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Report 85/12

REPORT ON THE APPLICATION OF GEOPHYSICAL SURVEYS TO GROUND-WATER EXPLORATION IN CRYSTAL-LINE BASEMENT TERRAIN, 1985

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British Geological Survey

Natural Environment Research Council

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CONTENTS

1 **PREFACE**

2 **COLLECTOR WELL PROJECT**

2.1 INTRODUCTION

2.2 ZIMBABWE

2.2.1 Introduction

2.2.2 Wedza area

2.2.2.1 St Lioba's School

2.2.2.2 Maruta School

2.2.3 Chiota area

2.2.3.1 Mukumba School

2.2.3.2 St Nicholas' School

2.2.3.3 Samuriwo School

2.2.3.4 Chisengeni School

2.2.4 Conclusions

2.3 MALAWI

2.3.1 Introduction

2.3.2 Chitedze

2.3.2.1 Background

2.3.2.2 Fieldwork

2.3.2.3 Conclusions

2.3.3 Ntcheu

2.3.3.1 Background

2.3.3.2 Fieldwork

2.3.3.3 Conclusions

2.3.4 Mponela

2.3.4.1 Background

2.3.4.2 Fieldwork

2.3.4.3 Conclusions

2.3.5 Chiwengo

2.3.5.1 Background

2.3.5.2 Fieldwork

2.3.5.3 Conclusions

2.3.6 Nathenje

2.3.7 Recommendations

2.3.7.1 Collector well sites

2.3.7.2 General considerations

3 **BASEMENT AQUIFER PROJECT**

3.1 ZIMBABWE

3.2 MALAWI

3.2.1 Sulphate-rich waters

3.2.2 Dambo studies

3.2.3 Conclusions

4 **SRI LANKA**

4.1 DATA-BASE COMPILATION

4.1.1 General considerations

4.1.2 Geophysics file structure

4.2 HAMBANTOTA DISTRICT

4.3 CONCLUSIONS

5 **ACKNOWLEDGEMENTS**

6 **REFERENCES**

APPENDIX: Selected resistivity sounding data with interpretations

FIGURES

1. EM34-3 traverse data; St Lioba's School, Wedza

2. Geophysical site location diagrams for Chitedze and Ntcheu

3. Geophysical site location diagrams for Mponela and Chiwengo

4. Traverse data related to sulphate-rich waters near Mponela

5. EM34-3 and magnetometer data across Chimimbe dambo, Malawi

6. Geophysical logs from a saline well near Tangalle, Sri Lanka

Front cover: photograph of adamellite outcrops in basement terrain near St Lioba's School, Zimbabwe.

1 PREFACE

The basement aquifer project involves a multidisciplinary approach to obtaining a better understanding of the occurrence of groundwater within shallow crystalline rocks and their overlying regolith of residual weathering products. The importance of such studies has been emphasized by the drought conditions experienced during recent years in this type of terrain in Africa. Collector wells represent one specific technique that has been adopted for exploiting water stored within the regolith more efficiently than by traditional dug wells and as an alternative to deeper boreholes.

Geophysics has been applied to several different aspects of the project but the main objective is to identify procedures for siting boreholes and wells to the best advantage. Desk studies (Carruthers, 1985; Wright and others, 1985) provided a background to subsequent fieldwork in 1985, mainly associated with siting collector wells in Malawi and Zimbabwe. Only electrical methods, resistivity 'sounding' and traversing with electromagnetic (EM34-3) equipment, were available for use locally and so the surveys were essentially qualitative in nature: the semsic refraction method had been recommended for providing more reliable estimates of depths to bedrock. A short visit was also made to Sri Lanka in order to set up a computer data-base system for compiling existing information and to formulate a programme for 1986. This report covers all aspects of the geophysical investigations undertaken in 1985.

2 COLLECTOR WELL PROJECT

2.1 INTRODUCTION

The concept underlying the use of collector wells in basement terrain is that by drilling out horizontally from the bottom of a dug well into laterally extensive, but relatively thin zones of higher permeability within the regolith the available groundwater can be exploited more effectively than by vertical boreholes; the well also acts as a small reservoir which buffers the effects of non-uniform demand during a 24-hour cycle. Some constraints are imposed on the use of this technique by the construction of the dug well. The brick-lined caisson method being adopted at present limits the depth to which the wells can be sunk - to a maximum of about 15m - and it is unsuitable for penetrating bands of rock. A drilling rig has been developed to operate within a 2m diameter shaft so that excavation and construction costs are minimized but the increased depth and storage available with a larger diameter well may be an advantage in some circumstances. A minimum depth for the well is set by the rest water-level and the need to maintain adequate saturated thickness and storage at the end of dry seasons: it is also preferable to reach the material with higher permeability which tends to occur near the base of the weathered profile, although radials can be inclined to tap deeper levels if necessary. Ideally, wells should be sited where water-levels are high but without there being a pollution hazard, where the regolith is free of boulders and bedrock lies at a depth of 15-20m: the need for, and effectiveness of, geophysical surveys in site selection are being assessed within this context.

