highly conductive cover.

Seismic data from the interfluve sites were suspect because of the restricted power of the energy source and the consequent uncertainty that true first arrivals had been timed; the deterioration in energy transmission is in itself an indication of the change in the nature of the regolith between the palaeodambo and the higher ground of the interfluve. Low velocities within the upper layers are clearly expressed in the time-distance plots with much longer travel times through the overburden.

At site S-7, between boreholes C2 and C3, the saprolite was divided into two zones: an upper layer 7-8m thick with a velocity of 1.3m/ms, typical of sandy clay or colluvium, and a layer of 1.8m/ms to a depth of about 25m; below this there was weathered rock with bedrock at an undetermined depth. The small increase in the thickness of saprolite indicated between this site and C2 is probably more than offset by an increase in elevation, to leave the surface of the weathered bedrock dipping down slightly towards C2. The EM34 traverse ET1b did not extend to this site but offset data from ET1a imply that the saprolite has a low conductivity here and that it correlates with C3 rather than C2.

There was little evidence of a zone of weathered rock around sites C2/B3/A4/A5 and although a 'hidden' layer of intermediate velocity could be present, a rapid transition from saprolite to fresh rock is predicted. The saprolite could be distinguished from the upper layer which had a velocity of only 0.7-0.8m/ms; this suggests a sandier, less consolidated layer attributable to colluvium lying above the saturated zone and beneath a thicker superfial cover. The saprolite, from a depth of 5-8m, was poorly defined and the range of from 1.1m/ms to 1.9m/ms in apparent velocity suggests that lateral variations were a factor. The underlying bedrock refractor also showed marked differences: the minus time velocities were consistent at 5-5.35m/ms from the two orthogonal spreads but the interpretation produced a large difference in depth, with a dip to the northwest. In view of the uncertainties regarding velocities and the number of layers present, it was surprising that the depths to bedrock given at the centre of the spreads, beside the boreholes, came out to be consistent with the drilling results at 17-23m. The best fit was obtained with a velocity of 1.6m/ms for the lower saprolite, with some evidence of a discontinuous additional layer of about 1.2m/ms which has to be added to give an interface near 11m. The resistivity soundings at this site also gave anomalous results suggesting that thicker saprolite to the north and west is probably associated with a change in bedrock lithology.

The borehole at C4 was completed at relatively shallow depth within quartzitic rock; as residual quartz can occur at higher levels this may not represent the bedrock. Two layers were distinguished in the upper part of the sequence, with velocities of 0.6m/ms and about 1.1m/ms, separated at a depth of 5-6m; the combination of low velocity and high resistivity indicate a relatively low clay content and sandy, unsaturated colluvium overlying soft saprolite would be expected here. An interpretation using what were inferred to be the true first arrivals from a deeper interface gave a depth of 14m to 'bedrock' with a velocity exceeding 5m/ms: these signals were weak, as would be expected from a thin band of harder rock. The strong later arrivals could also be interpreted in terms of an interface at 14m, but this now separated velocities of 0.75m/ms from underlying values of 2.4m/ms; the latter might originate (possibly as shear waves) from harder saprolite below a quartz band. The implied depth of 30m to bedrock is almost certainly an overestimate and the 18m given by the resistivity data should be more reliable.

A refractor velocity of 2-2.5m/ms was also apparent at the site C5/B4 and three components of the regolith could be distinguished: an upper saprolite or colluvium to 5-6m; soft saprolite to 9-12m; more compact saprolite or highly weathered, fractured bedrock to 20-25m above bedrock. The higher velocity component seems to distinguish C4 and C5 from the other sites but it is not clear if this is a function of lithology, degree of weathering or of fracturing, or a less obviously expressed change in the strength of the material. A bedrock velocity was not clearly defined and values ranging from 4.3m/ms to 5.9m/ms could apply: there was evidence in the data of both lateral variation and a dip to the west. The resistivity interpretation underestimated the depth to bedrock and is closer to the base of the soft saprolite derived from the seismic evidence. Only one sounding was taken here to avoid crossing a break in slope but the results may still be influenced by lateral changes: a more consistent model is obtained by introducing an additional layer above the bedrock although the evidence within the data for this is slight.

Shear wave data were collected at number of the sites in the Chimimbe dambo survey area but the results were generally disappointing due to the poor energy coupling at most locations and no satisfactory interpretations were possible.

2.3 Summary

(i) Conductivity profiles obtained using an EM34 instrument clearly delineated the lateral extent of the present, active dambo in terms of a thin upper layer of low resistivity which corresponds with smectite-rich clay deposits.

(ii) Conductivity data differentiated a zone of higher conductance and deeper weathering to the southeast of the dambo; this was associated with the presence of palaeodambo clay deposits overlying thicker saprolite.

(iii) Asymmetry in the conductivity profiles crossing dambos might be an indication of their lateral migration, leaving a 'tail' of thicker saprolite.

(iv) Resistivity sounding data were of variable quality suggesting that the interpretations may be distorted by lateral changes both within the saprolite and the underlying bedrock. Qualitative assessments are usually reliable but the data cannot be used to define the thickness and lithology of sub-divisions of the regolith without additional control.

(v) Resistivity interpretations showed the absence of a thick saprolite beneath the dambo but they also implied that the substrate was not fresh, massive bedrock; this was confirmed by the seismic data.

(vi) Seismic refraction results proved somewhat disappointing to the extent that they were less definitive than had been hoped. This was due in part to the lack of an effective energy source and also to the difficulty in defining velocities. The latter problem implies the absence of continuous, discrete layers in this type of weathering environment. However, the data did lead to more reliable interpretations than those provided by resistivity soundings alone.

(vii) Seismic sections over the dambo show a shallow depth to refractors representing weathered/fractured rock combined with lower velocities for the underlying bedrock. A thicker sequence of saprolite was identified which corresponded with the EM34/ESA data to the southeast of the active dambo.

(viii) Geophysical interpretations were in reasonable agreement with borehole control although the drilling did not extend deep enough for a full correlation to be made.

(ix) The geophysical characteristics which distinguish the active dambo from the typical interfluve response are a highly conductive superficial layer (arising from the grey clays) and a thin saprolite underlain by a thicker sequence of fractured bedrock. Magnetic anomalies can also be associated with dambos but they tend to be localized and less easily identified.

(x) The water table is rarely identified within a saprolite sequence unless it coincides with a change in lithology or if it occurs at shallow depth within thick sands.

The geophysical interpretations from Chimimbe dambo will be reviewed together with all the other sources of information (on core samples, borehole logging etc) when these are available to produce a synthesis of the results as a whole.

3. SRI LANKA

3.1 Previous work

Visits to Sri Lanka in April 1984 and October 1985 had been concerned mainly with getting information on the borehole siting procedures used locally and with assessing existing records. Meetings were held with representatives of a number of organisations involved in borehole siting on the earlier visit but the best contacts were established with the Water Resources Board (WRB) with whom technical cooperation projects had been undertaken on previous occasions. The application of resistivity methods has become an established part of the siting procedure used by the WRB and they possess a range of geophysical equipment which includes the ABEM SAS300 Terrameter, EM34-3, EM16 and EM16R VLF (very low frequency) receivers, proton magnetometers and signal enhancement seismograph instruments.

Some fieldwork had been undertaken in 1984-85 to demonstrate the potential use of the EM34-3 instrument and to check on the results that could be expected from seismic refraction surveys. When combined with the discussions held with the WRB geologists these formed the basis for deciding on the type of studies to pursue in the programme for 1986.

The invariable use of resistivity surveys by WRB in confirming the suitability of sites prior to drilling contrasts with the less rigorous approach adopted by other groups and this should provide a good check on the cost effectiveness of geophysics. In fact it is still difficult to get reliable information on which to judge this, partly because there is no comprehensive, centralised set of records including failed wells, but also because of the difficulty in isolating the contribution of geophysics to the success and overall cost of a completed borehole. It can be said, however, that the success rate of better than 90% achieved by WRB is not simply a reflection of the widespread availability of groundwater.

3.2 Computer modelling of 2D resistivity variations

The standard approach to modelling resistivity sounding curves assumes a horizontally stratified earth which can be fully specified in terms of layer resistivities and thicknesses. Thus, the technique should only be applied to defining the parameters of laterally extensive lithological units, where the term 'extensive' is considered relative to the thickness and depth of burial of any particular layer. The introduction of lateral variations into the model is not usually appropriate because of the wide range of alternative solutions that can be fitted even in the simpler cases; each model curve is in fact unique but the differences are often small in comparison to the accuracy and reliability of the field data.

Mineral exploration surveys are concerned with locating localized anomalies which cannot be represented adequately by a one dimensional model. Resistivity itself is rarely a primary exploration tool but the data are collected on a routine basis as part of the induced polarisation method; their interpretation is also handled within the same context. The sounding technique has little relevence in this application and the dipole-dipole electrode configuration is preferred for getting information on lateral variations at different depths. Thus the computer modelling programmes that have been developed relate mainly to this type of electrode array. Griffiths and Turnbull (1985) described an approach designed specifically for collecting and analysing resistivity data in this pseudo-sectional form with a Wenner array configuration: mapping shallow bedrock profiles was one particular example they cited as an application for the system and it does clearly allow for more accurate definition of dipping interfaces and of faulted contacts. The technique has yet to be applied widely enough to see whether the large increase in the quantity of data collected is accompanied by a significant increase in the reliability of their interpretation in the absence of additional controls.

The application of two-dimensional (2D) modelling considered for this project relates specifically to assessing the influence of lateral variations and fracture zones on the curves produced with an expanded Schlumberger array - the configuration most commonly used for routine groundwater surveys. A programme produced by Rijo (1977) for resistivity/IP modelling was available on the mainframe computer at BGS. This uses a finite element method in which a 2D mesh of triangular elements is defined. Each element is assigned a specific resistivity as required by the model and a matrix equation which defines the behaviour of the potential field throughout the mesh is assembled. The system of linear equations is solved in terms of a given set of source and receiver locations after incorporating the boundary conditions. As formulated, the programme was set up to calculate the response of a dipole-dipole array and so it had to be modified to simulate the Schlumberger configuration. This involved designing a mesh which covered an appropriate range of electrode spacings, recombining the calculated potentials correctly, checking the accuracy of the results as far as possible and producing an appropriate output in the form of a sounding curve.

The mesh needs to be kept relatively simple so that the models can be implemented easily and without excessive use of computer time; on the other hand, there must be sufficient detail where the electrodes are close together, near the centre of the array, and in the vicinity of inhomogeneities if the potential distribution is to be calculated correctly. A set of ten current electrode separations from 12m to 160m, for potential electrodes 4m and 12m apart, was taken to cover the range of interest although the resistivities were actually calculated for the reciprocal case - exchanging the role of current and potential electrodes - in order to reduce the amount of computation required. This is a realistic approximation to the type of layout used in the field and covers the spread lengths of most significance both in defining the thickness of regolith and in giving evidence of any fractures within the range of production drilling. The inclusion of two inner dipole electrode spacings allowed for a direct evaluation of the influence of array geometry on the field data. Details of the mesh and electrode locations are given in Figure 3.1 which shows an example of the standard computer output.

Tests on the accuracy of the modelling procedure were made by first simulating a horizontally layered case which could also be calculated using the standard mathematical filtering method (Ghosh, 1971). Initial results showed unacceptable discrepencies at wider electrode separations, and adjustments to the mesh such as increasing the number of elements and extending it further beyond the array limits produced little improvement. The cause was found to be an insufficient number of values used in defining the Fourier transformation within the programme: this in turn reflects the difference in scaling of electrode spacings in the Schlumberger sounding compared to the dipole-dipole pseudosection. After increasing the number of these terms the errors at the widest electrode spacings were reduced to about 1%, which was quite acceptable for this type of study.

Table 3.1 lists the values obtained from both 1D and 2D modelling programmes. The discrepency in apparent resistivity calculated for the closest spacings arises when the potential dipole spacing is significant relative to the current electrode separation: in the 1D calculation the potential gradient at the centre of the array is derived corresponding to the ideal Schlumberger array in which the potential dipole length tends to zero. For practical purposes a ratio between potential and current electrode separations of 1:5 is the recommended minimum. The size of the geometric effect is a function of both this ratio and the slope on the resistivity sounding curve: it can be a significant factor in assessing how to adjust the field data to offset the discontinuities observed on changing the potential dipole length (Mundry, 1980).

Table 3.1 Comparison of apparent resistivities derived from 1D and 2D computer modelling programmes.

INPUT MODEL:

layer number	resistivity ohm.m	depth to base m
1	400.0	2.0
2	40.0	7.0
3	180.0	15.0
4	3000.0	*****

CALCULATED VALUES:

Current electrode (AB) spacing m	Apparent resistivity ohm.m 1D programme (O'Neill,1975 filter)	2D programme MN spacing=4m	2D programme MN spacing=12m
12.0	117.2	132.2	*****
22.0	75.4	76.2	94.5
32.0	94.4	94.5	89.4
40.0	113.9	114.3	109.1
50.0	139.1	139.9	135.5
64.0	174.7	175.6	172.1
80.0	214.9	215.6	212.9
100.0	264.1	264.0	261.9
128.0	330.5	328.4	326.8
160.0	403.1	396.7	395.4

2D modelling results for the smaller potential dipole are illustrated in Figures 3.2-3.16; the output from the background 1D model (as calculated using the 2D programme) is also included as an indication of the relative change in apparent resistivity values. Alternative 1D models could be produced to fit the 2D data more closely, as shown by the two examples in Figure 3.17. It should be noted from Figure 3.1 that the mesh size is variable, with the element width being 1-2m to a distance of 90m from the centre of the model and then increasing rapidly; the depth scaling is also non-linear.

Model M1 refers to a 4-layer background case representing a thin cover of resistive soils, with saprolite to a depth of 7m and weathered and/or fractured bedrock to 15m, overlying massive bedrock. This is a typical type of sequence in basement terrain, producing an ESA curve with the final segment rising at close to the theoretical maximum of 45 degrees. The total conductance of 0.25S for the regolith is less than might be expected in Sri Lanka but this should allow for a clearer expression of the effects of adding fractures into the system.

The examples M1;L1-L3 show the result of locally reducing the thickness of the superficial layer from 2m to 1m. The disturbance of 2-5% is relatively small but the anomaly at electrode spacings D and E in case M1;L1 is of the type that would begin to influence the depth to bedrock interpreted from a 1D model. The examples F1-F4 introduce a steeply dipping zone with a width of 4-6m and a resistivity similar to that of the saprolite. A body of this size might relate to a fault but it is clearly much wider than the type of water-bearing fracture usually encountered. The increase in total conductance has the effect of widening the curve minimum but the overall shape of the curve remains smooth and it shows no obvious discontinuities to suggest that a 1D interpretation is inappropriate.

The form of the anomaly in M1;F1 is similar to that in M1;L1 and if the data for electrodes A-C are excluded then the relative amplitudes of the anomaly are 4% in both cases (as indicated in the diagrams by the ratio of 2D:1D model resistivity values given below the ESA curves). Changing the dip and location of the body does produce some change in the form of the anomaly but again this is relatively subtle in relation to the type of field data usually collected. The models are most sensitive to variations near the centre of the array, as would be expected.

The model M1;F5 shows that a set of fracture zones could produce a noticeable discontinuity in the ESA curve although it should be noted that a significant proportion of the original 'bedrock' has now been replaced and the causative bodies might reasonably be related to changes in lithology rather than to fractures as such.

Model M2 is similar to the first except for an increase in the resistivity of the saprolite to 40ohm.m for the background, and the introduction of more conductive, anomalous material into the 2D model. Examples F1-F3 now show a single 'fracture' zone associated with a broad section of higher conductivities in the overlying saprolite, due perhaps more aggressive weathering here. The increase in anomalous conductance leads to a deviation of larger amplitude from the 1D background level and the maximum curve slopes tend to exceed 45 degrees. However, it is only by including several of these zones within the model, as shown in the examples M2;L1-L3, that marked discontinuities are given in the ESA curve. The electrode separation at which the disturbance is seen is a function of the horizontal location of the anomalous zones and does not relate to the depth at which they occur below the centre of the array. The model M2;L4, with a sub-horizontal conductive zone of limited width below the centre of the array, also fails to reproduce the type of clear curve break which would identify the presence and depth of the fractured rock.

The results of the modelling studies can be summarized as follows:

(i) isolated faults or fracture zones in the bedrock with a width of less than 5m do not significantly influence the ESA resistivity data and their effect would usually be assimilated within a standard 1D model;

(ii) it is necessary to assume that fracture zones influence resistivities in the overlying saprolite in order to explain satisfactorily the amplitude of the anomaly required to produce a clear curve break;

(iii) models with a series of discrete anomalous zones provide the closest approach to distinctive breaks; these might reflect differences in lithology associated for example with gneissic or migmatitic rocks, or weathering along a system of joints in intrusive granite;

(iv) curve discontinuities do not obviously reflect the depth to a steeply-dipping source;

(v) changes within the upper layers may give anomalies similar to those from deeper sources.

A better understanding of the situation in the field would be obtained by utilizing the higher resolution of the EM methods to identify lateral variations; these could be incorporated into the 2D resistivity models to see if they account for anomalies in the sounding curve. Ideally, modelling studies which combined EM and resistivity data would be undertaken but there are significant mathematical and computational difficulties associated with solving the 2D case for a 3D EM source. The effects of simplified structures can be studied with analogue, tank techniques in which readings are taken directly from scaled models.

Results from Zimbabwe (Smith and Raines, 1988) obtained with the EM34 produced numerous examples of the anomaly troughs in the horizontal coil readings which are the expected response to narrow, steeply-dipping conductive zones. The extent to which such anomalies reflect changes in the bedrock profile due to an increased depth of weathering above fracture zones, rather than the effect of the fracture zone itself has yet be established. The conductance of a water-filled fracture is unlikely to be sufficient to generate the size of anomaly observed; if there is a high clay content then the fracture will probably show a low permeability and not represent a target. The vertical coil response is often relatively high over these features although it too should display the same type of anomaly over tabular bodies, albeit with the amplitude much reduced (by about 80%) due to poorer coupling. The vertical coil data have a shallower cause generated mainly from horizontal current flow and they indicate that the conductance of the overburden is higher. It seems probable that the horizontal coil anomaly is enhanced if not dominated by vertical current flow induced by local changes in conductivity and thickness in the saprolite coupled with the effect arising directly from the fracture zone within the bedrock.

3.3 Results from Tangalla/Hambantota district

3.3.1 Introduction

Following discussions with staff at the WRB regional office in Tangalla, in the southwest of Sri Lanka (see inset of Figure 3.29) a number of possible sites for further investigation were identified. These localities included boreholes showing well developed fracturing, large diameter dug wells which were under consideration for conversion into collector wells and areas where saline groundwaters occurred.

A comparison of borehole records and resistivity soundings did not indicate any obvious correlation between the presence of water-bearing fractures and discontinuities in the sounding curve. The reporting of fractures in a driller's log is to some extent subjective and varies with the experience of the driller and the interest that he takes in maintaining an accurate record. Similarly, the quality of the resistivity data will vary with the operator and local ground conditions.

As fractured rock was reported in a large proportion of the boreholes it would be surprising if some of the water-bearing zones did not coincide with ESA curve 'breaks' and one immediate objective was to establish whether there was in fact a causal relation linking them. Of 20 curves with significant looking breaks it was found that at more than half of the sites there was little scope for doing any more detailed surveys because of limited access or problems with man-made interference: this in itself suggested that the original results may have been distorted by near-surface effects. Two borehole sites were found where further work could reasonably be undertaken: at R299 a high yield of 3l/s was associated with multiple fracturing; at R336 only two fractures had been reported and a correspondingly lower yield of 0.3l/s obtained.

A small but significant proportion of the boreholes drilled in this district have encountered non-potable saline water and a higher concentration of these is found north of Hambantota. The distribution of these wells did not form a predictable pattern and the fluid conductivities also varied over a wide range. Geochemical studies were undertaken separately to investigate the origin of these waters but isotope data had already provided evidence that they were not a result of flooding or intrusion by sea water. Previous resistivity surveys had not shown any distinctive response from the saline areas but the opportunity was taken to do some additional studies here in association with an exercise in mapping the depth to hard rock.

3.3.2 Results around borehole R299

The terrain here was gently undulating and the existing borehole, yet to have a pump installed, was located in open, higher ground beside a track. Partly cultivated land allowed easy access and there were few fences to interfere with the electrical survey methods, though one did lie within 5m of the borehole. The main features of the driller's log for R299 were:

topsoil, clay and sand	0 - 7.45m
fine sand and clay	- 19.5m
quartz rock	- 22.0m
weathered quartz rock	- 26.0m
rock	- 46.0m

Fractures were inferred at depths of:

26m (0.25l/s);	30.2m (0.4l/s);	32.2m;	32.9m;
35m;	35.7m (0.7l/s);	38.7m (1.0l/s);	42m;
43.7m (1.5l/s);	45m (3l/s)		

with the figures in brackets representing the total flow of water being air-lifted during the drilling at that point. The hole was cased to 20m and water was first encountered at a depth of 23-24m.

Several aspects of this site seem favourable: the thick saprolite; the presence of quartzitic rock; the fractured nature of the underlying rock, and it is probably this combination of factors which leads to the high yield obtained.

The only adverse consideration is the relatively deep level of the water table, though given a high specific capacity for the well this should not cause any problems in the performance of a hand pump.

Table 3.2: EM34-3 data in the vicinity of borehole R299.

	N-S alignment		W-E alignment	
coil spacing	coil orientation: vertical	horizontal	coil orientation: vertical	horizontal
Site 1. 5m NE from R299:				
10 :	20	28	19	28.5
20 :	18	20	19	26
40 :	17.5	13.5	21.5	18
Site 2. 50m N from R299:				
10 :	17.5	22.5	18.5	24.5
20 :	15.5	16	18.5	20
40 :	16.5	11	21.5	18
Site 3. 50m E from R299:				
10 :	20	31	21	31
20 :	20	21	21.5	26
40 :	17.5	6.8	24	17.5
Site 4. 50m S from R299:				
10 :	20.5	20	22	24
20 :	19	16	21	18
40 :	18	11.5	21.5	16
Site 5. 42m W from R299:				
10 :	19	24	21	24
20 :	18	20	20	20.5
40 :	18.5	16.5	21	21

The original depth sounding (see Fig 3.18) obtained by WRB before confirming the site is consistent with the drilling results. The conductance of more than 1.3S given by the intermediate layers represented in the minimum of the curve is above average for this type of terrain, while the resistivities themselves are not low enough to imply that there is an excessive clay content. Some irregularities are apparent in the field curve beyond a current electrode separation (AB) of 30m and these could be taken as 'breaks' relating to the fractured rock found beneath the saprolite: the absence of a steeply rising final segment to the curve may be due either to the infuence of the breaks, to a lower bulk resistivity arising from the fractured nature of the bedrock or to the mineralogy of the compact rock at depth.

Conductivity data were obtained using the EM34 equipment beside the borehole and from four points within 50m of it as a preliminary check on the presence of lateral variations; these data are reproduced above in Table 3.2. At each site all combinations of coil spacing and orientation were measured in orthogonal directions about a fixed central point. Most of the apparent conductivities lay within the range 15-25mS/m (equivalent, after correction, to resistivities of 25-60ohm.m), decreasing noticeably only for the deepest penetration i.e. with the 40m horizontal coil configuration. Vertical coil readings showed little variation overall, suggesting that the upper part of the sequence was relatively uniform and without any zones of conductive clay or of resistive superficial material which might disturb the resistivity sounding data locally.

Horizontal coil values did show a systematic decrease in conductivity with depth and provided more evidence of variations between the sites. Measurements taken with the coils horizontal are sensitive to orientation errors and the data may also appear less consistent due to the larger response to lateral variations between and around the coils; they do however provide information which is not available using the vertical coil data alone, both by increasing the effective depth of investigation and by contributing additional data to improve resolution of layered sequences. At the 10m coil spacing they were almost invariably higher than either 10m or 20m vertical coil readings. This is probably in response to a layer of higher conductivity in the depth range 5-10m and it illustrates the difference in response characteristics between the vertical and horizontal configurations. Readings varied with direction for the 40m, and to a lesser extent for the 20m, coil spacings. The fact that the lowest values were recorded consistently with the north-south alignment suggests that they relate to anisotropy within the underlying rocks rather than to any spurious near-surface effects.

Additional Schlumberger (ESA) data were collected around the borehole site for comparison with the WRB and EM34 data and to check on the differences occurring within a radius of 50m; data from orthogonal spreads were again used as a check on near-surface lateral effects and anisotropy. Results from 5 sites centred within a distance of 30m from the borehole were similar in character but they varied significantly in the smoothness of the sounding curves and in the depth to 'bedrock' interpreted from them. Lateral variations were clearly one factor in that the curves from orthogonal soundings at the same site gave different results: depending upon the significance attached to particular aspects of the curves the number of layers could be increased from a minimum of three to five or more, and the interpreted depths to the resistive substrate varied from less than 20m to over 40m.

Irregularities or breaks in the curves were sensitive to the orientation of the spreads and they might have arisen from inhomogeneity in the upper layers of the sequence; however, the EM34 data had not highlighted any marked variations at these levels and the fact that the irregularities occurred mainly for AB/2 spacings in the range 15-40m was consistent with a source near or below the base of the saprolite. More systematic differences between orthogonal sounding curves are an indication of anisotropy within the underlying bedrock. This anisotropy can itself be an expression of fracturing, though foliation and banding in gneissic rock may produce a similar effect.

By interpreting the curves in relation to each other it was possible to arrive at more consistent models limited to three or four layers (see Figure 3.19).

The inferred 'average' depth to bedrock then comes to about 30m which is close to the figure of 26m derived from the drilling. It was necessary to allow the resistivity of the substrait to vary over the range 100-300ohm.m in order to limit the variation in depth. Anisotropy, which distorts both interpreted depths and resistivities, may be a factor in this and it was noticeable that the higher bedrock resistivities were interpreted from spreads oriented west-east as compared to north-south (contrasting with the EM34-3 response); this implies a dominant west-east trend to the fractures or banding within the rock. The resistivities are low for crystalline bedrock in Sri Lanka and equivalent values from Zimbabwe would be a factor of x10 higher. This may reflect differences in microstructure or rock/water chemistry but it also implies that the rocks here are more fractured.

There was some evidence of structure within the saprolite below the resistive superficial cover which had a thichness of 1.5-3m. The saprolite resistivity varied between 20ohm.m and 60ohm.m and in most cases the curve match improved after introducing a subdivision at a depth of 6-8m with the more conductive material beneath. This interface was identified in the drilling and it may correspond to a change to more clay-rich, moist saprolite. The quartzitic rock encountered in the borehole is not expressed as a separate layer within the models but it might explain irregularities observed around some of the curve minima.

A comparison of the predicted EM34-3 response, as calculated from the layered earth resistivity models, with the observed EM data showed that the results were broadly compatible though not directly equivalent. The relatively large orientation effects in the EM results are of similar magnitude to the differences due to equivalent resistivity models and it is not possible to allow for these effects. One systematic difference was that the near surface conductivities as measured with the 10m vertical coils were slightly higher than the values derived from the models: this might be caused either by miscalibration of the EM34-3 or by a hidden layer of lower resistivity which is not represented in the upper part of the models.

Measurements were taken along a set of traverse lines to see if any bedrock trends or evidence of fracturing could be detected. EM34 (at 20m and 40m coil separations), VLF and magnetometer data were obtained at a station interval of 10/20m on 4 north-south and on 2 west-east lines, each about 500m in length. Figures 3.20a and 3.20b show the results obtained along line 15W, measured relative to R299, as an example of the type of response that was obtained.

The VLF signal from the Australian transmitter was not very distinct but the larger scale variations were still significant in relation to the uncertainty in the measurements and the discrepencies between orthogonal traverse lines. Sections of apparent current density produced from the profile data using the Karous-Hjelt filter (1983) suggest a coherent pattern of relatively conductive zones lying along a WNW-ESE trend. This is close to the southeast direction of the transmitter for which the coupling between the signal and any conductors will be at a maximum: the borehole is sited just beyond the margin of one of these zones.

EM34-3 results were if anything more difficult to correlate and the variations appeared to be localized with no obvious structural controls: the changes in conductivity which coincided with VLF anomalies show that the latter are sensitive to variations within the saprolite as well as to any features of deeper origin. Conductivity values lay for the most part in the range 15-20mS/m (equivalent to 50-65ohm.m): vertical coil readings at 20m and 40m separations were very similar and most of the differences between horizontal coil values could be related to the influence of more conductive zones in the saprolite. Comparison of EM34-3 results with the values predicted on the basis of the resistivity interpretations showed that the latter were usually too low, implying that layers of higher conductivity are required within the models. A better fit is achieved by increasing the complexity of the models so that thinner conductive layers are separated by a resistive zone: such models are in fact more compatible with the cored borehole log as discussed below.

Magnetic values lay within a range of 20nT after correcting for diurnal fluctuations but local anomalies as well as larger scale changes were still apparent. The basement rocks themselves rarely show a strong magnetization and short wavelength anomalies may be caused by iron concentrations within residual soils rather than by variations at the bedrock surface; the longer wavelength features may arise from changes in composition within the bedrock and the saprolite derived from it.

Traverse data are consistent with the resistivity interpretations in showing a relatively deep bedrock overlain by a weathered zone within which localized differences in thickness and composition occur. Higher magnetic values found to the southeast of the grid were not associated with changes in conductivity by which to identify a change in the bedrock. In the absence of any obvious drilling targets, the site for a cored borehole, C299, was selected in open ground nearly 60m southwest from R299. A resistivity sounding curve here had shown some irregularities and a reduced conductance for the regolith, with depth to bedrock interpreted at 22m for the simplest 3-layer model.

The cored borehole passed through 10-11m of clayey sand before encountering weathered, garnetiferous gneiss with hornblende and biotite to a depth of 14m; a band of clay to 14.3m marked a transition to a different, granulitic gneiss which continued to about 31.5m when the biotite gneiss reappeared. Coring proved very difficult in what appeared to be highly fractured material and recovery was only 30% to the bottom of the hole at 35m. Detailed descriptions of the cores provided by WRB confirm the presence of numerous fractures within 'slightly to moderately' weathered bedrock. Most of the fractures recorded are steeply dipping though extensive sub-horizontal fracturing may account for core loss. The fracture planes are usually rough and slightly weathered; some slickensides were observed on low angle fractures in the biotite gneiss near the bottom of the borehole.

There is no correlation in detail between the first resistivity interpretations and the drilling results. A sounding located 20m further south had indicated that lateral variations were a factor; a depth of perhaps 28m to the more resistive substrait was interpreted here but there were differences between orthogonal soundings and both curves showed minor irregularities. More complex models of the type shown in Figure 3.21 give a better fit to the borehole log. An interface at 4.5m separates the upper 'sandy clays', possibly with kaolin-rich clays causing their higher resistivity, from the clayey sands of the main saprolite; at 10-11m the resistivity is increased within the dry, weathered rock and fractured granulitic gneiss; the underlying zone of lower resistivity from 19-21m to 30-35m is representative of highly fractured rock; the reduction in fracture intensity, and the associated change in rock type, cause the resistivity to rise again.

No satisfactory resistivity logs were obtained from C299 and so the validity of the 'improved' interpretation remains in doubt. Some evidence was provided from resistivity measurements in R299 (Figure 3.18) which showed that values remained lower from the bottom of the casing at 20m, to a depth of about 30m. The 16" normal gave resistivities of 100-200ohm.m; these were reduced for the 64" normal and 18' lateral arrays to 65ohm.m and 40ohm.m respectively, getting close to the layer resistivity interpreted from the ESA data. The longer arrays have a larger radius of investigation and their lower values are attributed to current flow paths within fractures and joints by-passing the more resistive rock close to the borehole. Between 30m and 40m depth the 64" normal values increased steadily to reach 200ohm.m before falling back to 130ohm.m towards the bottom of the hole at 46m where more than half of the borehole yield was obtained. The 18' lateral log, which should give the most representative value for the bulk resistivity of the rock, increased only to about 100ohm.m; values at similar depths in other boreholes were generally much higher and again the log data confirm qualitatively at least the interpretation of the surface ESA data. The 16" normal, which gives the best resolution of narrow anomalous zones, suggested that 3-4 harder bands were separated by softer or fractured rock, agreeing approximately with the driller's report.

Good quality natural gamma and resistivity logs recorded from several of the boreholes in the Tangalla district showed interesting variations in response throughout the sequence; these probably relate to changes in mineralogy as well as to the presence of fractures. At R299 there was a correlation between thin zones of higher gamma count and the fractures reported in the driller's log; these were more apparent in the biotite gneiss than in the granulitic, quartz-rich rock and there was no evidence from the log that the borehole had fully penetrated the zone of fracturing. It was also noticeable that the saprolite gave a relatively low response except near its base.

Additional detail shown on the gamma logs may arise from unreported fractures which did not yield water because of clay infill or lack of continuity. The resistivity logs typically gave the highest values from the 16" normal; lower values measured with increasing penetration of the harder formations indicates that the bulk resistivity is influenced by an effective increase in secondary porosity when sampling a larger volume of the rock. This also explains why resistivities for the bedrock interpreted from surface ESA data are often less than might be expected from the logs.

The general conclusions drawn from the work here are that:

(i) site specific features did not account for the relatively high yield at R299 and the fracturing within the bedrock is not confined to a narrow zone;

(ii) resistivity data indicate qualitatively the favourable nature of the area by the low values, 100-300ohm.m, obtained from the deeper bedrock; the presence of minor irregularities or breaks in the sounding curves reflects variations near the base of the more weathered rock rather than fractures at depth;

(iii) quantitative resistivity interpretations are unreliable due to lateral variations, anisotropy and their inherent ambiguity; a more consistent result is obtained by combining the results from a number of sites with orthogonal soundings but gross errors can still be expected unless the data are controlled by borehole information including resistivity logs; the most reliable parameter that can be derived from the interpretation is layer conductance above resistive bedrock;

(iv) gamma logs provide information on the nature of the sequence but more data are needed to see if they can be characterized to assist in correlating results from different boreholes on either a local or a regional scale.

3.3.3 Results around borehole R336

This site lay beside a small valley with moderate relief and relatively good access. The borehole yield of 0.3l/s was adequate, but with few fractures recorded by the driller it provided a contrast with the much more productive conditions at R299. The geological environment appeared similar: granulitic gneiss and hornblende-biotite migmatite, with the foliation seen in an exposure on the hill nearby showing a strike direction of N60W (close to the trend identified near R299 where there were no exposures for control) and a dip of 40-45 degrees to the southwest. The driller's log gave:

topsoil	0 - 1.3m
clay and sand	- 4.3m
sandy rocks	- 15.1m
rock	- 46m

- fractures at 21m and 31.6m gave total yields of 0.15l/s and 0.3l/s respectively during drilling; static water level was at about 16m.

A more detailed description of the samples referred to very highly weathered rock and lateritic clay within the top 12.5m overlying moderately weathered granulite.

The original WRB resistivity sounding did not produce a smooth curve but it indicated resistive material at shallow depth; a marked break at an AB/2 spacing of 20m could have been caused either by a lateral discontinuity or by a more conductive zone below 12m. Additional soundings were taken at two sites, one slightly above and the other below the elevation of R336, during the initial resurvey at this location. Although the sites were separated by only 50m they showed a quite different response: the first gave no evidence of a layer resistivity less than 100ohm.m while at the lower second site, orthogonal spreads confirmed the existence of a conductive saprolite layer to a depth of about 20m. Following this clear indication of an improvement in conditions, VLF, EM34-3 and magnetic data were obtained along four traverse lines crossing the valley.

The profile data are presented in Figures 3.22a and 3.22b. The in-phase VLF anomaly is expressed mainly in the form of a maximum with an amplitude of 30% which migrates to the south (negative distance values) for the more easterly traverse lines; although there is some indication of the classic crossover response to a conductive zone, the anomaly is more typical of a single contact between more resistive and conductive ground. Current density pseudo-section plots suggest that the width of the zone is restricted to perhaps 50-100m. The smaller, but still significant out-of-phase anomaly is evidence that the effect is not of topographic origin.

EM34-3 values were obtained only for the vertical coil configuration because of the difficulties in maintaining alignment over the undulating ground. These show that apparent conductivities increase from background levels of 7-10mS/m to reach more than 20mS/m near the location of the VLF anomaly. The anomaly alignment is oblique to the traverses at approximately N55W, agreeing closely with the geological data. The feature is less clear on line 130E, possibly because it swings more to the south, but another anomaly high is encroaching from the north; this suggests that there may be lithological control on the weathering profile which produces bands of more conductive ground.

There was only slight evidence of a magnetic anomaly corresponding to the change in conductivity. However, an easterly reduction in gradient over the length of the traverses is apparent which may reflect a change in rock type or deeper structure.

R336 had been sited to the south of the main VLF anomaly and so C336, a cored borehole, was located within the conductive ground just to the north of the VLF crossover to test conditions within the more promising zone, at a distance of 65m east from R336; it should also have been close enough to the crossover to take advantage of any narrower conductive zone associated with the contact. Drilling confirmed the presence of a much thicker saprolite here with sandy clays to 4m underlain by medium-coarse sands to 25m. There was good core recovery from 28m to the bottom of the hole at 53m within a biotite gneiss, locally garnetiferous and with hornblende. The gneissic texture was not well developed but the rock type appears to differ from the quartz/feldspar rich unit, classified as granulite or charnockite, found in R336. This is partly supported by the lack of similarity in the gamma logs between the two holes though this could simply represent the degree of variation within the same formation: the response from the bedrock in the cored hole is similar to, or in the section 32-39m is less than that from R336, which is surprising in view of the larger diameter of the latter.

Numerous fractures were identified in the core with more than 40 of these being described as well developed, although the extent to which they have transmitted water was not established. Pyrite occurred commonly along the fracture planes which were usually rugose but only slightly weathered. Graphite was noted occassionally and chalcopyrite and bornite were present along one fracture plane. Most of the fractures dipped steeply, at 70-80 degrees, with a subsidiary set at 30-40 degrees to the horizontal. A caliper log run in this hole showed marked rugosity for 3.5m below the casing, from 28m. The only other borehole irregularity occurred, at 43.7m where the gamma log, although variable over this section of hole, gave no distinctive response.

After withdrawing the casing the hole backfilled to a depth of 41.5m but this still allowed resistivity logging of the upper section of the weathered zone which is usually inaccessible. The main differences from R336 can be seen in Figure 3.23:

in R336 all three logs gave resistivities of 200-400ohm.m over the interval 18-32m while in C336 values remained at 10-30ohm.m to a depth of 28m;

in R336, values decreased slightly between 32m and 36m, where additional inflow was noted during the drilling, before rising rapidly to around 1000ohm.m; in C336 resistivities increased directly to higher levels below a depth of 31m.

The 'normal' logs showed a similar high-low-high pattern in the lower part of the two boreholes, although the values reached in C336 were significantly higher than at R299. The 4m displacement in this feature is accounted for in part by the lower ground elevation at C336. The measurement point used for the lateral logs is between the pair of more closely spaced potential electrodes which lie below the current source; the logs give an asymmetric response as the resistivity is suppressed over the full length of the electrode array (nearly

5.5m) when it passes into a thick, more resistive formation while the values tend to be enhanced immediately above the lower boundary. This accounts for the apparent discrepency in defining the base of the weathered zone between the normal and lateral logs as seen in Figure 3.23. Logged fluid conductivities in the range 20-40mS/m were a little higher in R336 than in both C336 and R299. There was no simple relation between resistivity and gamma logs. Thus, while a high gamma count and a slight reduction in resistivity were given by the fracture at 21.7m in R336, another prominent gamma peak at 30m had no associated resistivity anomaly.

No yield test data were obtained from C336 and it is not clear whether a production well here would have given a significantly improved performance by drawing from the thicker weathered zone. The geophysical survey did however successfully identify a marked change within the weathering profile over a distance of 60m, suggesting that R336 was not sited to the best advantage. Evidence for this feature was provided from resistivity ESA data but it was identified and mapped most readily using EM traversing techniques. This type of result also indicates that geophysics can contribute to the siting of dug wells by mapping changes in the depth to the harder bedrock.

3.3.4 Results from saline wells near Hambantota

The origin of the saline water found in a number of boreholes in the district around Hambantota is the subject of continuing investigation. In practical terms there remains a need to drill boreholes in populated areas which are known to have a high risk of contamination and, as the distribution of saline wells does not fall into a simple pattern, any survey techniques which can discriminate against the worst areas would be useful; even if the water is of poor quality it can still be used for some domestic purposes and so reduce the demand on potable supplies.

Reconnaissance measurements with the EM34-3 beside five of the more saline boreholes showed an anomalous conductivity profile at each site. The response was markedly anisotropic at R224, R303 and R322 with conductivities close to the surface exceeding 100mS/m. Horizontal coil values fell sharply as the spacing was increased from 10m to 40m and as the vertical coil readings also tended to decrease this indicates that a resistive layer, probably bedrock occurred at relatively shallow depth; higher values were obtained with the coils aligned parallel to the regional strike. A thicker conductive layer was suggested elsewhere: at R304, within about 300m of R303, the conductivities for the upper layers were less but horizontal coil values remained high at the 40m coil spacing; at R327, there was little anisotropy but conductivities actually increased from 20m to 40m coil spacing.

Borehole logging of R303 and R304 confirmed the difference in resistivities to depths of 50m (see Figure 3.24a):

fluid conductivities were lower in R303, 1500mS/m as against 3000mS/m, but the resistivity logs for R304 gave values about three times higher than in R303;

short normal resistivities increased rapidly from 30ohm.m to 150ohm.m over the depth interval 16-19m in R304 and subsequently levelled off at 250-300ohm.m; in R303, values did not exceed 100ohm.m until about 30m depth and below this there were additional zones of reduced resistivity;

values from the long lateral array, which is least affected by the borehole column, reached about 1500ohm.m in R304 but they were still generally less than 500ohm.m towards the bottom of R303.

Fluid conductivities did not increase systematically with depth although both holes were capped and not yet in use; this tends to support the view that the salinity originates in the weathered zone rather than as the discharge of older waters from depth along fractures. A very low effective porosity would also be needed to explain the high formation resistivity at R304 if the hard rock does contain such conductive water. The measured resistivities in both boreholes were lowest with the 16" normal and unusually high for the long lateral, in contrast to the more typical reducing values noted at the end of section 3.3.2; this was found to be a feature of boreholes where the fluid conductivities were higher and it suggests that there is a reduced intensity of fracturing within the bedrock in these cases.

The lack of equivalence in logging results between R303 and R304 is reflected in both the EM34-3 data and the original WRB resistivity soundings. The EM34-3 values are influenced by localized effects but they clearly respond to a much larger volume of ground than that sampled by the borehole logs. It may therefore be misleading to attempt a direct comparison between them in ground where both anisotropy and lateral effects occur. Apparent resistivities were lower at R303 (seee Figure 3.24b) with an interpretated conductive layer of 10ohm.m from 5m to 14m and the possibility that the subsequent resistive band is underlain by a more conductive zone; a similar type of model can be applied to R304 although the conductances are less are only a simpler 4-layer model is really justified. There is little more than a suggsestion of the lower conductive zone below 20m depth in the borehole resistivity logs and the values given by the lateral are much higher than would be expected.

Additional work was undertaken at another pair of adjacent boreholes, R296 and R297, where high salinities had been found. The WRB resistivity soundings gave no indication of a conductive layer attributable directly to poor quality water. At R296 the upper soils were underlain by a resistive zone from 2.5m to 10m, suggesting a hard, dry formation such as weathered bedrock rather than saprolite. A layer with a conductance of about 0.7S occurred below this, possibly representing more fractured, water-saturated rock to a depth of 30m. R297 was 270m to the west where the conductive zone was limited to a depth of 10-12m; however, at the wider AB/2 spacings the apparent resistivity values were not increasing, a result of either lateral changes or the presence of less resistive bedrock at a depth of 25m.

Resistivity logging of the boreholes again showed marked differences between them. The response from R296 was unusual in that the highest values were obtained from the top of the hole: over 600ohm.m, 2000ohm.m and 5000ohm.m respectively for the short and long normal, and for the long lateral arrays. Minimum values occurred in the depth range 14-20m before increasing again less rapidly; this shows some qualitative agreement with the resistivity model althouh the sounding was almost certainly distorted by lateral changes. The fluid resistivities of 0.35-0.5ohm.m are approaching the value of 0.2ohm.m expected from sea water, emphasizing the poor quality. A discontinuity in the fluid log at a depth of 16-17m coincides with the minimum values on the short normal log and suggests an entry point to the borehole at a fracture or within a more weathered zone. In R297 the fluid resistivities were somewhat higher at 0.8ohm.m. Resistivities were lowest in the upper section of the logs but formation resistivities, uncorrected for the borehole fluid, remained less than

700ohm.m, even for the long lateral; below a depth of 18m the values varied irregularly within a relatively narrow range to the bottom of the hole at 60m.

An EM34-3 traverse along the track passing beside the boreholes showed that R296 was sited close to a marked break in the conductivity profiles at all coil configurations; the ground to the east, down a slight topographic gradient, was highly conductive with values approaching 200mS in the upper layers. In contrast, R296 itself was within the most resistive section of the shallower part of the profile and while conditions appeared slightly better at R297 the most favourable location would have been expected between the two. Given the saline groundwater within the boreholes and at shallow depth on the lower ground, the presence of a thicker sequence of saprolite or more weathered bedrock might still represent a site for a dug well if there is local recharge during the rainy season.