Short visits were made to Zimbabwe and Malawi following the recommendations of Dr Wright (1985) to review progress on the established project in the former, and to assist with the recently initiated project in the latter country. Three and a half weeks were spent in each country during July-August 1985 and about half of this time was available for active fieldwork; the remainder was taken up mainly with data interpretation and reviewing previous reports. An EM34-3 conductivity meter was brought from the UK to provide a rapid means of evaluating new sites and Terrameter SAS300 sets with boosters were available for resistivity surveys. The fieldwork was undertaken in cooperation with the local Water

Departments which are supporting the projects in conjunction with the ODA. A subsequent visit of 10 days made to Malawi in October 1985 provided the opportunity to carry out surveys at an additional site and to review progress on the exploratory drilling. The two weeks spent in Sri Lanka prior to this followed up the contacts made in the previous year (Herbert and others, 1984). A visit to a district office in the south of the island provided examples of the type of data obtained for routine borehole siting and also gave access to an area suggested for study in 1986.

2.2 ZIMBABWE

2.2.1 Introduction

The four collector wells completed in 1984 had proved sufficiently successful to justify continuing support for the feasibility studies (Wright and others, 1985). Yields and performance had been enhanced in line with expectations and the relatively high costs incurred were attributable to logistical problems, combined with extensive site investigation studies involving both geophysical - resistivity - surveys and test drilling. It remained to be shown that costs could be brought down to more competitive levels and that adequate yields could be obtained where required.

The nature of the basement and its regolith in Zimbabwe is complex with marked variations in thickness and lithology over short distances. A particular concern for well siting is that even where the regolith is thick it may contain boulders or more persistent bands of residual rock at high levels. In those areas where the 'African' surface has been preserved the weathering profile is likely to be less variable and developed to more than 25m depth: the problem here may be that with a collector well limited to 15m it would not draw efficiently on the more permeable section towards the base of the regolith. Over the more extensive areas of 'Post-African' surface, compact rock frequently occurs at shallow depth and the form of the regolith/bedrock interface is unpredictable. This means that site investigation costs can vary considerably and a corresponding flexibility will be needed in setting budgets for these wells. The problems that can be expected were clearly illustrated during this visit.

In order to maintain efficiency in well construction operations it is desireable to have work proceeding at two neighbouring sites. The two pairs of sites being assessed at this time were near Wedza and in the Tribal Trustland of Chiota district, respectively about 150km and 80km south of Harare. Extensive resistivity surveys had already been carried out at three sites by the Water Department, with test drilling of six holes at each of the sites near Wedza, but in no case had the location of a well been finalized.

Chiota district was chosen for further investigations partly for logistical reasons in that it lies between Harare and the Wedza sites. The area is known to have given difficulties in providing satisfactory borehole yields and so the prospect that collector wells could overcome these problems was obviously attractive. Four schools had been put forward as being in need of additional water supplies, but of these one was on a ridge where relatively deep water-levels were expected, and a second looked unpromising because of the extensive outcrops of rock.

2.2.2 **Wedza area**

2.2.2.1 St Lioba's School

This site to the east of Wedza lies within the outcrop of the Younger Granite suite which is characterised by large, blocky exposures of rock. Resistivity data had been collected in the standard form of mini-soundings adopted locally which gives values for 4-6 current electrode separations of between 10m and 140m using a Schlumberger configuration at intervals of about 50m along selected traverse lines. A large area was covered by the surveys partly in order to assess the possibilities for commanding a bigger catchment in another valley but resistivity values were generally high throughout. Indications of a more promising conductive zone were picked up within about 800m of the school and the results of further detailed surveys proved encouraging enough for six holes to be drilled. Boreholes at lower elevation to the south showed a thick clay sequence but conditions improved to the north approaching a fault inferred from the interpretation of aerial photographs. It was thought that a site closer to, or within, the fault zone might give an enhanced yield and so additional surveys were undertaken over a period of two days during this visit in an attempt to locate the fault more precisely and to see if it appeared favourable as a well site.

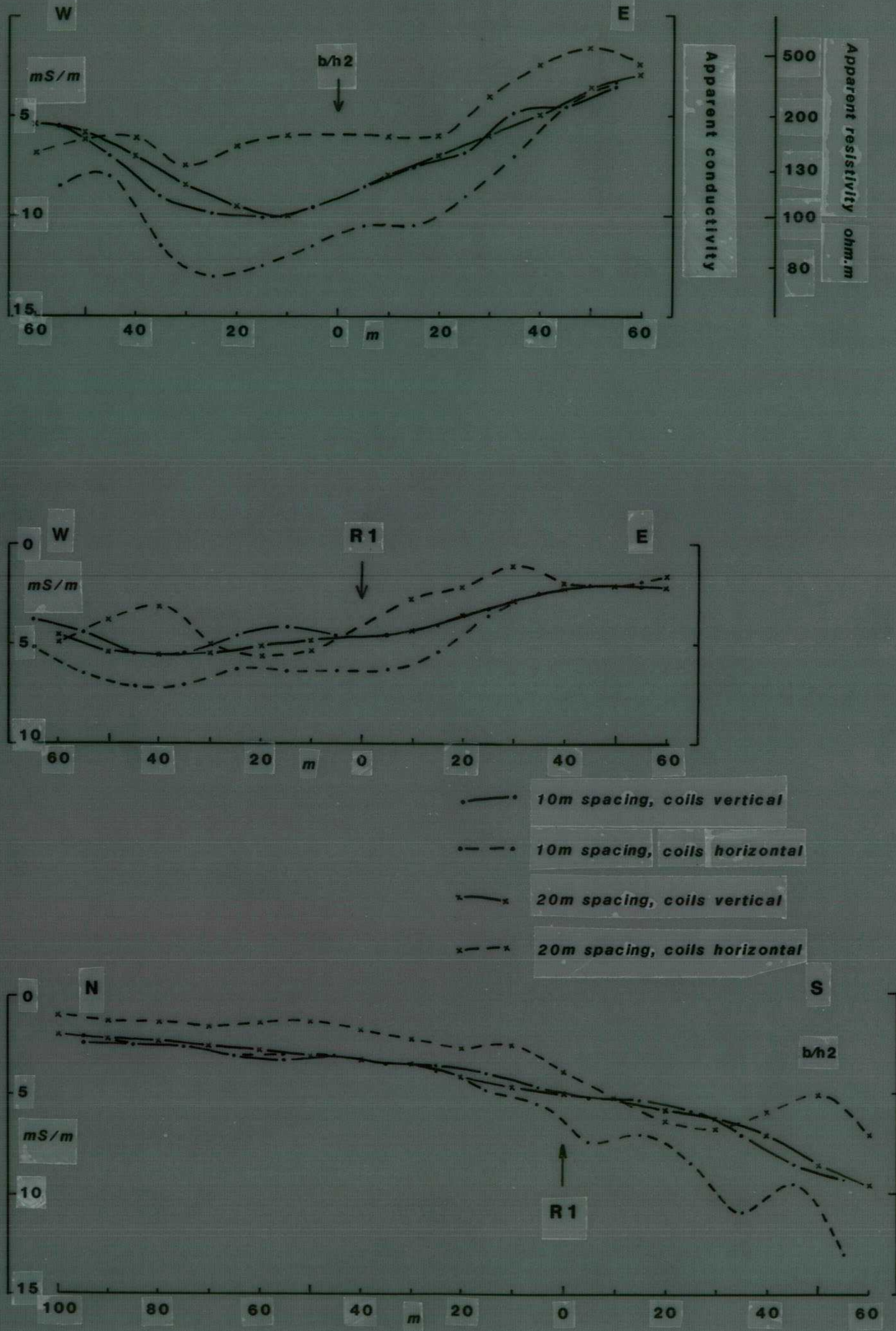

Fig 1. EM34-3 traverse data: St Lioba's School site, Wedza

When faced with a thick file of data sheets representing the work of several weeks the reaction is to scan results quickly and to pick out only the most obvious features. It is unfortunate that the data collected locally are not presented routinely in a more easily assimilated form, such as profile sections or contoured maps, which could provide a coherent framework for interpretation; some of the results were available diagrammatically in plan using a colour code, though not for the area of immediate interest. In view of the inconsistencies between different data sets and the limited time available, no analysis of these results was attempted beyond establishing that the boreholes lay within a relatively narrow zone of higher conductivity trending N-S.

EM34-3 traverses of 100m length were centred on boreholes 5 and 2 to confirm the existence of the conductive channel and to provide some correlation with the borehole information. A third W-E line was then set out by geophysical survey point GP72, between borehole b/h2 and the fault to the north, where resistivities remained relatively low: conductivity levels were reduced noticeably here but a zone of higher values was still apparent (see Fig 1). Expanding Schlumberger array data from R1 centred near GP72 showed the H-type curve typical of basement terrain: high resistivities in the superficial layer; lower values representing regolith and weathered bedrock; higher values again from the underlying massive bedrock. The results from an orthogonal resistivity sounding were similar to the first: the main difference was in the implied resistivity of the underlying bedrock, with the array crossing the fault giving a higher value. The true resistivity of the intermediate layer is not defined by the sounding curves and the range of equivalent solutions allows for the base of the regolith to be shallower than 9m or deeper than 20m as its resistivity is varied from 20-25ohm.m to about 100ohm.m (see R1 in Appendix). Borehole evidence suggests that an interface at 5½-6m depth is attributable to the water-table and that a depth to bedrock of 15m for a regolith resitivity of 60-70ohm.m might reasonably be expected: alternatively, a thinner, more conductive sequence including a clay-rich, semi-confining layer may be present as implied by the difference in EM34-3 values at 10m and 20m spacings. Certainly, the traverses showed that GP72 lies on the margin of the zone of thicker regolith of the type found at b/h2 with a quite rapid transition, both to the north and east, to a sequence having apparent resistivities greater than 200ohm.m throughout.