The poor seismic energy transmission properties of the weathered bedrock suggest that the 'interface' at the base of the saprolite is irregular. There was evidence of three layers below the low velocity, superficial cover:

- layer 1 - velocity 0.7-1.1m/ms to about 5m depth
  - probably represents dry, loose sandy material;
- layer 2 - velocity of 1.7-2.1m/ms to about 15m depth
  - taken to represent highly weathered and fractured rock;
- layer 3 - velocity in the range 4-5m/ms
  - suggests bedrock with some fractures.

It is likely that the true first arrivals from the harder rock were missed so that the calculated depths to it will be overestimated. Results near R296 confirmed the evidence from the EM34 of shallower bedrock, at about 3m depth, beside and to the west of it, with a thickening of the saprolite to the east; the longest travel times, suggesting depths to bedrock of as much as 15-20m, occurred in the ground between R296 and R297.

Six shallow boreholes were drilled subsequently over a distance of 350m along the traverse line passing the two existing wells. They encountered hard rock at depths ranging between 3.5m at a site 20m to the west of R296, and 11.4m at a distance of 90m downslope to the east. One site east of R297 penetrated to 9m within softer material but the adjacent borehole, towards R296, met hard rock at only 4.5m. This last result was difficult to reconcile with the qualitative geophysical indications of the thickness of saprolite and it may be that the borehole hit a localized band of hard rock above the general bedrock level. Seismic velocities of less than 2m/ms appeared to extend to a depth of at least 15m here, suggesting that any shallower bedrock is highly fractured.

Water was struck only in the two boreholes to the east of R296. The fluid conductivity was 369mS/m (3690uS/cm) at the lower site and 164mS/m from the shallower borehole closer to R296. These values are a factor of ten less than those logged in the original, capped wells, as would be expected from the infiltration of recent rainwater to shallow levels; an increase in conductivity between depths of 9m and 12m suggests that the fresher water occurs only as a thin lens. There is no evidence that the poor quality originates mainly from the discharge of deeply circulated water and, though this may still be the exlanation, a shallow source would be expected. Saline water filling major fractures should give a characteristic EM conductive 'dyke' response which was not apparent here; however, the relatively low apparent resistivities recorded at the wider spacings in the sounding curves could be an expression of saline water penetrating a less well developed fracture system from above.

3.3.5 Ohmara dug well site

This large diameter dug well was a possibility for conversion into a collector well and the relatively open ground around it made it an appropriate site for undertaking trial geophysical surveys. Resistivity, EM34 and seismic data were collected here to see if the depth to hard rock could be determined reliably and if there was any anisotropy within the upper part of the bedrock which could guide the direction of radial drilling.

Resistivity soundings showed that the upper part of the saprolite, beneath the topsoil, had a low resistivity in the range 5-20ohm.m, extending to a depth of 2.5m. An intermediate layer was interpreted in most cases with a resistivity of 30-50ohm.m overlying bedrock at 7-8m. This layer was not clearly defined and so there was a corresponding uncertainty in the expected depth to hard rock; in some cases it could be omitted altogether.

Conductivity profiles crossing the site showed a steady increase in values over the slightly rising ground to the northwest; this originated within the upper part of the sequence and probably corresponded to thicker saprolite over an approximately horizontal bedrock surface. Equivalent apparent resistivities were 100-200ohm.m with the 20m horizontal coils, compared to 30-50ohm.m with 10m vertical coils, indicating a shallow depth to hard rock. Irregularities in the 10m horizontal coil data which were not reproduced with the 20m spacing may represent local variations on the base of the saprolite though more detailed studies would be needed to ensure that the anomalies were genuine. VLF anomalies were also detected, mainly in the in-phase component; the E-phase measurements provided by the EM16R unit should be ideally suited to mapping local variations in resistivity in this type of environment but the data were not sufficiently reliable due the low signal strength obtained.

Five shallow boreholes were drilled over a distance of 150m along the main traverse, with two more offset by 25m on an orthogonal line. They all indicated a similar sequence:

1.5-2.5m to the base of the upper sands;
4.5-6.5m to the base of highly to completely weathered material;
underlain by slightly to moderately weathered rock.

The level of agreement with the resistivity data is acceptable given that the mechanical strength of the top part of the bedrock does not preclude its being sufficiently weathered and porous to give a resistivity closer to that of the saprolite than to the more massive rock.

Seismic results confirmed a shallow depth to rockhead with little indication of any zones of intermediate velocity which could have been interpreted as thicker saprolite. The velocity of 3.5-5m/ms was consistent with an irregular bedrock surface comprising bands of more fractured or weathered material within the harder rock. It was not possible to carry out a detailed quantitative analysis due to the variable data quality and lack of good bedrock arrivals.

3.4 Results from Anuradhapura district

Anuradhapura lies in the north-central part of Sri Lanka, some 170km from Colombo (see inset of Figure 3.29). Work undertaken a little to the east of Anuradhapura was concerned specifically with evaluating the thickness of saprolite in connection with collector wells. Two sites were selected near Mihintale: the first, by the existing collector well at Kurundankulama, 6km west of Mihintale; the second, beside a small temple at Karuwalagasheena, 8km east of Mihintale, where a well was under construction.

The surveys here also formed part of a training exercise to introduce a variety of geophysical techniques to the WRB geologists. Resistivity, EM, magnetic and seismic refraction data were collected to demonstrate the use of the equipment and to compare the response of the different methods.

3.4.1 Mihintale site 1

Most of the work here was undertaken in an open field about 150m square and centred 150m west of the existing collector well; a second dug well lay within the field as shown in the sketch map (Figure 3.25). Water table lay at a depth of 9m in banded, weathered granite with fracture alignments along N300E and N20E; soft weathered rock occurred at a depth of 3m with a harder formation below about 6m.

Resistivity ESA data were in the typical form of an H-type curve although they were best fitted by subdividing the intermediate zone to give four layers:

topsoil:	80-120ohm.m	to	0.5-1m;
saprolite:	30-60ohm.m	to	2.5-5m;
weathered rock:	60-120ohm.m	to	14-20m;
bedrock	>800ohm.m.		

Depths to bedrock interpreted from orthogonal soundings about the same centre point differed by as much as those from separate locations; this suggests that there is an irregularly weathered surface without any marked overall slope. By their nature, resistivity ESA data tend to give an average depth over the spread length, biassed towards conditions in the central area covered by the potential dipole.

Profiling with Schlumberger array current electrode separations of 20m and 60m gave some indication of lateral variations across the site. For a simple case of overburden on top of bedrock, a depth section can be derived if the closer spacing defines the resistivity in the upper layer and the wider spacing lies on the steeply rising limb of the sounding curve, thus fixing the conductance of the sequence above it. In this case the 20m spacing was considered to give an average resistivity for the upper layers in order to calculate apparent depths to bedrock. These lay for the most part in the range 15-20m with the greatest variation occurring along the northernmost line; resistivities were highest to the west.

VLF/EM16 data from five lines showed a systematic variation, more especially in the out-of-phase component; this changed from negative to positive along a NNE heading and suggested a trend along a NW-SE direction. EM34 data at 10m and 20m coil spacings on the western line gave less evidence of this lateral change. The conductivities of 17mS/m for the upper part of the sequence, decreasing to about 8mS/m at depth, were more consistent with the lower end of range of equivalent saprolite resistivities derived from the sounding curves.

Magnetometer readings varied over a range of 80nT indicating that magnetic minerals were associated with the bedrock but without displaying any overall pattern on the small scale of this survey.

Seismic records along three lines provided evidence of time anomalies which indicated variations in both the thickness and velocity of the saprolite. Two refractors were identified below the superficial layer:

layer 1 - velocity 1.2-1.6m/ms to a depth of 2-10m
- attributed to saprolite;

layer 2 - velocity 2.0-3.0m/ms to a depth of 10-20m
- attributed to weathered rock;

layer 3 - velocity 5.0-5.5m/ms (some evidence of anisotropy)
- fresh bedrock with few fractures.

The refractors were not obviously continuous, as might be expected within a residual weathering profile.

Shallow drilling undertaken at two locations, M1/B1 and M1/B2, with an air hammer rig indicated a sequence of:

2-3m to the base of sand, clay and decomposed rock;
8-11m to the base of variably weathered granitic/biotite gneiss;
11-13m to base of boreholes within slightly weathered, fractured rock with evidence of a change in mineralogy between hornblende-biotite and granitic gneiss.

The intermediate layer showed alternate bands of more and less weathered material but it appeared to be more heavily weathered in general at site M1/B2.

The correlation between the drilling and the geophysical interpretations was reasonable in qualitative terms but the depths to relatively fresh rock were apparently overestimated by about 30% from both resistivity and seismic data. This is probably due in part to a difference in the definition of 'bedrock', with the geophysical response being sensitive to a reduction in the competence of the rock on a larger scale, which is not reflected in the drilling samples. Thus, the rock at the bottom of the boreholes would be classified geophysically as being fractured rather than massive.

A dug well would normally penetrate the soft saprolite and be completed within the underlying zone of weathered and fractured rock, using crow bars or occasionally explosives to break up the harder material. In terms of the layering interpreted from the geophysical data, the best estimate of the depth to the base of the saprolite is obtained from the most conductive layer of the resistivity models while an indication of the maximum practical depth to which a well could be taken is given by the base of the upper refractor with a velocity 1.2-1.6ms/m. The geophysical substrate almost invariably lies within the more compact bedrock.

3.4.2 Mihintale site 2

The situation at this site differed from the first in that there was an obvious, if gentle topographic slope with some outcrop or residual boulders of weathered rock. A well being dug near the bottom of the slope had encountered rock at a depth of 6.5m below lateritic and highly weathered material; an existing well about 200m away had been taken to a depth of 7m, with saprolite and weathered rock from a depth of 3m. The fractured granitic gneiss in the wells showed evidence of a steeply dipping set of joints trending approximately N-S, parallel to the regional strike.

The geophysical results were dominated by a change in the weathering profile which occurred at the break of slope below the new well. It was expressed most clearly here in the VLF profiles (see Figures 3.25-3.26) by a negative in-phase component anomaly with an amplitude of 30%, indicative of a steep contact with more conductive material to the east. This was confirmed by resistivity traverses which showed a change from 20-30ohm.m to 100-180ohm.m for a current electrode separation (AB) of 20m, and from 30-60ohm.m to 150-250ohm.m for an AB of 60m. Calculated apparent depths to the east averaged about 16m; those to the west exceeded 20m but the calculation is no longer valid in that the smaller spacing is now too large to provide a realistic approximation to the resistivity of the overburden. Irregularities in the profiles over the higher ground implied a shallow but uneven depth to bedrock.

Resistivity ESA data from locations RS1 and RS2 reflect the differences observed in the traverses with the total conductance of the interpreted models decreasing from 0.6S to 0.14S and depths to the resistive substrate rising from about 18m to 10m. RS3 was sited in the transition zone near the main VLF anomaly and the curve from data at the wider electrode separations rise at more than 45 degrees in response to the more resistive ground offset from the line of the array; the results were useful in that they showed a more conductive component to the saprolite than was seen elsewhere and so, although the depth to the substrate was relatively shallow, the total conductance was intermediate between that for RS1 and RS2. Resistivities of 10-35ohm.m interpreted for the overburden on the lower ground suggest that the saprolite is rich in clays and that permeabilities will be low.

Seismic refraction results confirmed a marked change in the weathering profile between the new well and the lower ground to the east. This is seen clearly in the time-distance plot for line S1 in Figure 3.27 though it is the spreads with a more northerly alignment, parallel to the discontinuity, which provide better data for a quantitative interpretation. Line S3 illustrates the response over the shallower bedrock.

The interpretations derived from S1 could be simplified to a three layer case:

layer 1 - velocity 0.25-0.4m/ms to a depth of 1.5m
- topsoil and saprolite;
layer 2 - velocity 2.5m/ms to a depth of about 10m
- weathered, highly fractured rock;
layer 3 - velocity of 4m/ms
- fractured bedrock.

There was reasonable evidence that at least one and perhaps two additional 'layers' were present in the weathered zone with velocities of 1.3-1.5m/ms and 1.8-2.0m/ms to depths of about 2m and 5m respectively; these could represent lateritic, colluvial material and clays or highly weathered rock respectively, giving a closer correlation with the evidence from the well.

Line S4 was located some 30m to the east of S3, on the lower ground. The model interpreted here resolved four layers:

layer 1 - velocity 0.25-0.4m/ms to a depth of 1m
- topsoil;
layer 2 - velocity of 0.8m/ms to a depth of 3-5m
- loose, dry material of 0.8m/ms;
layer 3 - velocity of 1.1-1.5m/ms to a depth of about 14m
- saprolite;
layer 4 - velocity of 4m/ms
- fractured bedrock.

Thus, within a distance of 30m the depth to seismic bedrock decreases by 5-6m to the west (including 2m due to the higher ground elevation) and the velocities through the weathered zone are almost doubled. The combination of these effects gives rise to the time anomalies and the gross differences in apparent velocities between the forward and reversed profiles recorded from S1.

A series of shallow boreholes drilled at this site gave good agreement with the geophysical interpretations as can be seen from the results which are summarized below. The distinction between overburden and weathered rock is somewhat subjective but it gives an indication of the likely limit to the 'diggability' of the formation:

borehole	depth to base of:		notes:
number	overburden	weathered rock	topsoil of clayey sand to 1m;
M2/B1	4m	not proved to 13.5m	- fresher rock at 6m and 13m;
M2/B2	6m	not proved to 14m	- highly weathered throughout;
M2/B3	4m	11m	- fresh granite at 14m;
M2/B4	1m	4.5m	- fresh granite at 7m;
M2/B5	4.5m	13m	- drilled to 14m;
M2/B6	1m	4m	- drilled to 5m.

No obviously anomalous material was found at M2/B1 which would explain the local time delay observed in this area; it is probably an effect of the lateral change in velocity combined with the refractor geometry in the transition zone at the bottom of the slope. The highly weathered material found in M2/B2 was moist below 4-5m and this would account for the increase in velocity to 1.4m/ms observed on line S4; more aggressive weathering in this zone would also explain the higher conductivities.

3.5 Results from Pelwatte/Monaragala district

Monaragala lies towards the southeast of Sri Lanka (see inset of Figure 3.29), flanking the central highlands, and although still within basement terrain the data here complement the other results in terms of geographic distribution. The surveys were concentrated in the vicinity of the second of three recently drilled WRB boreholes near Pelwatte on land forming part of a large commercial sugar estate where relatively high yields were needed. The drilling had proved particularly successful here in providing test yields of 4.5l/s from the first two sites and a little over 1l/s at the third, from boreholes taken to depths of 52-62m.

The rocks which outcrop locally are a typical migmatitic gneiss with a dip of about 70 degrees and a strike direction of 320-330 degrees along the foliation. Geological mapping within this district had shown the presence of major fold structures and also of metasediments such as the crystalline limestone encountered near the bottom of the first borehole.

Depths to the base of weathered rock in the boreholes were only 10-15m but it was noticeable that a large number of fractures had been reported within the bedrock in the driller's logs. These sites were selected on the basis of resistivity surveys and it was of interest to note that a borehole drilled without such preliminary investigation work, beside the main road about 4km from the estate, by another organisation was abandoned as dry at a depth of 76m. The resistivity data collected subsequently at this site are shown in Figure 3.28 with the results the deep cored hole PB7 near Pelwatte borehole 2 for comparison; on this evidence of less than 5m of overburden underlain by highly resistive bedrock, with the implication that there are few fractures, such a site would usually have been rejected.

Figure 3.29 is a sketch map showing the location of the geophysical surveys and the points drilled subsequently near the second WRB borehole site at Pelwatte. Shallow drilling was intended mainly as a check on the depth to bedrock, with one deep cored borehole to investigate the extent of fracturing; all the boreholes were in fact drilled with the same rig which provided cores once the unconsolidated material had been penetrated. The rest water level was about 5.5m in the original borehole and 4.5m in the deep cored borehole.

Traverse data obtained along a N-S line, 25m to the east of the borehole bring out the main features of the results (see Figures 3.30-3.31). At the southern end of the line conductivities are relatively low; the EM34-3 all lie in the range 10-20mS/m indicating that there is no marked resistivity contrast between the overburden and the bedrock although the low phase angle of 25 degrees measured with the EM16R equipment does indicate that a more conductive upper layer is present. The resistivity ESA RS3 at grid location 25E/260S (given as distance relative to the original borehole) gave a depth of only 4-5m to the base of the overburden of resistivity 40-100ohm.m, this range probably being exaggerated by lateral variations in layer thickness. The resistivity of only 150ohm.m attributed to the upper bedrock to a depth of 25m implies that it is fractured. Use of this resistivity model gives good agreement with the observed EM34-3 values. Shallow borehole PB5 at the same point penetrated 4.5m of medium to coarse sand overlying slightly weathered to fresh bedrock with occasional, well developed fractures; no fractures were present in the 1m of core to the final depth of 11m. The thickness of overburden defined by the depth at which coring commenced was 7-7.5m; this is taken to include the soft saprolite.

Within a short distance to the north of PB5 the EM34-3 data begin to diverge with a marked increase in the conductivity of the upper layer as measured by the 10m coil spacing. ESA point RS4 at 25E/130S was located in this zone and while the depth to bedrock was only increased to 5-6m the resistivity of the overburden had fallen to 10-15ohm.m suggesting a higher clay content; again the resistivity model reproduces the observed EM34-3 values.

A further increase in the conductance of the upper layers is observed beyond 25E/60S and borehole PB6 showed the presence of clays within the superficial layers. This site, at 25E/25S, was chosen to lie near a 'crossover' point on the VLF profile which is the type of response expected above a conductive zone. The saprolite here extended to a depth of 9m overlying slightly weathered bedrock, becoming fresher below 12m. Fractures were well developed with some wider zones of fracturing, including one of at least 0.5m in which the borehole terminated at 16m.

Results from PB3 at 25E/5S and PB6 were essentially similar showing that the VLF anomaly is not the product of a localized change within the weathering profile. A distinctive increase in the EM16R phase occurred near this point in the traverse and with apparent resistivities of only 10ohm.m a significant increase in the depth to bedrock might be expected. ESA data from RS8 are also consistent with this interpretation in that a layer of <20ohm.m extends to a depth of 18-19m above a substrate of <200ohm.m. The other factor to note here was that the EM34-3 response was starting to invert, with the conductivity at depth as measured with the wider vertical coil spacings exceeding that in the upper layers; there was also a marked increase in the horizontal coil values at 20m spacing, while at 40m spacing a negative trough was developing. The model derived from RS8 predicts correctly the 10m coil response but wrongly implies decreasing 20m and 40m values.

The original borehole at the grid origin had found hard rock at only 12m depth and there was no obvious way in which the weathering profile thickness could be varied to explain the observed conductivity pattern. Geophysical logging at this site showed in fact that a highly conductive zone with resistivities 1-3ohm.m occurred from 13m to 22m, while the fluid conductivities within the borehole itself were 500-1000mS/m (5000-10000uS/cm), putting the water quality in the brackish-saline range. The borehole had been capped since completion several weeks prior to this logging and during a subsequent pump test the fluid conductivity stabalized at a lower value of 205mS/m; thus the poorer quality water may be restricted to the upper zone with much better water in the more productive, deeper aquifer.

EM34-3 values indicate a conductive zone with a width of at least 20m and an apparent dip to the north. Resistivity sounding RS9 at 25E/50N was located near the centre of this zone and the model interpreted here gave typical overburden resistivities of 15-30ohm.m to a depth of 15m, below which a more conductive zone of 8ohm.m continued to nearly 30m. The cored borehole at this site was taken to a depth of 55m. Overburden thickness was only 2m but the rock was highly fractured to a depth of nearly 7.5m. Graphite flakes were observed, randomly distributed throughout the samples obtained from the following 12m of drilling, together with a large number of fractures; some pyrite was also noted. Well developed fractures occurred to the bottom of the borehole although their frequency decreased below 45m; between 30m and 40m depth there were numerous examples of slickensides suggesting that this was part of a fault zone. A section of the geological description as provided by a WRB geologist is reproduced in Figure 3.32.

Further north, near 25E/95N, the resistivity data from RS7 still showed the influence of the conductive zone; this might be attributed to the lateral effect of the current electrode to the south crossing the main anomaly but the EM16 response and the drilling results suggest the site is just within the fault zone. PB4 provided little evidence of graphite within these rocks but there was secondary pyrite on several of the fracture planes; slickensides were also observed. The borehole was taken to a depth of 20m with coring from 3m. Highly fractured rock extended to 10m and below this the number of major fractures decreased steadily with depth.

The main feature of the seismic results from S1-S5 along a part of line 25E was the change of velocity through the conductive zone: the overburden velocity increased from 0.6m/ms to 0.9m/ms while the deeper refactor velocity decreased from 4.5m/ms to only 2.6m/ms; this is attributed to the presence of highly fractured rock here. The apparent velocities for the bedrock were faster when shooting towards the south and this is probably due as much to the foliation of the gneissic rock as to any overall slope on the bedrock surface. The thickness of overburden was in the range 5-10m with the lower values over the conductive ground: the dip in the topography over this section of the traverse accounted for an elevation change of 1-2m.

Seismic data from S6 on the parallel traverse 91E showed a thick unconsolidated layer of 0.4m/ms to a depth of 4.5-5m and then weathered rock of 2m/ms to 10-15m; this was underlain by bedrock with a velocity in the range 4.5-5m/ms. No anomalous EM response was detected along this line (see Figure 3.31) and the conductivities were similar to, if a little higher than the southern part of line 25E near RS4; the interpretation for RS5 made the conductive overburden 1m thicker here at 6.5m and the bedrock appeared less resistive in comparison with RS4. Borehole PB1 indicated overburden to 9m (as given by the depth at which coring started) with saprolite coming in below a cover of fine to medium sand at a depth of 1m. Highly fractured rock was cored to 11.5m but below this the intensity of fracturing appeared to be less than along the northern part of line 25E; the borehole was only taken to 14m.

West-east traverses along lines through 0N, 50N, 100N and 152N picked up the conductive zone using the EM34-3; it appeared to be centred near 25E/50N and elongated along the direction 10-20 degrees east of north. There was some evidence that the zone continued at least as far as a NW-SE line about 300m from the original borehole although the anomaly was not fully established here due to the presence of mature sugar cane; investigation of its southward extension was also curtailed for practical reasons.

A resistivity ESA RS6 at 152N/70E and aligned west-east was clearly distorted by lateral variation due to the restricted width of the conductive zone and the interpreted depth to resistive bedrock was only 10m. The shallow borehole PB2 drilled closer to the centre of the anomaly at 152N/50E found overburden and highly fractured rock to a depth of 9m and slickensides were again seen on the fracture planes below this, together with traces of graphite, pyrite and possibly magnetite. A seismic line here showed the low velocity superficial layer extending to about 6m, in good agreement with the depth to the base of the sands given from the drilling; there was also evidence of an increase in bedrock velocity away from the conductive zone.

The results of the drilling and a comparison with the interpreted resistivity and seismic models is given in Table 3.3.

Table 3.3 Summary of drilling and geophysical results from Pelwatte site

	borehole number						
	PB5	PB1	PB6	PB3	PB7	PB4	PB2
total depth drilled m	11.3	13.7	16.2	15.4	54.9	20.4	14.6
depth to start of coring	7.3	9.1	8.2	6.1	3.4	3.0	6.1
depth to first coherent core	7.3	10.1	10.1	12.0	7.3	10.1	9.1
number of distinctive fractures	3	2	10	8	146	15	8
longest unfractured core length	0.9	<0.3	0.6	0.5	1.3	2.0	0.3
depth to base of upper sands	4.6	3.0	7.6	1.5	0.9	3.0	6.1
depth to base of saprolite	4.6	9.1	9.0	6.1	2.1	3.0	6.1
depth to rock - resistivity	3	6.5	6.5	19	24	7.5	8.5
depth to rock - seismic	xxxx	5	8	9.5	5.5	9.5	5.5

Frequency distribution plots of dip angles on the fracture planes showed the greatest number lying in the range 20-40 degrees, similar to the foliation within the bedrock. PB3, PB4 and PB6 had a bias towards steeper dips but the deep borehole PB7 gave a more uniform spread over the range 20-90 degrees. The slickensides, observed only in the cores from PB2, PB3, PB4 and PB7, tended to occur on the more steeply dipping fracture planes.

The apparently favourable indications obtained from the original resistivity survey are almost certainly attributable to the spread crossing the conductive zone within 30m to the north of its centre where the bedrock is in fact at a shallower depth; the presence of graphite and the poorer quality water in the borehole may only be secondary features associated with a major fracture zone which accounts for the high yield in the borehole. Geophysical traversing rapidily established the presence of the lateral discontinuity and could be used to map the extent of the feature; it also helps to set the site in a geological context.

3.6 Summary

i. Conditions over the crystalline basement terrain in Sri Lanka vary within the country but in general they can be distinguished from those encountered during the fieldwork in Africa. One significant factor may be that annual rainfall is usually higher here. At a practical level, access problems are more acute due to the more intensive land usage either by cultivation or natural vegetation; interference from man-made sources is also common. The weathering profile differs in that while hard rock is often encountered within 10m of the surface its geophysical response is similar to that from more weathered rock.

ii. Resistivity ESA results provide a general guide to the nature of the sequence and they are useful for excluding unfavourable sites; qualitative interpretations are often adequate for assessing if a location has adverse aspects or if it more promising than elsewhere.

iii. Surface conditions are often unsuitable for extensive traversing of the type undertaken in African terrain and wire fences may interfere with EM techniques. In many parts of Sri Lanka this appears to be unnecessary in that fracturing is relatively extensive and the precise site of the borehole is not critical to obtaining a reasonable yield.

iv. The experience of WRB is that a success rate of better than 90% is obtained when rural supply boreholes are sited following geophysical, mainly ESA resistivity, surveys. This does not allow for boreholes suffering from quality problems such as high flouride or salt levels or iron precipitation. A greater but unquantified proportion of dry holes result if sites are chosen on the basis of convenience alone.

v. The geophysical results do not provide a unique interpretation and it is not always easy to make a precise correlation between them and drilling information; however, the results of the more extensive surveys undertaken for this study did invariably give a reasonable qualitative guide to subsurface conditions. Surveys of this type can be justified in areas with particular problems or where higher yields are necessary.

vi. Care is needed in assessing geophysical surveys for dug well sites to distinguish between the saprolite which can be dug with relative ease and the upper section of the weathered rock which contains hard fractured blocks. A combination of resistivity and seismic methods offers the best chance of locating the transition to within 20%: changes in thickness can be mapped with more accuracy. It is rarely possible to identify the depth to water from the geophysical data and, as always in this type of work, a knowledge of local conditions is very important.

4. DISCUSSION OF RESULTS FROM COLLECTOR WELL SITES

4.1 General comments

Geophysical surveys were undertaken on a regular basis as part of the site selection procedure for locating collector wells in the first pilot project undertaken in Zimbabwe. The main priority of the geophysics was to outline areas where the depth to bedrock was sufficient to permit construction to the planned depth of about 12-15m, thus ensuring adequete storage capacity. Information on the other critical factors, such as the rest water levels, formation permeabilities and the presence of lateral variations which would indicate preferred orientations for drilling the radials, was obviously required if possible.

Most of this work was done by staff of the local Water Department using reconnaissance Schlumberger resistivity profiling techniques with detailed follow-up in more promising areas. The results illustrated that, while high resistivities are a good indication of unsuitable ground conditions due to shallow bedrock, it is very difficult to interpret the data quantitatively in terms that correspond with the experience of subsequent test drilling and well construction. This is attributed in part to the degree of ambiguity inherent in the resistivity method but it is also a function of the highly variable nature of the regolith on a local scale; as resistivity values are based on sampling a relatively large volume of ground in comparison with the effective depth of investigation, their resolution is limited.

Another difficulty arises in relating the electrical properties of saprolite and weathered bedrock to their mechanical strength. Chemical processes, essentially related to the formation of clay minerals, partly determine the bulk resistivity of the material together with its porosity and fluid content. Conductive paths can be formed through a rock matrix at an early stage by alteration at the surface of its constituent mineral grains and this means that layer resistivities can suggest promising zones which turn out in practice to be too hard for well construction. Drilling results can also prove misleading in this respect, as for example when corestones are mistaken for the bedrock surface, but in some cases the resistivity interpretations consistently predicted saprolite below levels at which boreholes encountered hard rock.

4.2 Results from trial surveys

A limited amount of supervised geophysical fieldwork was undertaken in Zimbabwe at three of the sites chosen for the second series of collector wells, namely near the schools of Mukumba, St Nicholas and St Lioba. Once again it was necessary to rely on electrical methods using resistivity soundings and electromagnetic traversing with an EM34-3 in an attempt to find sites suitable for testing by exploratory drilling. All of the localities were in marginal areas where borehole success rates in the past had been poor, and bedrock outcrops were common. In these circumstances the first objective was to find any sites where there was some possibility of success, accepting that the risk factor would be high. The work done and the results obtained have been described elsewhere (Carruthers, 1985) and what follows is a summary, reviewing the surveys in the light of additional information.

4.2.1 Mukumba School, Zimbabwe

Resistivity interpretations had indicated that depths to bedrock could be as much as 18m for a regolith resistivity of 60ohm.m in the area recommended for drilling to the west of the school: in fact, none of the four boreholes here penetrated more than 6m before encountering hard rock and apart from some seepage through the superficial layers there was no water. This discrepency was accounted for within the range of equivalent solutions that fitted the field curves though it meant reducing the resistivity in the regolith to about 20ohm.m and the introduction of an intermediate layer of 150-200ohm.m above resistive bedrock. Even with this correction the depths to bedrock, now associated with the upper surface of the intermediate layer, came out somewhat too deep. The sounding curves were of H-type (having a minimum) and, with high values in the top 2-5m, measured apparent resistivities did not fall below 100ohm.m. There was, therefore, no direct evidence that the saprolite had such a high conductivity; the range of equivalent solutions was also increased because the field data were subject to minor distortions due to near-surface variations.

Some control was in fact available which limited the number of acceptable interpretations. This was provided by the EM34-3 equipment for which readings can be simulated using a layered-earth resistivity model. The EM response is more sensitive to changes at higher levels of conductivity and so the problems of equivalence occur over a different range. That is to say, equivalent resistivity models can give significant differences in predicted EM34-3 values. In this instance the EM34-3 readings corresponded more closely with the model having a thinner, conductive regolith though the variation was relatively small. The most sensitive parameter for detecting the difference was the ratio between horizontal coil readings at 10m and 20m separation: in one example this was 1.15 for the original interpretation and 1.4 after adjustment to fit the borehole depths more closely; the ratio of observed EM34-3 values was 1.65 which implies an even thinner conductive layer. Another useful indicator in these circumstances is the ratio between vertical and horizontal coil readings at a separation of 20m: with a thicker conductive layer this is close to or slightly less than one, while in the other case it is 1.13. Clearly, with a more complete analysis of the data at the time of the survey, drilling of these sites would have been a low priority.

An area on the opposite side of the road to the east of the school appeared more favourable on the basis of both resistivity and EM34-3 data, though only a limited amount of work was done because a supply point here would not have been convenient. There was a marked lateral variation with EM34-3 values at 20m coil separations increasing from 7-8mS/m to over 15mS/m in a distance of 100-200m. Resistivity interpretations put resistive bedrock at depths of at least 20m below a sequence comprising 1-2m of resistive soils, conductive saprolite of 20-40ohm.m to a depth of 7-12m and an intermediate layer of 50-100ohm.m. The one borehole drilled into this zone encountered 'very hard' granite at a depth of 11.5m.

While this clearly represented an improvement on the initial sites the bedrock depth was still about 50% less than predicted and the hole was bailed dry within a short time. The problems of equivalence were less severe and the only explanation available is that the resistivity of the hard rock itself is low, and equates with the intermediate layer. A reduction in bulk resistivity could be explained by weathering along joints and fractures which provides current flow paths around large blocks of hard resistive rock. The possibility that the bedrock was layered horizontally, with bands of hard rock separated by weathered fracture zones within its upper section, or that boulders had been encountered, was not borne out by the drilling results though only 1-2m of the rock were penetrated. Again there is not enough control on the mineralogy to say whether more than one rock type is present. The pattern of resistivity variation across the area does indicate some zoning and, even if this arises from the nature or thickness of the regolith, it probably reflects properties of the bedrock beneath.

The only other data which seemed worth further investigation were picked from the earlier survey. Two resistivity soundings near the marshy area of the 'vlei' west of the school showed a conductive superficial layer. The rising, A-type curves, gave a better indication of the intermediate layer resistivities though suppression rather than equivalence meant that the sequence was not resolved clearly. Depths to resistive bedrock were still in the range 13-18m with two components to the overlying material having resistivities of about 30ohm.m and 100ohm.m; there was no reason to suppose from the earlier drilling that both components would represent softer saprolite here but, in the event, better results were obtained and a well site was located. Six holes drilled over a distance of 150m illustrated the degree of lateral variation with depths to hard rock ranging from 6m to over 17m. This may be reflected in the EM34-3 readings with 20m horizontal coils which oscillated between adjacent stations: the variations were outside the range attributable to errors in the alignment of the coils and the results were noticeably more consistent elsewhere. Additional sounding curves also showed distortions due to lateral changes.

4.2.2 St Nicholas' school, Zimbabwe

Surveys were undertaken initially working downslope and west from the school towards an existing borehole. A series of eight soundings supplemented by EM34-3 data showed a distinct change in response from the regolith across a zone of standing water associated with a spring line. Above the spring line the minimum layer resistivity was about 200ohm.m to a depth of 12-18m and there appeared to be no significant development of saprolite. Further downslope the conductivity of the sequence as a whole increased steadily; this could indicate a change in lithology but it was attributed mainly to a thin, upper layer with compact, if weathered, rock still occurring at shallow depth. EM34-3 results did reveal some more promising zones though they were too far from the school to be of immediate interest.

The results from close to the school were not encouraging as the conductance of the regolith was so low. However, an EM34-3 traverse had shown slightly higher values near the southwest perimeter fence and additional work here confirmed that conditions were more favourable. Sandy soils gave very high resistivities and the excessive electrode contact resistances reduced the accuracy of the measurements; they also led to problems with equivalence when interpreting the results. Nevertheless, depths to compact rock of 12-18m were derived for saprolite resistivities of about 60ohm.m. The upper resistive layer extended to 4-6m, at which depth either water table or a transition from clean sand to clayey sand was expected.

In the light of the drilling at Mukumba it was anticipated that the saprolite would prove to be thinner and more conductive than the original interpretations suggested; the EM34-3 values correlated better with a model putting rockhead at no more than 10m. The boreholes actually proved to be consistent with an intermediate case giving depths to bedrock of 11-14m and a site to the southeast of the school was selected for the well. The first borehole, sited further downslope to the west as a check on the 'resistive regolith' and on the existence of a shallow water table, did encounter rock at shallower depth.

Variations in conductivity were mapped using both resistivity and EM equipment though results from the EM34-3 should be more reliable for detecting conductive targets. The response is determined by the conductance of the saprolite, that is a combination of its thickness and conductivity, and so the changes cannot be correlated directly with the depth to bedrock. Higher readings at the 10m horizontal coil orientation are indicative of a more conductive saprolite; if, also, the ratio of vertical to horizontal coil readings at 20m spacing is close to or less than one then depths to resistive bedrock should exceed 10-15m, though the precise relations depend on the layer parameters of the overburden.

4.2.3 St Lioba's school, Zimbabwe

Little time was available for extra work at this site and the objective was to see if an inferred fault had any geophysical expression by which its location could be fixed, on the basis that it might represent a zone of enhanced permeability. EM34-3 traverses beside existing exploratory borehole sites - which had been selected following extensive resistivity surveys - showed that they lay within a localised zone of relatively high conductivity. Drilling had proved depths to bedrock exceeding 20m but at three of the six sites there were bands of hard granite at higher levels while low permeability clayey material occurred in others.

The form of this zone was not fully defined but it clearly died out quite rapidly towards the 'fault' to the north. Resistivity soundings on either side of the lineation proved a resistive sequence to the north and a more conductive regolith to the south, similar to the results found west and east of St Nicholas' school. By assigning a resistivity of 80-100ohm.m to the saprolite south of the contact a depth to resistive bedrock of 18m was derived. Subsequent drilling at the same point (borehole 8) encountered very hard granite at only 4.5m. The conductivity of the saprolite must be significantly higher than initially assumed and the site was probably too close to the northern margin of the transition zone, but even after allowing for this it is not possible to reconcile the data; the depth to 'bedrock' lies within the resistive cover overlying the conductive layer in any model and the readings available from two orthogonal soundings gave consistent results with no indication of lateral effects. It seems that either: the bedrock itself is conductive here - which is inconsistent with the EM34-4 data; the hole went into an isolated raft of hard rock; or, there was a location error.

EM34-3 traverses across the lineation suggested that it lay just inside the limit of an area of shallow, resistive bedrock to the north and it might represent a major joint line; there was no anomaly that could be associated with a wider zone of weakness. The contact could also demarcate a change in rock type, from granite to a micaceous gneiss for example, tying in with the rising contours on the bedrock surface derived from the drilling data. The geophysical results show a boundary that swings round to the south rather than one following the more easterly heading of the lineation: a resistivity sounding 30m east of b/h 8 ressembled that to the north, while to the west of the borehole a saprolite response was maintained. This is consistent with the fact that the well site, where bedrock was nearly 19m below surface, was found only 50m to the southwest of b/h 8.

4.2.4 Mponela, Malawi

Preliminary geophysical surveys at Mponela took as there starting point an existing borehole, IR50, which had produced a high yield from relatively shallow depth. In view of the extensive sulphate deposits associated with a large dambo to the west of the town, most of the work was concentrated in the smaller dambo system to the east of the main road from Lilongwe.

Results obtained near IR50 could be interpreted simply in terms of conductive saprolite overlying bedrock at a depth of 10-12m; alternatively, the addition of a layer of 30ohm.m between 8m and about 25m depth produced an improved fit to the sounding data and was more consistent with the driller's borehole log on the assumption that it represented harder, weathered bedrock. An EM34-3 traverse eastwards from IR50 across the dambo showed that the total conductance of the regolith decreased significantly approaching the dambo and maintained a lower level beyond it at least as far as the second tributary channel. High values from over the dambo itself were typical of the response due to a thin cover of grey/black smectite clays. An ESA site on the east flank of the dambo also produced a typical curve showing relatively resistive material at a depth of 6m: this has been shown to relate elsewhere (see Section 2.2) to hard rock separated by zones of much softer, weathered material.

Data obtained near the site selected for the northerly well predicted bedrock depths of about 25m though there was some evidence that lateral variations in lithology and saprolite thickness might be significant. An EM34-3 traverse again showed that the sequence became more resistive approaching the dambo while highly conductive graphitic schists occurred within 400m to the north. Three resistivity soundings in the area gave slightly different responses which could have quite different implications for a collector well site. One, oriented N-S about 50m west of the well site, suggested a thick saprolite, to as much as 25m; a second, some 70m further south and aligned W-E, gives either a shallower resistive bedrock at 16-18m or a harder band above weathered rock at this level; the third, 150-200m to the south, is similar to the IR50 site and distinguishes conductive saprolite from an intermediate layer (?weathered rock) of 50-60ohm.m below 8m to a depth of 20-25m.

An exploratory borehole near the well site was most consistent with the last interpretation in that harder material was encountered towards the bottom at about 20m. The dug well did not penetrate the saprolite though it was becoming harder below 11m; this type type of material is consistent with the resistivity results and without a known depth to the bedrock the interpretations cannot obviously be modified. It is not clear whether the different resistivity models represent genuine lateral variations within the sequence or if they are a function of the ambiguities inherent to the method. The change along the EM34-3 traverse does suggest that the well is sited within the more resistive environment of the dambo and beyond the area of thicker saprolite to the west.

Results near the southerly well site showed a higher conductance for the layers above resistive bedrock. The overburden was divided into two zones with the deeper layer resistivity being only 25ohm.m for a depth extent of 8-35m: this suggests the presence of thicker saprolite here rather than of the weathered bedrock found at the northern site. High resistivities in the top 3-4m were consistent with the occurrence of laterites. The exploratory borehole PC3 confirmed the resistivity interpretation to the extent that a thick weathered sequence was proved and massive bedrock had not been encountered at the final depth of 35m; the high clay content, and thus poor aquifer properties, matches with the relatively low layer resistivity.

Other data from closer to and east of the dambo again showed a change to a more resistive environment: about 250m beyond the dambo, ESA site R9 indicated the presence of harder, resistive material within 12m of the surface. Thus it appears that the nature of the regolith changes markedly from west to east. Test drilling at the resistivity sites R2 and R9 confirmed the interpretations in a qualitative sense with the predicted depths to 'bedrock' of 6m and 12m respectively, relating to a thickening of the weathering profile of this order.

Two ESA sites by the large dambo west of the main road had sandy/lateritic soils and a more resistive saprolite than elsewhere. An interface at 12-15m depth could relate to the base of this saprolite over weathered rock though again the important intermediate layer is poorly defined. If water quality problems were not a consideration this area would seem best suited for a collector well if the thickness attributed to the saprolite is correct and its higher resistivity reflects a lower clay content.

4.3 Summary

At most of the sites investigated in Zimbabwe the resistivity interpretations proved to be overoptimistic in predicting bedrock depths; this only serves to emphasize the value of the reconnaissance surveys in discounting large areas from further investigation. Without widespread drilling control it is not possible to say that some good sites may have been rejected but all the evidence suggests that high resistivities are associated with hard rock at shallow depth.

Where interpreted depths were too large this resulted from the use of too high a resistivity for the saprolite: the 'typical' mean values selected had to be resolved into two components, a thin conductive saprolite overlying a zone of intermediate resistivity; the reduced resistivity of hard rock is attributed either to a degree of alteration within the rock matrix or to secondary porosity effects related to jointing and fractures.

Semi-quantitative analysis of the EM34-3 data in combination with the resistivity interpretations reduced the range of thickness attributable to the saprolite. EM34-3 data collected with 10m-20m coil separations are considered to be more reliable and more diagnostic than resistivity traversing; the need to maintain correct coil alignment can be offset against the fact that no direct electrical contact has to be established with the ground.

When starting work in a new district it is necessary to build up experience of local conditions before appropriate layer parameters can be established. Thus better results should be obtained if more sites are required in a limited geographical area. It is important that geophysical surveys form part of an integrated exploration approach with drilling control being provided at an early stage with a regular review of results as a project progresses.

There was no evidence that standard electrical methods by themselves have sufficient resolution to locate well sites in marginal conditions or to assist in fixing directions for radial drilling. Seismic techniques might provide better control but they too will be subject to error if lateral variations occur over short distances. The main role for geophysics is to eliminate areas underlain by shallow bedrock and to indicate where distinctive variations occur so that exploration boreholes can be sited effectively. The results should be checked after each hole has been completed to avoid unnecessary drilling, to update the interpretation model and to initiate more fieldwork if necessary.

5. GENERAL CONCLUSIONS AND RECOMMENDATIONS

The main points arising from the studies have been covered in the summaries at the end of the individual sections and will not be repeated here in detail.

i. Quantitative interpretations of resistivity soundings frequently prove unreliable when compared directly with drilling control. Nevertheless, the data can be used successfully as a basis for site selection in areas where success depends on bulk properties of the sequence, either in terms of thickness of overburden or of zones of more fractured bedrock.

ii. In conditions of shallow bedrock where aquifers are limited to highly localized features of the weathering profile it is essential that traversing techniques are employed; an EM method will almost invariably be more effective than resistivity unless apparent resistivity levels over productive zones are unusually high (>150ohm.m).

iii. A combination of geophysical techniques will usually lead to a better interpretation than any one used alone. For rural supply boreholes there may be no need, or a lack of time or resources to optimize site selection; more effort may be justified in difficult areas or when higher yields are needed.

iv. Geophysical surveys should not be undertaken in isolation from consideration of other techniques and general hydrogeological principles.

v. Further model studies are needed to establish the cause of EM anomalies and their relation to the aquifer system. Field trials of the latest generation of time domain EM equipment are considered essential; these techniques offer the best potential for improving success rates.

vi. The effectiveness of seismic techniques has yet to be proved. They do not appear to be justified for routine surveys in preference to electrical methods but they have a place in more detailed studies. Further trials of the shear wave method are needed to see if more information can be obtained on the mechanical properties of the overburden and weathered bedrock.

vii. There remains a shortage of good correlation data for making a general assessment of the economic benefits attributable to the use geophysical surveys in development projects. Specific studies have established their cost effectiveness.

ACKNOWLEDGEMENTS

All the data discussed in this report were collected in collaboration with the local governmental water supply departments in Malawi, Sri Lanka and Zimbabwe. The assistance in terms of staff, transport and resources provided by these organizations is gratefully acknowledged, with especial thanks to those members of staff who participated directly in the concentrated spells of field work.

The British High Commissions provided invaluable assistance with clearing equipment through Customs and also in supplementing local transport.

The project as a whole is funded by the Overseas Development Administration.