Site R2 on the northern side of the fault confirmed that conditions were different with the conductance (thickness/resistivity) of the regolith reduced from 0.15S to 0.03S (see Appendix). Orthogonal arrays were again similar and showed higher bedrock resistivities crossing the fault. The absence of any distinctive discontinuity in the curves suggests that no major fracture zone is associated with the fault and it might simply relate to a change in lithology. A sounding 35m east of GP72 ressembled those north of the fault though the intermediate, (?)weathered bedrock layer appeared to be thicker and less resistive at 200-250ohm.m. A conductive layer is still evident to a distance of 40-50m west and slightly upslope of GP72.

The resistivity values attributable to the regolith near GP72 are consistent with a continuing improvement in aquifer properties northwards from b/h2 and a further test hole was recommended to check on conditions here: in view of the likelihood of a significant reduction in the depth to rock, a site some 10m to the southwest was preferred. The geophysical evidence is of structural or lithological control giving rise to enhanced weathering within a zone aligned approximately N-S which extends nearly as far as the geologically interpreted W-E fault: there are no anomalies to confirm that open fractures are present along the photo-lineation itself. However, radials could have been drilled from this location towards the fault line to exploit any fracturing which may be present. Subsequent boreholes found hard rock at a depth of only 6.5m below GP72 while within 20m further north and west it was at 5.0m and 7.5m respectively. These depths correspond with the top of the most conductive layer interpreted from the resistivity data and if the air-drilling was not stopped by boulders within the regolith it must be that the upper section of the bedrock here is in itself unusually conductive due to alteration/fracturing, the mineralogy or poor-quality water. At the final site, b/h10 drilled 50m west-southwest of GP72 using water, a rock core was obtained from a depth of 18.5m. This is much more consistent with the resistivity interpretations and suggests that the air-drilling results have to be treated with caution.

2.2.2.2 Maruta School

The drilling of six exploration holes in a localised target, selected after comprehensive resistivity coverage of the whole area, had revealed the presence of hard bands of rock within a regolith sequence extending down to more than 20m. The high yield of over 1l/s obtained from borehole 1 was not confirmed by an adjacent, virtually dry hole within 2m of it: further tests had still to be carried out to check these results, but it seems likely that either the flow was augmented artificially - the first test was made in the rainy season - or the aquifer lies below the 15m depth envisaged for a well. Another major concern was to find a site free from rock as, apart from adding to excavation costs, the shallow bands encountered to date may be too thick for a caisson to be sunk safely through them.

Measurements were taken along four lines of EM34-3 traverse, laid out to pass boreholes 1, 2, 4 and 5 and to enclose the large termite mound near which the most promising indications had been obtained previously. Conductivity values at 10m and 20m coil spacings lay in the range 5-10mS/m and while variations did occur on the profiles there were no obvious structural trends crossing the grid. Results obtained near the low-yielding borehole 2 suggest that higher conductivities represent a greater clay content rather than implying any reduction in the risk of encountering boulders or residual rock. A transitional point by the northeast of the termite hill was chosen for an orthogonal pair of resistivity soundings. The curves differed somewhat, confirming the presence of lateral variations, though their interpretations were consistent. Despite high surficial resistivities the bulk resistivity of the regolith was quite well-defined at 100-120ohm.m from 3m to about 25m depth. The resistivity of the underlying layer was significantly less than at St Lioba's as might be expected given the change in bedrock from adamellite to the older gneiss complex.

The resolution of the electrical and EM techniques is not sufficient to identify or trace the thin bands of rock which concern the choice of well site but the data do bring out several points. First, the depth to bedrock is probably greater than 20m and a collector well with horizontal radials may not tap the most favourable zone close to this level. Second, the interpreted resistivity of the regolith appears relatively high for a thick, saturated sequence: this implies either a predominance of coarser material, a deep water-table, or that alternating layers of hard/soft material are present. Third, lateral variations across the site are consistent with there being irregularities in both the total thickness and character of the regolith. The site of the resistivity sounding may be close to a change to shallower bedrock to the southeast: conductivity levels are similar to those near b/h1 and significantly lower than at b/h2 and b/h5, but the thickness of regolith could still be too great for exploiting the transmissive zone, unless the radials are inclined. Subsequent re-testing of b/h1 confirmed that the earlier high yields were not representative. The low yield from an additional hole drilled by the resistivity sounding proved no more encouraging: depth to bedrock was 18m and the presence of multiple layering within the regolith is again indicated as the reason for the overestimate in the resistivity interpretation. More information is needed on the groundwater system to explain the poor results obtained here but it may be simply that with shallow bedrock around the site and low permeability clays forming the bulk of the regolith where it is thicker there is little water to draw on.