REFERENCES

Ghosh D P, 1971. Inverse filter coefficients for the computation of apparent resistivity standard curves for a horizontally stratified earth. Geophys. Prospecting 19, 769-775

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

Karous M and Hjelt S E, 1983. Linear filtering of VLF dip-angle measurements. Geophys. Prospecting 31, 782-794

Mundry E, 1980. Short note: The effect of a finite distance between potential electrodes on Schlumberger resistivity measurements - a simple correction graph. Geophysics 45, 1872-1875

Omorinbola E O, 1983. Shallow seismic investigation for location and evaluation of groundwater reserves in the weathered mantles of the Basement Complex in southwestern Nigeria. Geoexploration 21, 73-86

O'Neill D J, 1975. Improved linear filter coefficients for applications in apparent resistivity computations. Bulletin of Australian Society of Exploration Geophysicists 6, 104-109

Ovaskainen E, 1984. Case study of the use of refraction seismic surveys for the siting of boreholes for handpumped supplies in Western Province, Kenya. (Proceedings of the Harare Symposium, July 1984). IAHS publication 144

Rijo L, 1977. Modeling of electric and electromagnetic data. PhD thesis, Univ. of Utah

Sjogren B, 1984. Shallow refraction seismics. (London: Chapman and Hall)

Basement Aquifer Project Reports

Carruthers R M, 1985. Review of geophysical techniques for groundwater exploration in crystalline basement terrain. Rep. Reg. Geophys. Res. Group Br. Geol. Surv., No. RGRG 85/3

Carruthers R M, 1986. Report on the application of geophysical surveys to groundwater exploration in crystalline basement terrain, 1985. Rep. Reg. Geophys. Res. Group Br. Geol. Surv., No. RGRG 85/12

Smith I F and Raines M G, 1987. Geophysical studies on the basement aquifer in Masvingo Province, Zimbabwe. Rep. Reg. Geophys. Res. Group Br. Geol. Surv. Project Note 87/7

Smith I F and Raines M G, 1988. (in press).

Separate reports have been prepared for other studies, such as geochemistry, weathering processes, borehole logging etc, undertaken as part of this project; a related project concerned with the siting, construction and performance of collector wells is also a source of relevant information including geophysics. Details of reports currently available can be obtained from the Overseas Hydrogeology Group, British Geological Survey, Wallingford, UK.

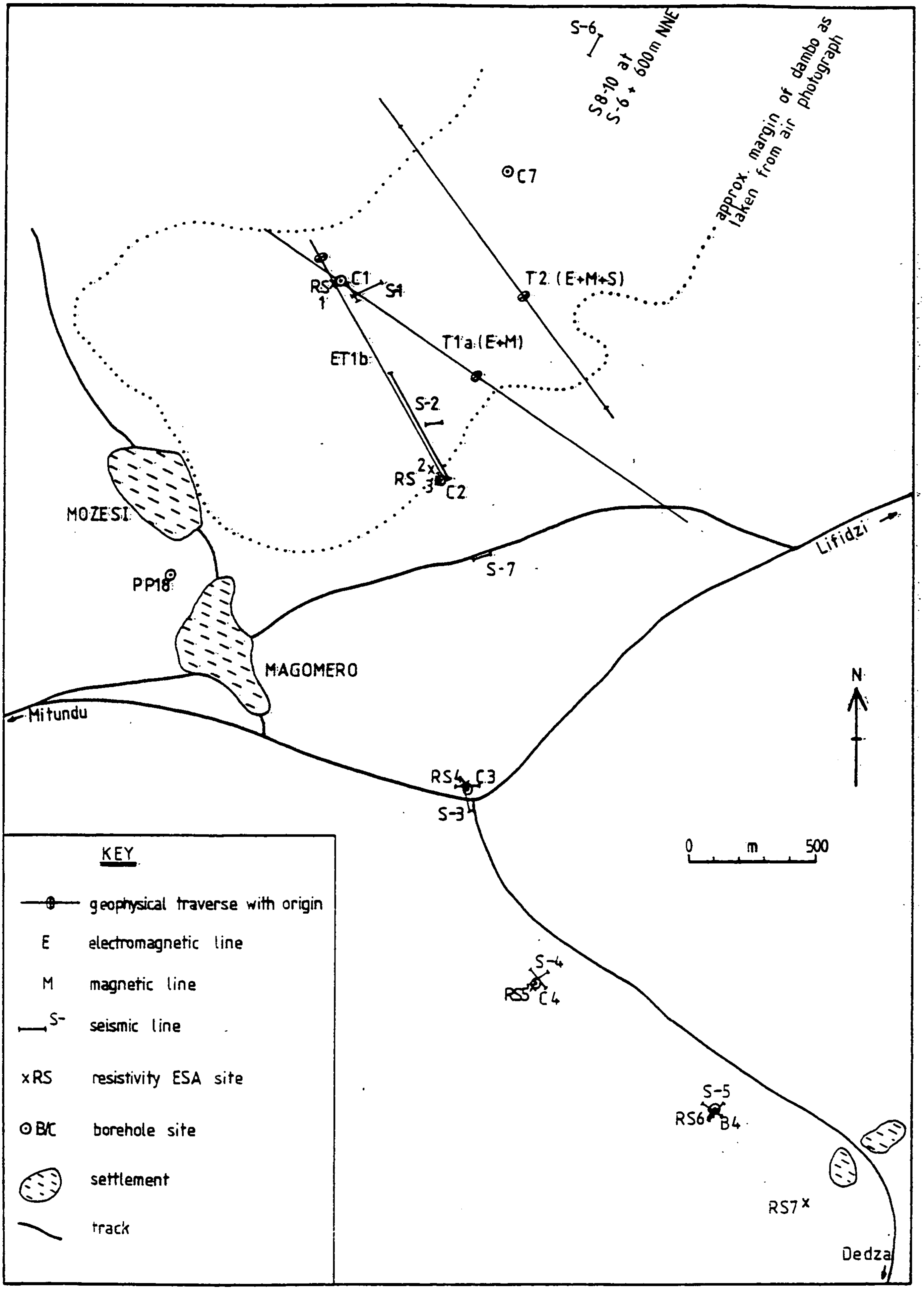


Figure 2.1 Sketch map of site locations at Chimimbe dambo, Malawi

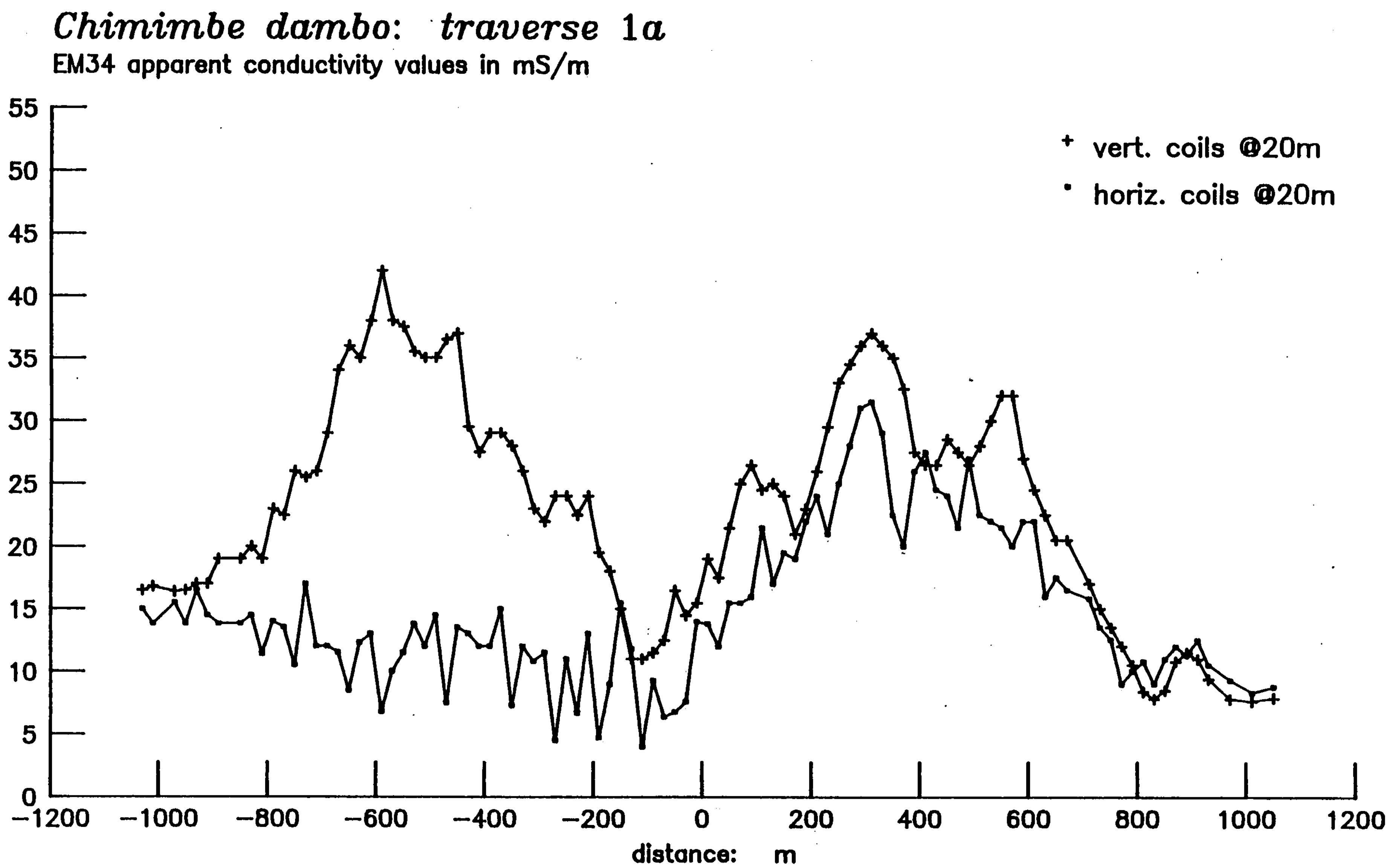


Figure 2.2a EM34 conductivity profiles along traverse T1a, Chimimbe

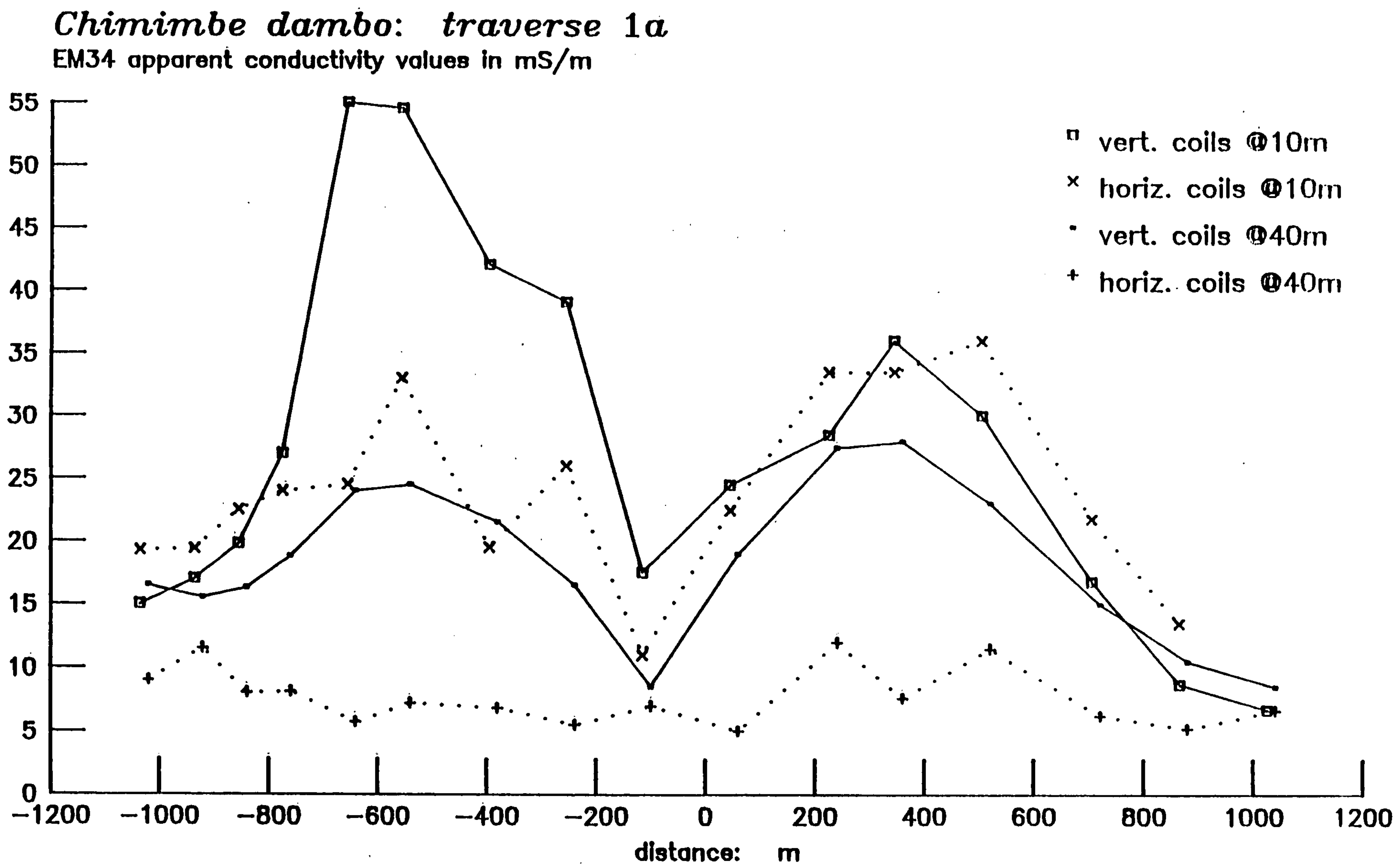


Figure 2.2b EM34 conductivity profiles along traverse T1a, Chimimbe

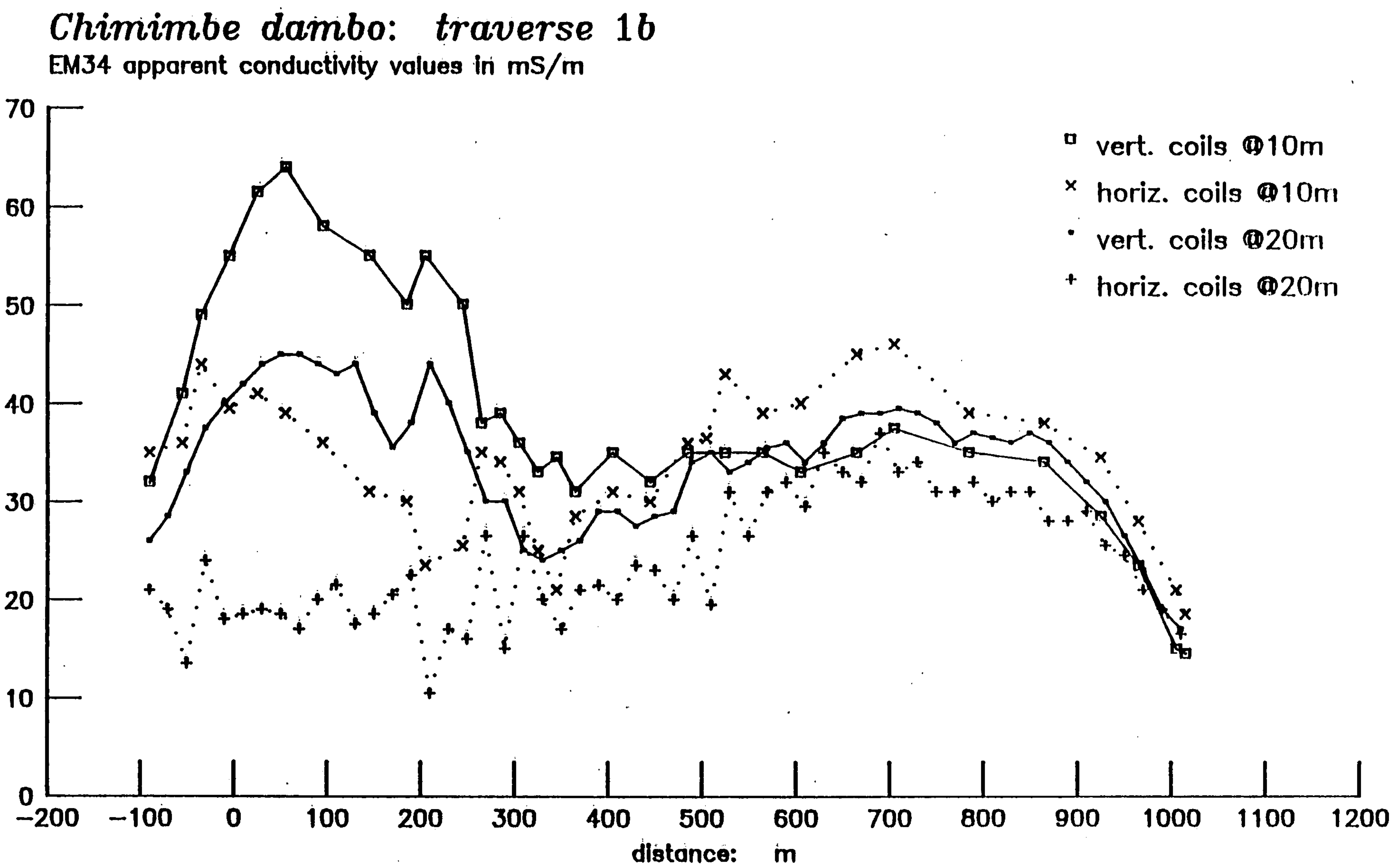
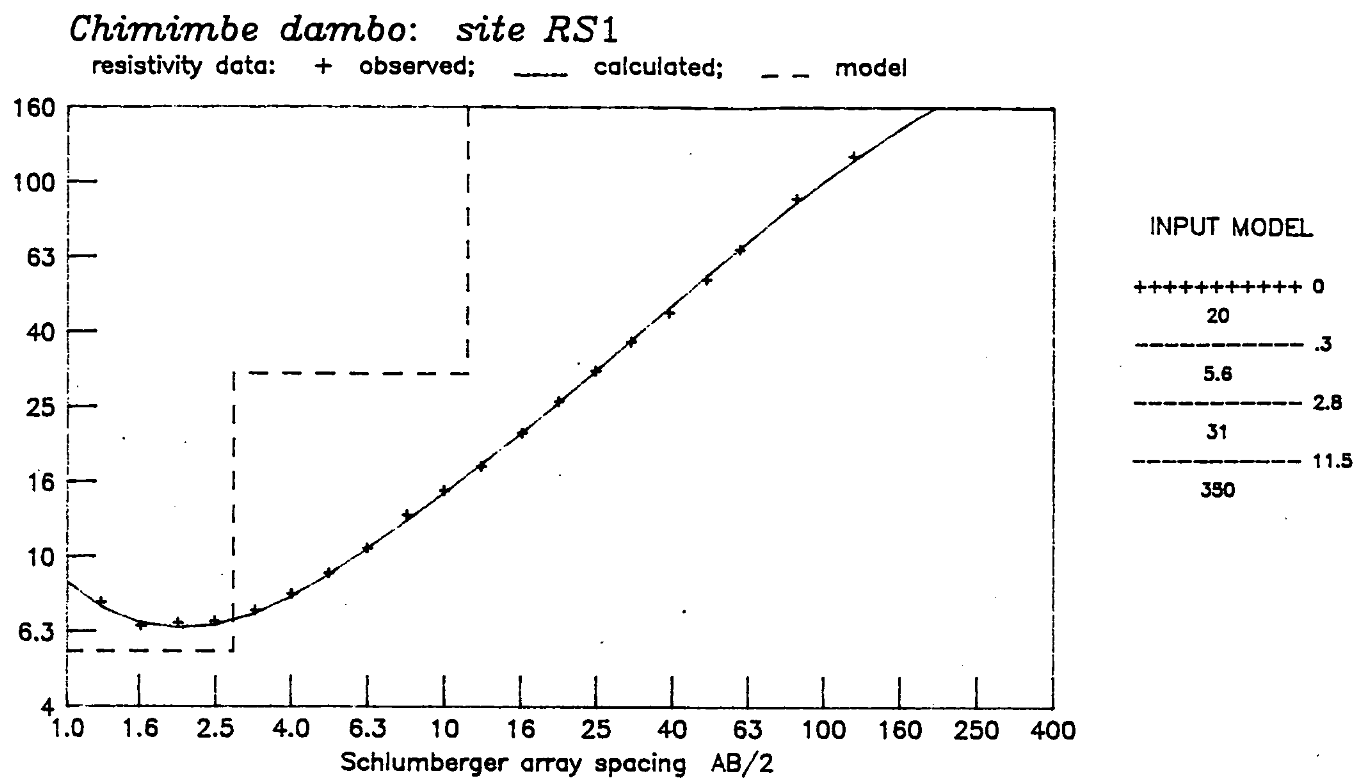


Figure 2.2c EM34 conductivity profiles along traverse T1b, Chimimbe



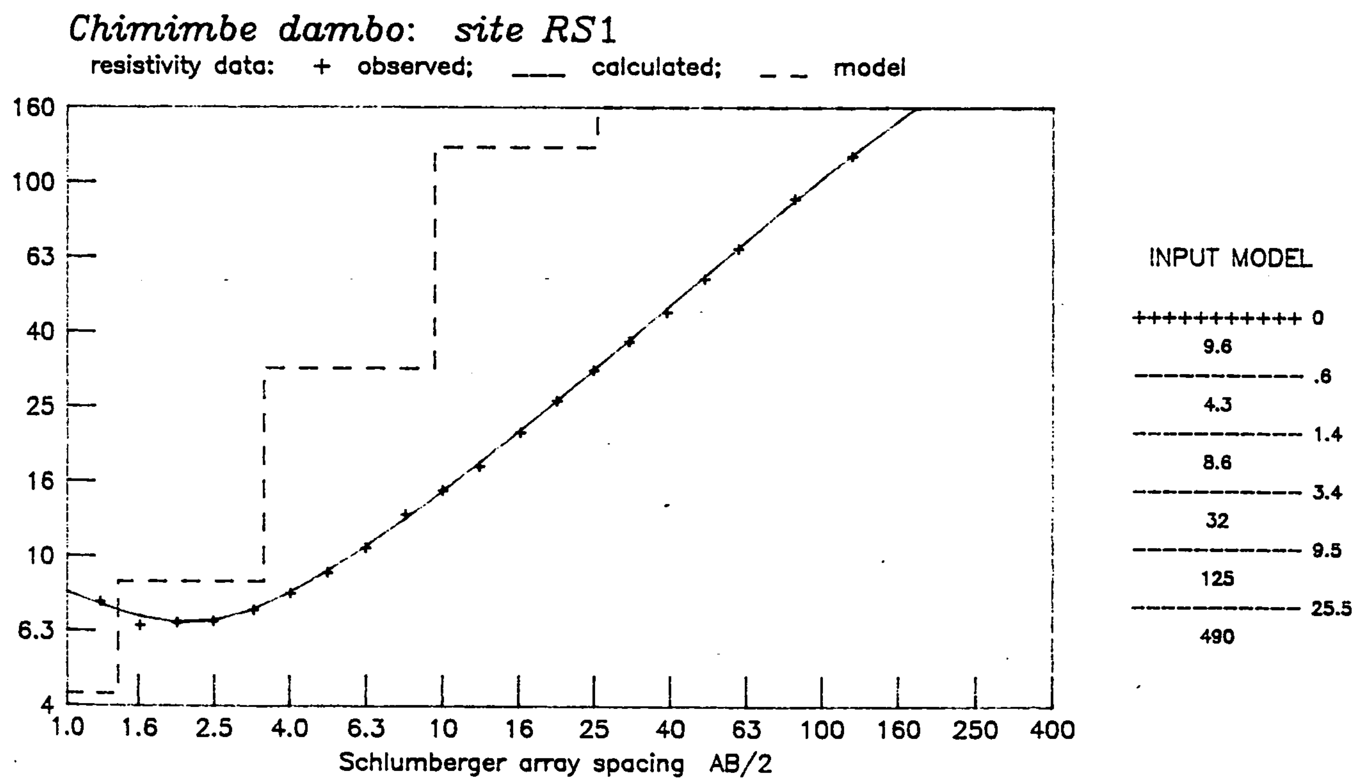
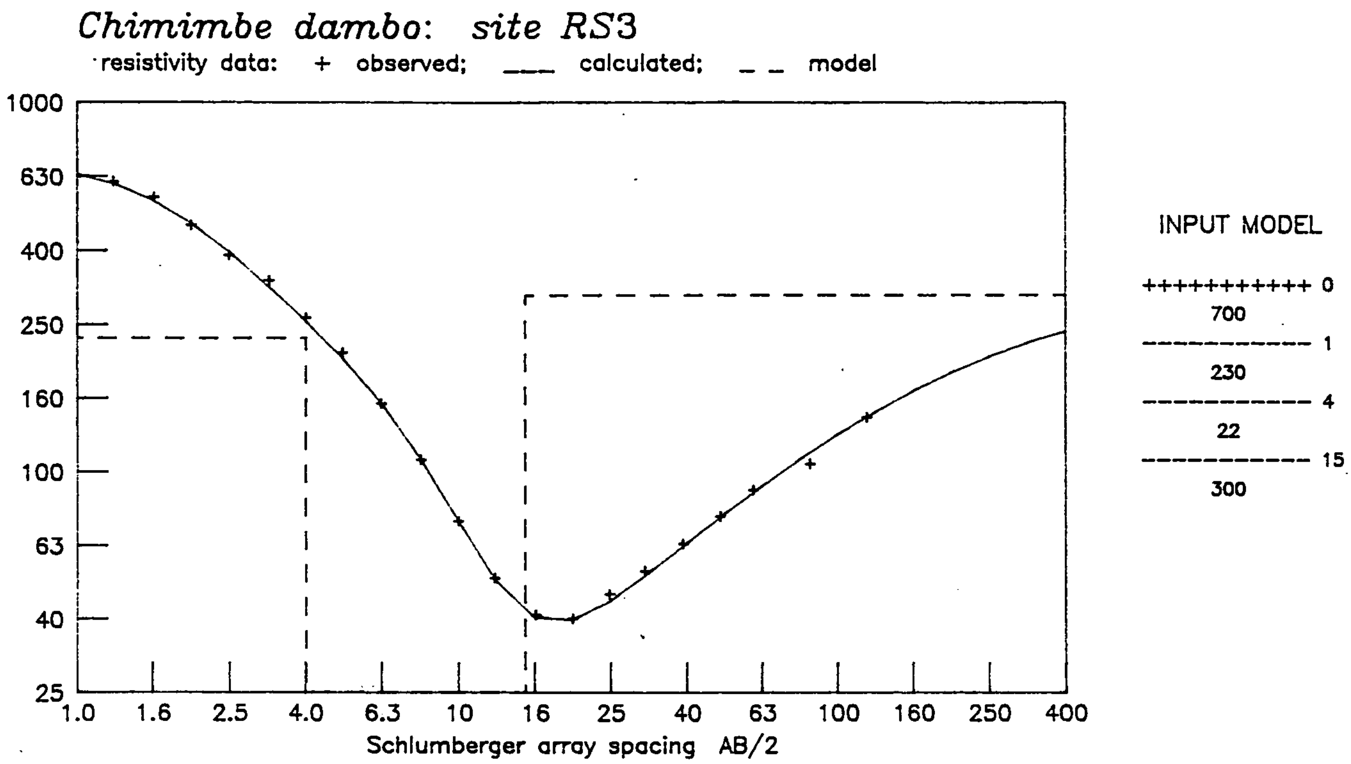


Figure 2.3 Alternative resistivity interpretations near borehole C1, Chimimbe



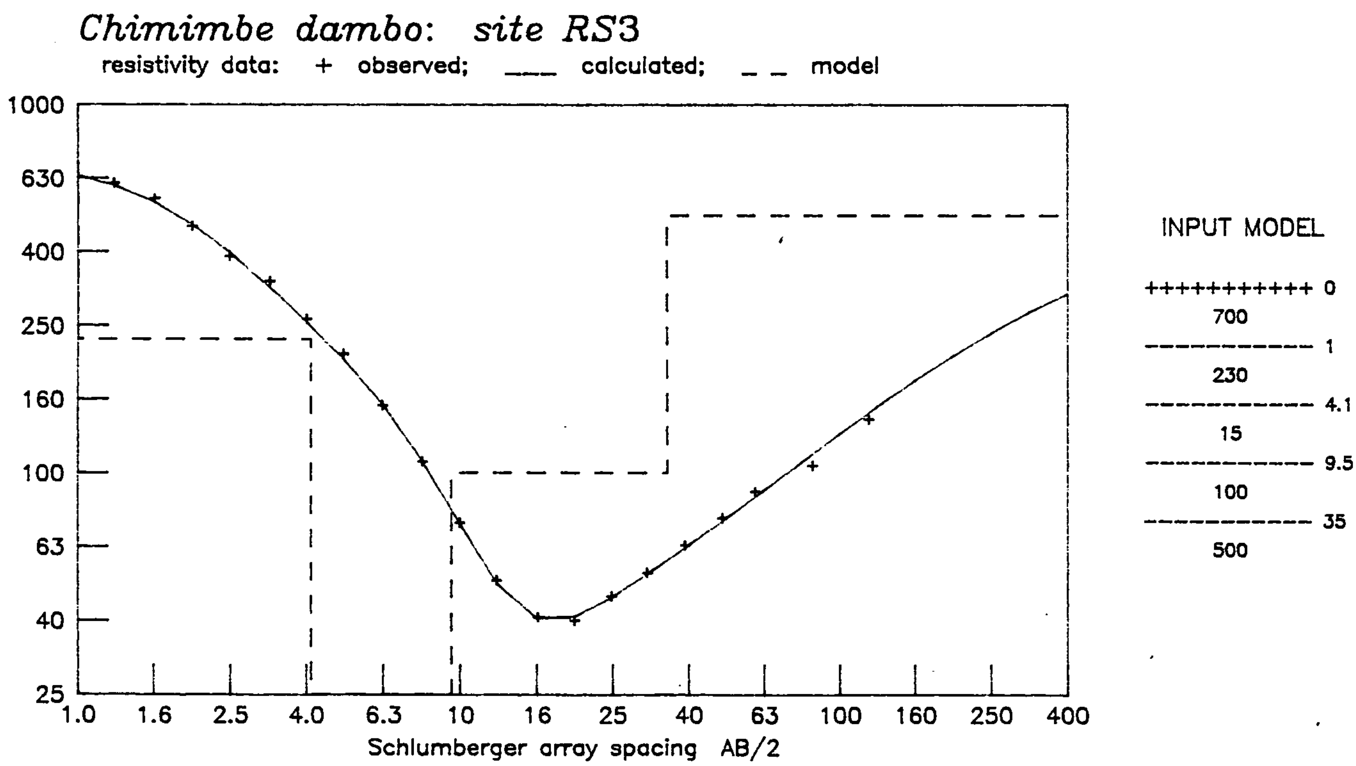


Figure 2.4 Alternative resistivity interpretations near borehole C2, Chimimbe

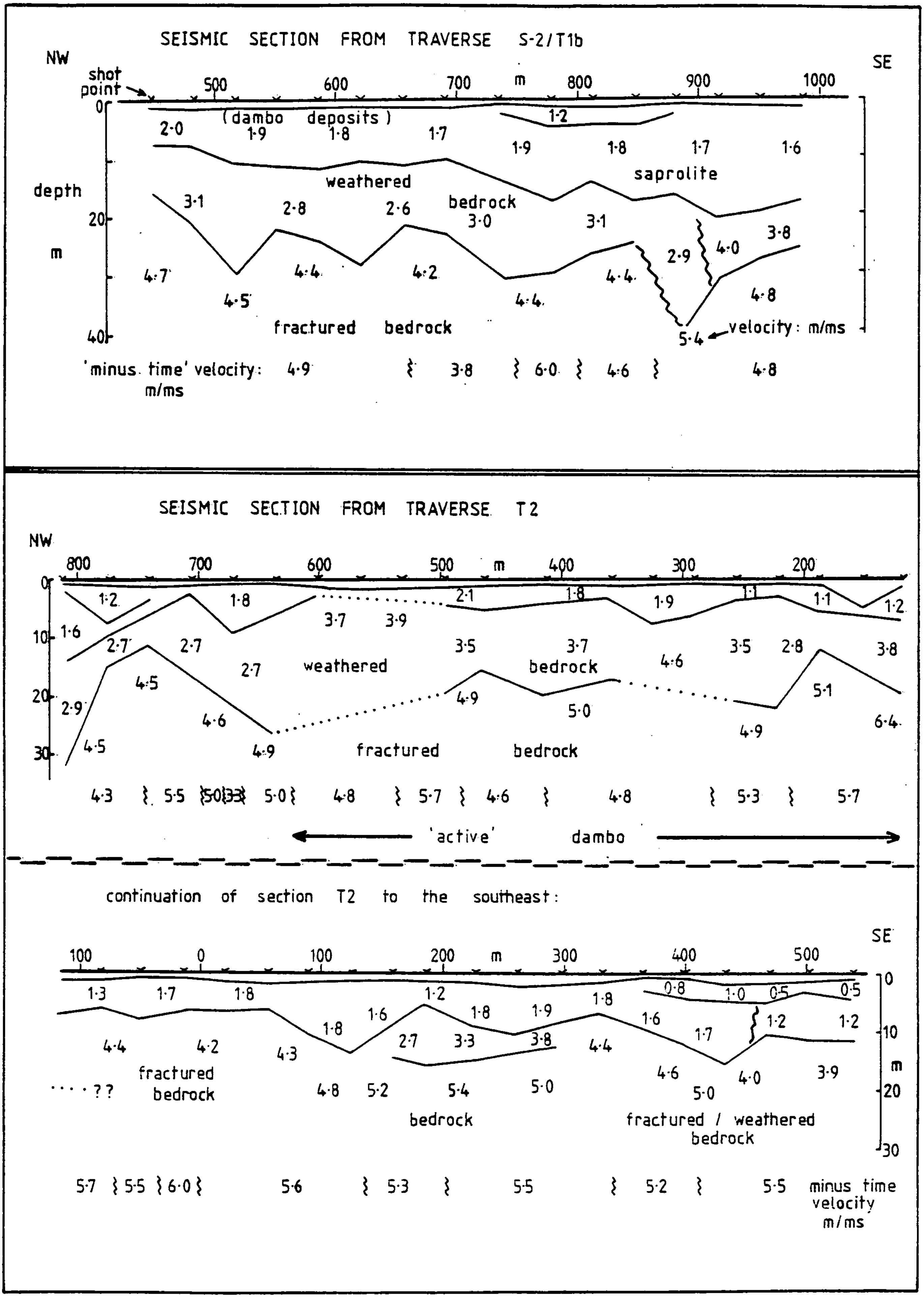


Figure 2.5 Interpreted seismic depth sections from lines ST1b-2 and T2, Chimimbe

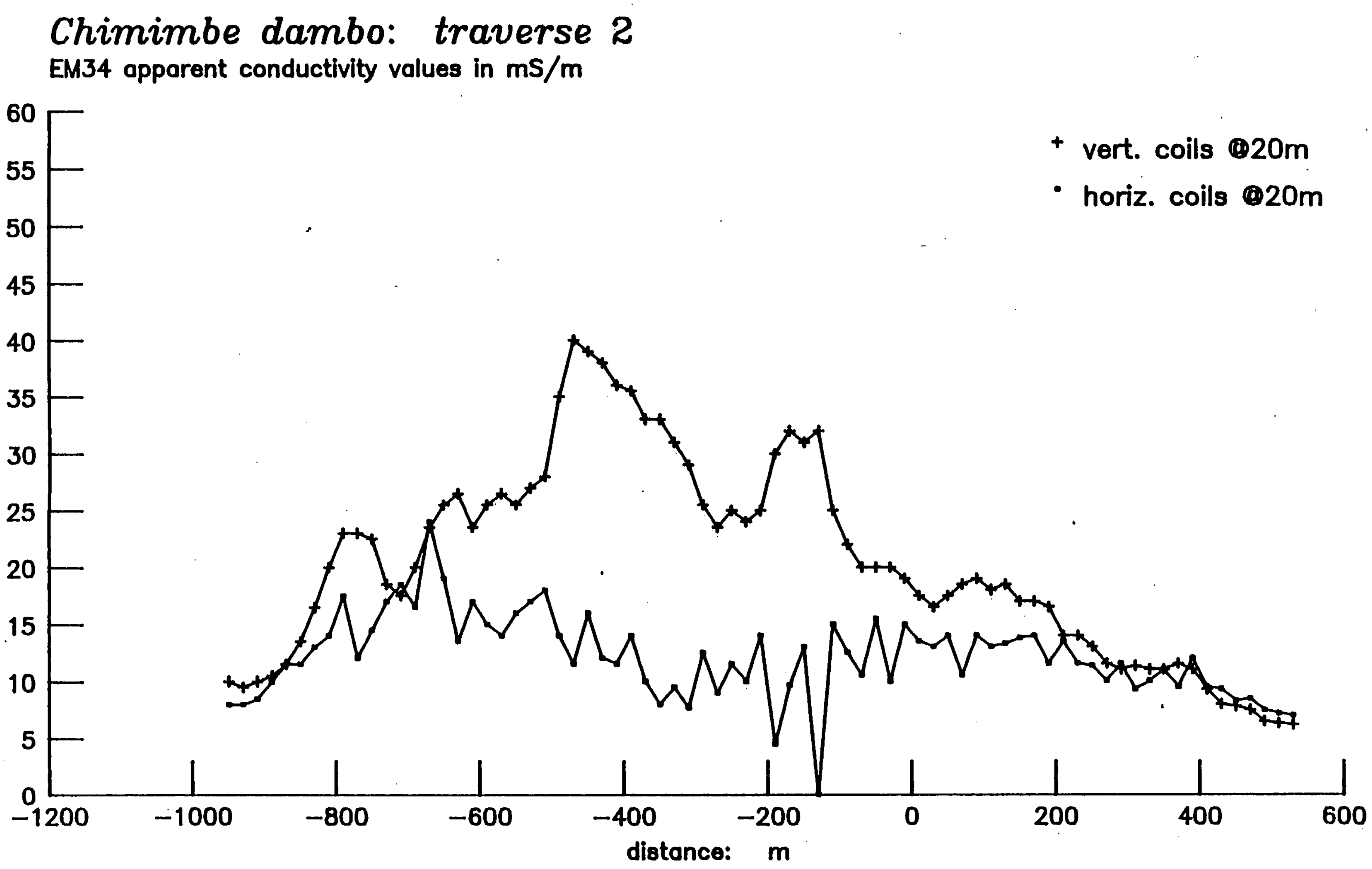


Figure 2.6a EM34 conductivity profiles along traverse 2, Chimimbe

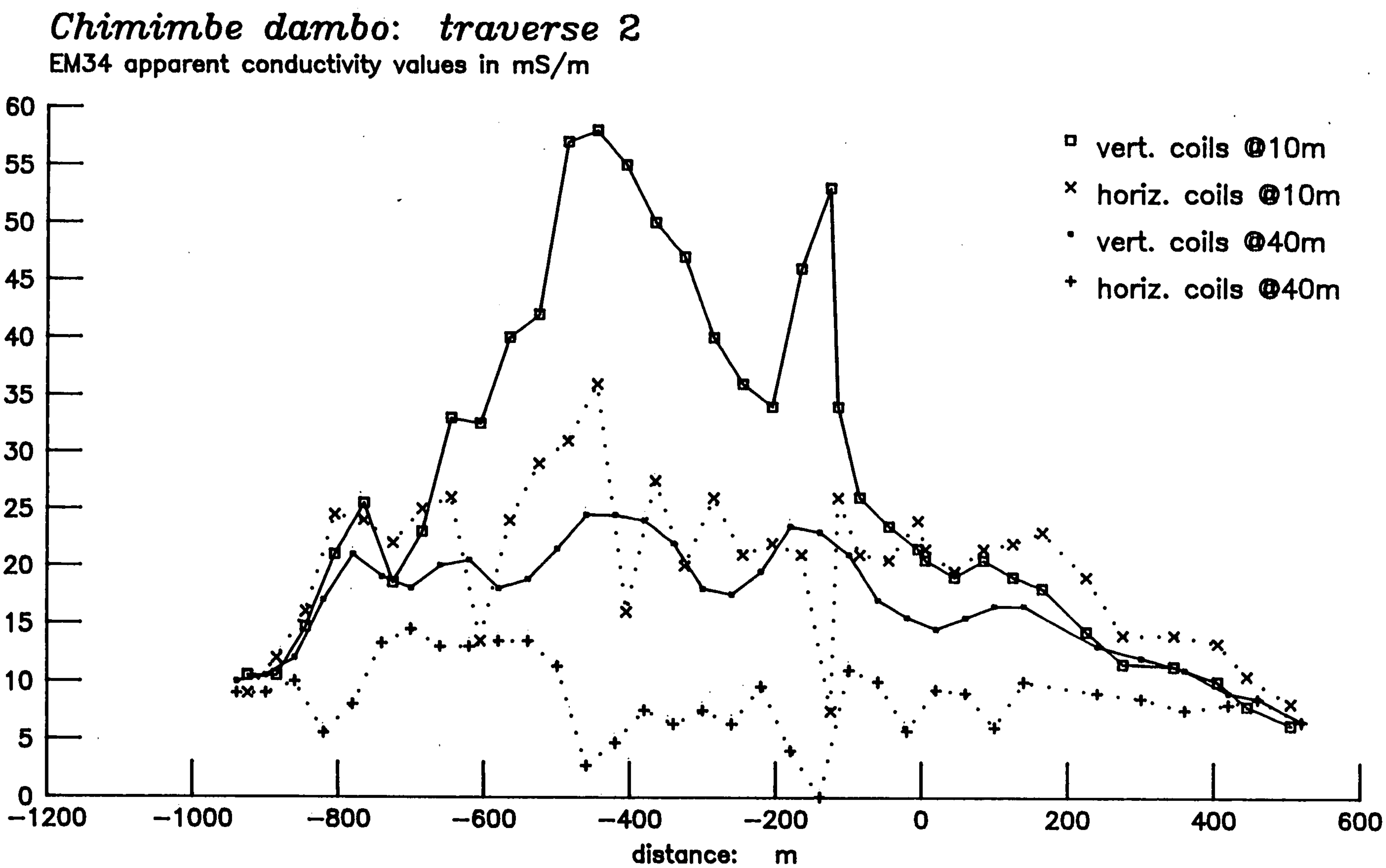
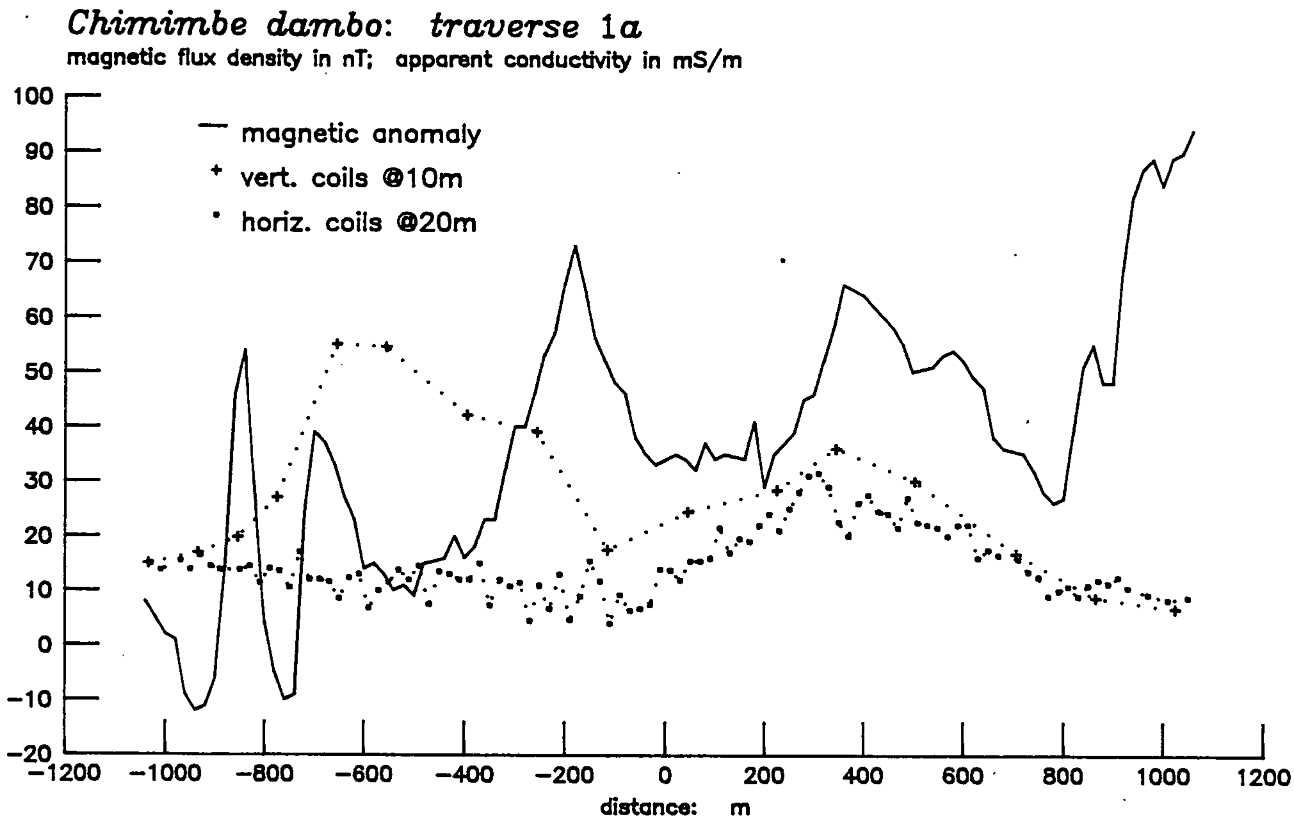