2.2.3 **Chiota Area**

2.2.3.1 Mukumba School

Resistivity surveying had been under way for several weeks without any specific sites being identified: the intention was for a rig to be available near the beginning of this visit. In order to evaluate the existing data quickly and to identify any trends within them, the values obtained at the widest current-electrode separation were plotted and contoured, though it was necessary to omit nearly half of the results due to the unreliability of one data set. A level can be fixed for the apparent resistivity above which an area is regarded as unprospective by assuming that the values are a measure of the conductance of the overlying regolith; that is, they lie on the steeply-rising segment of the sounding curve. Taking an upper limit of 125-150ohm.m for the required resistivity of regolith with a thickness of at least 13m implies a minimum conductance of about 0.1S. For the current electrode spacing of 140m used in this survey apparent resistivities then needed to be less than 700ohm.m. This criterion meant that at least half of the area surveyed, including most of that alongside the road, could be rejected immediately. The highest conductances of over 0.5S were found some 500-700m east of the main road serving the locality, while the school to be supplied lies to the west of it. In view of the traffic hazard and the distance involved for a site in this more prosopective area further work was concentrated on the west side of the school where the ground falls away into a vlei. A less resistive zone of restricted width trending NW-SE had been outlined by the reconnaissance survey: its main expression was on the middle-lower slope to the vlei, but a deflection in the high apparent resistivity contours along the road appeared to represent a continuation of the same feature. Available expanding array resistivity data collected at a dozen points confirmed that the area east of the road looked more promising in terms of regolith development, but the likelihood of there being shallower rest water-levels, combined with the easier access to the school, seemed to justify exploratory drilling between the school and the vlei.

Two points, GP22 and GP35, on the lower ground had produced an ascending, A-type curve, showing conductive superficial deposits with typical regolith values of 80-100ohm.m to about 14-18m depth (see Appendix). Apparent resistivities for the H-type curves obtained over the middle ground rarely fell below 100ohm.m and it was necessary to assume that similar values of 50-100ohm.m applied to the regolith here to give the interpreted depths to bedrock of 12-20m in the zone of interest: the thickness of 1-4m given for the upper resistive material was taken as representative of the unsaturated zone in this area. These preliminary interpretations of the 'sounding' curves were biassed towards defining a maximum, rather than a minimum depth to compact rock - bearing in mind the effects of equivalance as noted in section 2.2.1.1 - so that potential sites would not be overlooked in the investigation.

EM34-3 traverses at 10m and 20m coil spacings brought out the lateral variations, in particular at the southwest margin of the conductive ground where values fell to 2-4mS/m, equivalent to resistivities of 250-500ohm.m, strongly suggesting the presence of shallow rock. Maximum conductivities of 10-15mS/m were almost invariably obtained with the 10m horizontal coil configuration, as would be expected from the H-type resistivity curves. The exception to this occurred on a section of traverse near the vlei where conductivities decreased rapidly with depth of investigation from relatively high values: this is consistent with a thin cover of clay overlying the more usual regolith/bedrock sequence. Resistivity soundings confirmed that total conductances of 0.15S are maintained to the northwest as indicated by the continuity of the EM34-3 data. Orthogonally-oriented arrays showed the influence of lateral variation at some sites, but it was not clear that these originated from shallow bedrock; the discontinuities given when potential electrode spacings were increased provided evidence of near-surface inhomogeneities and high electrode contact resistances were thought to be another cause of erratic data points.

A drilling site was selected from the most promising resistivity interpretations close to the school. The intention was to drill with air so that there would be good control on the depth to any water 'strikes' down the hole though the method imposes limitations on the ability to core through rock. In the event this proved to be important, especially when combined with the inadequacies of the new compressor which came with the rig and the fact that rock was encountered at unexpectedly shallow depth. The sounding at GP301 had been interpreted with resistivities of 55-60ohm.m extending to 16-18m depth: one of the orthogonal pair of curves was not fitted exactly at the minimum but this was not considered significant in comparison with the accuracy of the field data. Drilling proved a sequence of sand with silt, becoming more clayey to 5½m; a further one metre of weathered rock - described by the driller as sandstone - and then hard 'granite' to the total depth of 8m. The other holes, located near GP291, GP292 and GPR1 to cover an area of about 100m square, all met rock within 5m of the surface; water was found in small quantity at 2-2½m depth, the zone tapped by the shallow pits dug locally for minor irrigation, but there was no increase in flow with depth. In view of this and the limited capacity of the rig, there was a possibility that the weathered zone extended beneath a band of residual rock although the consistency of the drilling results made this unlikely. Redrilling with water at one site was abandoned after penetrating about 2½m of rock.