Figure 2.6b EM34 conductivity profiles along traverse 2, Chimimbe



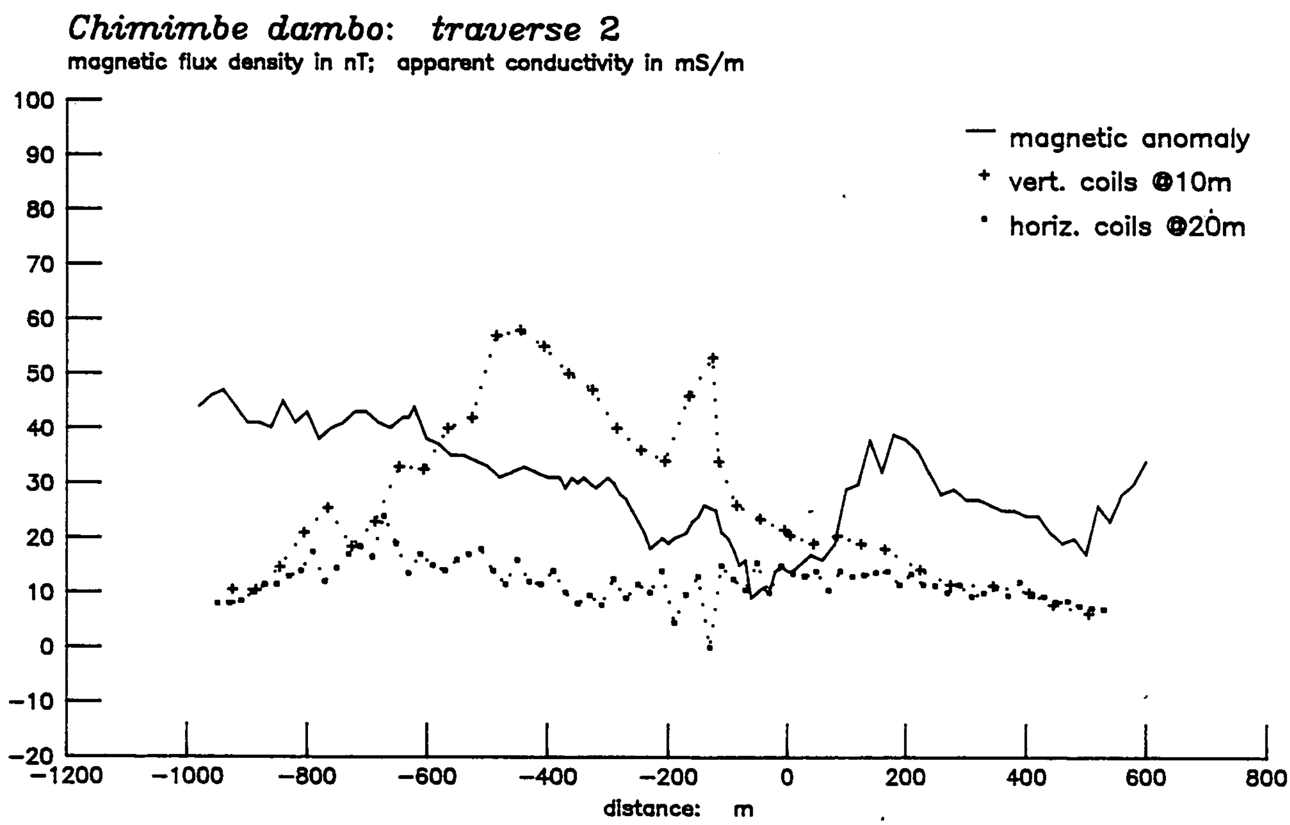


Figure 2.7 Magnetic and EM profiles from T1a and T2, Chimimbe

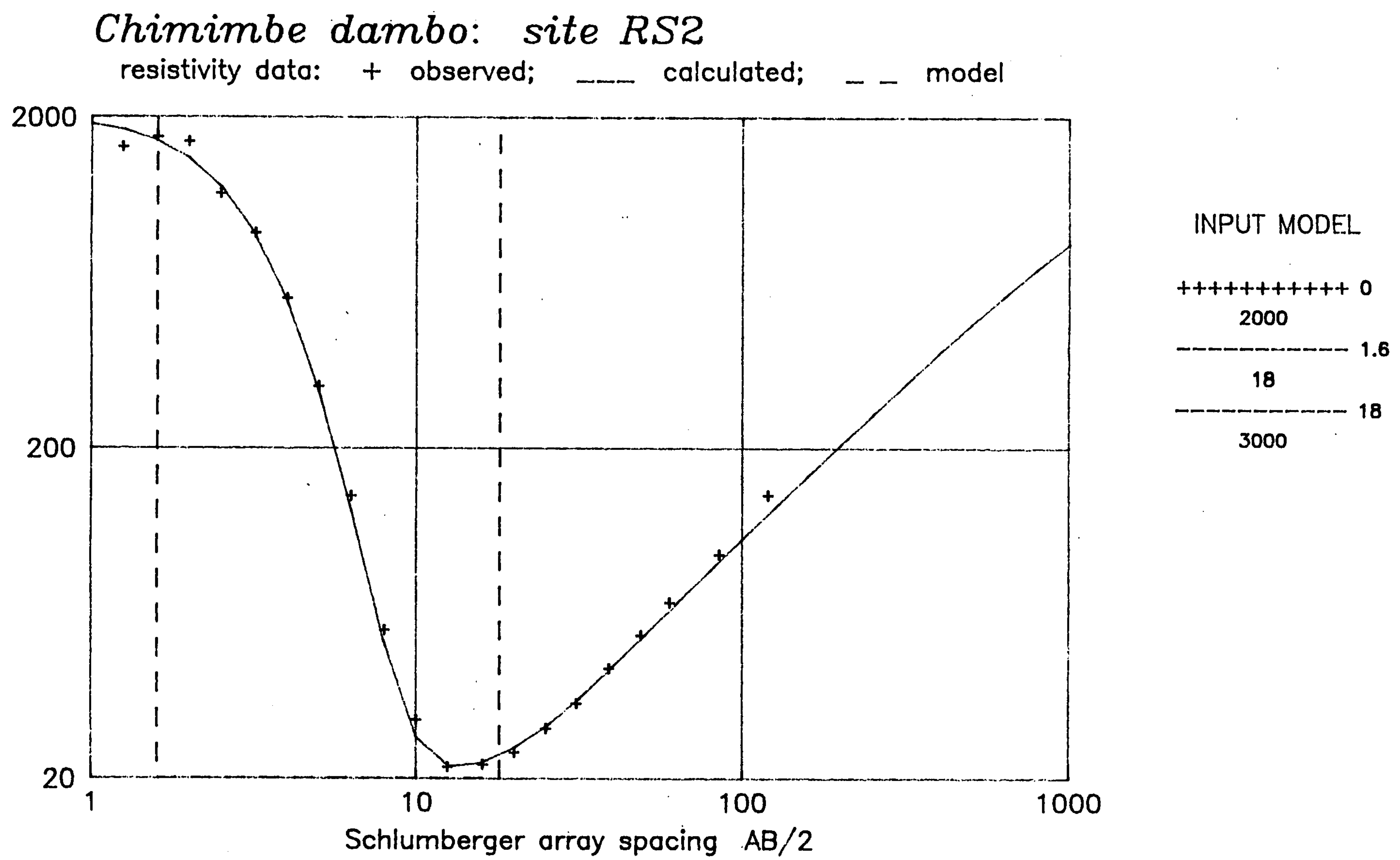
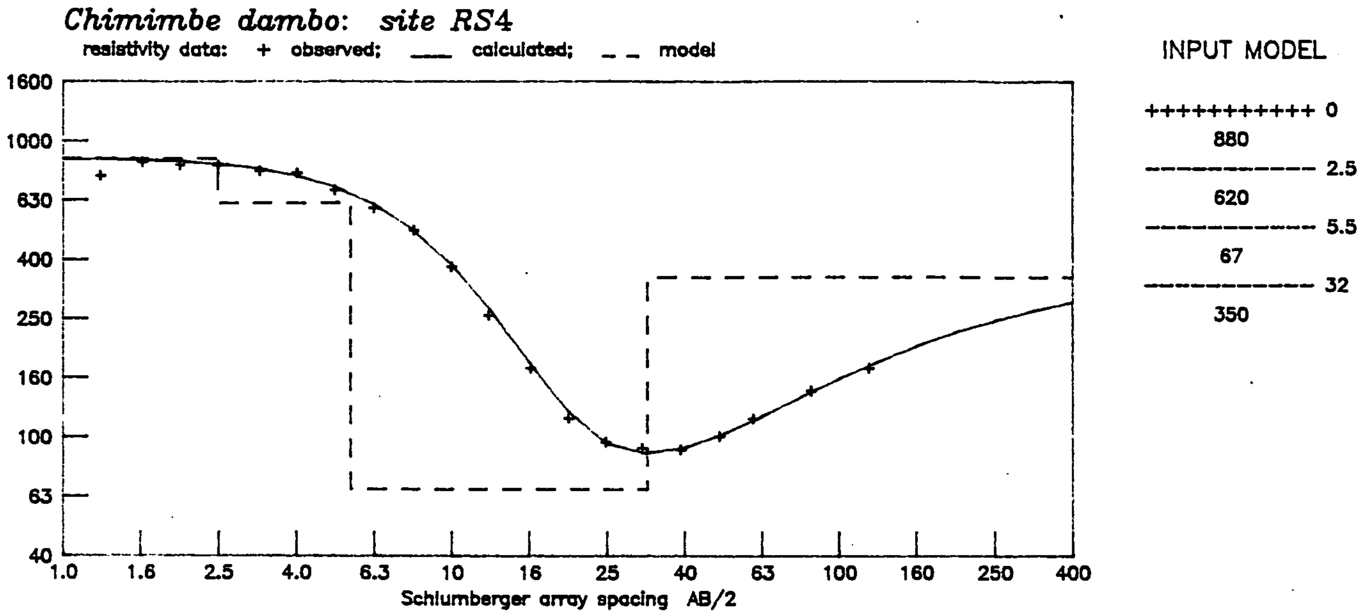


Figure 2.8 Resistivity (ESA) results near borehole C2, Chimimbe



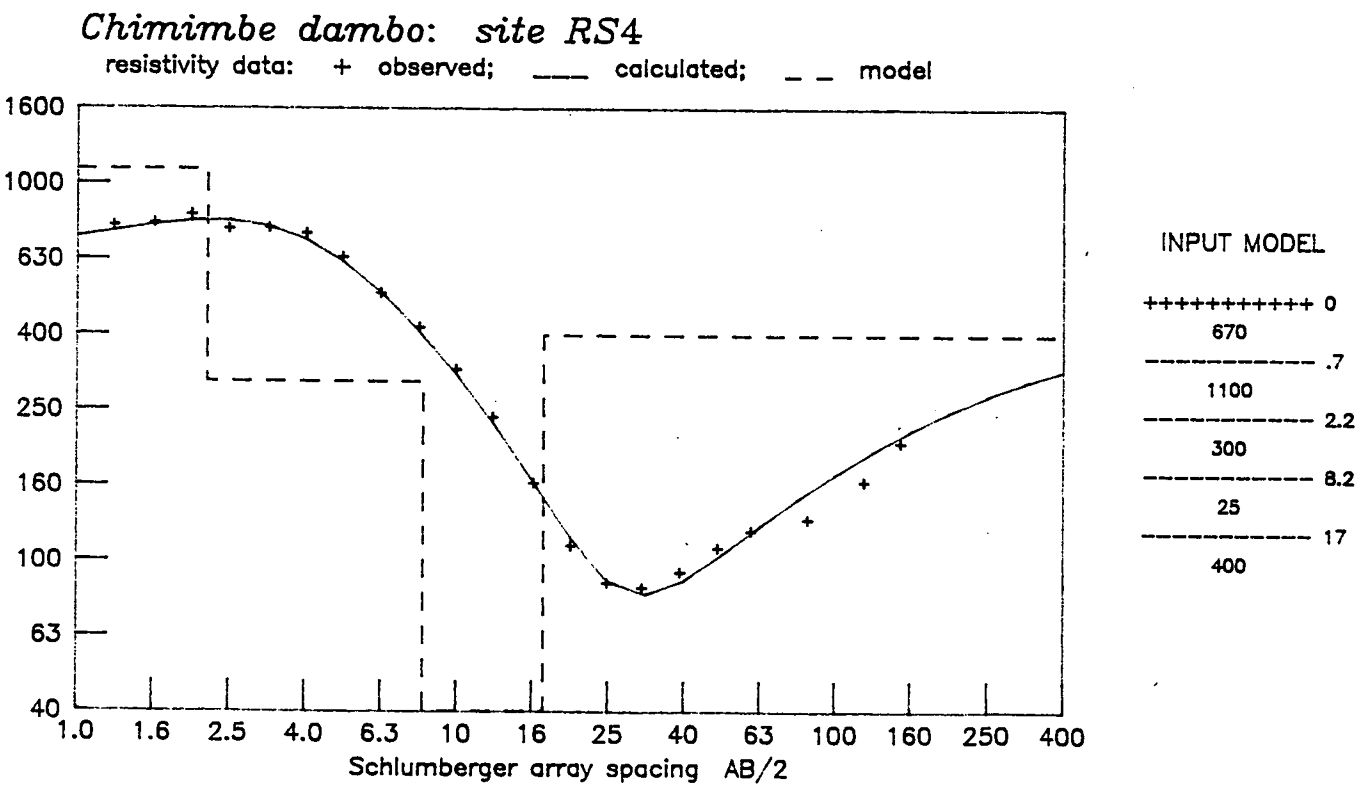


Figure 2.9 Orthogonal ESA resistivity results near borehole C3, Chimimbe

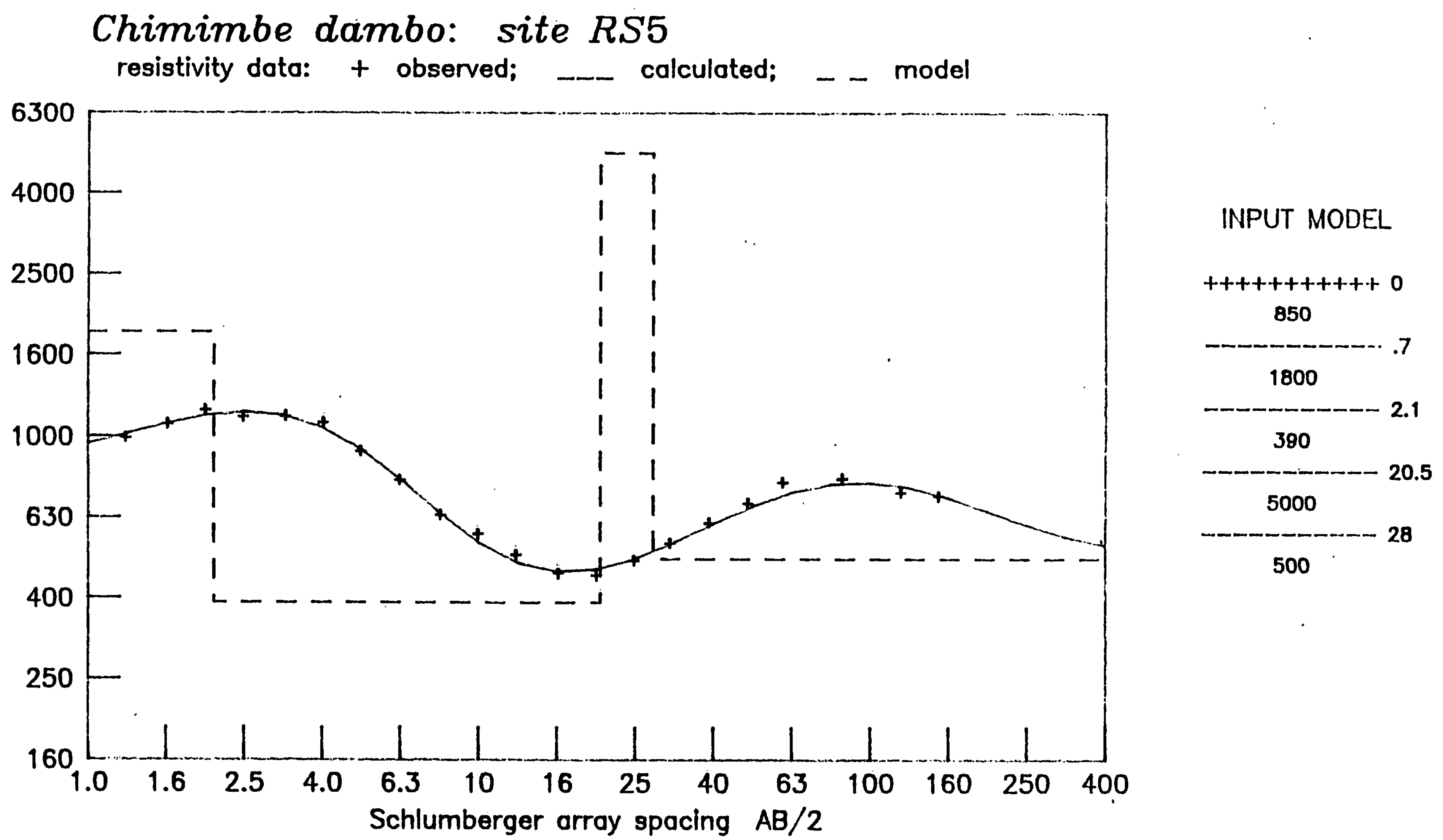


Figure 2.10 Resistivity (ESA) results near borehole C4, Chimimbe

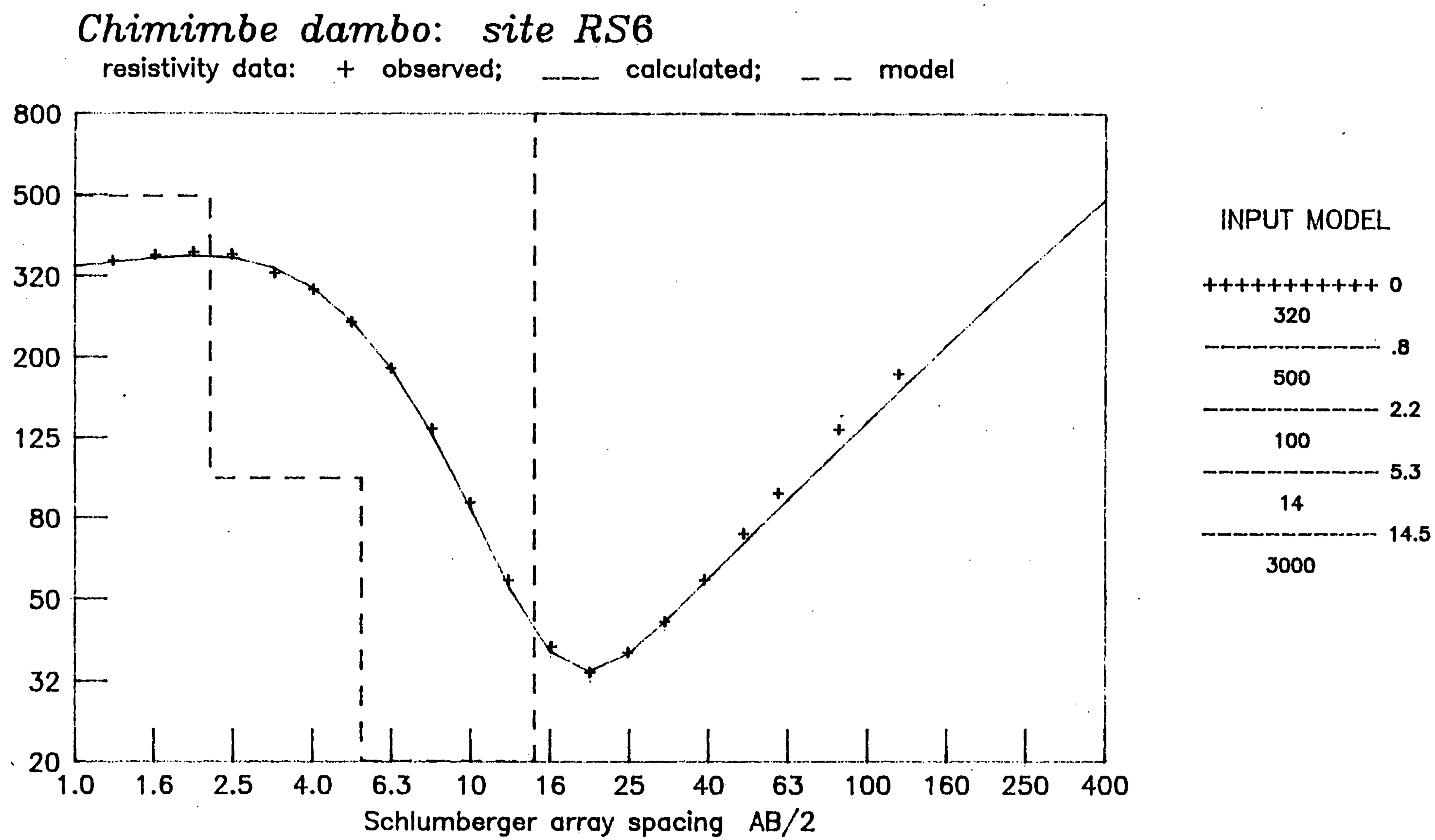


Figure 2.11 Resistivity (ESA) results near borehole B4, Chimimbe

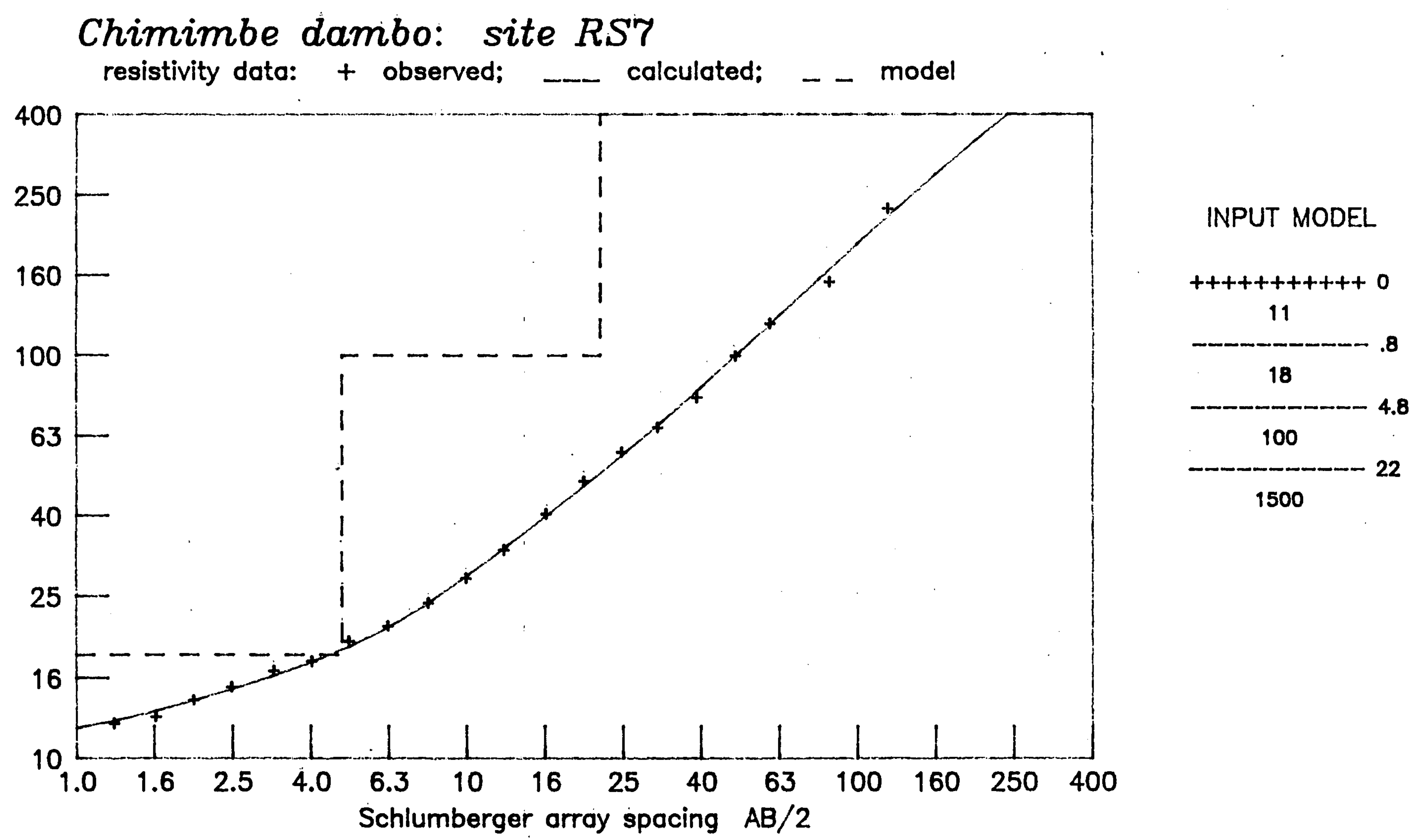


Figure 2.12 Resistivity (ESA) results from site RS7, Chimimbe

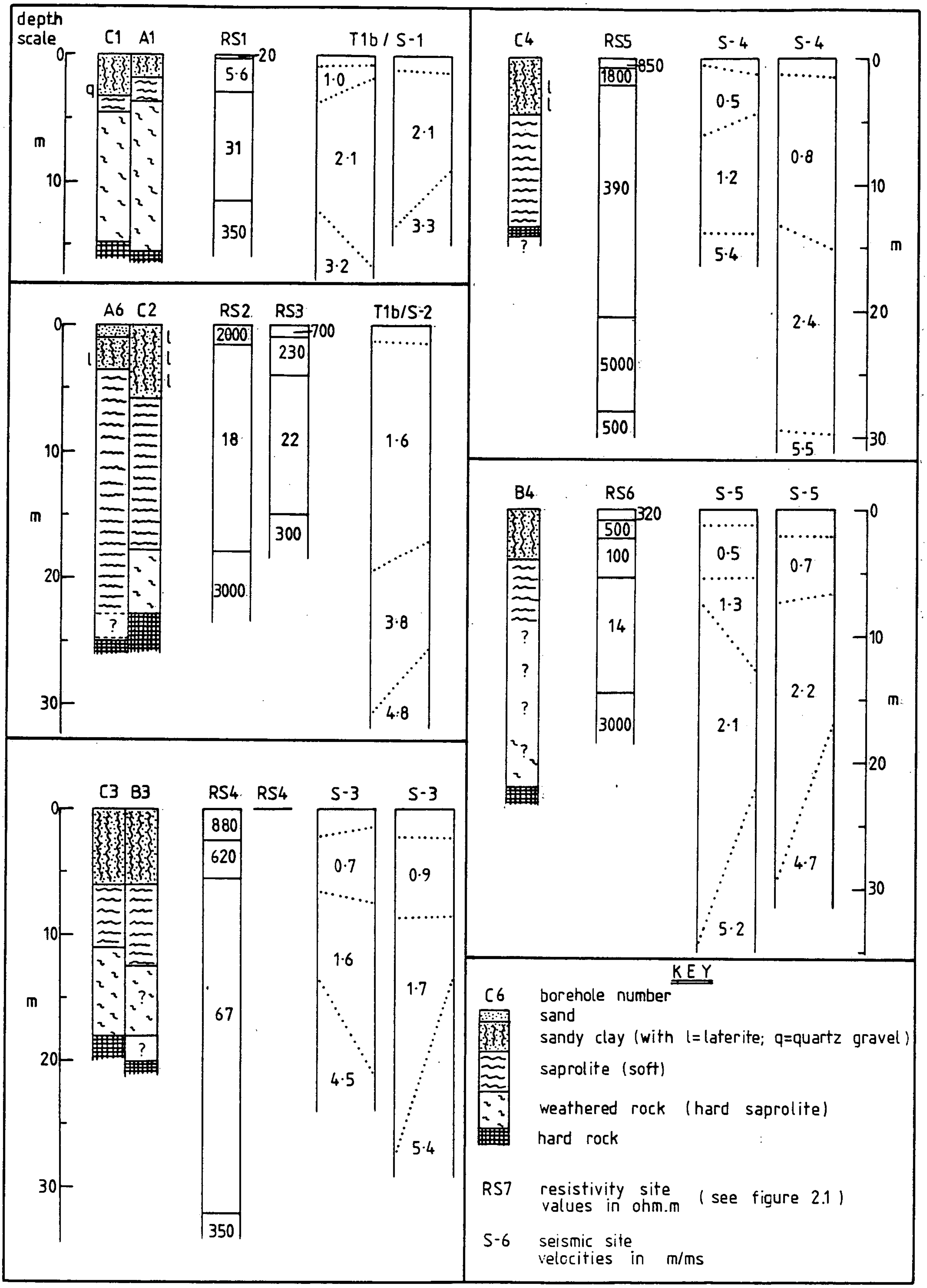


Figure 2.13 Comparison of resistivity, seismic and borehole log interpretations, Chimimbe dambo

```
PROJECT NAME:
   BASEMENT AQUIFER:  FRACTURE ZONE SIMULATION
MODEL NAME:
   BSAQ: M2;F4
# OF X NODES =  113
# OF Z NODES =   18
# OF X ELEMENT GROUPS =   17
X ELEMENT GROUP #S
          1       1       1       1      32       2       5       2      22       2
          5       2      32       1       1       1       1
X ELEMENT GROUP SPACINGS IN METRES
      500.0   120.0    30.0    10.0     2.0     1.0     2.0     1.5     1.0     1.5
        2.0     1.0     2.0    10.0    30.0   120.0   500.0
# OF Z ELEMENT GROUPS =    9
Z ELEMENT GROUP #S
          2       2       2       1       4       2       2       1       1
Z ELEMENT GROUP SPACINGS IN METRES
        0.5     1.0     2.0     3.0     5.0    10.0    20.0    60.0   350.0
ELECTRODE X NODE LOCATIONS
    10    18    25    30    34    38    41    43    46    51    55
    59    63    68    71    73    76    80    84    89    96   104
ELECTRODE Z NODE LOCATIONS
     1     1     1     1     1     1     1     1     1     1     1
     1     1     1     1     1     1     1     1     1     1     1
ELECTRODE LOCATIONS NODE #S
   163   307   433   523   595   667   721   757   811   901   973
  1045  1117  1207  1261  1297  1351  1423  1495  1585  1711  1855
MEDIA RESITIVITY (OHM-METERS)
       400.0
        40.0
       180.0
      3000.0
        20.0

.........1.........2.........3.........4.........5.........6.........7.........8.........9.........0.........1..
         K       J      H    G   F   E  D C  B    A   P   P   A    B  C D  E   F   G    H      J       K
1111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111
1111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111
1111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111
2222222222222222222222222222222222222222222222222222222222222222222222222222222222222222222222222222222222222222
2222222222222222222222222222222222222222222222222222222222222222222222222222222222222222222222222222222222222222
2222222222222222222222222222222222222222222222222222222222222222222222222222222222222222222222222222222222222222
3333333333333333333333333333333333333333333333333333333333333333333333333333333333333333333333333333333333333333
3333333333333333333333333333333333333333333333333333333333333333333333333333333333333333333333333333333333333333
4444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444
4444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444
4444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444
4444444444444444444444444444444444444445555555555555555555555555555555544444444444444444444444444444444444444444
4444444444444444444444444444444444444445555555555555555555555555555555544444444444444444444444444444444444444444
4444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444
4444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444
4444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444
4444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444
4444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444
.........1.........2.........3.........4.........5.........6.........7.........8.........9.........0.........1..
```

Figure 3.1 2D resistivity ESA models: definition of mesh parameters

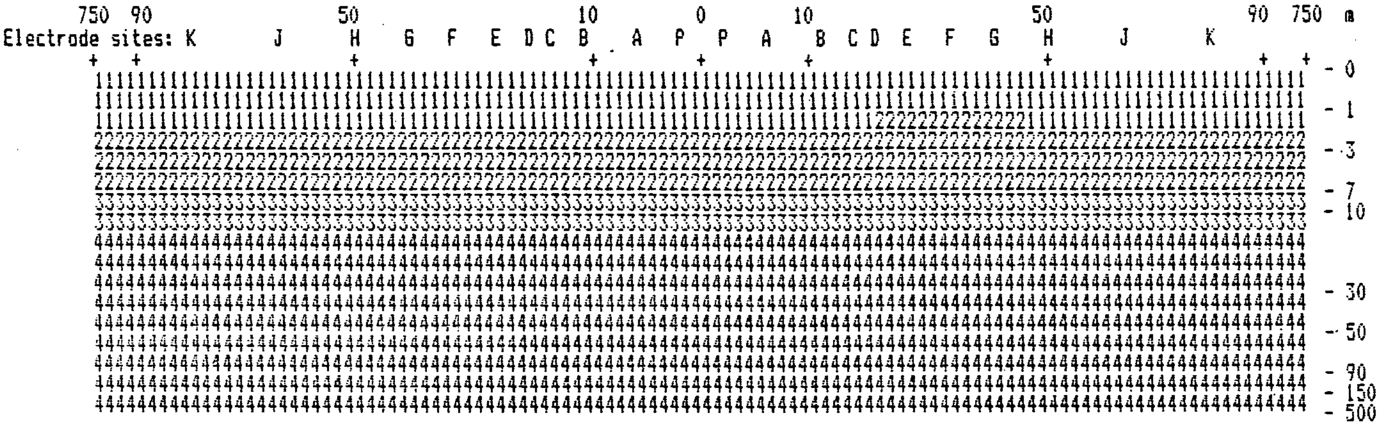
2D RESISTIVITY MODELLING RESULTS

Reference: BSAQ/M1;L1

MODEL PARAMETERS:

medium	res	depth(backgrnd)
(1)	400.0	to 2.0
(2)	25.0	to 7.0
(3)	180.0	to 15.0
(4)	3000.0	to))

DEPTH SECTION:



SCHLUMBERGER ARRAY RESPONSE:

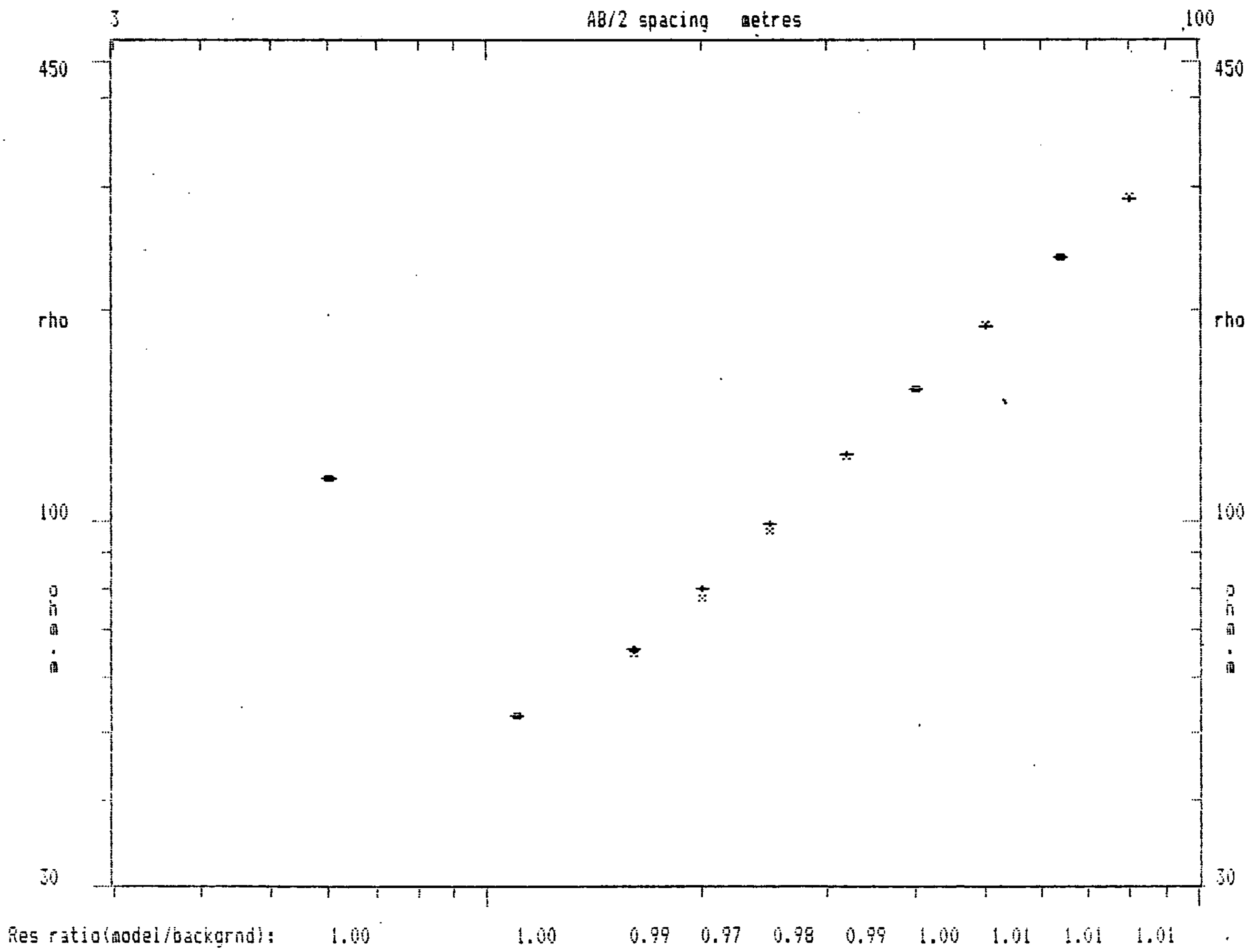


Figure 3.2 Simulated ESA results over a 2D model. Reference: BSAQ/M1;L1

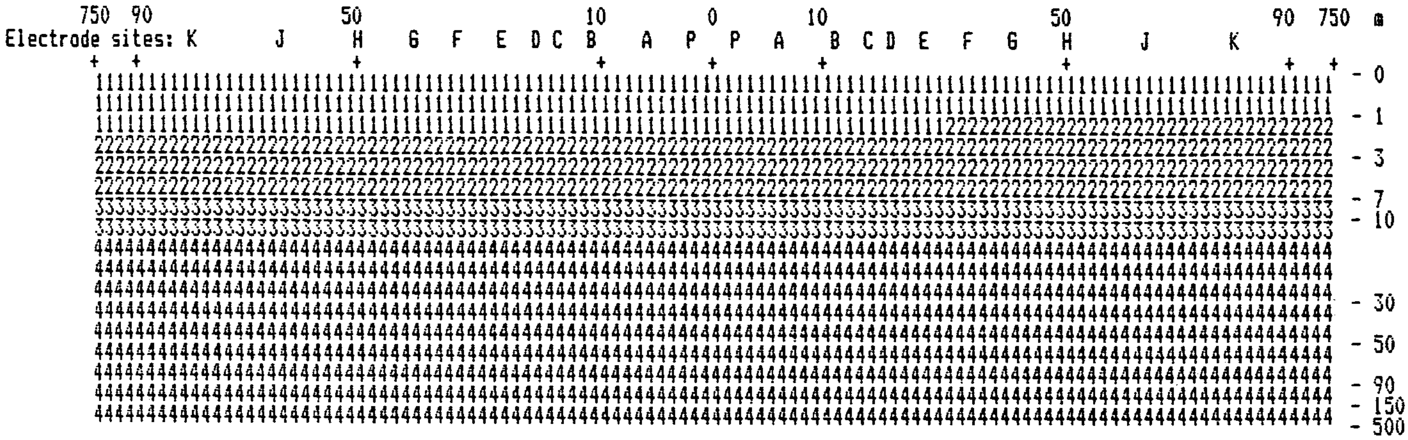
2D RESISTIVITY MODELLING RESULTS

Reference: BSAQ/M1;L2

MODEL PARAMETERS:

medium	res	depth(backgrnd)
(1)	400.0	to 2.0
(2)	25.0	to 7.0
(3)	180.0	to 15.0
(4)	3000.0	to))

DEPTH SECTION:



SCHLUMBERGER ARRAY RESPONSE: × 2D model value + 1D background value

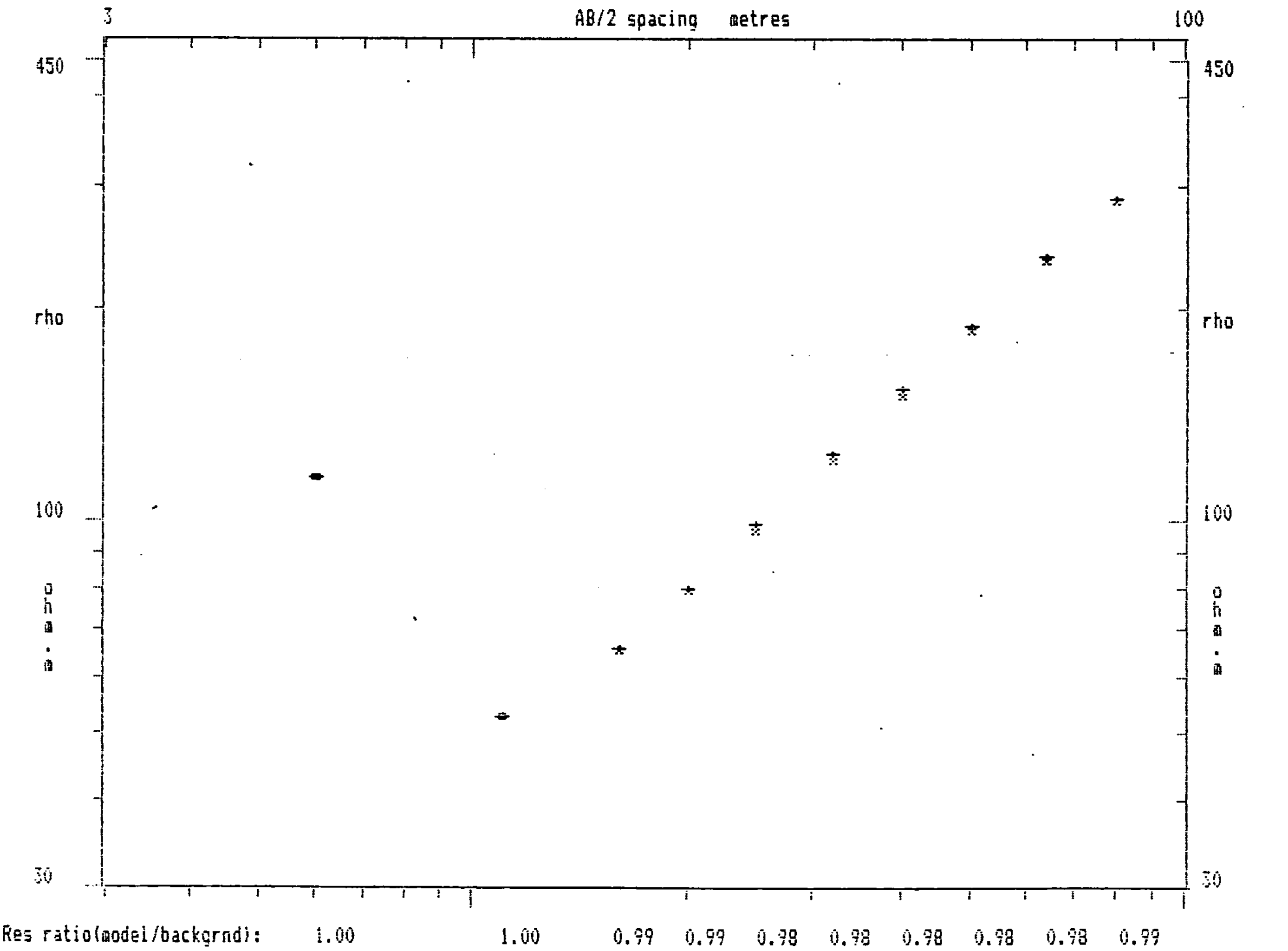


Figure 3.3 Simulated ESA results over a 2D model. Reference: BSAQ/M1;L2

2D RESISTIVITY MODELLING RESULTS

Reference: BSAQ/M1;L3

MODEL PARAMETERS:

medium	*res*	*depth(backgrnd)*
(1)	*400.0*	*to 2.0*
(2)	*25.0*	*to 7.0*
(3)	*180.0*	*to 15.0*
(4)	*3000.0*	*to))*

DEPTH SECTION:

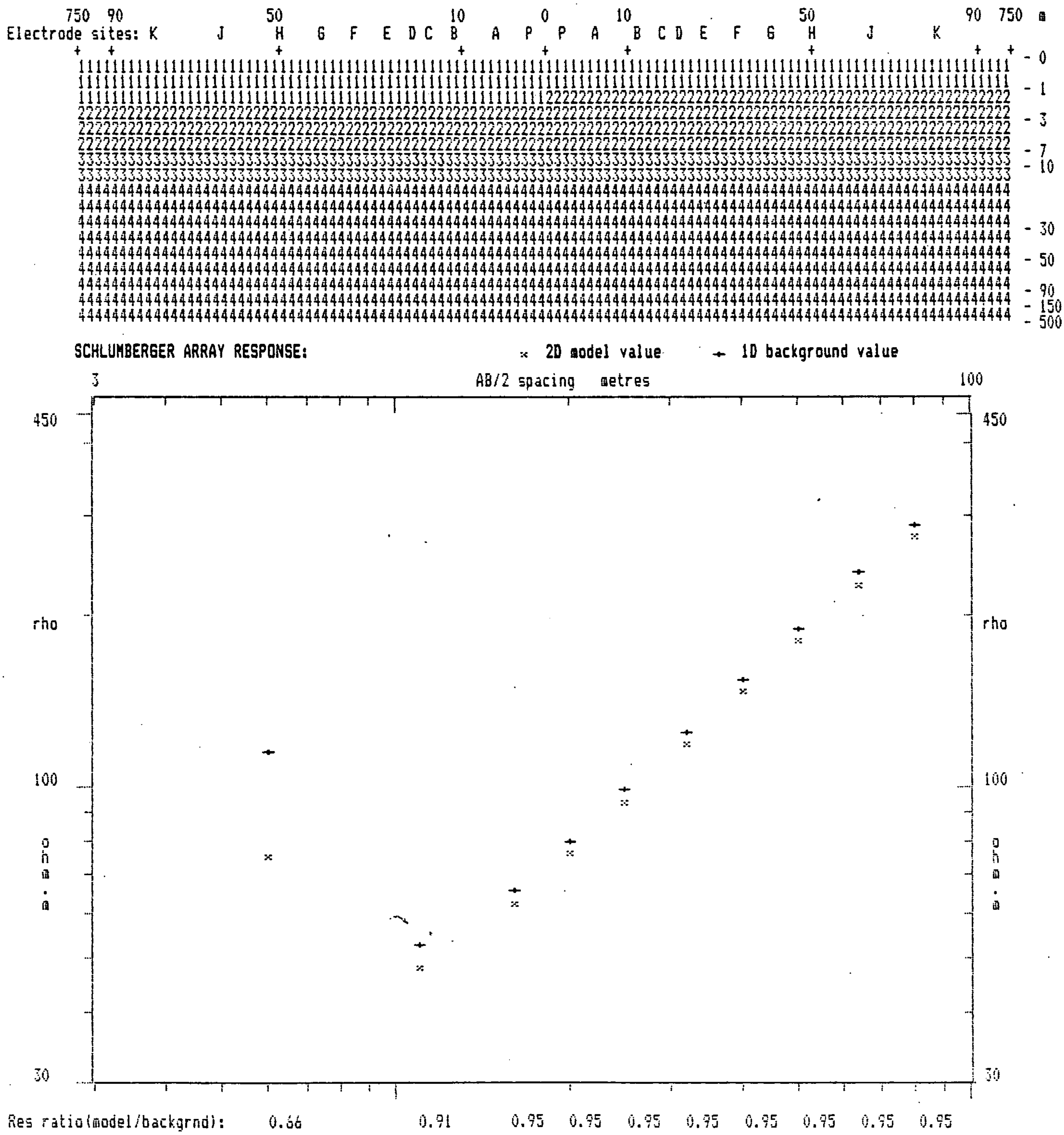


Figure 3.4 Simulated ESA results over a 2D model. Reference: BSAQ/M1;L3

2D RESISTIVITY MODELLING RESULTS

Reference: BSAQ/M1;F1

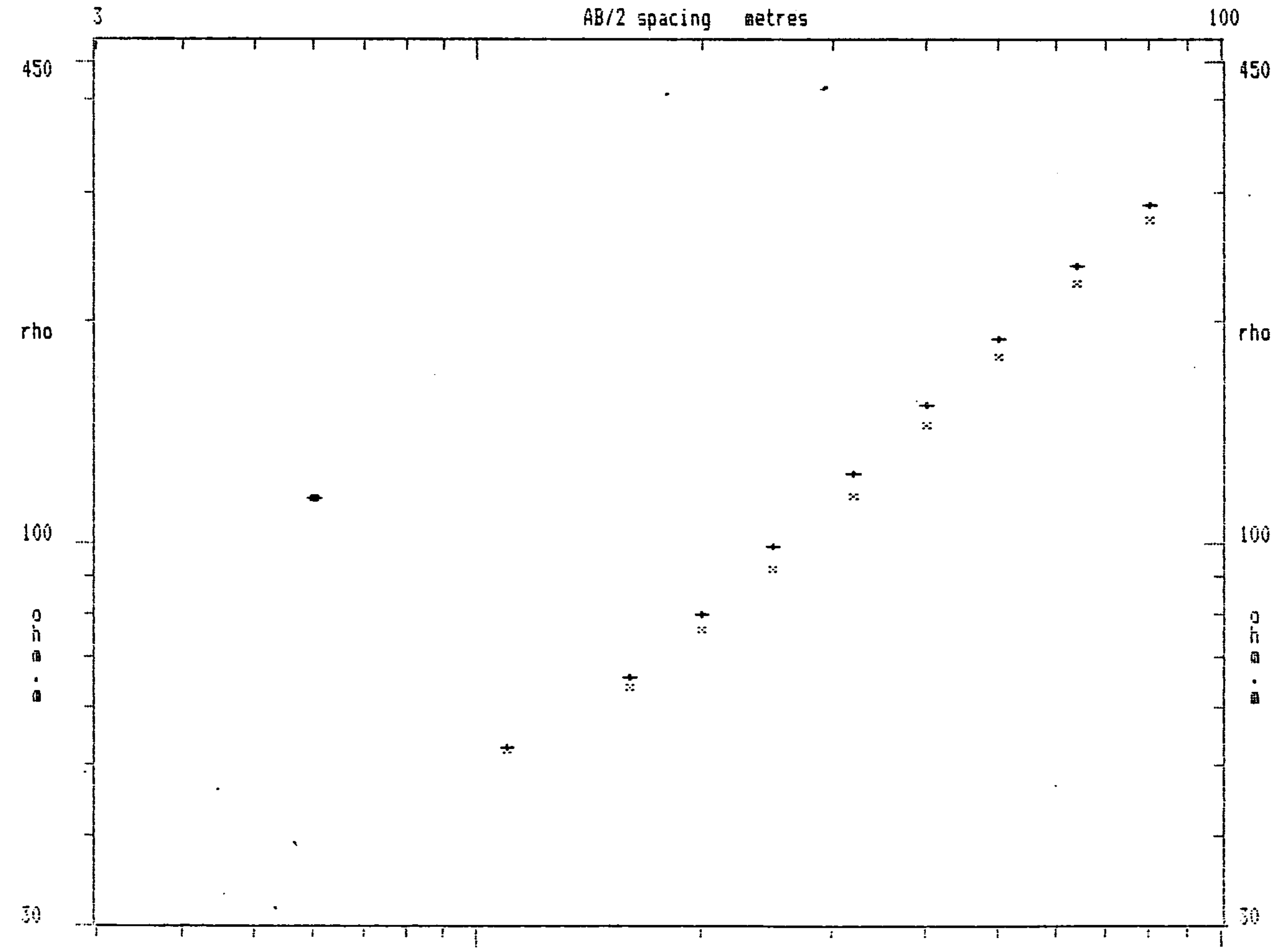
MODEL PARAMETERS:

medium	res	depth(backgrnd)
(1)	400.0	to 2.0
(2)	25.0	to 7.0
(3)	180.0	to 15.0
(4)	3000.0	to))

DEPTH SECTION:

```
          750  90                           50                          10            0            10                          50                         90  750  m
Electrode sites: K        J         H     G    F    E  D C  B     A    P    P    A     B  C D  E    F    G    H        J         K
                 +   +                      +                           +             +             +                           +                         +    +
111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111 - 0
111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111 - 1
111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111
222222222222222222222222222222222222222222222222222222222222222222222222222222222222222222222222222222222222222222222222222222 - 3
222222222222222222222222222222222222222222222222222222222222222222222222222222222222222222222222222222222222222222222222222222
222222222222222222222222222222222222222222222222222222222222222222222222222222222222222222222222222222222222222222222222222222 - 7
333333333333333333333333333333333333333333333333333333333333333333333333333333333333322233333333333333333333333333333333333333 - 10
333333333333333333333333333333333333333333333333333333333333333333333333333333333333322233333333333333333333333333333333333333
444444444444444444444444444444444444444444444444444444444444444444444444444444444444422244444444444444444444444444444444444444
444444444444444444444444444444444444444444444444444444444444444444444444444444444444422244444444444444444444444444444444444444
444444444444444444444444444444444444444444444444444444444444444444444444444444444444422244444444444444444444444444444444444444 - 30
444444444444444444444444444444444444444444444444444444444444444444444444444444444444422244444444444444444444444444444444444444
444444444444444444444444444444444444444444444444444444444444444444444444444444444444422244444444444444444444444444444444444444 - 50
444444444444444444444444444444444444444444444444444444444444444444444444444444444444422244444444444444444444444444444444444444
444444444444444444444444444444444444444444444444444444444444444444444444444444444444422244444444444444444444444444444444444444 - 90
444444444444444444444444444444444444444444444444444444444444444444444444444444444444422244444444444444444444444444444444444444 - 150
444444444444444444444444444444444444444444444444444444444444444444444444444444444444422244444444444444444444444444444444444444 - 500
```

SCHLUMBERGER ARRAY RESPONSE: × 2D model value + 1D background value



Res ratio(model/backgrnd): 1.00 0.99 0.97 0.95 0.93 0.93 0.94 0.94 0.95 0.95

Figure 3.5 Simulated ESA results over a 2D model. Reference: BSAQ/M1;F1

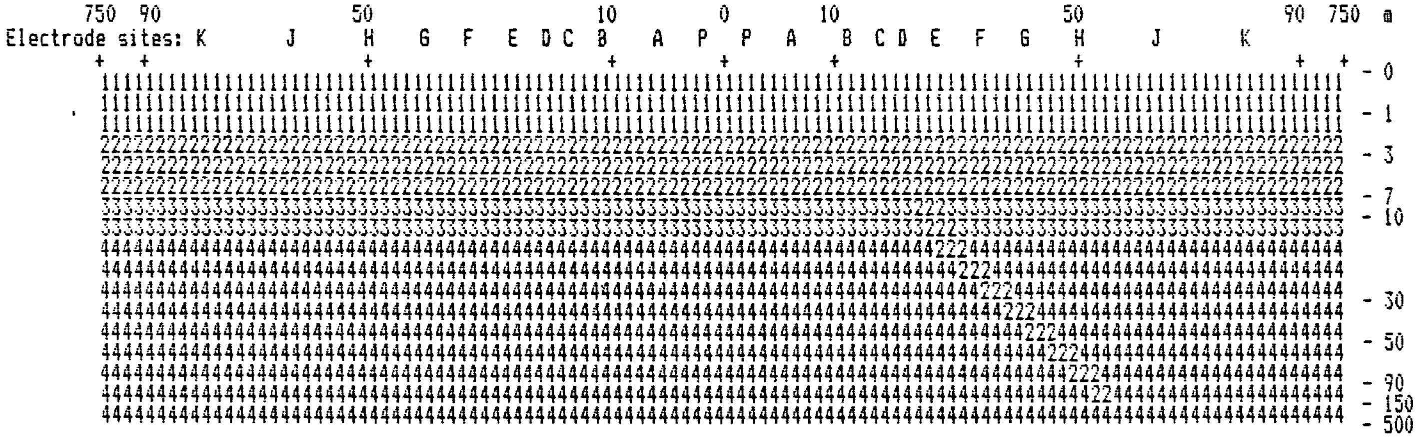
2D RESISTIVITY MODELLING RESULTS

Reference: BSAQ/M1;F2

MODEL PARAMETERS:

medium	res	depth(backgrnd)
(1)	400.0	to 2.0
(2)	25.0	to 7.0
(3)	180.0	to 15.0
(4)	3000.0	to))

DEPTH SECTION:



SCHLUMBERGER ARRAY RESPONSE:

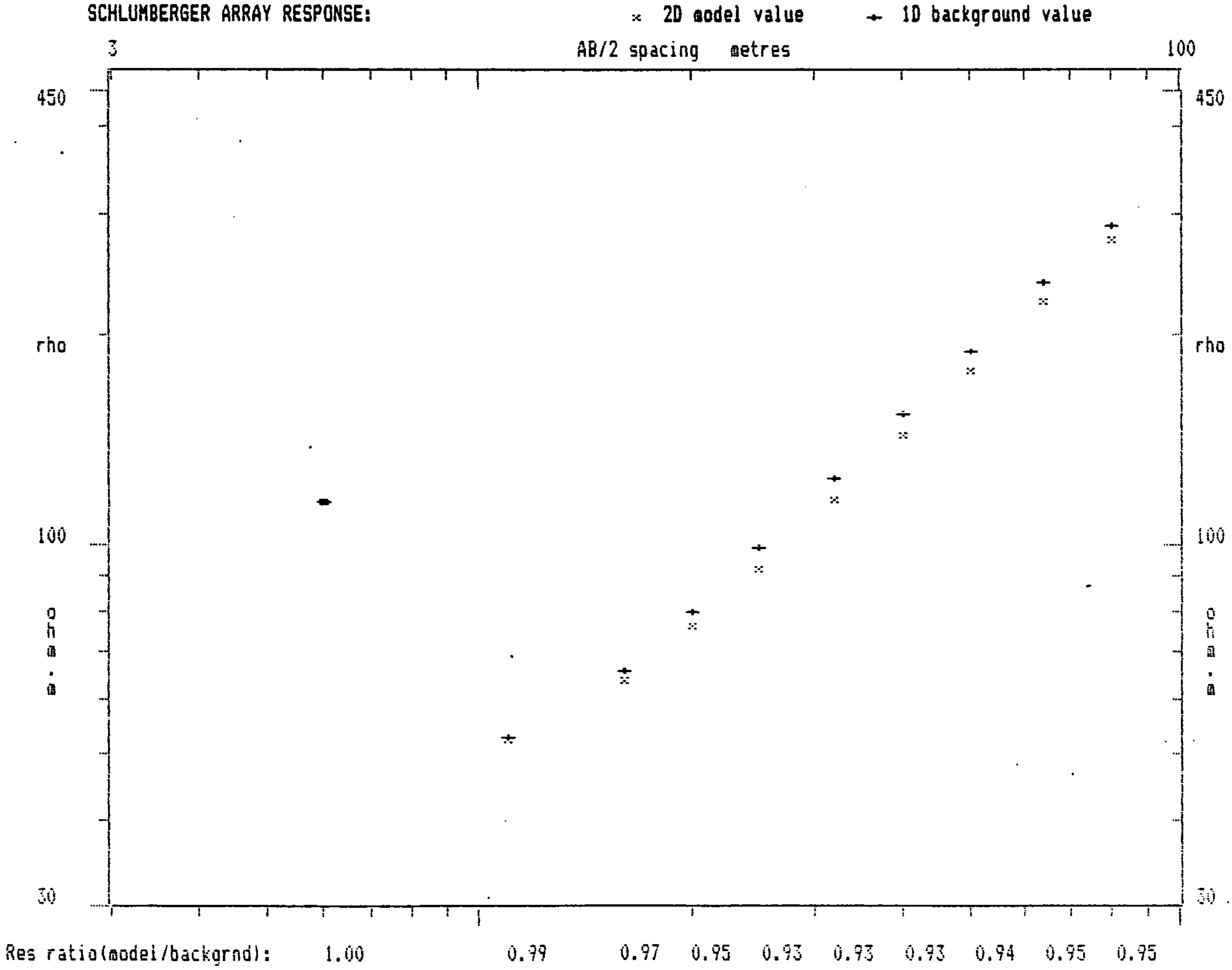


Figure 3.6 Simulated ESA results over a 2D model. Reference: BSAQ/M1;F2

2D RESISTIVITY MODELLING RESULTS

Reference: BSAQ/M1;F3

MODEL PARAMETERS:

medium	res	depth(backgrnd)
(1)	400.0	to 2.0
(2)	25.0	to 7.0
(3)	180.0	to 15.0
(4)	3000.0	to))

DEPTH SECTION:

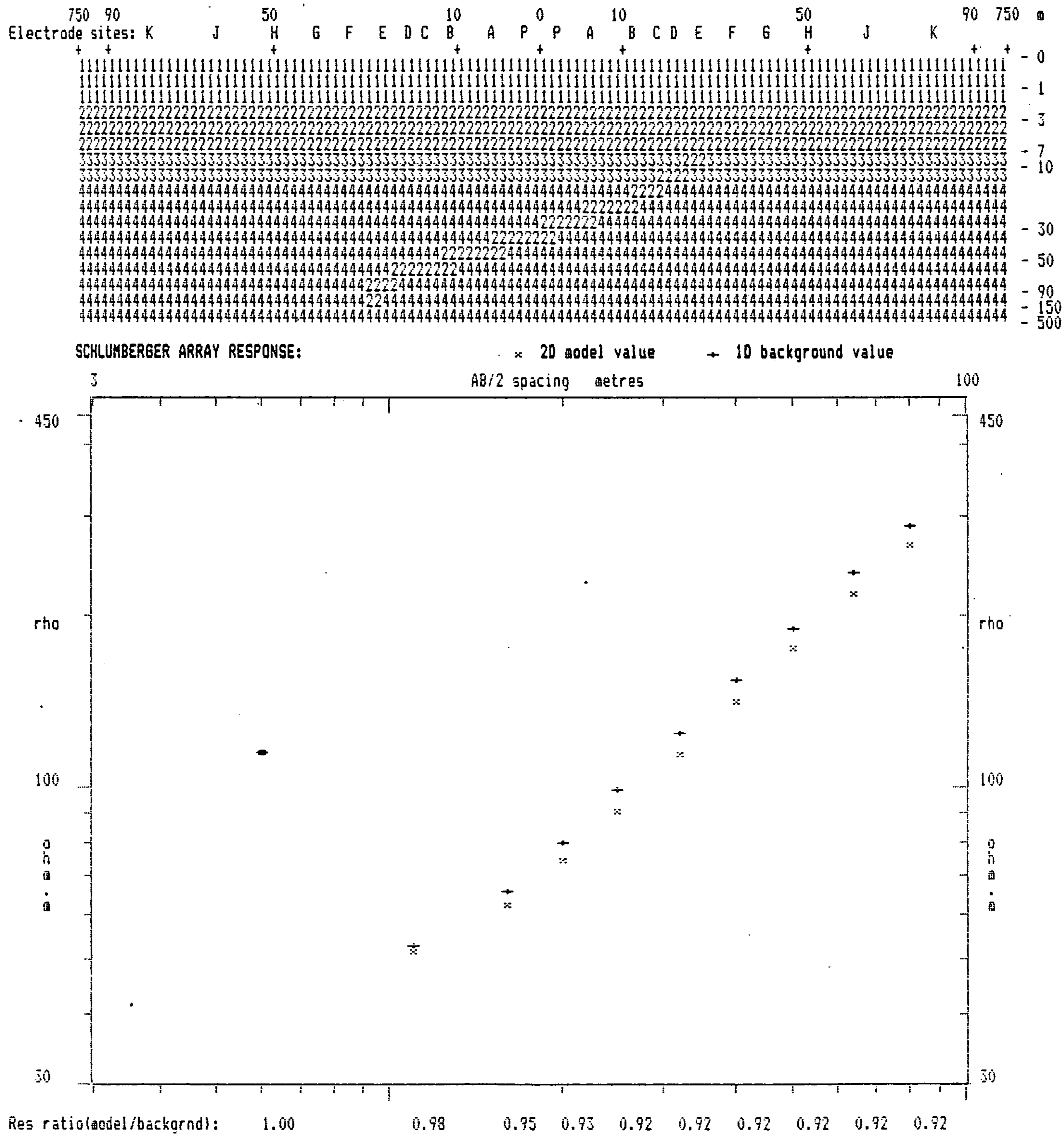


Figure 3.7 Simulated ESA results over a 2D model. Reference: BSAQ/M1;F3

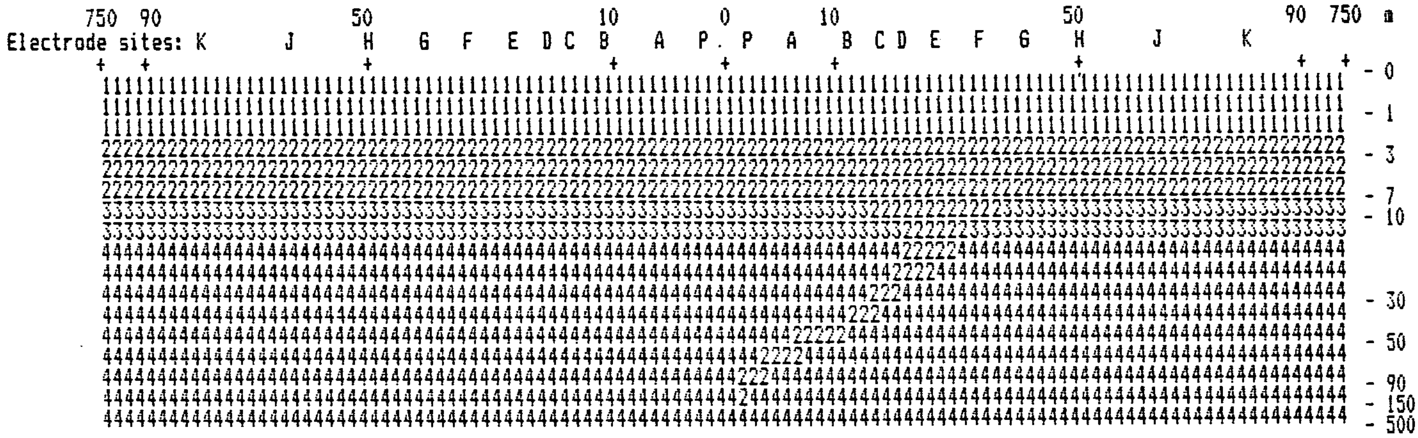
2D RESISTIVITY MODELLING RESULTS

Reference: BSAQ/M1;F4

MODEL PARAMETERS:

medium	*res*	*depth(backgrnd)*
(1)	*400.0*	*to 2.0*
(2)	*25.0*	*to 7.0*
(3)	*180.0*	*to 15.0*
(4)	*3000.0*	*to))*

DEPTH SECTION:



SCHLUMBERGER ARRAY RESPONSE:

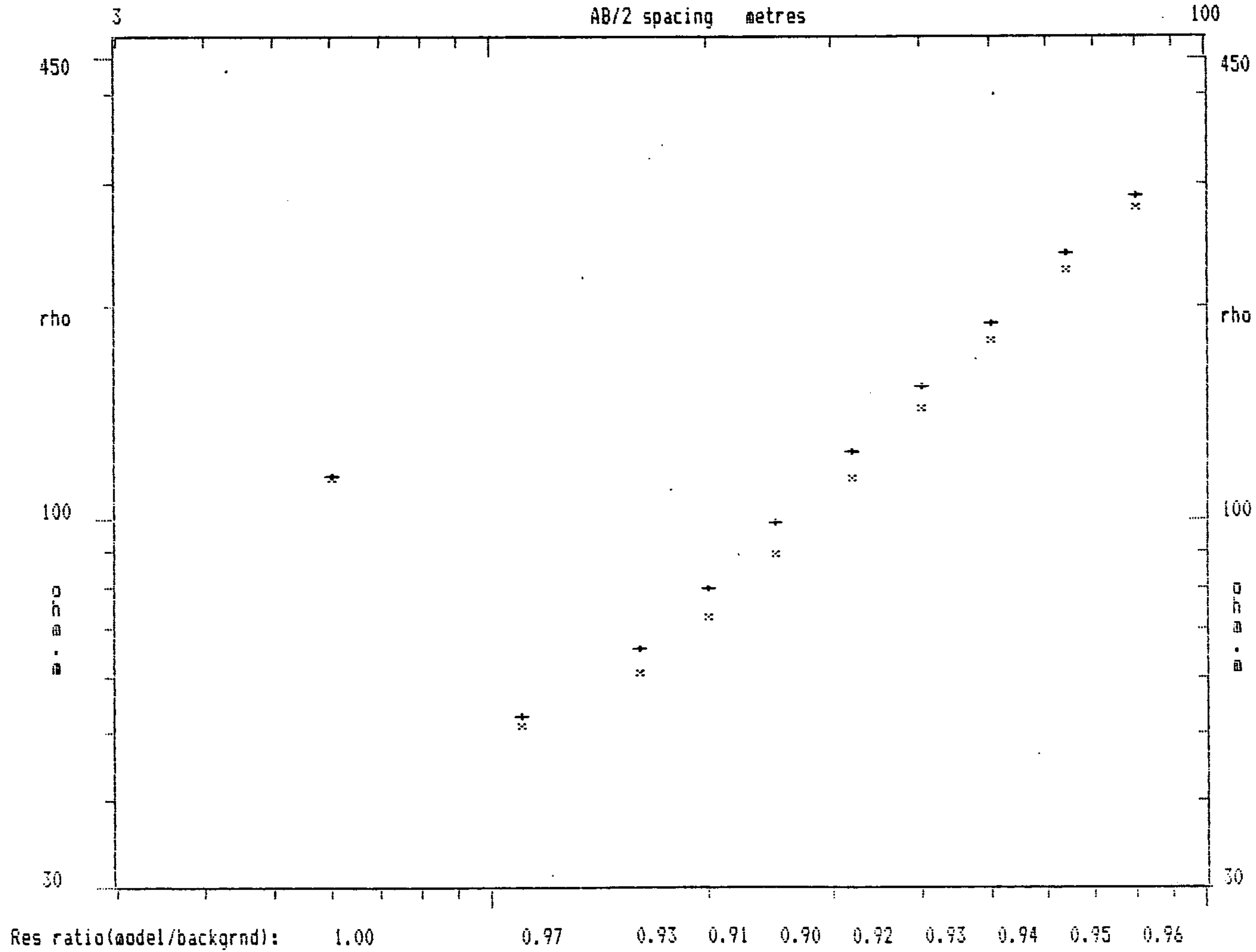


Figure 3.8 Simulated ESA results over a 2D model. Reference: BSAQ/M1;F4

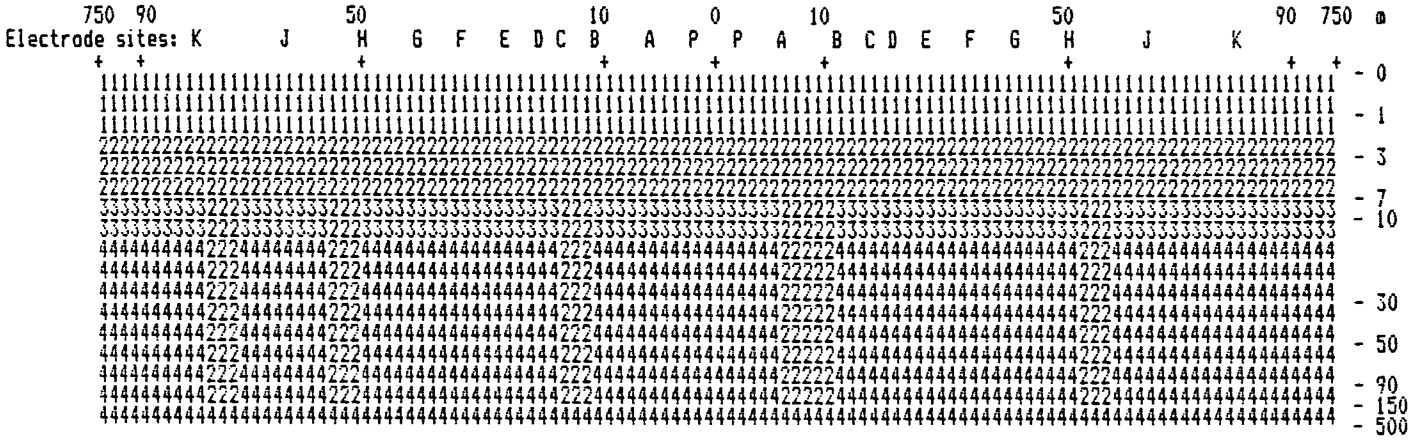
2D RESISTIVITY MODELLING RESULTS

Reference: BSAQ/M1;F5

MODEL PARAMETERS:

medium	res	depth(backgrnd)
(1)	400.0	to 2.0
(2)	25.0	to 7.0
(3)	180.0	to 15.0
(4)	3000.0	to >>

DEPTH SECTION:



SCHLUMBERGER ARRAY RESPONSE: × 2D model value + 1D background value

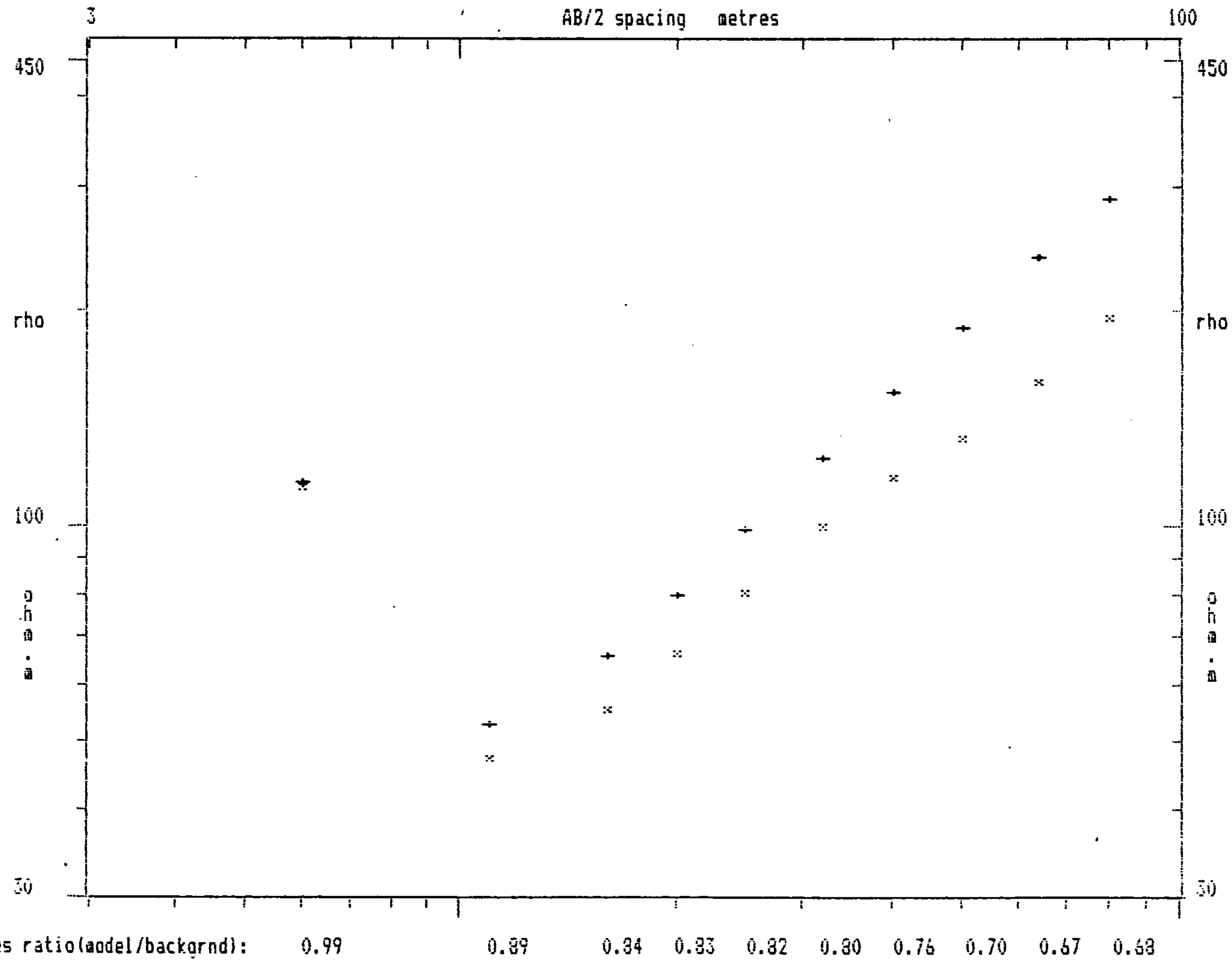


Figure 3.9 Simulated ESA results over a 2D model. Reference: BSAQ/M1;F5

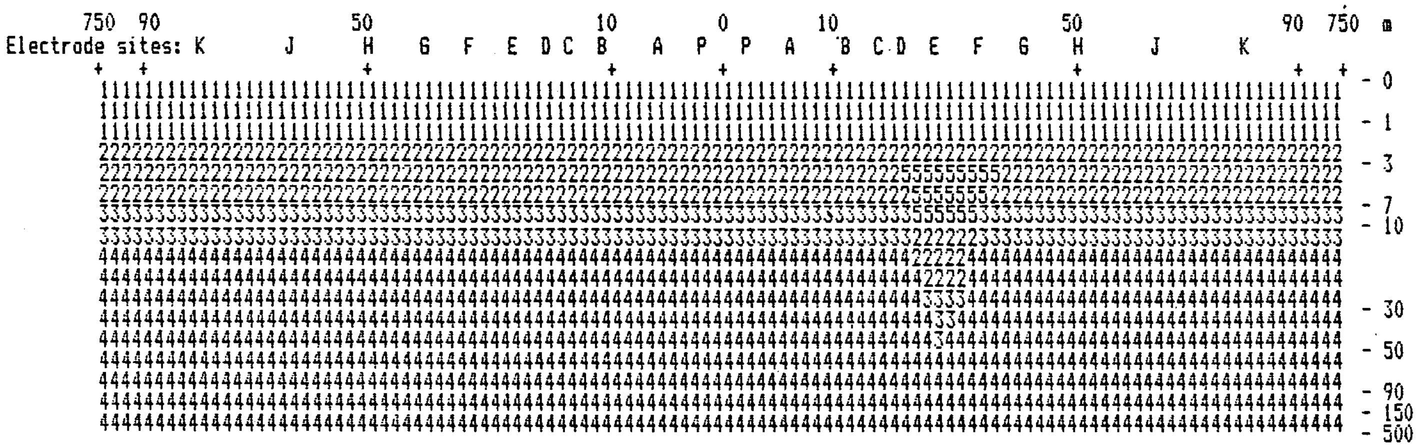
2D RESISTIVITY MODELLING RESULTS

Reference: BSAQ/M2;F1

MODEL PARAMETERS:

medium	res	depth(backgrnd)
(1)	400.0	to 2.0
(2)	40.0	to 7.0
(3)	180.0	to 15.0
(4)	3000.0	to))
(5)	20.0	

DEPTH SECTION:



SCHLUMBERGER ARRAY RESPONSE: × 2D model value + 1D background value

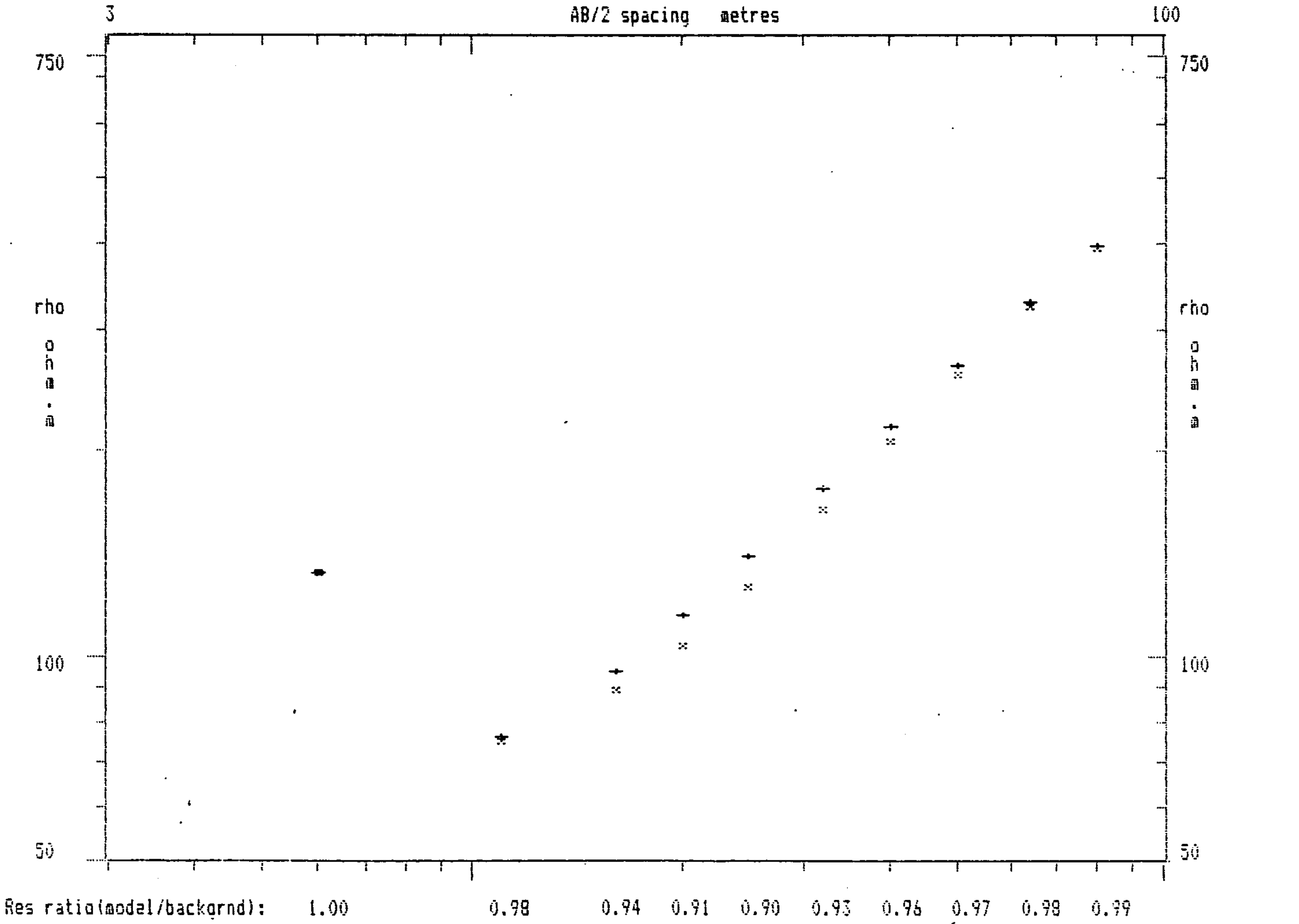


Figure 3.10 Simulated ESA results over a 2D model. Reference: BSAQ/M2;F1

2D RESISTIVITY MODELLING RESULTS

Reference: BSAQ/M2;F2

MODEL PARAMETERS:

medium	res	depth(backgrnd)
(1)	400.0	to 2.0
(2)	40.0	to 7.0
(3)	180.0	to 15.0
(4)	3000.0	to))
(5)	20.0	

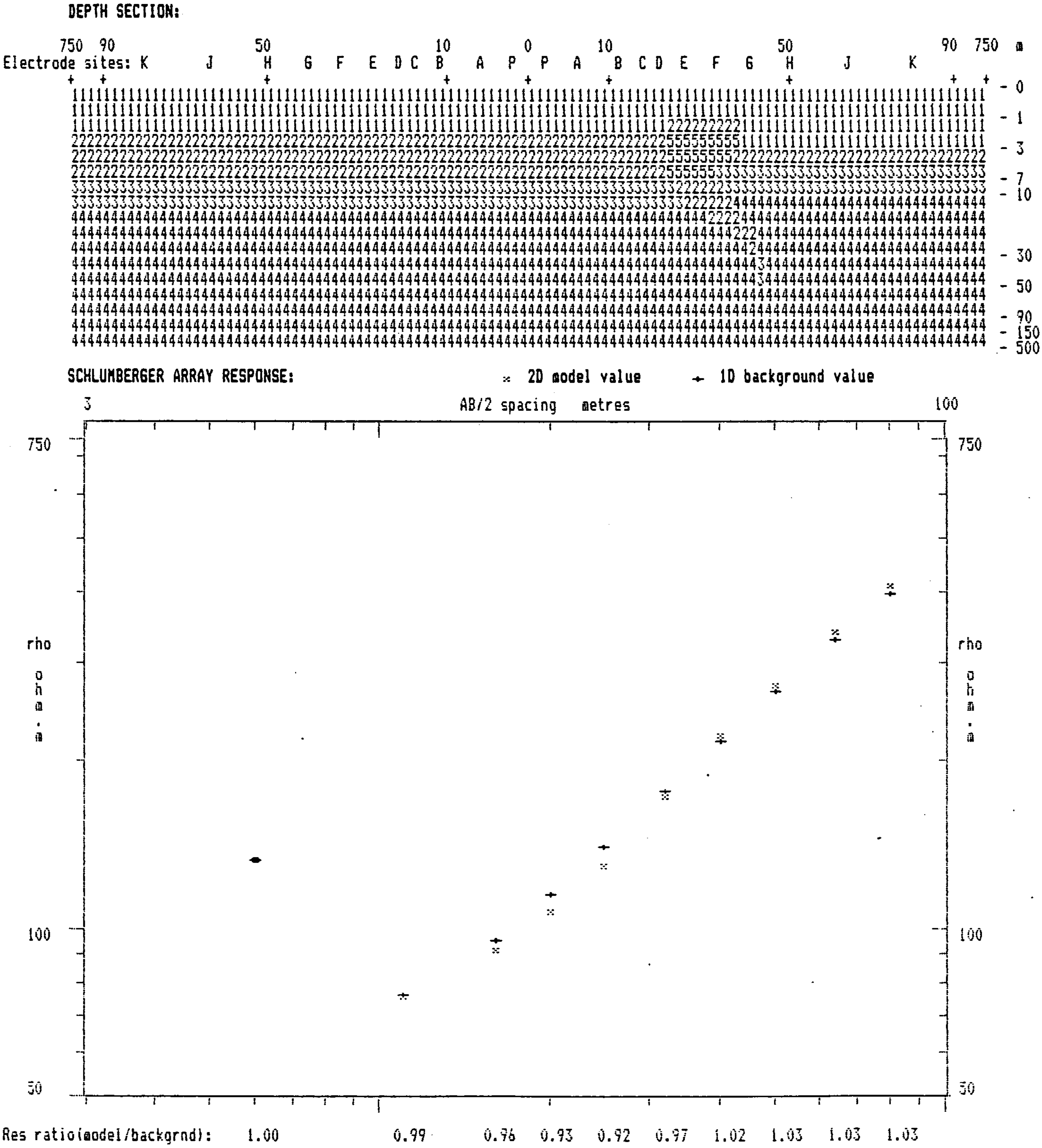


Figure 3.11 Simulated ESA results over a 2D model. Reference: BSAQ/M2;F2

2D RESISTIVITY MODELLING RESULTS

Reference: BSAQ/M2;F3

MODEL PARAMETERS:

medium	res	depth(backgrnd)
(1)	400.0	to 2.0
(2)	40.0	to 7.0
(3)	180.0	to 15.0
(4)	3000.0	to))
(5)	20.0	

DEPTH SECTION:

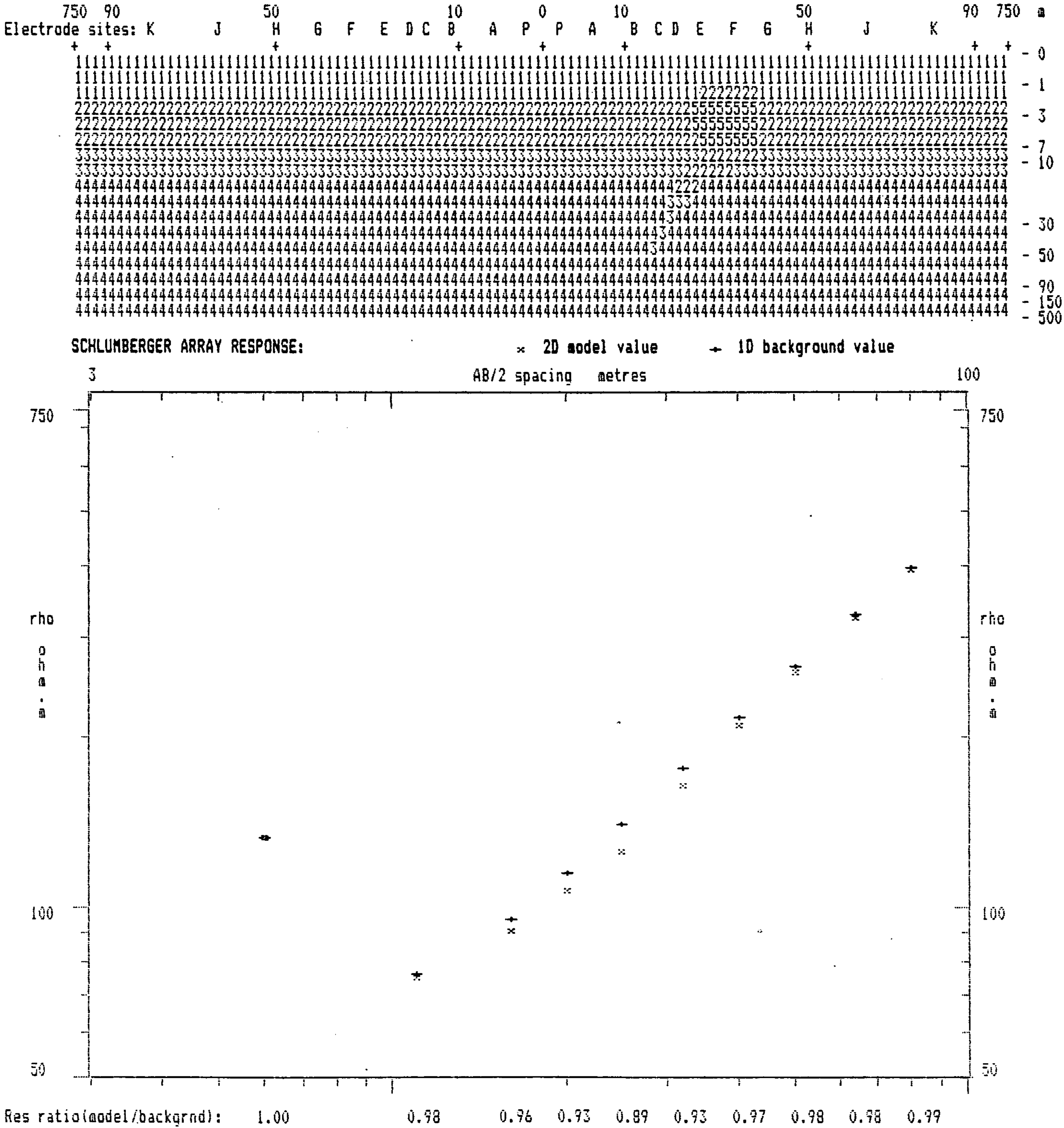


Figure 3.12 Simulated ESA results over a 2D model. Reference: BSAQ/M2;F3

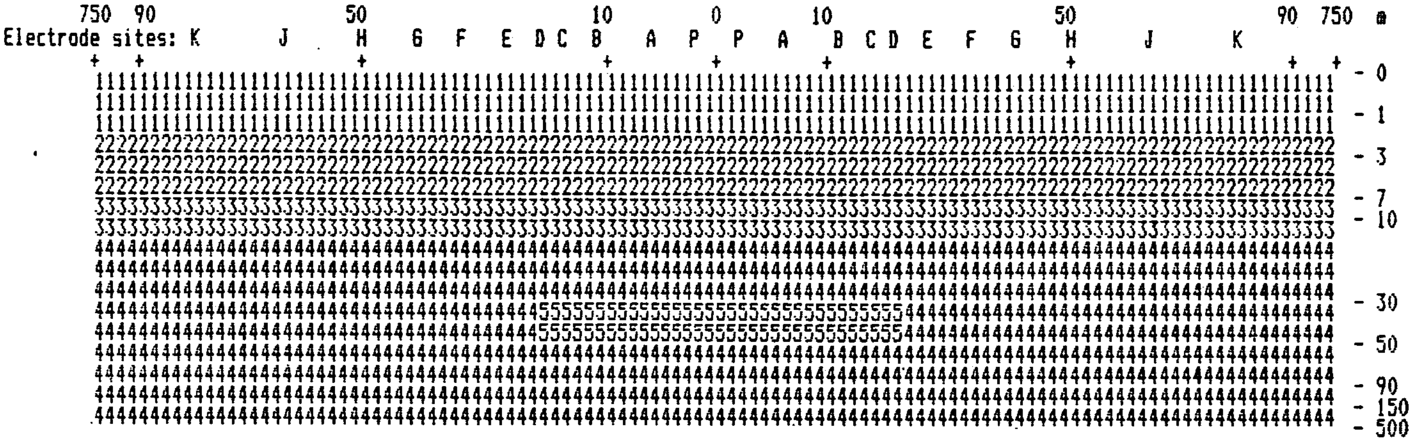
2D RESISTIVITY MODELLING RESULTS

Reference: BSAQ/M2;F4

MODEL PARAMETERS:

medium	res	depth(backgrnd)
(1)	400.0	to 2.0
(2)	40.0	to 7.0
(3)	180.0	to 15.0
(4)	3000.0	to »
(5)	20.0	