Reinterpretation of the resistivity data in the light of the borehole information showed that two adjustments were necessary to reconcile the results. First, related to equivalence, the thickness and resistivity of the upper part of the weathered profile had to be reduced. Second, related to suppression effects, the basic H-type, three-layer solution had to be replaced by a four-layer, HA case with the introduction of an additional layer having a resistivity of 150-300ohm.m, intermediate between that of the regolith and bedrock (see Appendix). A consequence of these changes was to make the resistivity models more compatible with the observed EM34-3 values obtained near the sites. The EM results had been used to map the extent of the conductive zone but it is clear in retrospect that a more quantitative analysis would have restricted the range of resistivity interpretations. Even so discrepencies remain between the geophysical data and the drilling results, with the former indicating a greater depth to compact, massive bedrock. At GPR1 the depth of 4m to 'very hard' granite can be fitted to the resistivity curves, but in this case the EM34-3 values do not allow for such a necessarily thin, highly-conductive upper layer to be present. A trial survey line using a single-channel, Huntec FS-3 seismograph found at the Water Department was sited beside this borehole to see if a more reliable estimate of bedrock depth could be obtained. A reversed refraction spread of 60m was recorded with a metal plate and either a hammer or a 50kg weight was dropped from a height of about $1\frac{1}{2}$m as the energy source. The data were interpreted using the standard formulae for uniform dipping layers and 'first-arrival' times to give depths to bedrock of 10-12m, in close agreement with the original resistivity model. This unexpected result may have been coincidental as the travel times were almost certainly overestimated due to recording events later than the true first arrivals, and also to the unreliability of the instrument datum and calibration. The three-layer case gave velocities of 1.8m/ms for the intermediate layer - to be expected from regolith or highly weathered rock - and about $4\frac{1}{2}$m/ms for the bedrock below it: the superficial layer had a thickness of nearly 3m and a velocity of 0.4m/ms. Unfortunately the seismograph only came to light at the end of the visit and there was no time for further trials with it; on the geophysical evidence available the depth to fresh bedrock could not be less than $7\frac{1}{2}$m near GPR1.

The only other sites thought to be worth testing in the area west of the school lay near GP22 and GP35 where apparent resistivities increased continuously with depth from low values near the surface. The layering is poorly defined on the sounding curves, but resistivities of less than 100ohm.m were predicted to a depth of 13-20m; with this type of curve the range of equivalence is reduced and suppression is more of a problem. If shallow bedrock is present then clearly its resistivity must be unusually low. The possibility of a conductive bedrock has also to be considered in relation to the results obtained east of the road where resistivities of less than 100ohm.m must extend to depths of over 20m, even if residual bands of resistive rock are present at higher levels. The transition from shallow bedrock to (?)thick regolith can be seen between GP221 and GP224 where apparent resistivities at 140m current electrode separation fall from 2000ohm.m to 150ohm.m. Further north-east, at GP192 and GP210, resistivities of 50-100ohm.m are interpreted to 20-35m depth while at GP227 a more conductive layer of less than 20ohm.m is found to 20m depth: if a thinner layer with lower resistivity occurs it is then necessary to bring in material of intermediate resistivity below this in order to match the curve, leaving the depth to the resistive substratum little changed. Reconnaissance EM34-3 traverses at 20m coil spacing gave similar values with the coils vertical and horizontal, in approximate agreement with predictions from the resistivity models. Weathered dolerite might conceivably be present here, in which case the best prospects would be near its contacts with the country rock. If the regolith is thick it may also be necessary to pick a more marginal site in order to find permeable material accessible to a collector well.

Subsequent drilling finally identified a potential well site near GP22/35. At GP22, b/h6 was terminated at 16m without reaching hard rock and yielded 0.3l/s. The borehole lay within the area of the vlei liable to flooding and this made it unsuitable for a well. The resistivity sounding here was interpreted as showing shallower resistive bedrock than at GP35, further from the vlei, where b/h7 found very hard granite at only 10m: the end of the curve from GP22 was rising at an angle of more than 45° and the depth to bedrock must decrease quite rapidly away from it. At b/h8, between GP22 and GP35, a relatively good yield of 0.1l/s was obtained with weathered granite from 8m and hard granite below 12½m depth. Both of the orthogonal resistivity soundings were unusual for the area in that: the total conductance for the regolith was high; there was no evidence of the intermediate layer of conductive bedrock; despite the obvious influence of lateral variations the interpreted depth to bedrock of 12-15m were of the right order. A collector well is to be constructed near this point.