DEPTH SECTION:



SCHLUMBERGER ARRAY RESPONSE: × 2D model value + 1D background value

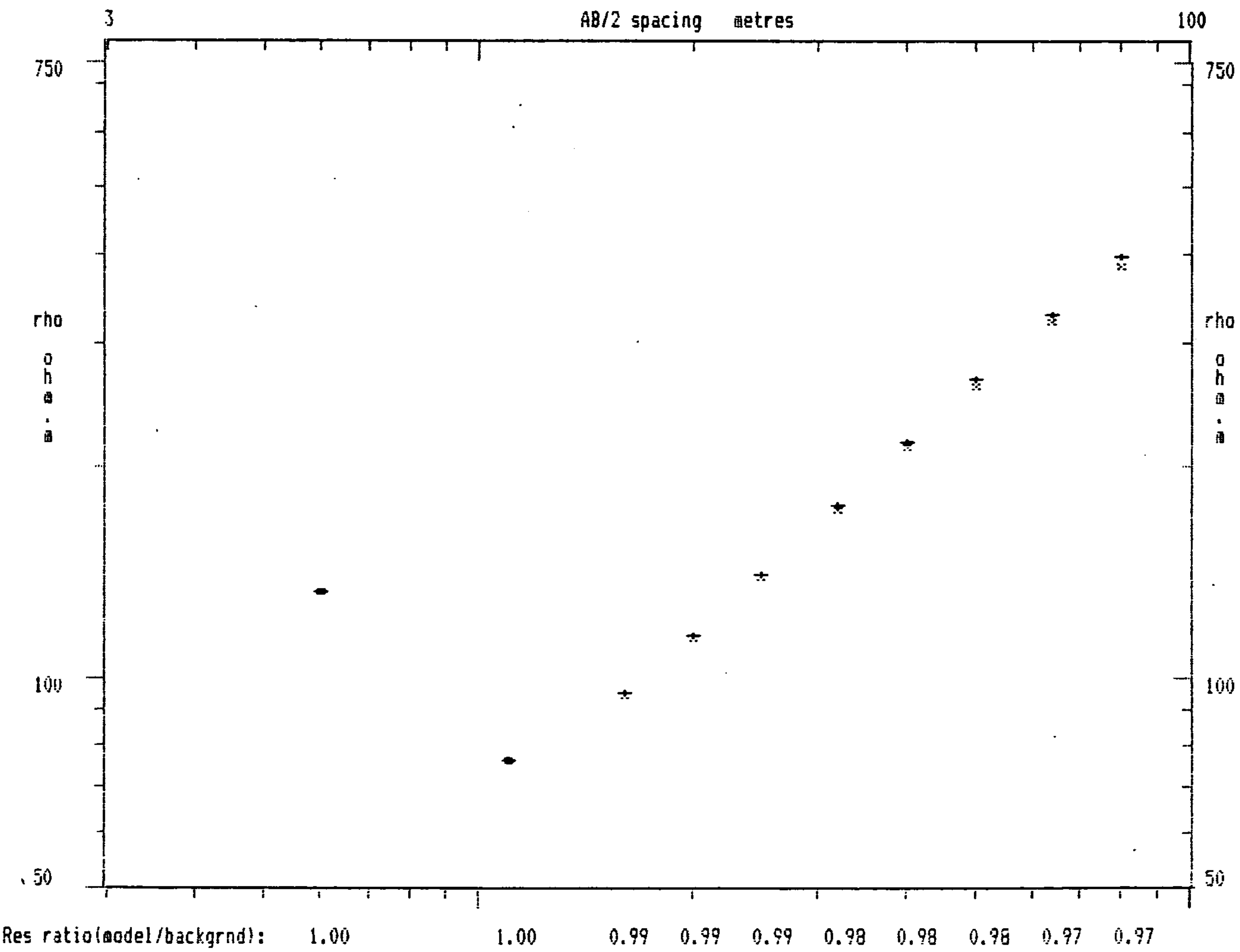


Figure 3.13 Simulated ESA results over a 2D model. Reference: BSAQ/M2;F4

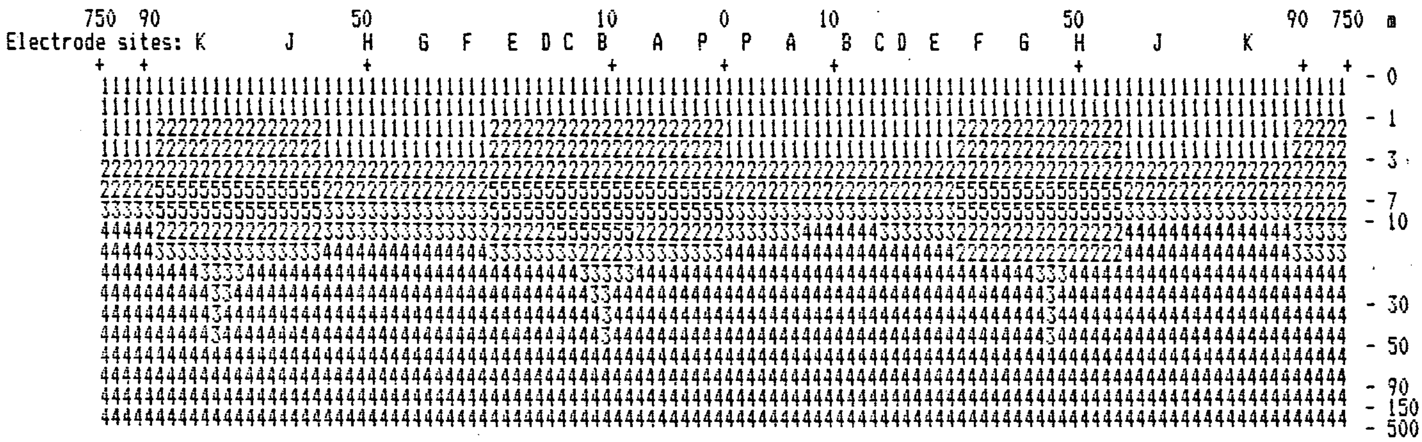
2D RESISTIVITY MODELLING RESULTS

Reference: BSAQ/M2;L1

MODEL PARAMETERS:

medium	res	depth(backgrnd)
(1)	400.0	to 2.0
(2)	40.0	to 7.0
(3)	180.0	to 15.0
(4)	3000.0	to))
(5)	20.0	

DEPTH SECTION:



SCHLUMBERGER ARRAY RESPONSE: × 2D model value + 1D background value

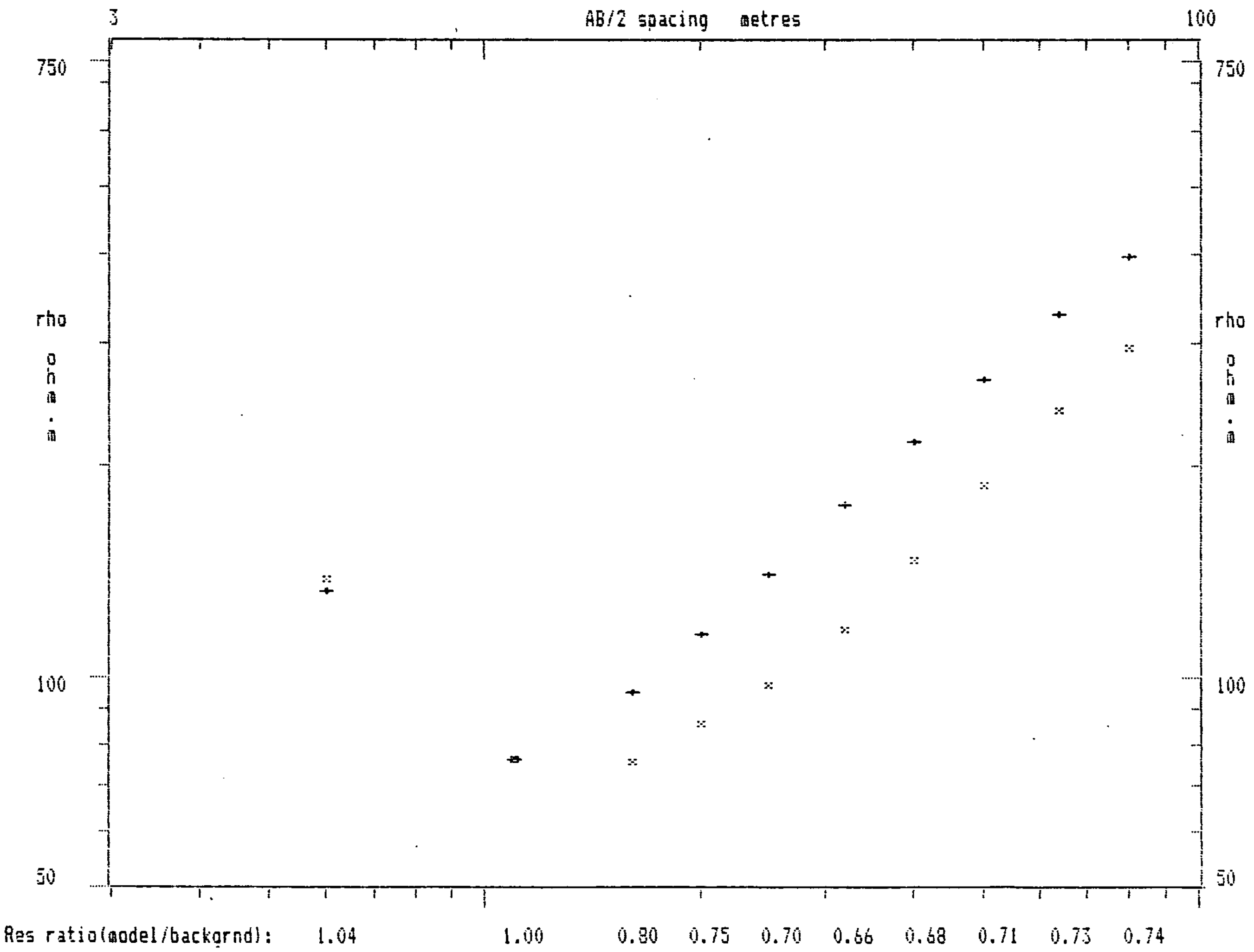


Figure 3.14 Simulated ESA results over a 2D model. Reference: BSAQ/M2;L1

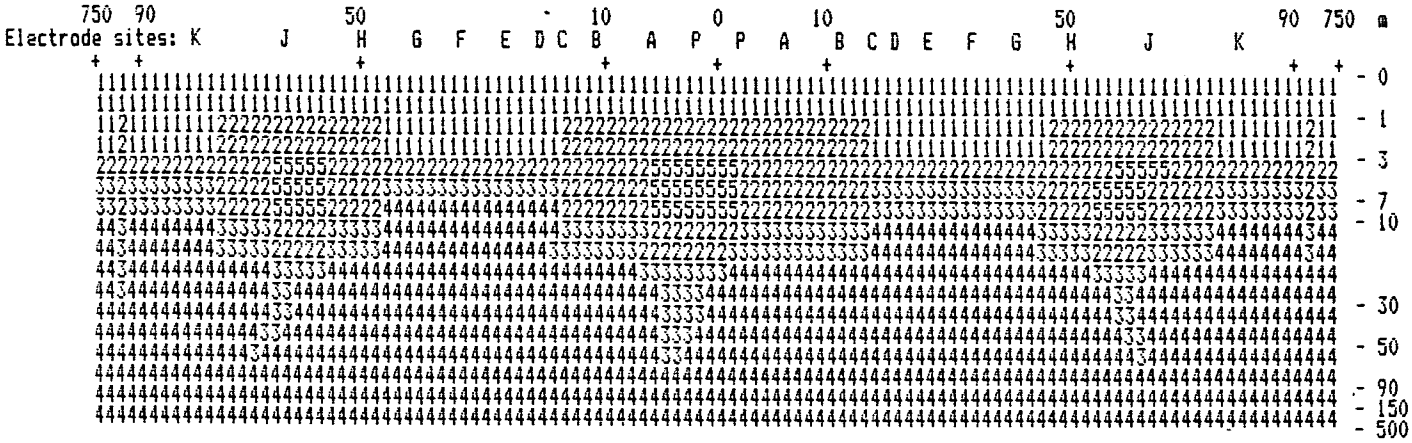
2D RESISTIVITY MODELLING RESULTS

Reference: BSAQ/M2;L2

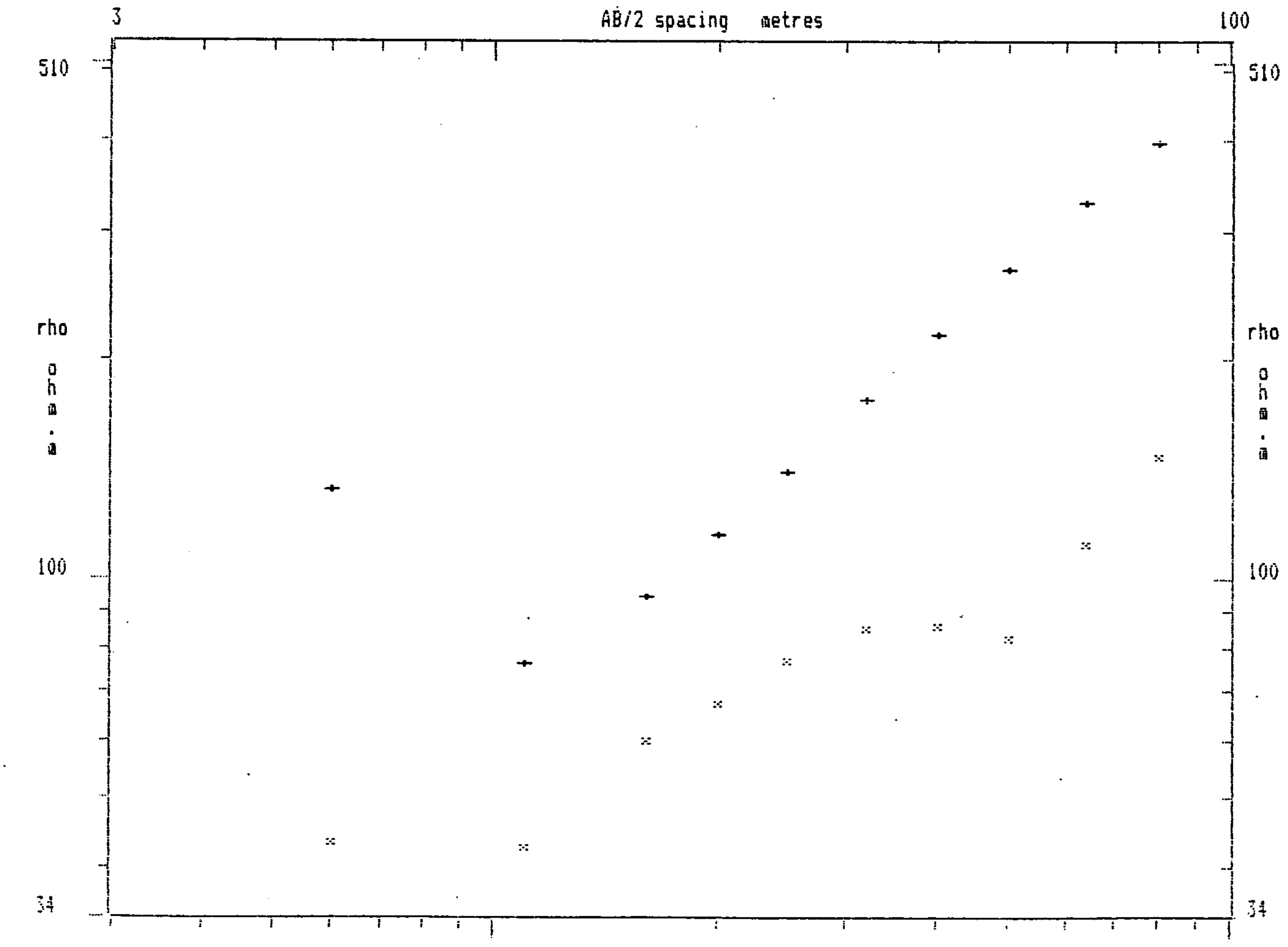
MODEL PARAMETERS:

medium	res	depth(backgrnd)
(1)	400.0	to 2.0
(2)	25.0	to 7.0
(3)	180.0	to 15.0
(4)	3000.0	to))
(5)	20.0	

DEPTH SECTION:



SCHLUMBERGER ARRAY RESPONSE: × 2D model value + 1D background value



Res ratio(model/backgrnd): 0.33 0.56 0.63 0.59 0.55 0.49 0.40 0.31 0.34 0.37

Figure 3.15 Simulated ESA results over a 2D model. Reference: BSAQ/M2;L2

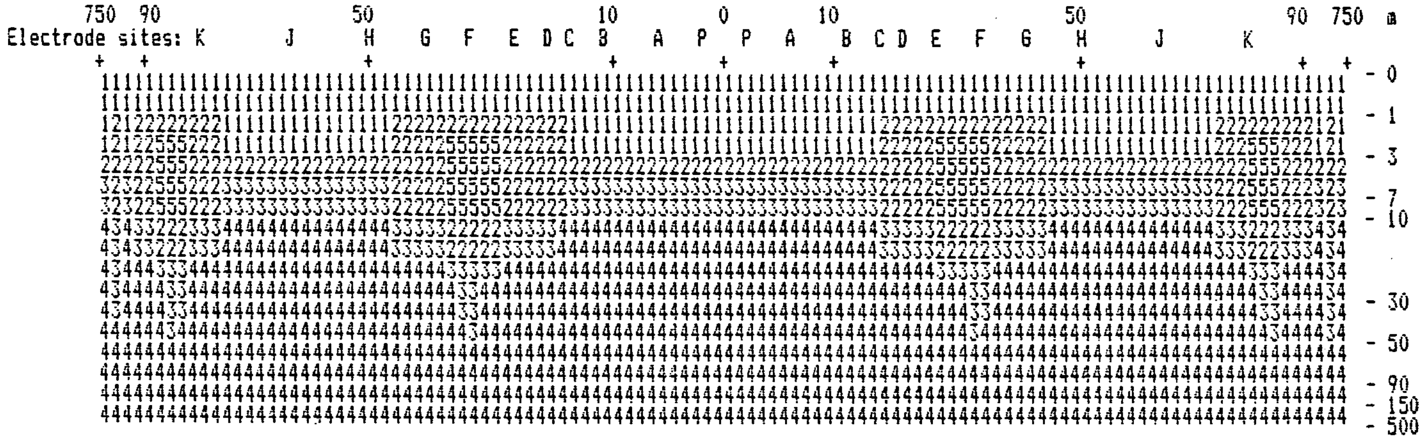
2D RESISTIVITY MODELLING RESULTS

Reference: BSAQ/M2;L3

MODEL PARAMETERS:

medium	res	depth(backgrnd)
(1)	400.0	to 2.0
(2)	40.0	to 7.0
(3)	180.0	to 15.0
(4)	3000.0	to >>
(5)	20.0	

DEPTH SECTION:



SCHLUMBERGER ARRAY RESPONSE: × 2D model value + 1D background value

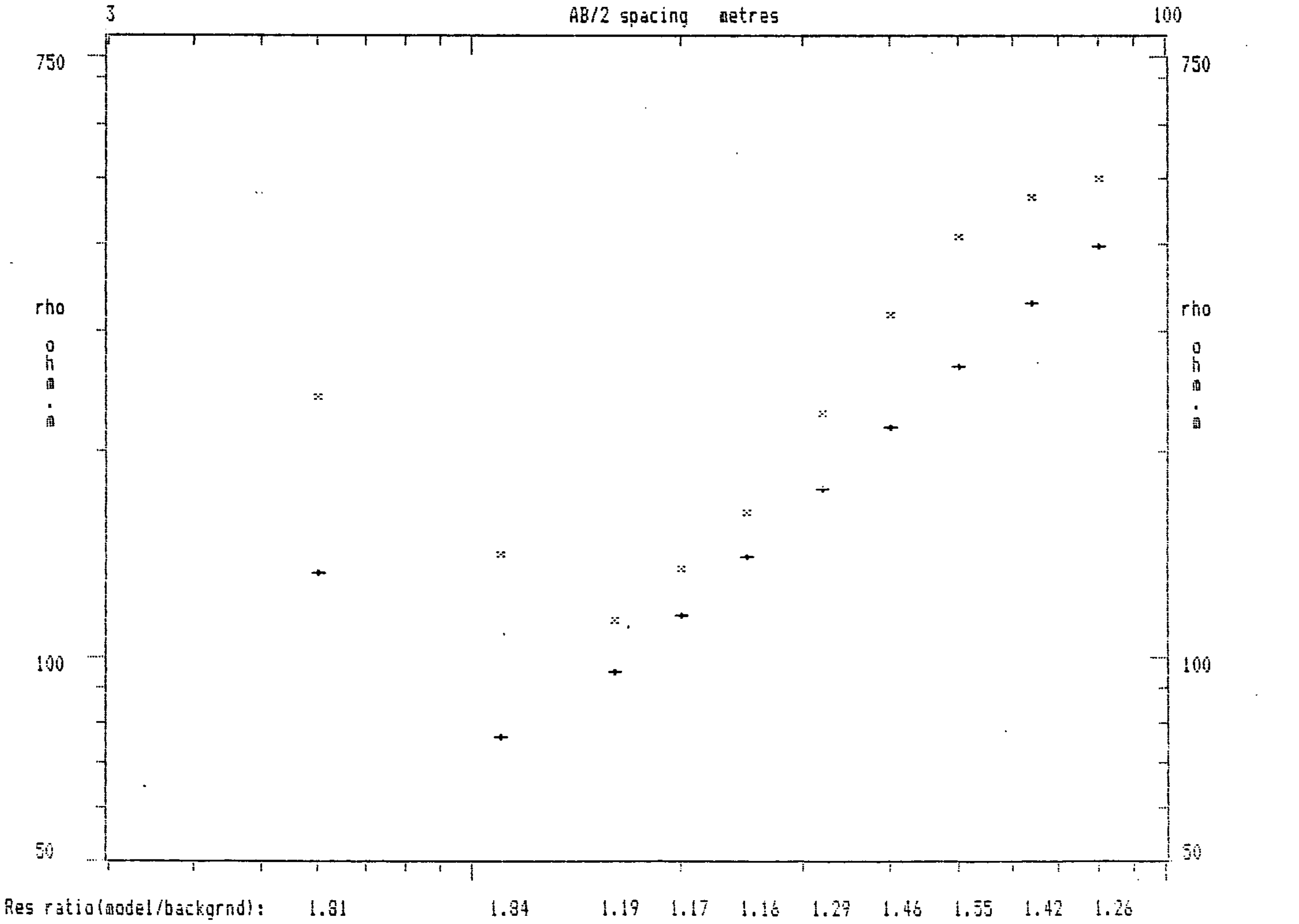
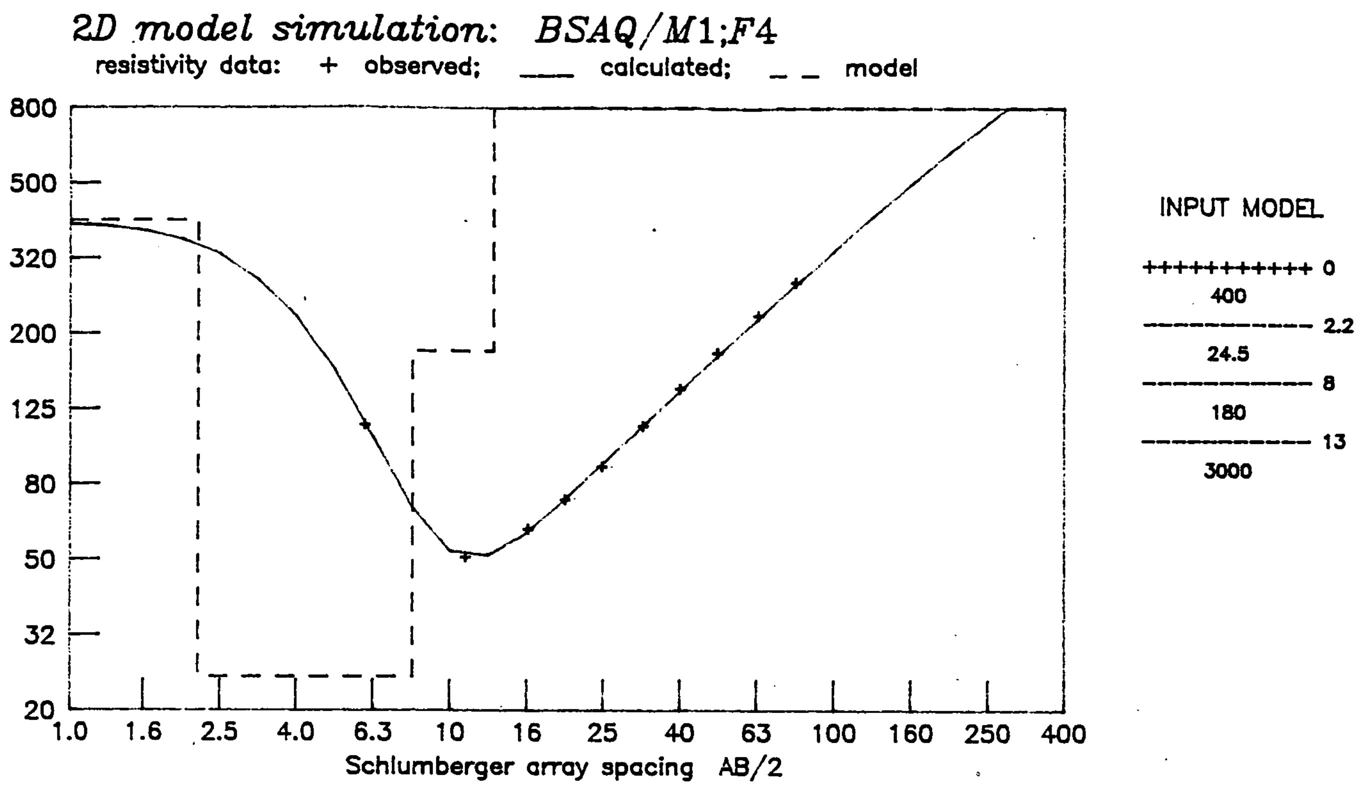


Figure 3.16 Simulated ESA results over a 2D model. Reference: BSAQ/M2;L3



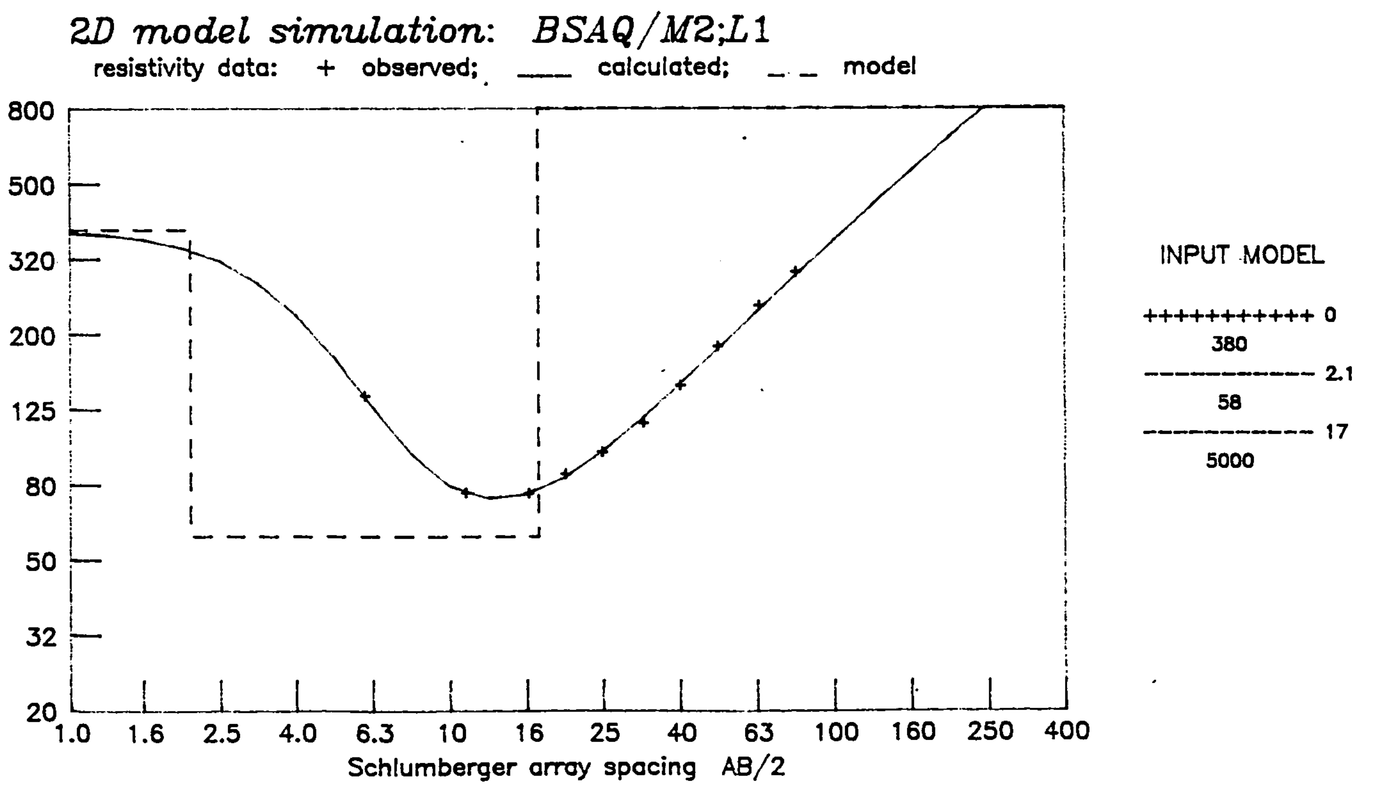
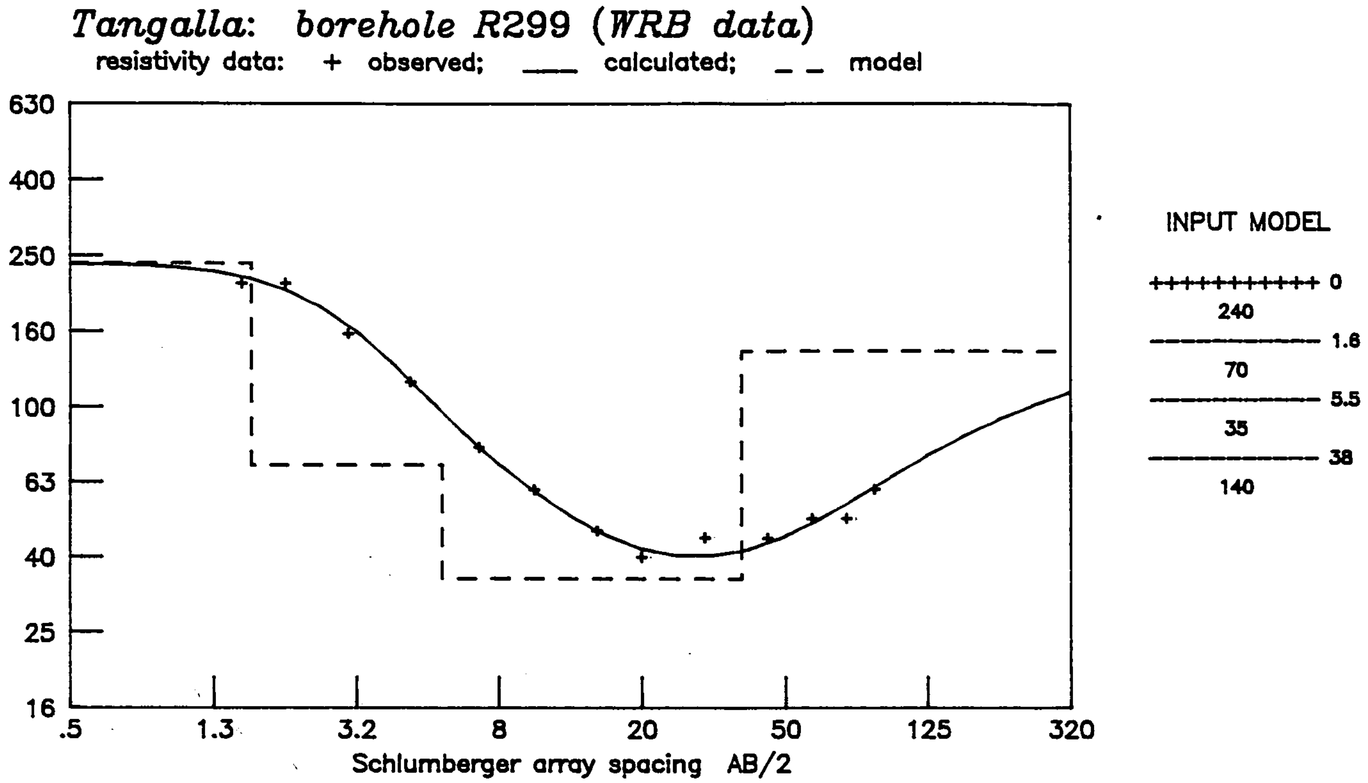


Figure 3.17 Alternative 1D resistivity models to fit 2D output values



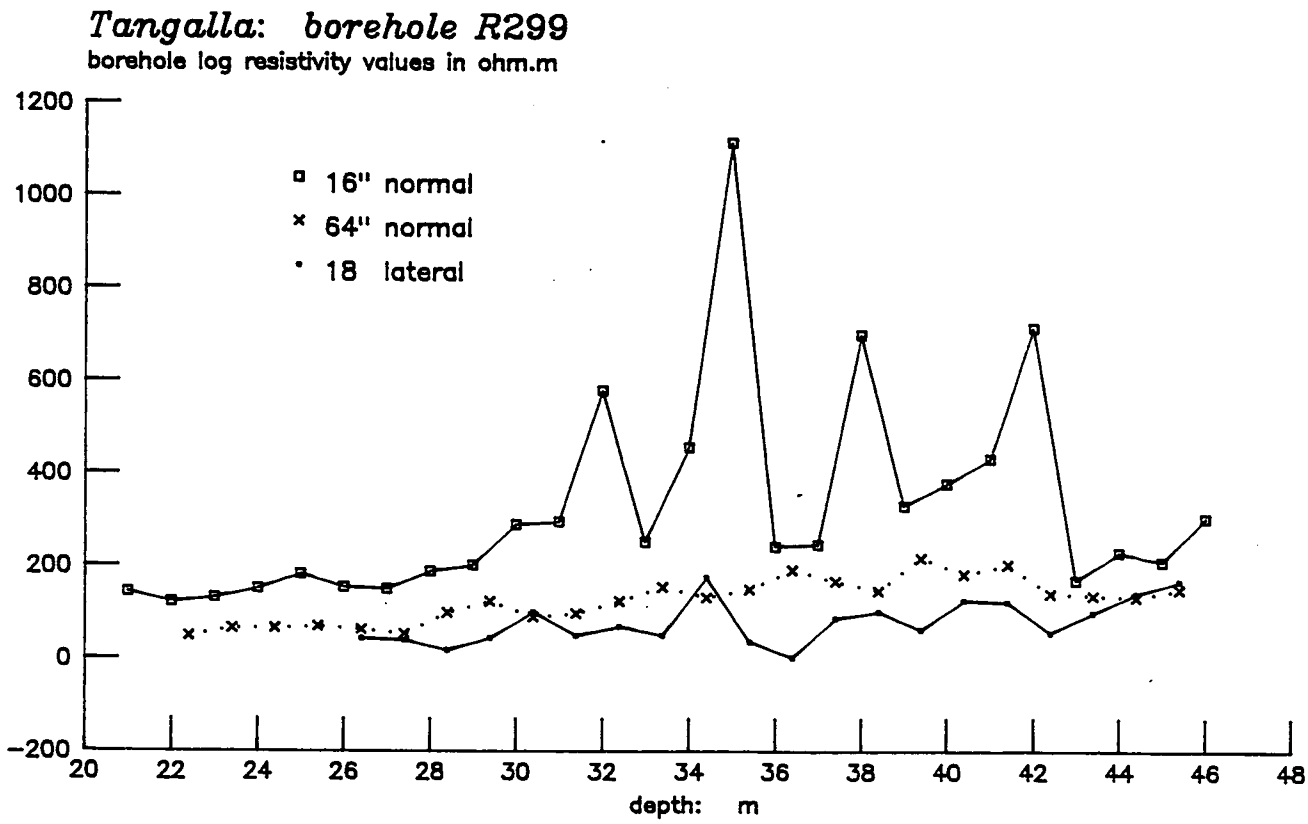
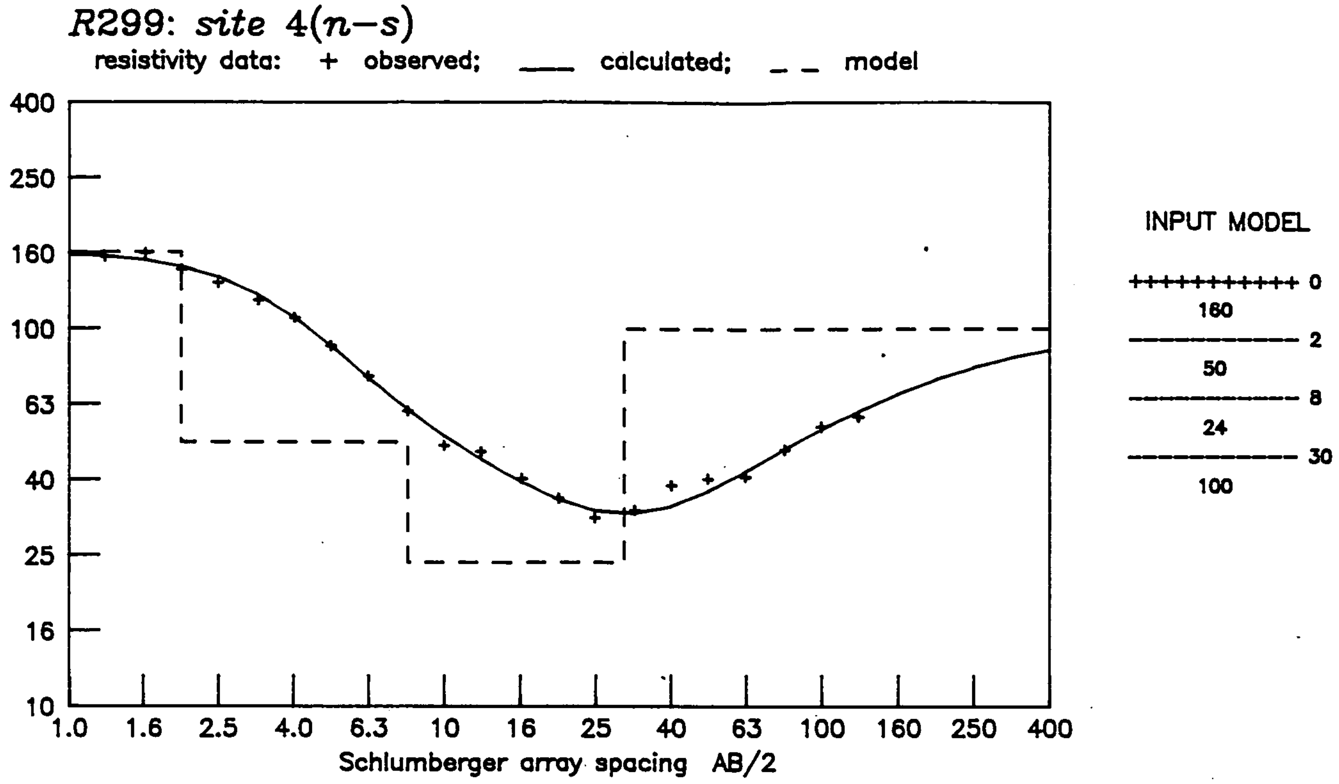


Figure 3.18 Resistivity ESA and borehole log data from R299, Tangalla



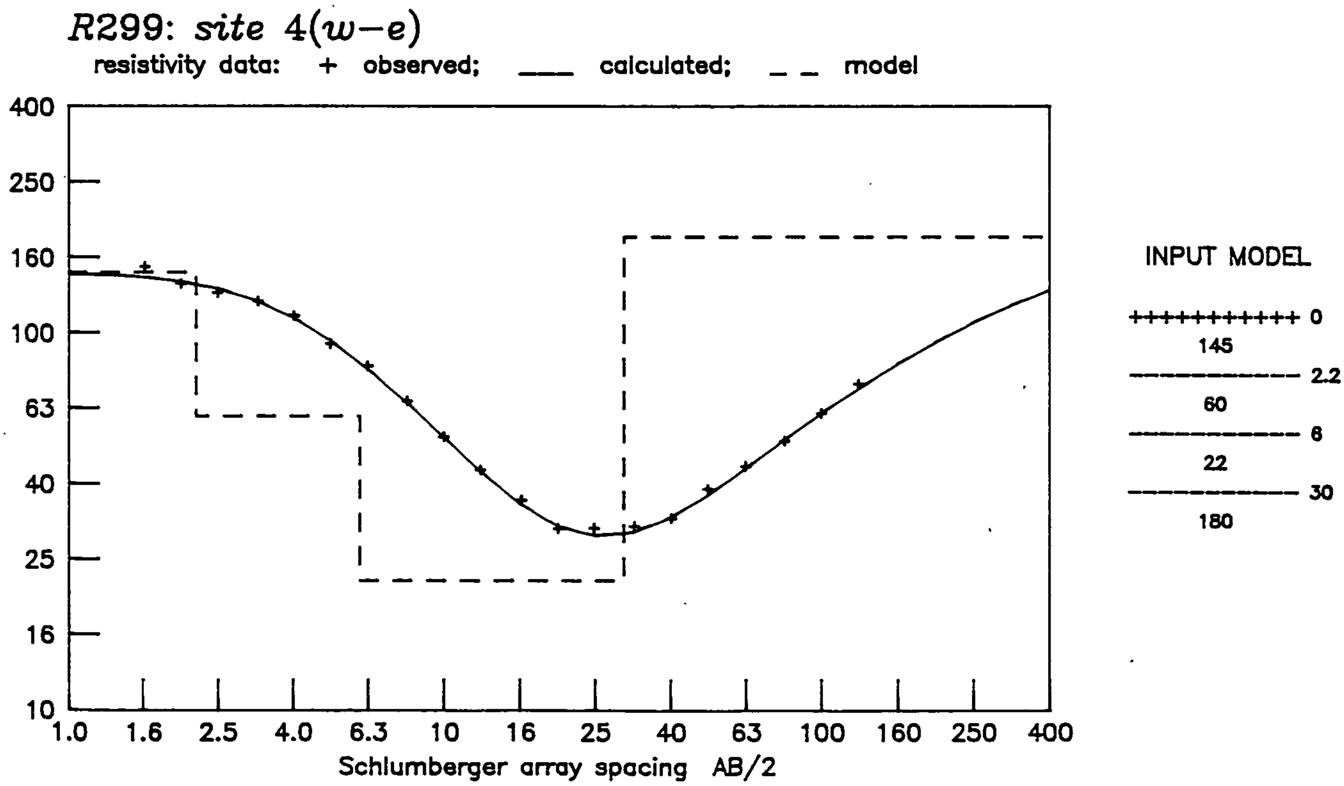


Figure 3.19 Orthogonal ESA resistivity results near borehole R299, Tangalla

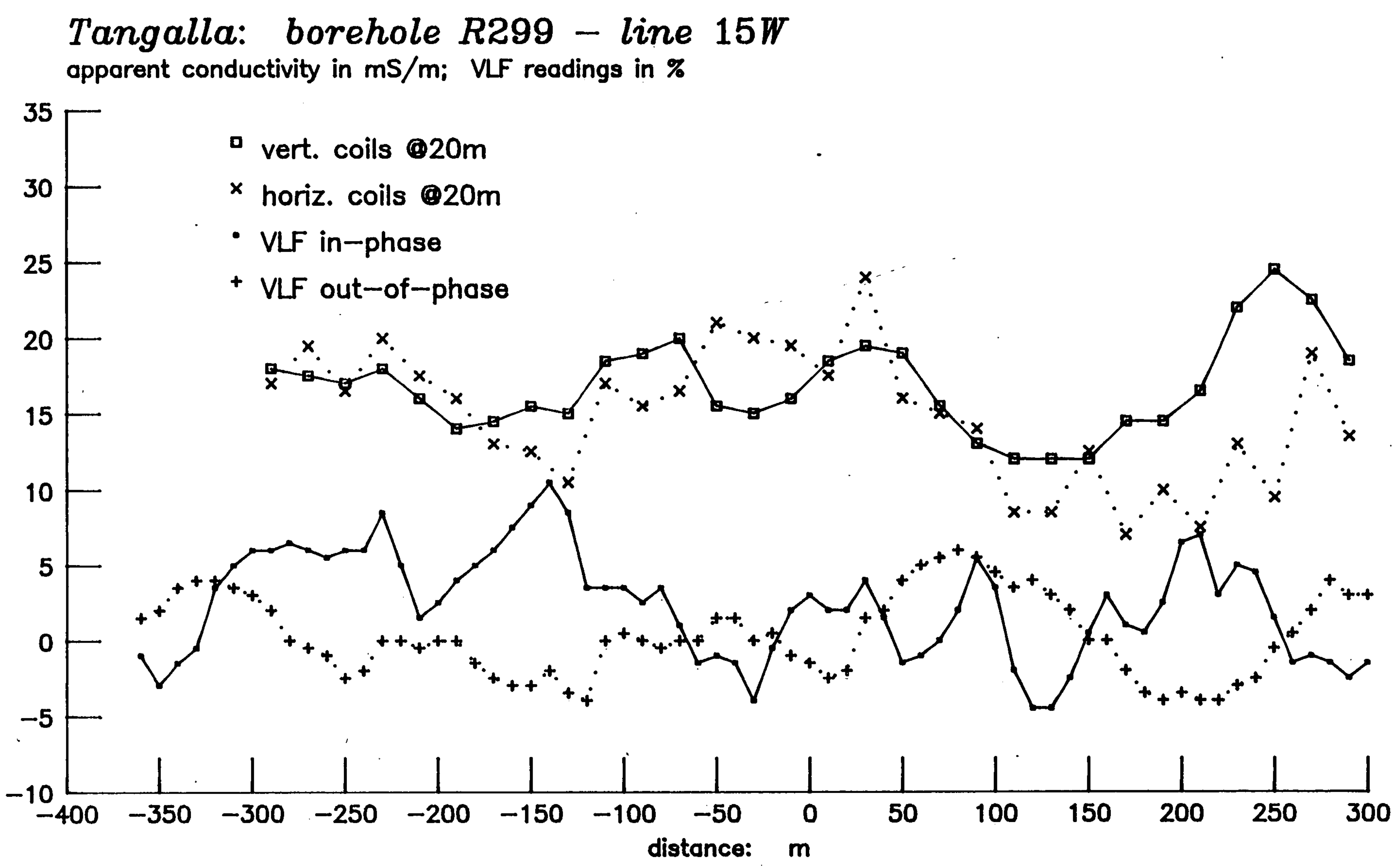


Figure 3.20a EM34 and VLF profiles along traverse 15W by R299, Tangalla

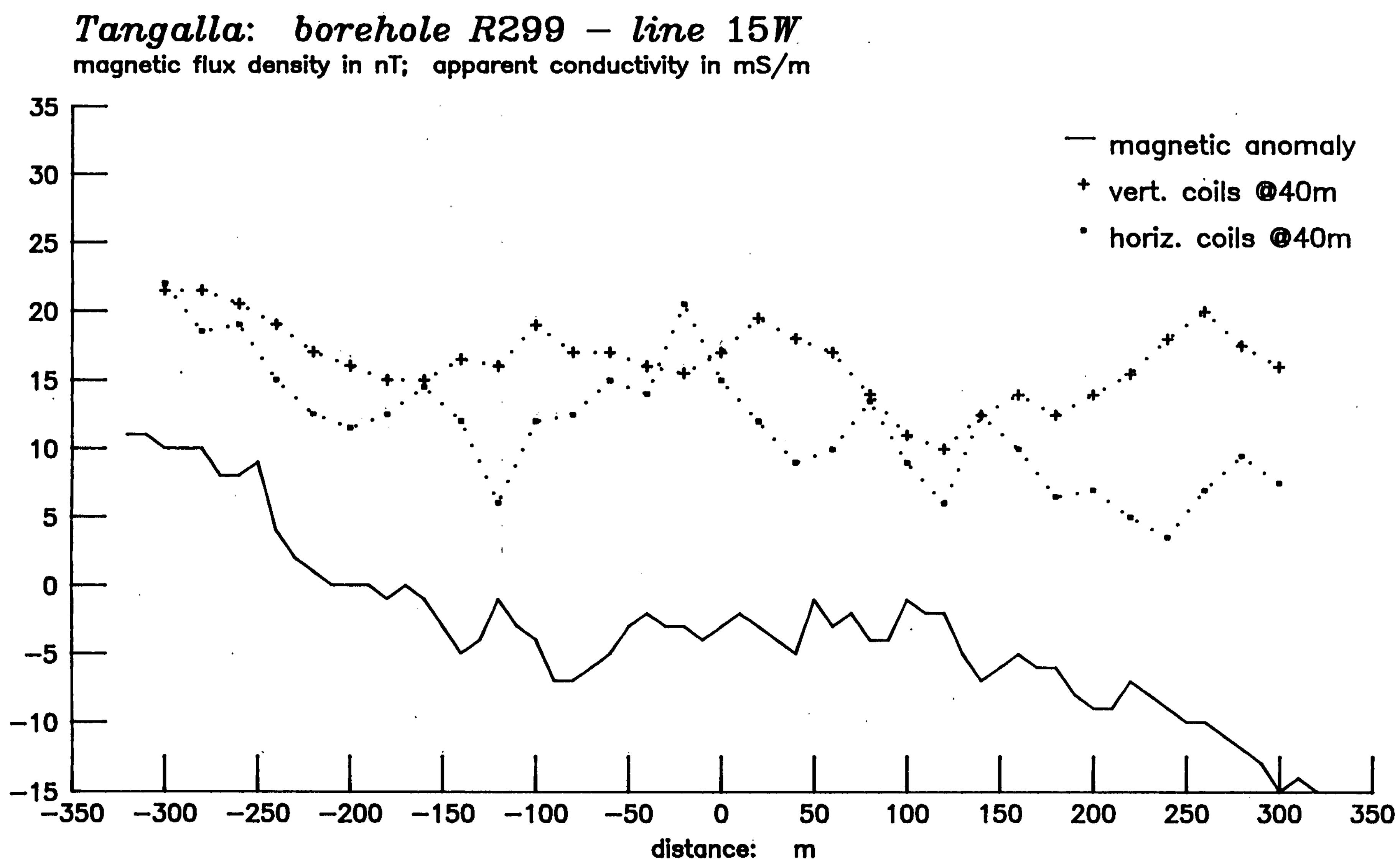
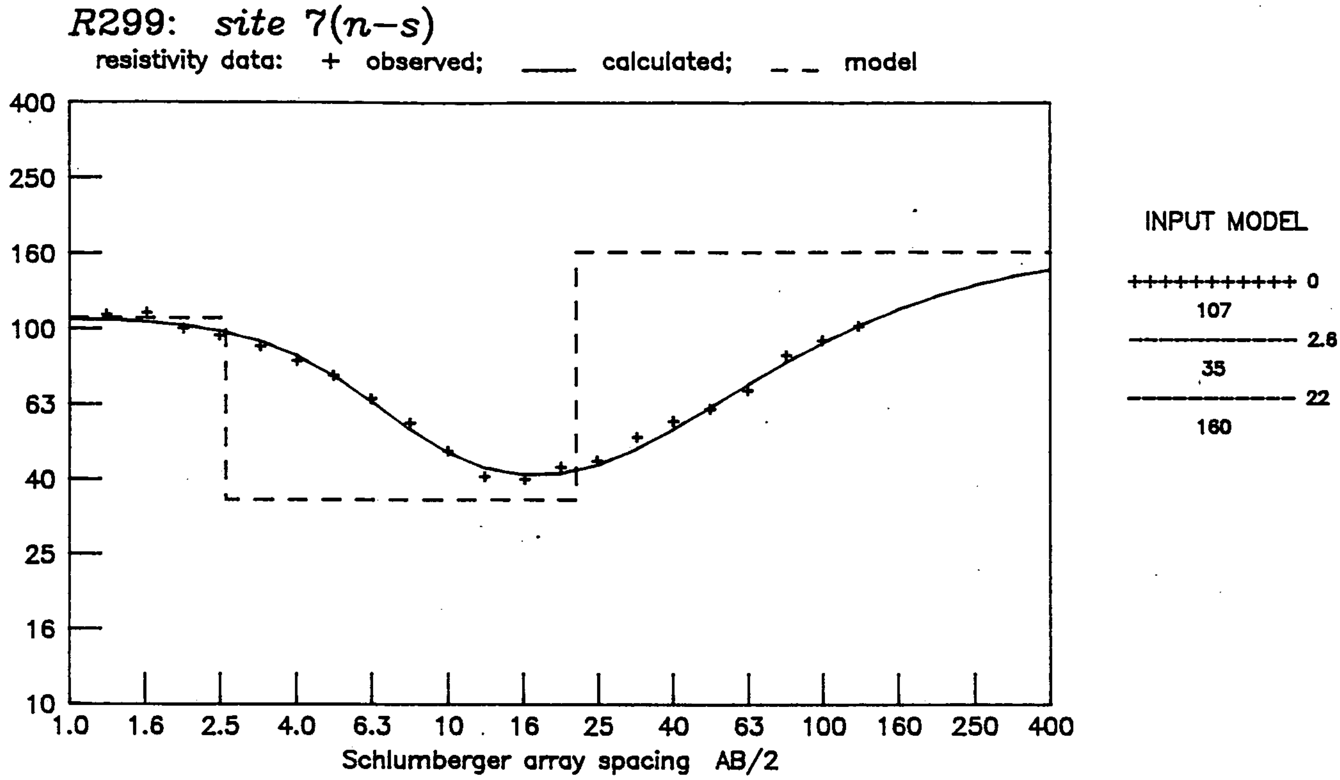


Figure 3.20b Magnetic and EM34 profiles along traverse 15W by R299, Tangalla



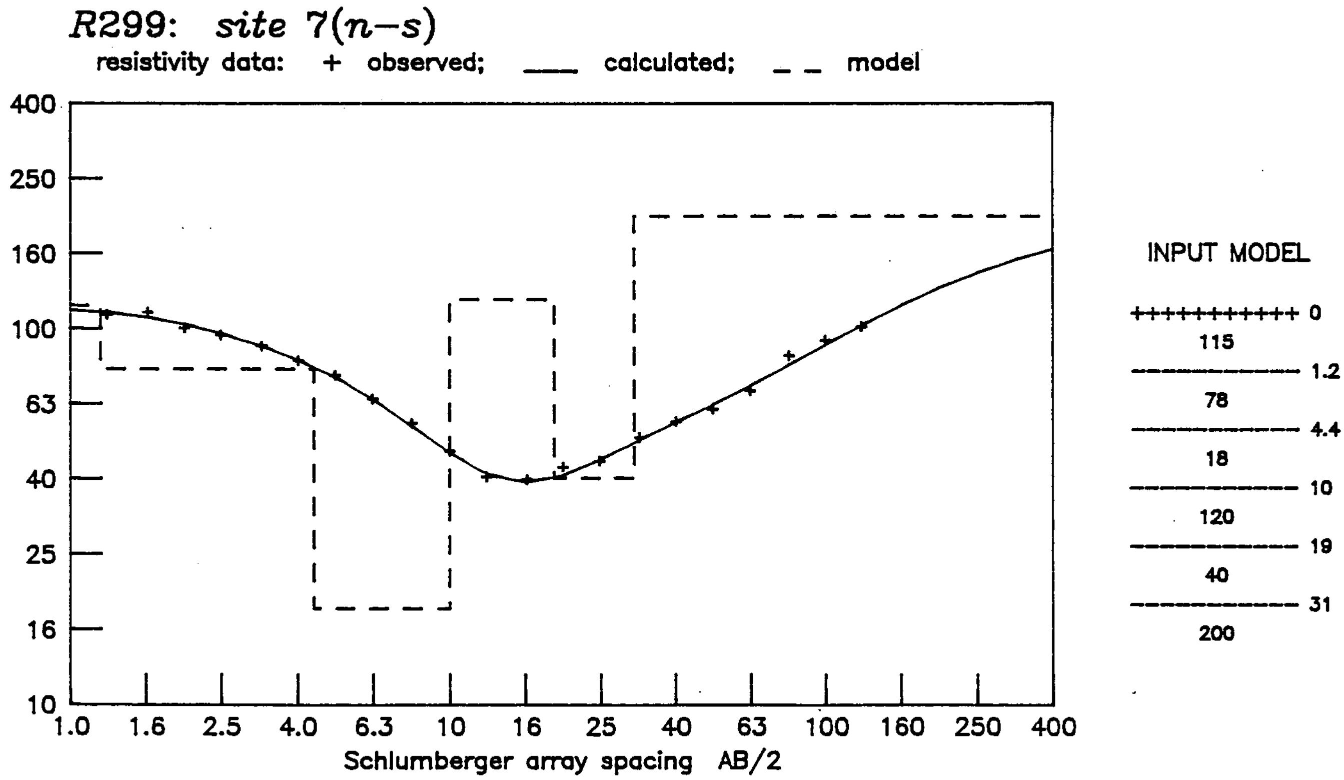
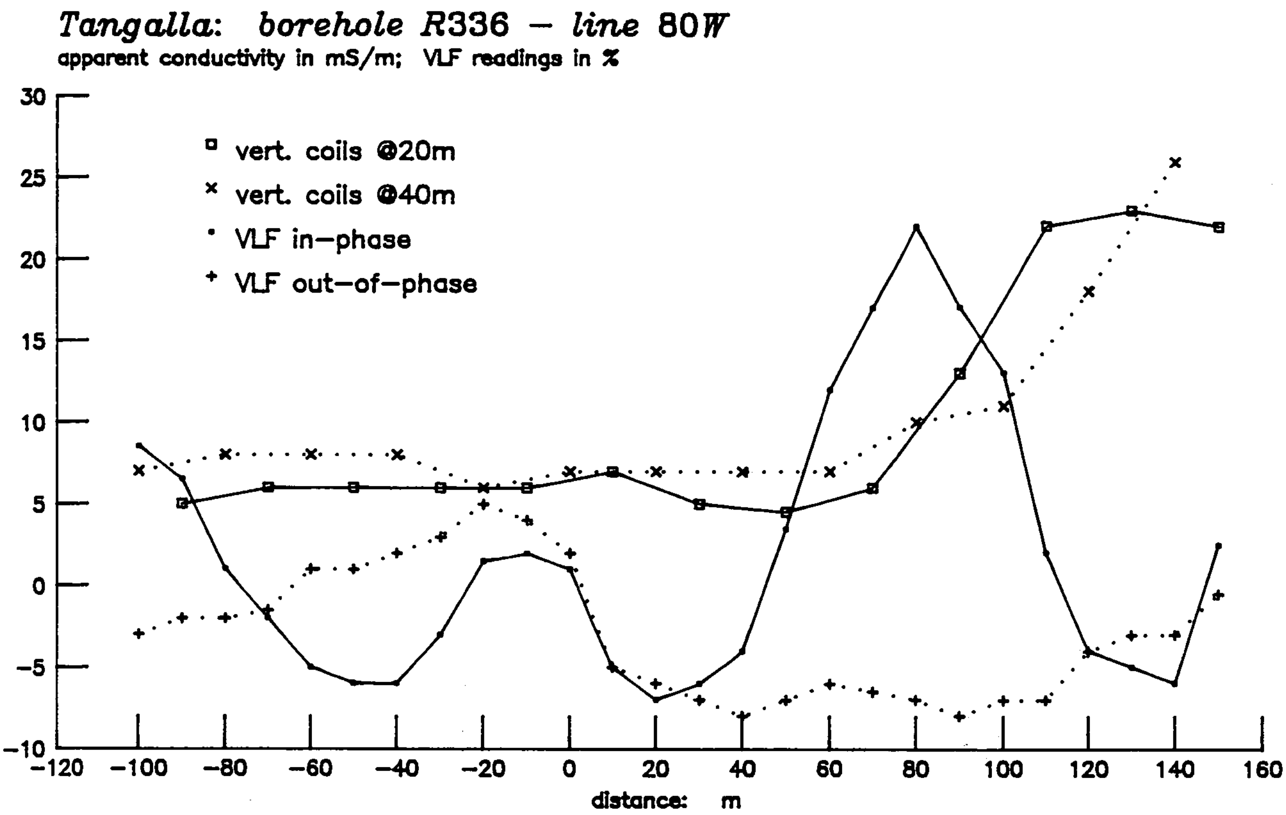


Figure 3.21 Alternative resistivity interpretations for C299, Tangalla



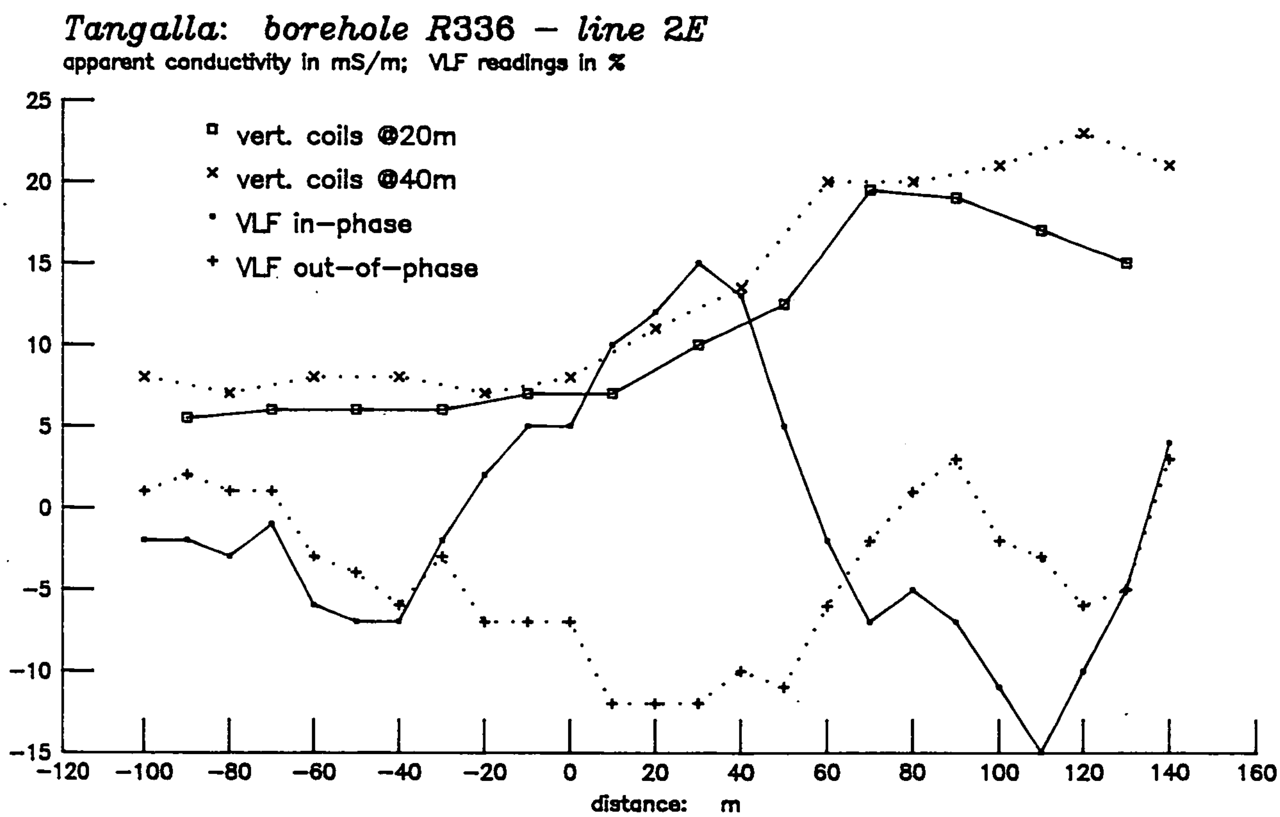
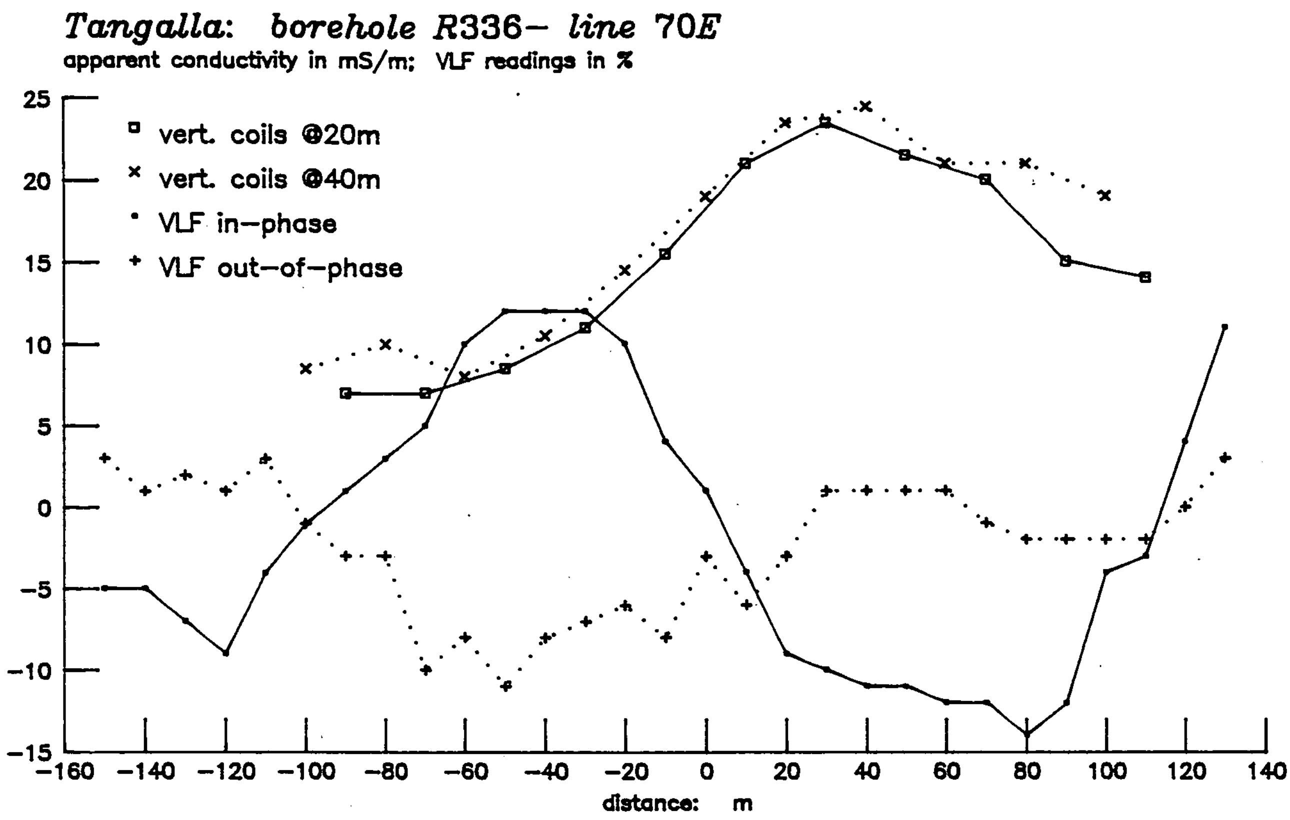


Figure 3.22a EM34 and VLF profiles along lines 80W and 2E by R336



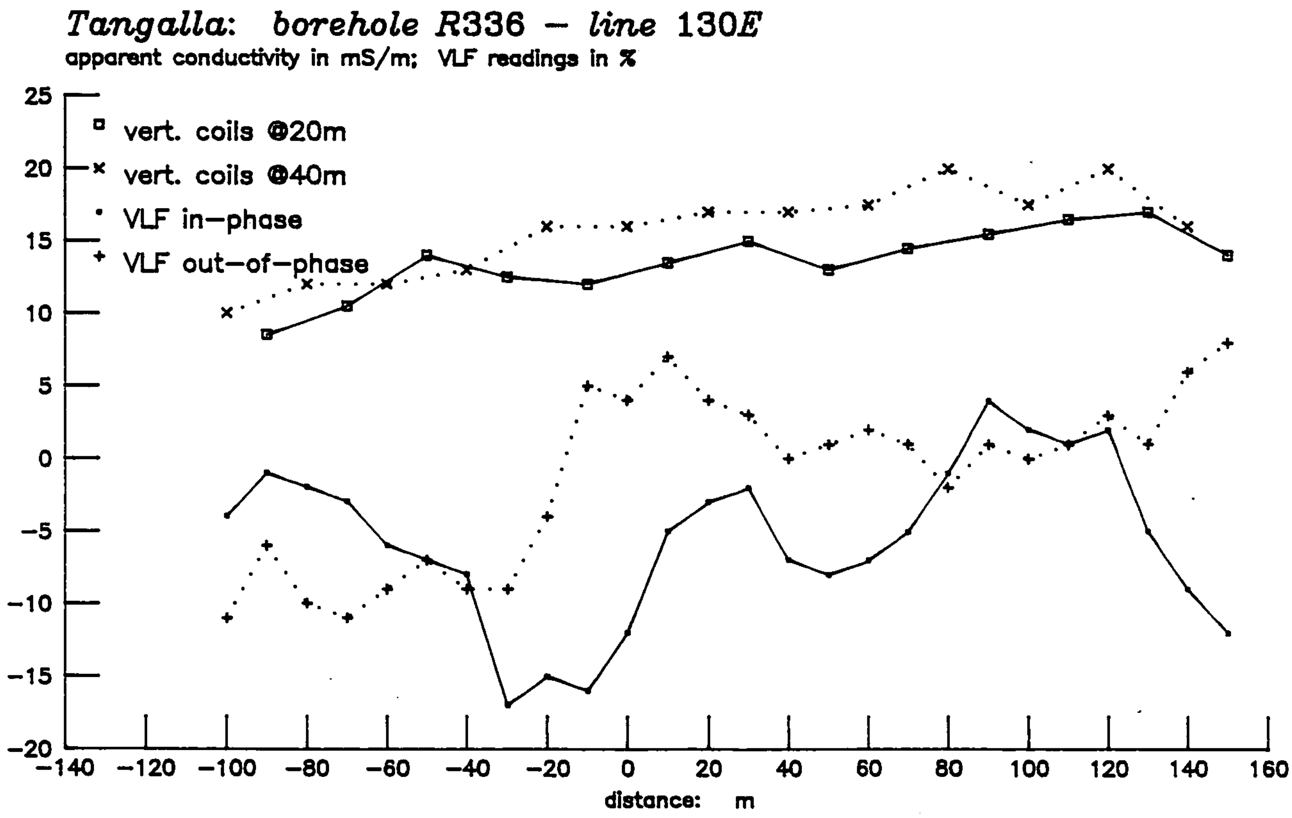
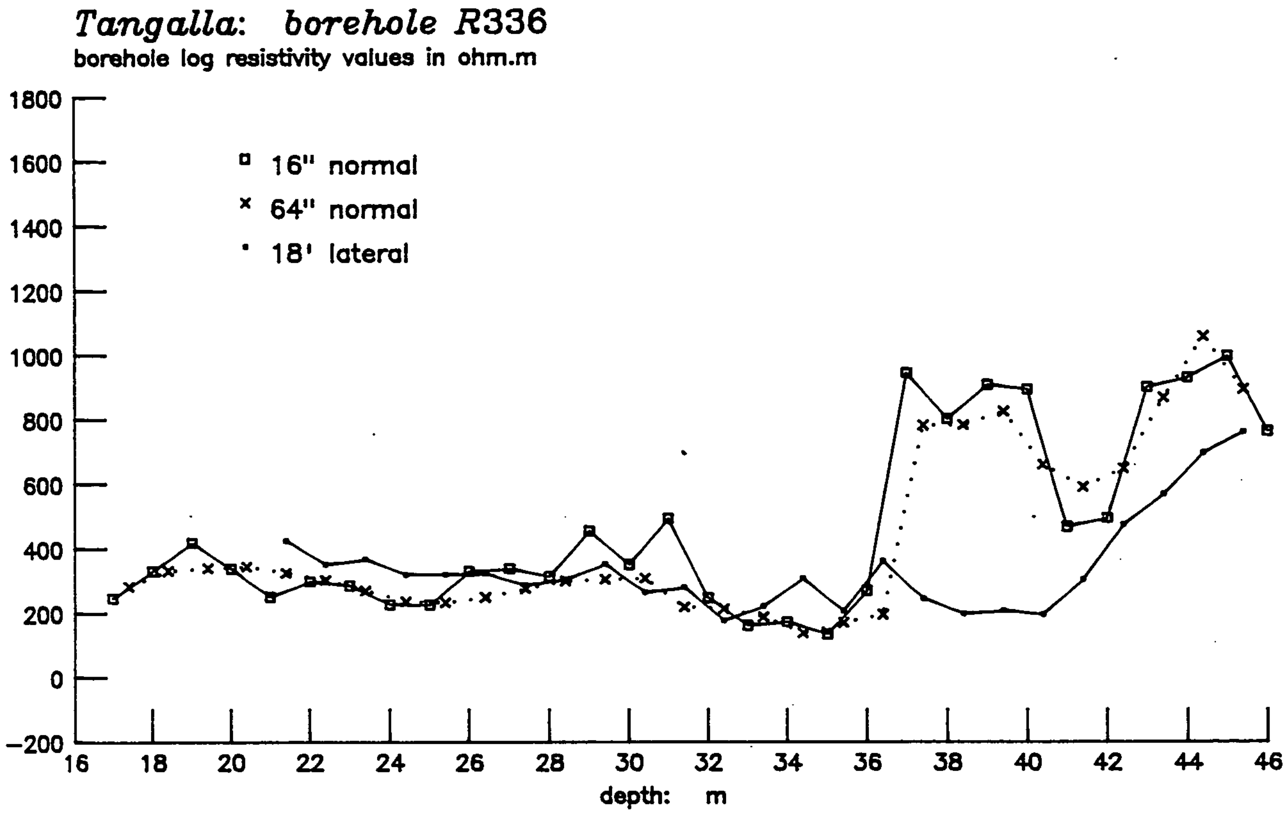


Figure 3.22b EM34 and VLF profiles along lines 70E and 130E by R336



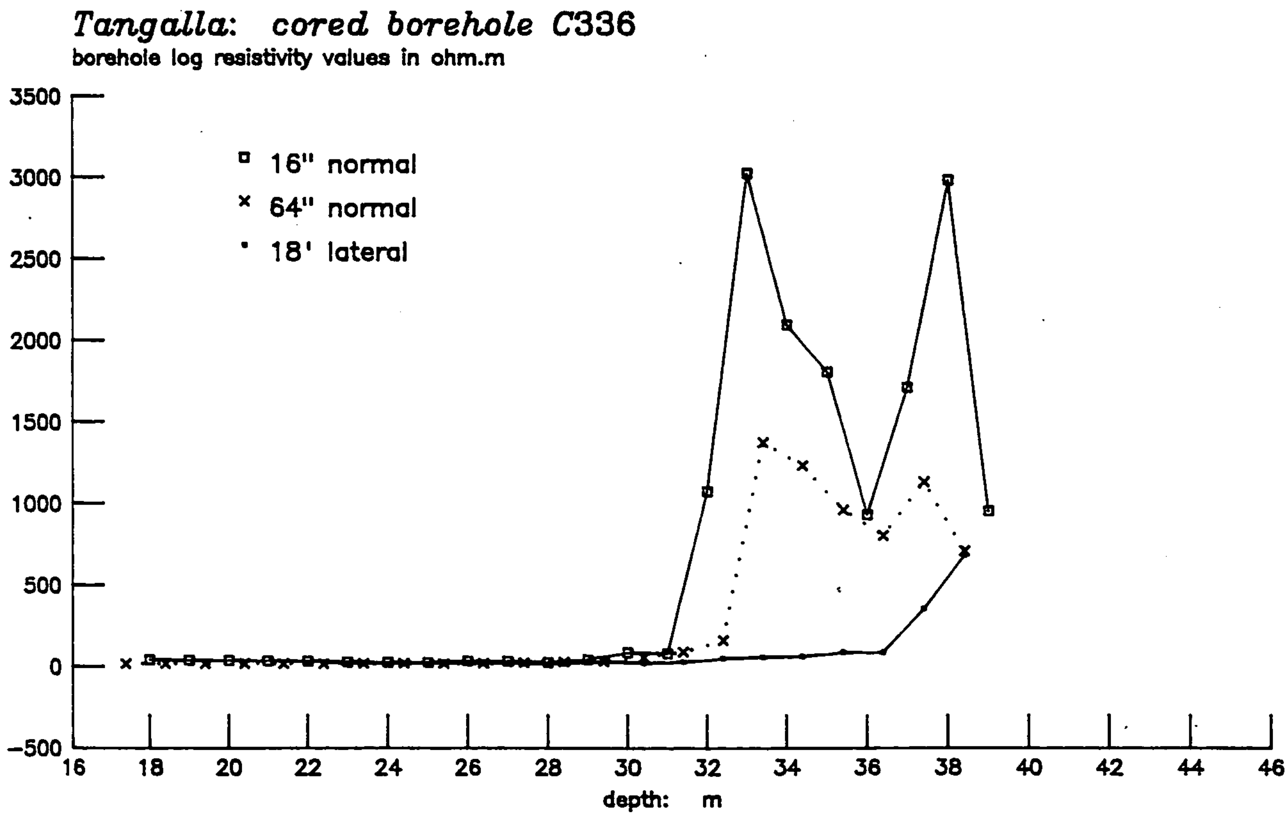
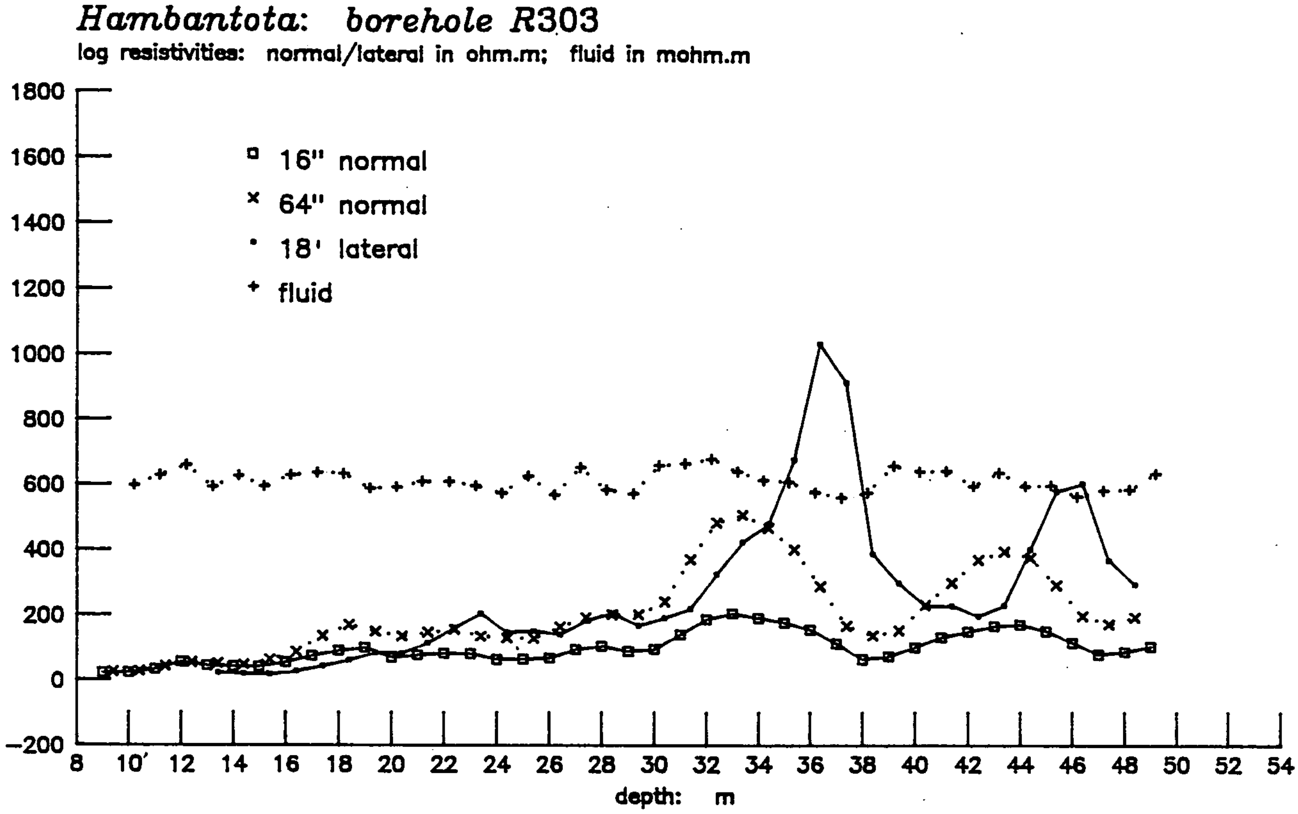


Figure 3.23 Comparison of borehole logs from R336 and C336, Tangalla



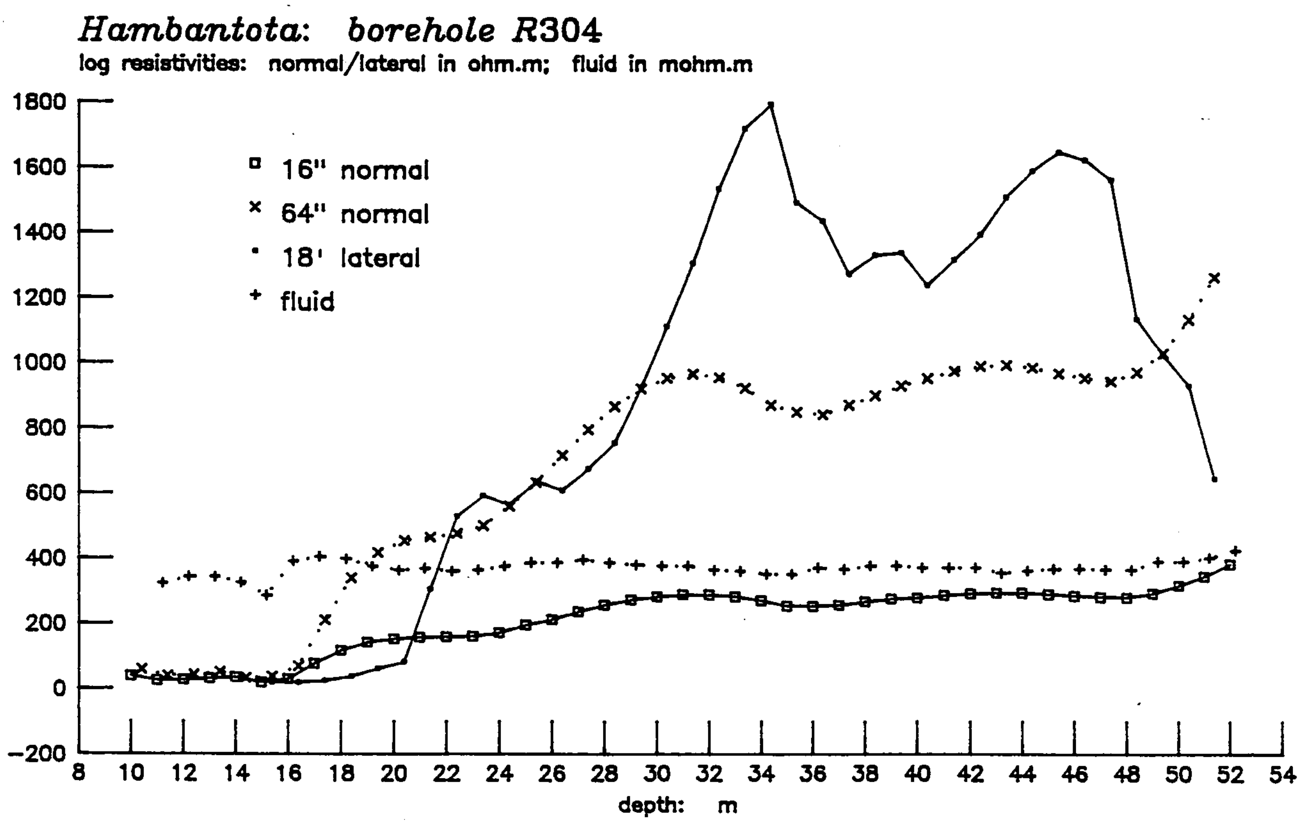
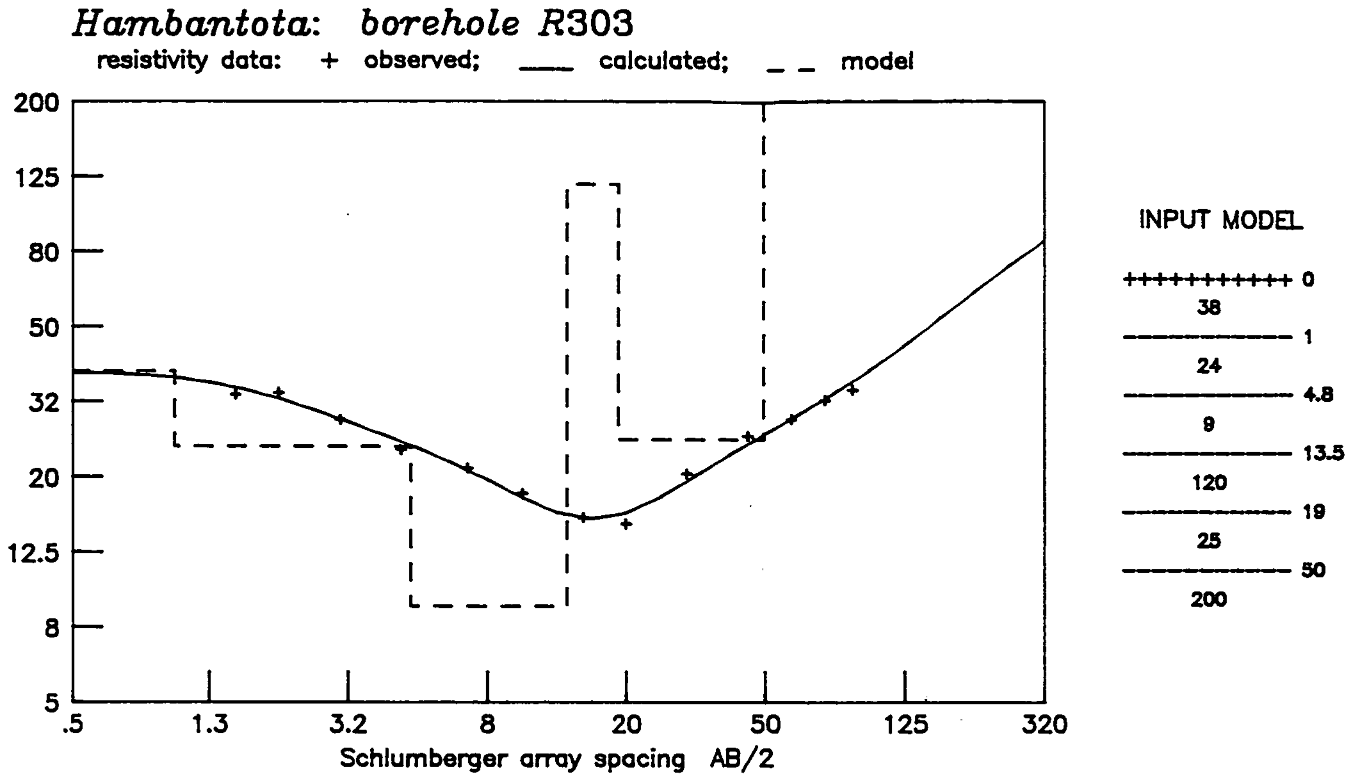