Borehole b/h9 was drilled at GP228 (see Appendix) as a check on conditions east of the road and met 'very hard' granite at 11.5m. As noted above this seems to confirm that zones within the bedrock itself are unusually conductive; in the absence of borehole logging or physical property measurements on core samples this conclusion remains unconfirmed but it is consistent with the anomalous findings to the west of the school. This is the type of information that needs to be archived for reference in subsequent work as the existence of such an overlap in resistivities for bedrock and the regolith is clearly significant in routine well siting. The interpretation of the orthogonal pair of soundings picked out an interface at 2.5-3m corresponding to the water-table across which resistivities decreased from over 500ohm.m to about 20ohm.m. A lower interface at 7-10m depth relates to the base of the regolith which was described as comprising silty sands. The resistivity increased to only 50-100ohm.m to a depth of 25-35m before a resistive substratum was detected although the curves do show lateral variations which could be misleading. Drilling was abandoned at 12½m and so the nature (and reality) of any change at the interpreted depth is conjectural but, in view of the reported hardness of the formation drilled into, a change in lithology rather than in fracturing/alteration characteristics is indicated.

2.2.3.2 St Nicholas' School

Surveys were initiated at this school so that any drilling sites could be tested during the visit though, in the event, problems with the rig delayed its arrival here. Readings were taken initially on two reconnaissance lines of EM34-3 traverse down the slope to the west of the school. A 20m coil spacing with both vertical and horizontal coil orientations gave consistently low values of 2-3mS/m over the first 200m, to an area of standing water which was related to a spring line: it was only after a further 100m that vertical coil readings increased significantly towards 10mS/m. A series of eight resistivity soundings along the first of these lines indicated very high near-surface resistivities by the school, and on the lower ground values were still over 2500ohm.m The large resistivity contrasts prevented accurate definition of the intermediate layers because of equivalence but with low conductances, of less than 0.1S, the prospects seemed poor: even if depths to fresh bedrock were as much as 17m the overlying material was likely to be compact weathered/altered rock and the EM34-3 values suggested that a more conductive layer might be present with a shallower overall depth to bedrock. The existence of this conductive layer was more obvious further to the west where the resistive cover was thinner. The resistivity of the bedrock was lower to the west and it may be that the spring line is associated with the subcrop of a band of harder, more resistive rock against the topographic slope.

Traverses with the EM34-3 in a north-south direction brought out two areas of interest. Conductivities increased markedly at the southern end of the most westerly line and resistivity sounding R9 confirmed that conditions here were quite different with the regolith extending to 16m and possibly to over 20m for resistivities of 20-50ohm.m: the shallower depth is obtained by assuming additional conductive layers as against a more homogeneous sequence. This potential site is over 600m downslope from the school and, in an effort to find somewhere more convenient, attention was directed towards the southern end of the most easterly traverse where a slight, but definite increase in conductivity occurred. Resistivity traversing over a regular 40m grid was undertaken together with resistivity soundings and EM34-3 profiles to the south and east of the school. These outlined a zone of limited potential with some similarities to that at Mukumba School. The main difference here was the occurrence of dry sandy soils which made the collection of reliable resistivity data difficult because of high contact resistances at the electrodes. Interpretation of the sounding curves implied depths to bedrock of 12-15m for resistivities of 60-100ohm.m within the regolith. Resistivities for the surface layer went as high as 50,000ohm.m and the thickness of 1½-5m given for the upper resistive zone was taken as an indication of the depth to water-table. There was also evidence of a layer with an intermediate resistivity of several hundred ohm.metres between the regolith and hard bedrock although it was identified on only a few curves: this might represent a weathered or fractured component of the same bedrock or a difference in lithology. a comparison with the results from west of the school left open the question of whether the lateral variations, which clearly do occur, are an expression of differences in rock type or a function of changes in the thickness of the components within a similar sequence. The predicted EM34-3 response is insensitive to changes in the resistivity model. Apparent conductivity levels were invariably highest for a 10m horizontal coil configuration but even so values reached only 7½mS/m compared to a background of 2-3mS/m. The importance of taking measurements with the coils horizontal was illustrated by the greater amplitude of the anomaly recorded with this configuration.

Additional reconnaissance survey lines were located north of the school and also northwest of it, closer to the line of wet ground and a spring which is utilized for minor irrigation. However, the resistivities were consistently high and there was nothing to encourage further exploration. It was recommended that test drilling start at the lower, western limit of the conductive zone near the school where shallower water was expected: there were indications of a thicker regolith further east, but a newly-dug trench had not encountered water to a depth of 4m. Following the drilling results from Mukumba it was assumed that the resistivity interpretations here represented a maximum thickness for the regolith and the possibility that depths to bedrock could be no more than 8m was recognized. Subsequent boreholes have given bedrock depths of 7-15m, increasing to the east. Initial pump test data were anomalous and further work was needed to establish that an adequate supply of water could be maintained before confirming a collector well site.

2.2.3.3 Samuriwo School

This school had been given a low priority on the initial inspection of proposed sites because of the abundance of rock outcrop, the subdued topography and the evidence of the few existing dug wells which had encountered rock at shallow depth below a relatively deep water-table. Reconnaissance resistivity traversing was undertaken to see if there was any evidence of pockets of deeper bedrock and to provide a comparison with the data from the other sites. The high measured apparent resistivities - typically over 1000ohm.m for current electrode spacings of 10-80m - were consistent with the surface evidence of shallow bedrock and the absence of any significant development of regolith. Although the area traversed within a period of 2 days was relatively small, the nature of the environment and the results obtained were discouraging even by previous standards and the investigations were abandoned.