Figure 3.24a Comparison of borehole logs from R303 and R304, Hambantota



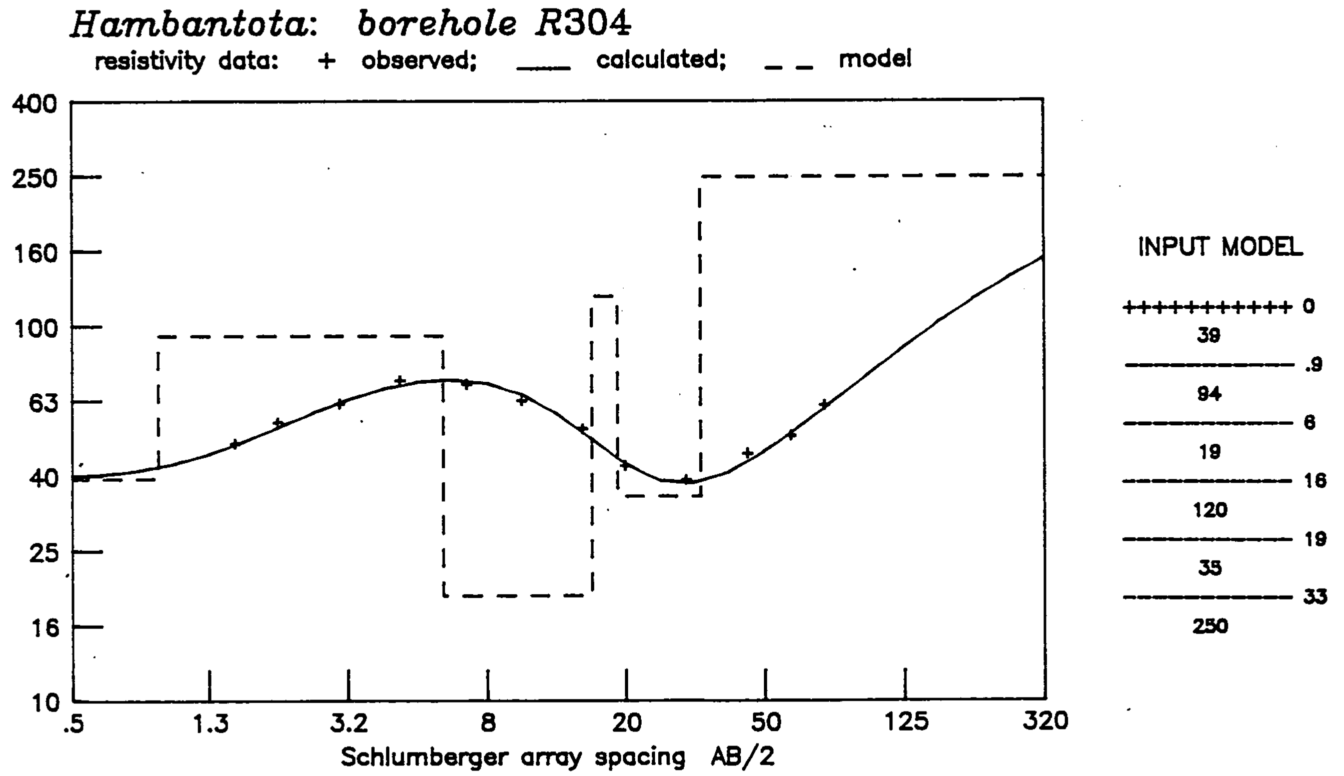


Figure 3.24b Comparison of ESA results from R303 and R304, Hambantota

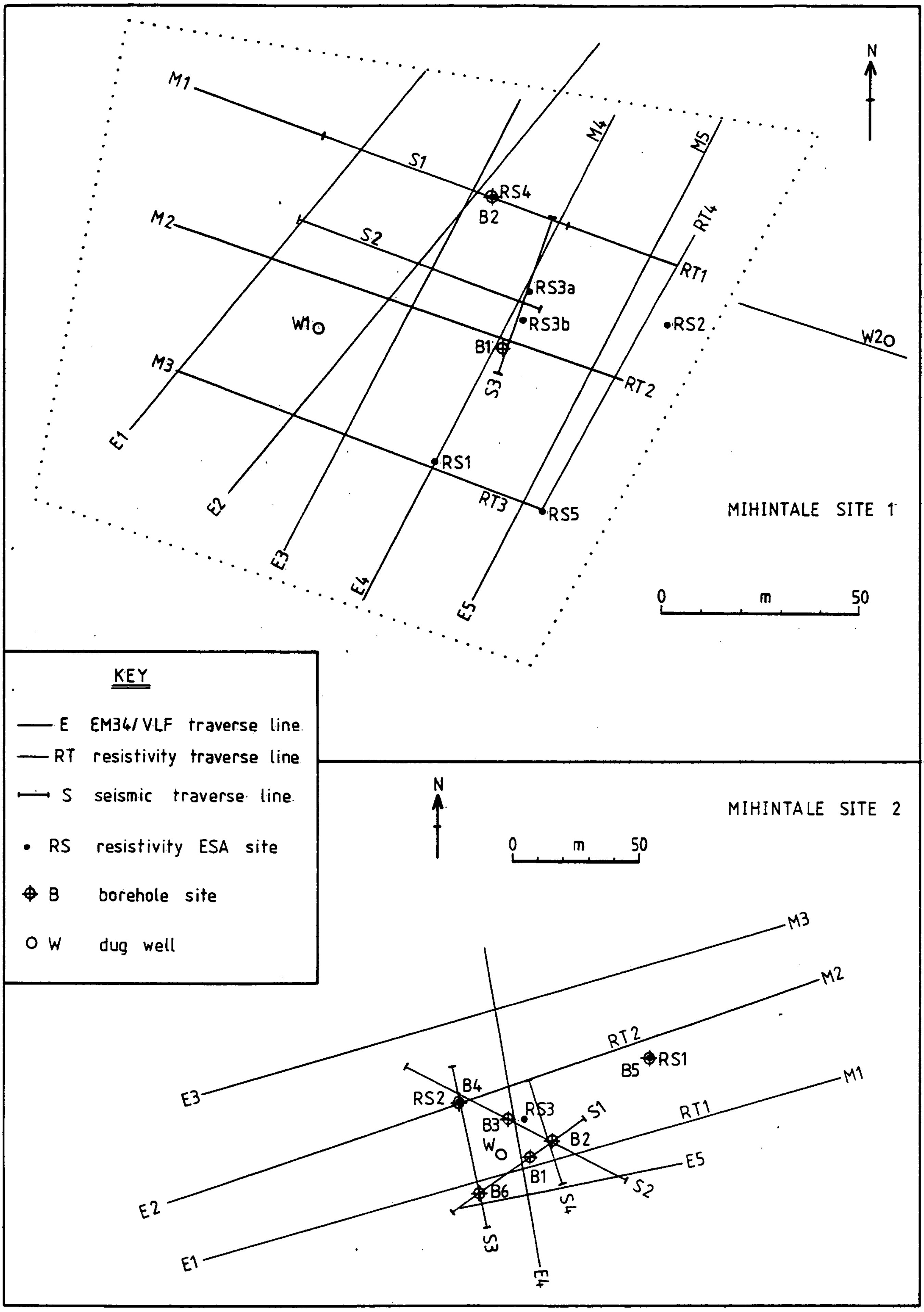
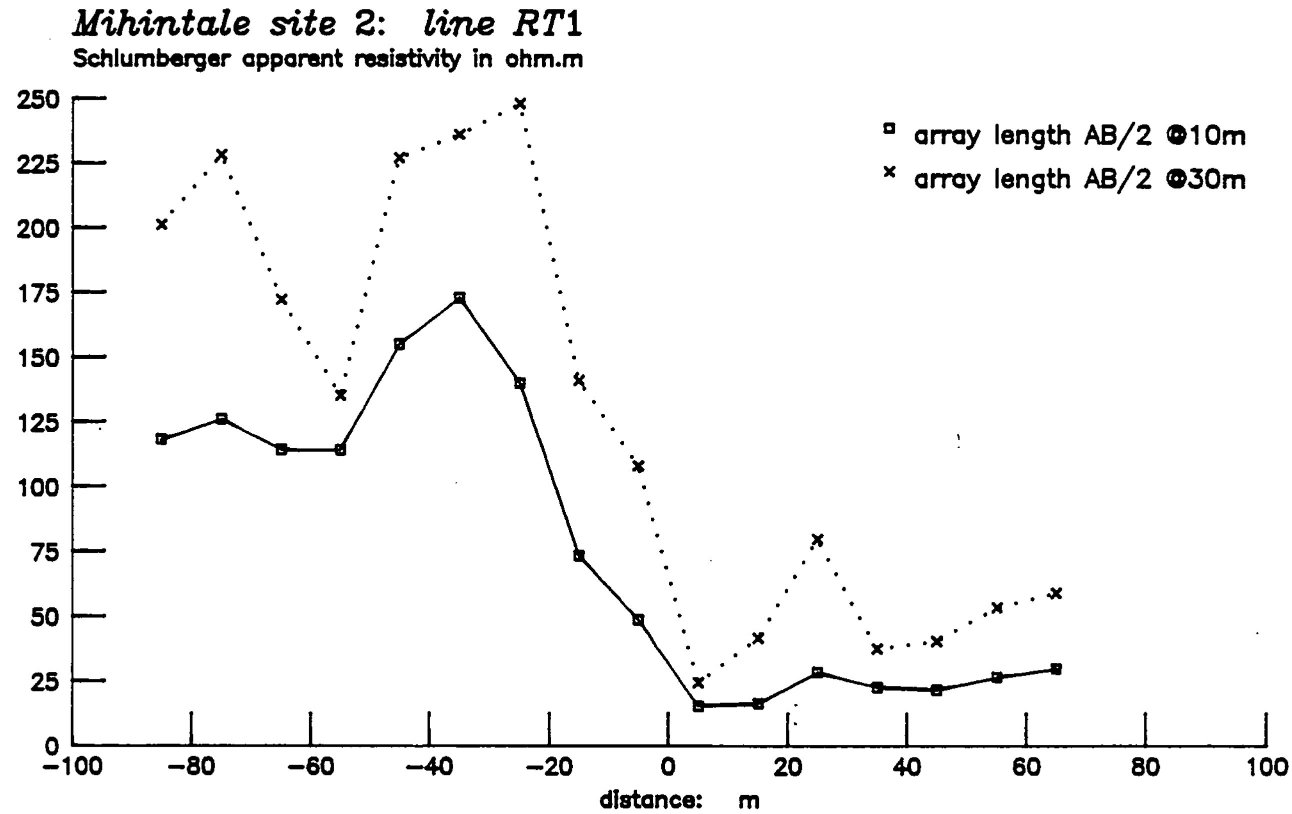


Figure 3.25 Site location diagrams for sites 1 and 2 near Mihintale, Anuradhapura



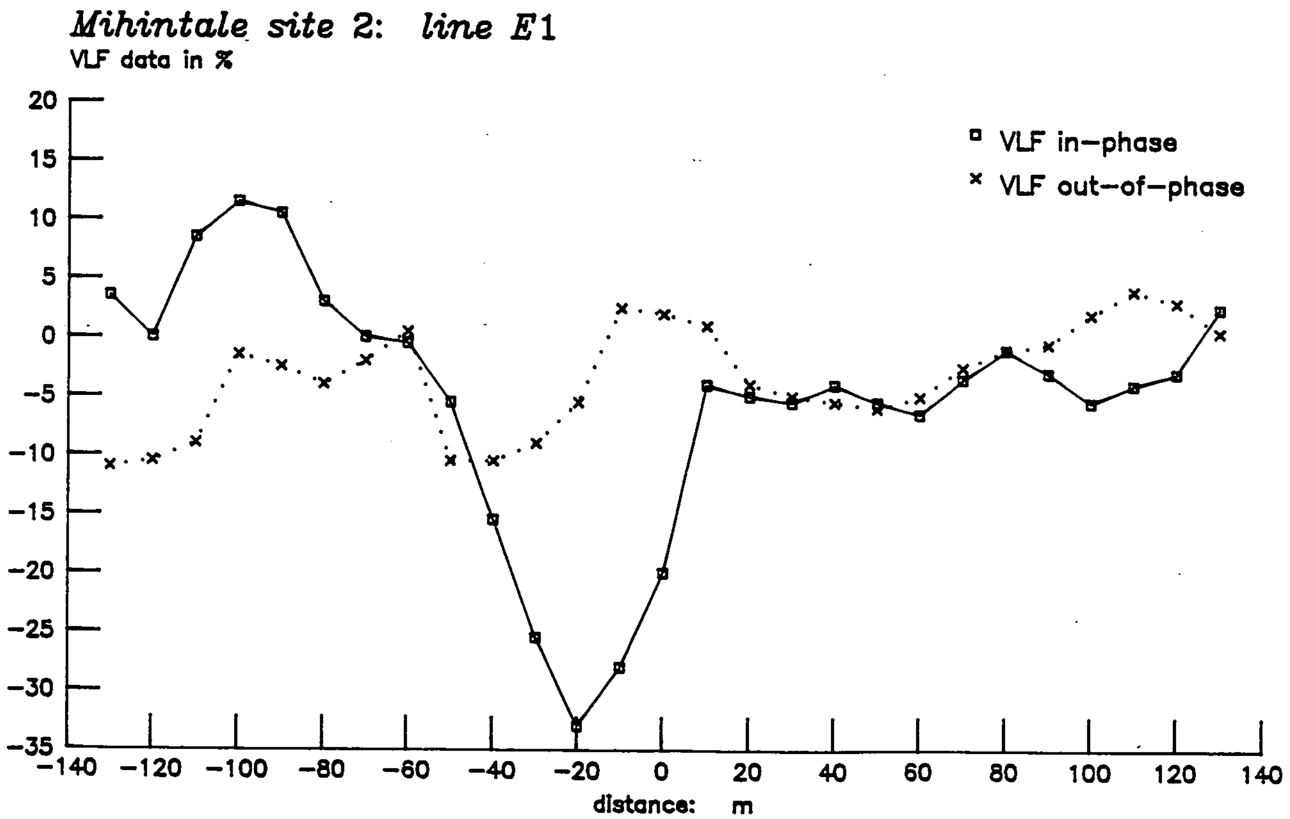
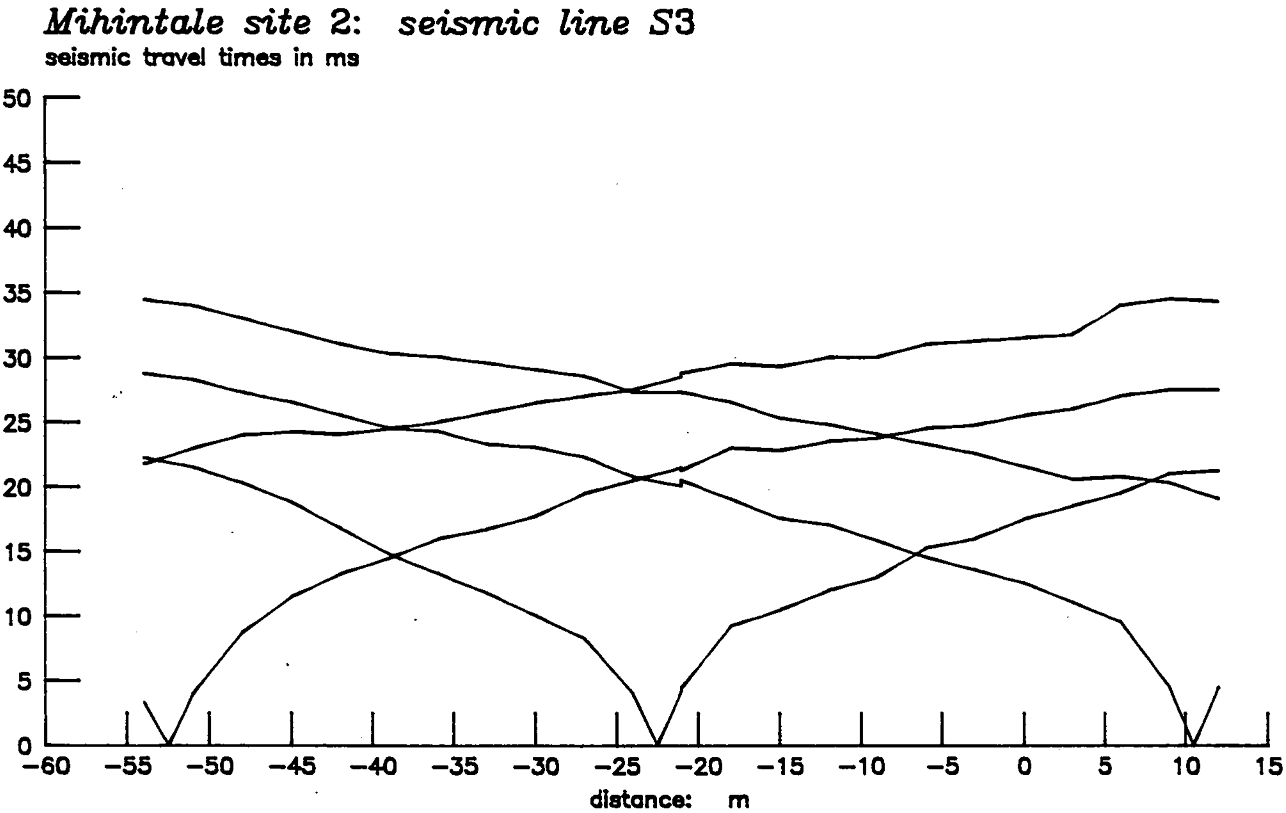


Figure 3.26 Resistivity and VLF data from line 1, Mihintale site 2



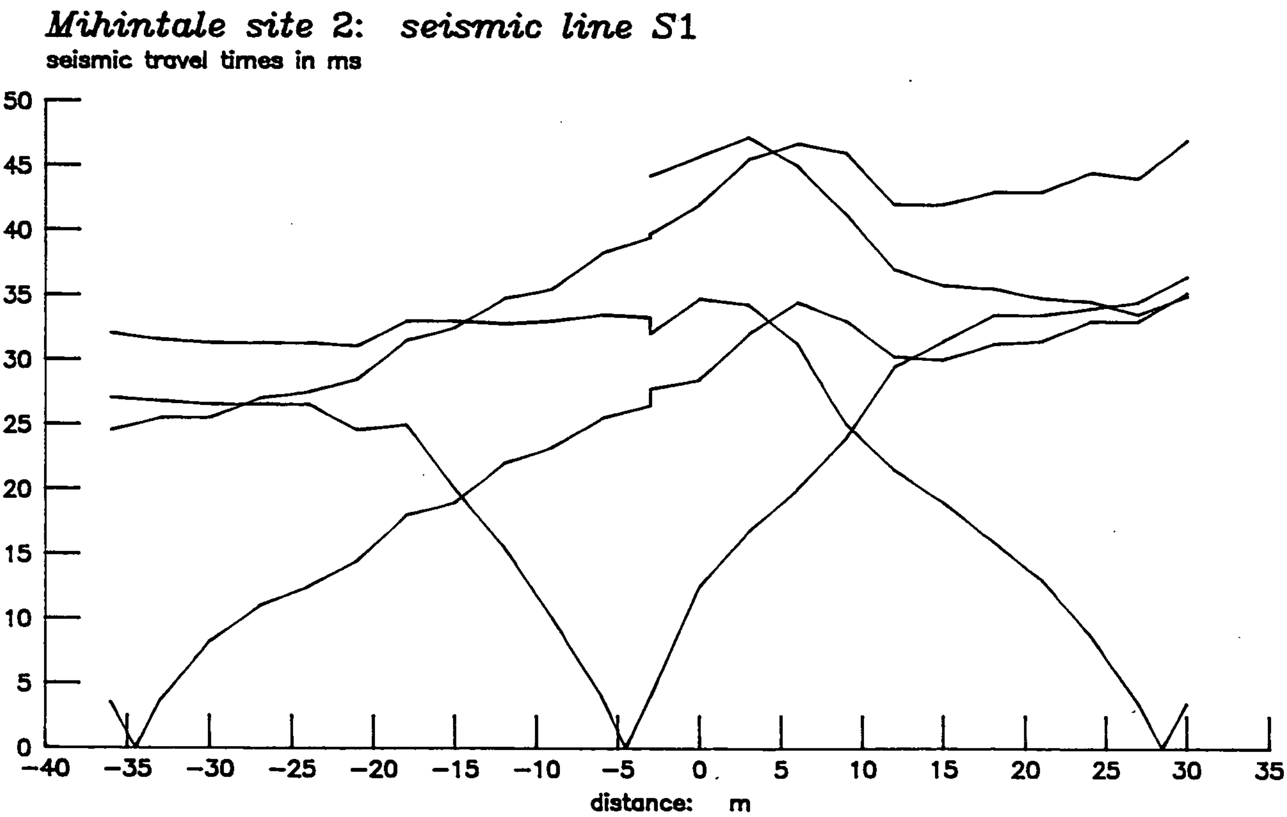


Figure 3.27 Seismic refraction data from Mihintale site 2

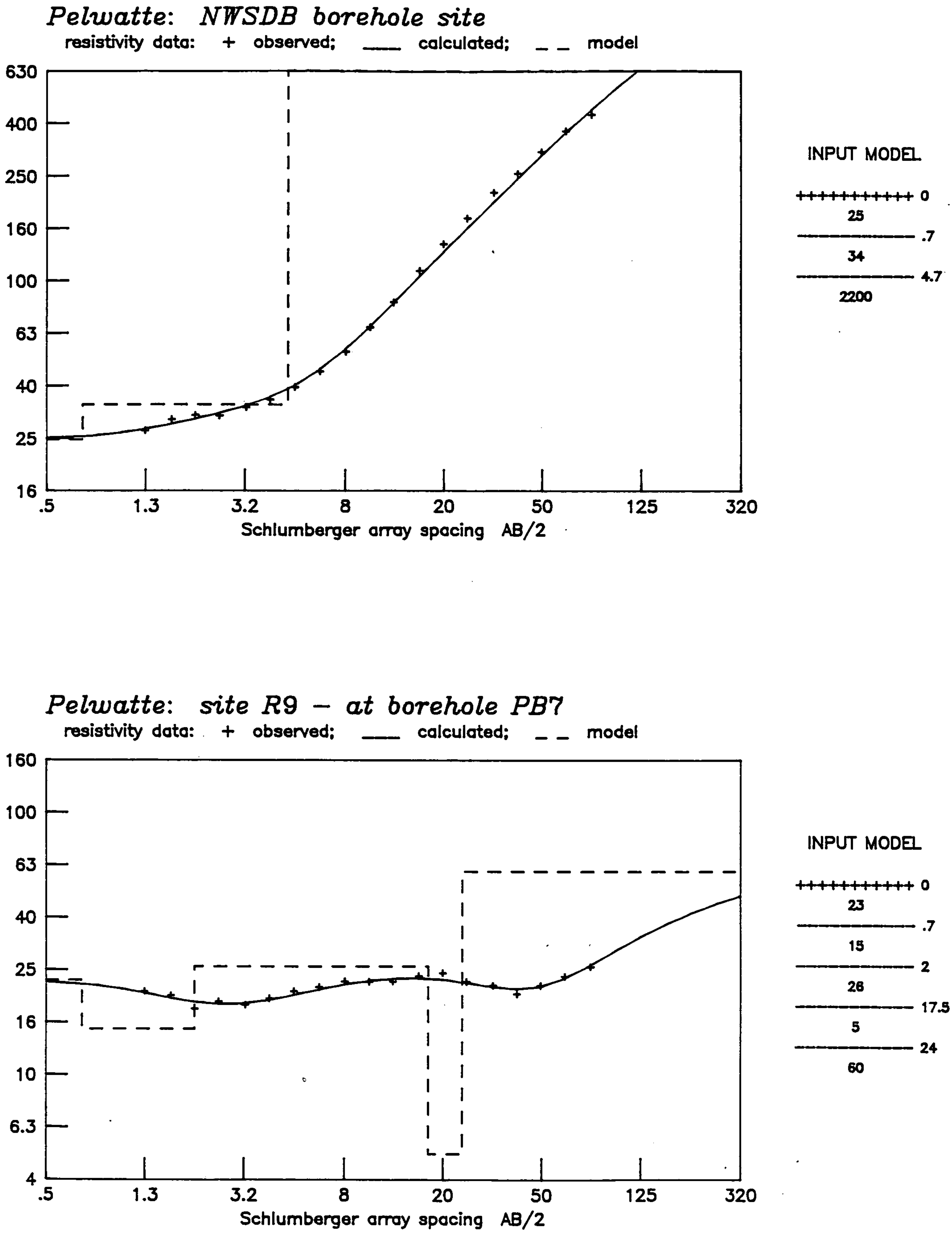


Figure 3.28 Comparison of ESA results from Pelwatte area, Monaragala

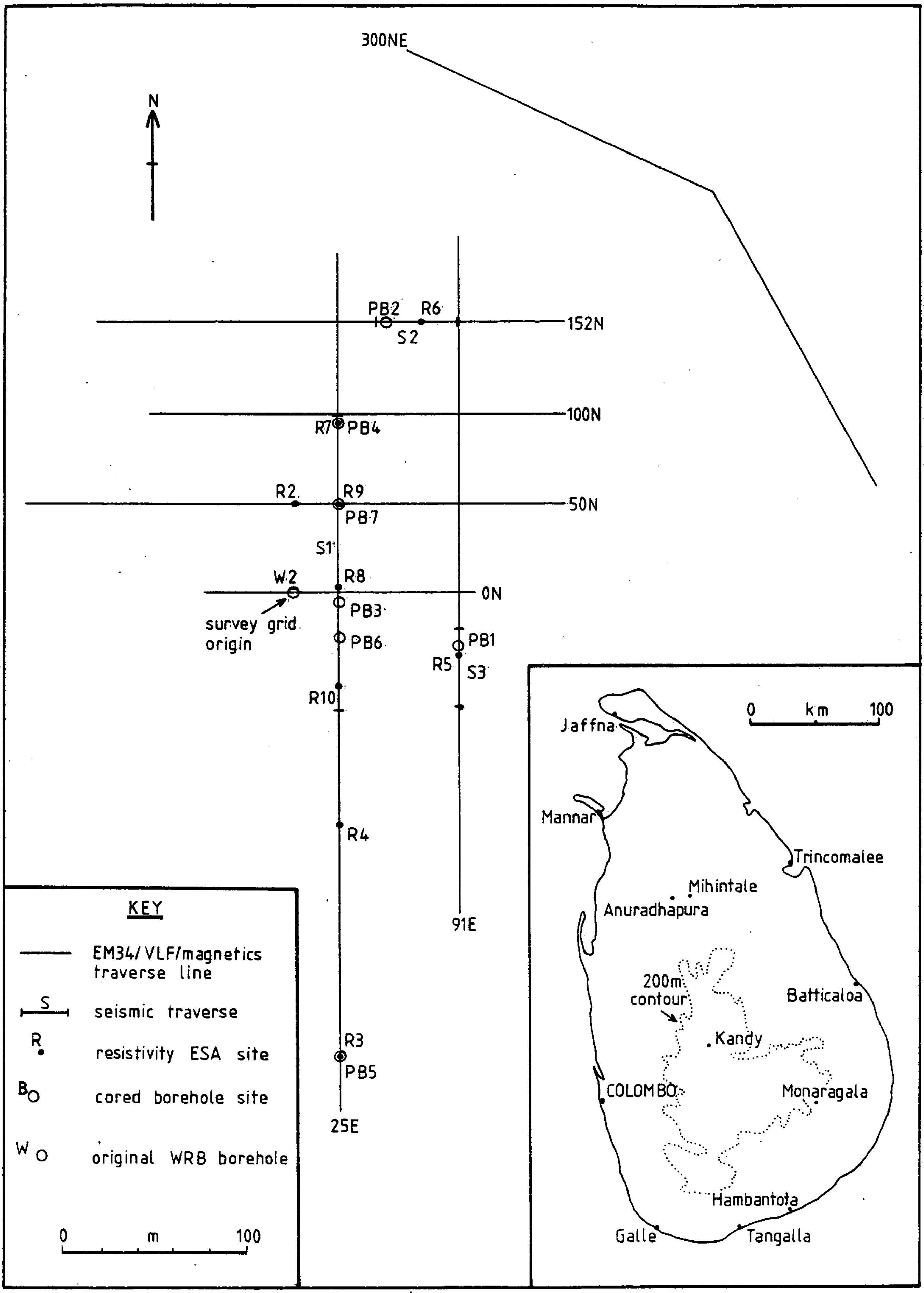


Figure 3.29 Site location sketch map for Pelwatte borehole 2, Monaragala
INSET: map of survey locations within Sri Lanka

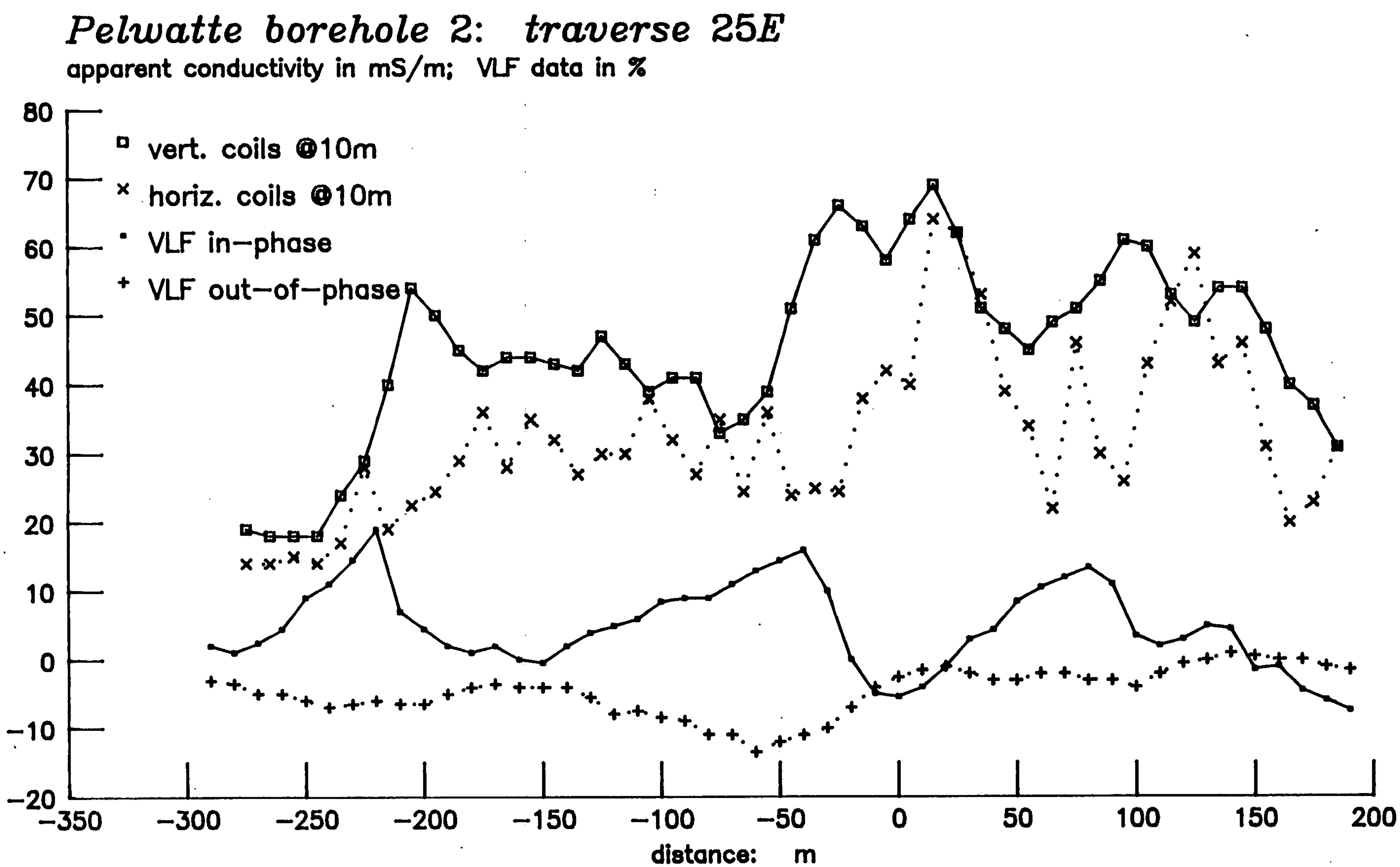


Figure 3.30a EM34 and VLF profile data from line 25E, Pelwatte

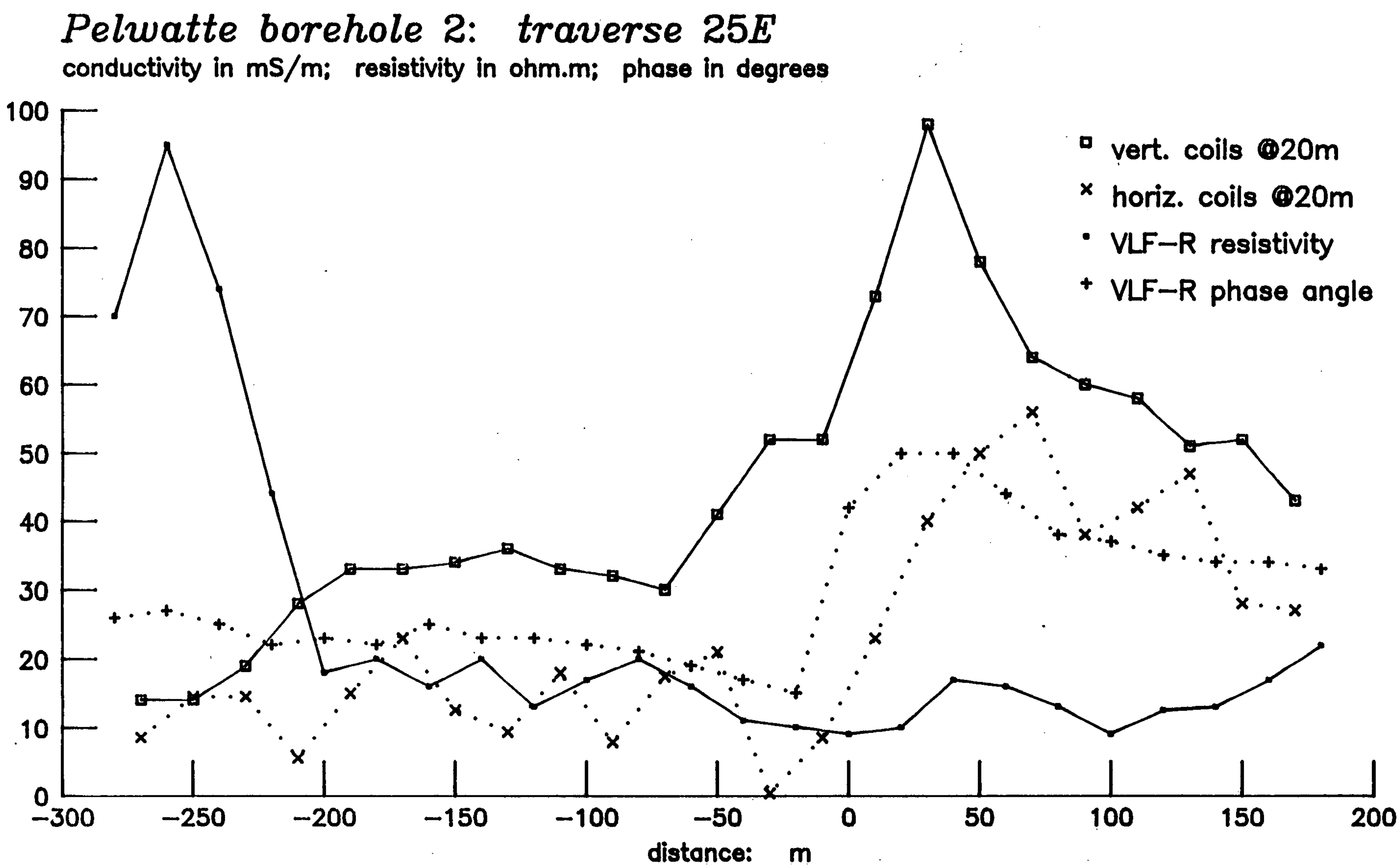
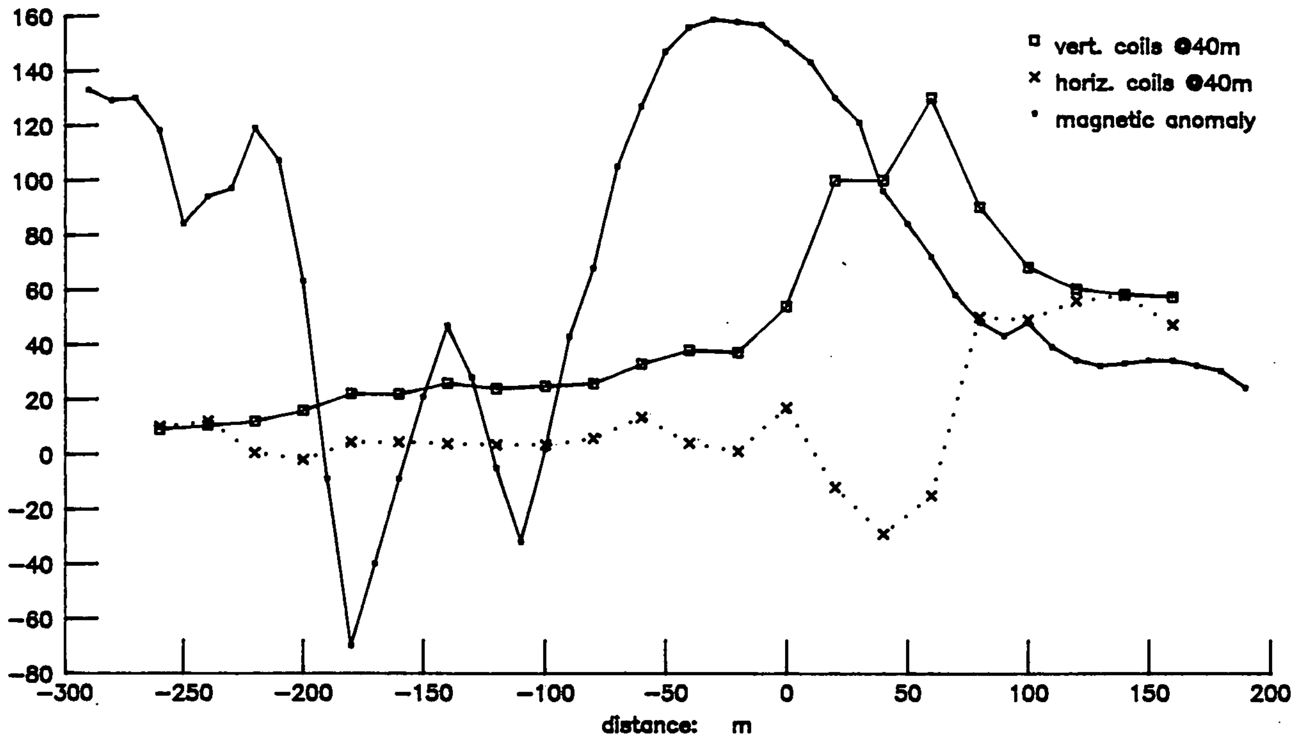


Figure 3.30b EM34 and VLF-R profile data from line 25E, Pelwatte

Pelwatte borehole 2: traverse 25E

apparent conductivity in mS/m; magnetic flux density in nT



Pelwatte borehole 2: traverse 91E

apparent conductivity in mS/m; magnetic flux density in nT

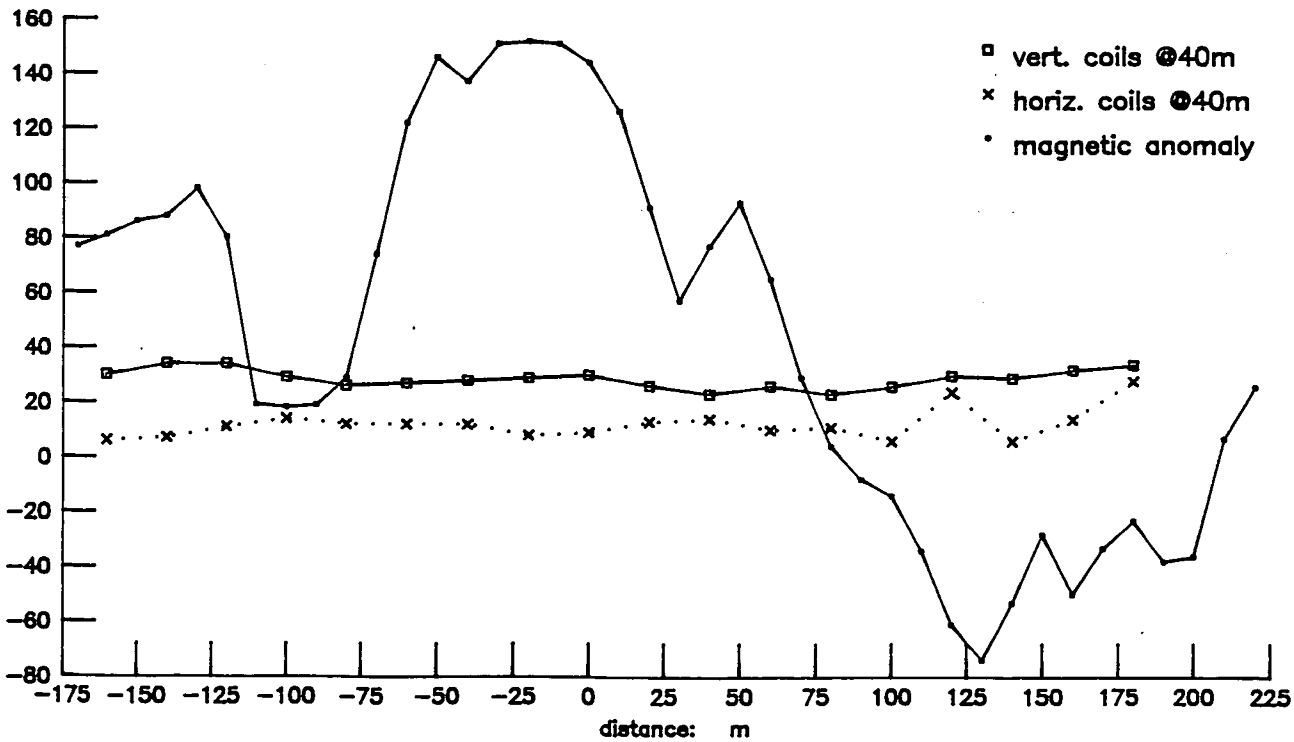


Figure 3.31 EM34 and magnetic data from lines 25E and 91E, Pelwatte

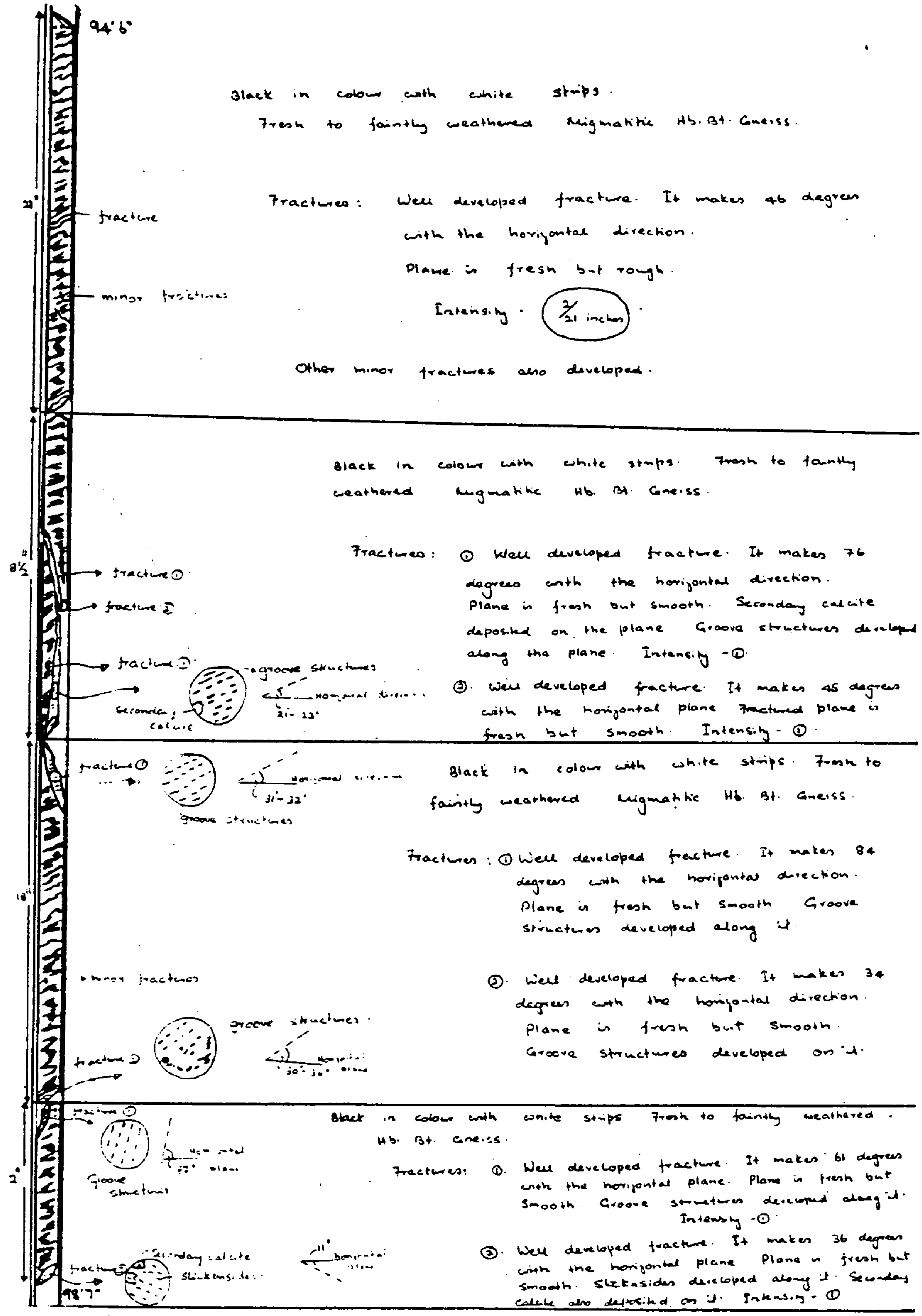


Figure 3.32 Example of geological description of core from borehole PB7, Pelwatte