2.2.3.4 Chisengeni School

Trial surveys were undertaken at Chisengeni following the poor initial results of the drilling at Mukumba School, to see if it might be a better alternative. Data collected by the local geophysical team showed some higher conductivities in the two dambos below the school which were tested by drilling. Hard rock was encountered at 9-11m depth while the resistive substratum occurred at over 20m. The EM34-3 equipment was not tried here though it could have helped in identifying the presence of any thin conductive zones within the regolith or in supporting the resistivity interpretation of a thicker intermediate zone. The shallower rockhead was associated with better well performance but the final Mukumba site was thought to be more suitable for a collector well.

2.2.4 **Conclusions**

The resistivity surveying undertaken for borehole siting by the Water Department is qualitative in nature, an approach justified by its success in local terms. Results are evaluated in the light of experience and 'rules of thumb' governing what range and rates of change in apparent resistivity are favourable: the calculation of apparent layer resistivities makes it easier to set general guidelines. Fieldwork is carried out by technical assistants whose understanding of the principles of the technique is limited and, given a lack of close supervision, the quality of the data is not always good. This tends to be offset by the large quantity of the data collected. The absence of a data-base or quantitative interpretations relating resistivity values to borehole control means that there is no information of the type needed to define depths to bedrock in the marginal environments being investigated for collector wells.

The value of the resistivity method for reconnaissance work in basement terrain was confirmed: large tracts of the areas surveyed appeared quite unsuitable for a collector well on the basis that high apparent resistivities preclude the presence of an adequate thickness of saturated regolith. While no obviously unfavourable sites have been drilled the possibility of missing any significant development of saturated regolith in this way seems remote.

The EM34-3 conductivity meter provides a more efficient means of obtaining traverse data than the resistivity method: difficulties with high electrode contact resistances are avoided; the lateral resolution is better for a given depth of investigation; the system is more portable and quicker to set up so that anomalous readings can be checked and followed-up more easily. The results obtained during the visit showed that useful data can be collected in a resistive environment if sufficient care is taken with coil orientation and the instrumental zero. The advantage of having readings at different coil spacings and orientations was apparent in qualitative surveys for confirming the existence of an anomaly: horizontal coil readings are more sensitive to changes at depth and to thin, steeply dipping zones but the data are susceptible to errors in coil alighnments; corresponding anomalies in the vertical coil response give more confidence to the interpretation as well as providing an indication of conductivity variations with depth.

There is little evidence that detailed surveys have contributed to identifying the best specific sites for a well. In the Wedza area, where drilled depths to bedrock exceed 15m, problems were encountered both with thick clay sequences and, at Maruta School, with boulders or bands of hard rock which were not predicted: test yields are generally low within the depth range of a well with horizontal radials. At Mukumba School, in Chiota district, the depth to bedrock was significantly overestimated at the initial drill sites chosen on the basis of more limited surveys, but including full depth soundings as well as traverses. There were pointers to the presence of shallow bedrock in the relation between EM34-3 results and the resistivity interpretations, as well as in differences between orthogonal sounding curves, but uncertainties are almost inevitable in conductivity/resistivity data in this type of environment. Where adequate depths to bedrock are the main concern the seismic refraction technique can provide more reliable interpretations, particularly if used in conjunction with electrical methods, and future studies should make provision for its inclusion.

One of the restrictions in assessing geophysical data relates to the lack of control on the interpretations until relatively expensive drilling is undertaken. The most effective exploration strategy would be to complement EM traversing and resistivity depth soundings with seismic surveys and a much cheaper drilling rig, possibly a power auger: promising indications should then be tested with a rig powerful enough to prove bedrock without any ambiguities due to boulders or residual bands of rock.

2.3 MALAWI

2.3.1 Introduction

The project in Malawi was still in its initial stages at the time of the visit and had been taken only to the point of a preliminary appraisal of existing borehole records for the six townships proposed for sites by the Water Department. The choice of sites was based on the need for additional water supplies and it reflected the difficulties experienced previously in meeting the demand from boreholes. Total requirements have been projected as lying in the range 350-800m^3/day, or about 4-9½l/s, and the construction of collector wells is considered to be a viable proposition if at least half of the need can be met by them.

The reliability of much of the borehole data is questionable for a variety of reasons: locations often prove to be incorrectly plotted; quoted yields may overestimate the longer term capacity of an aquifer with limited storage and recharge, or underestimate the capacity where poor borehole design and construction are significant; water 'strikes' may indicate the more permeable zones but minor inflow at higher levels has probably been missed in many cases, as suggested by shallower rest-levels in what is likely to be an essentially continuous, if anisotropic aquifer; lithological descriptions are not standarized and it is difficult to know what degree of coherence is attributable to 'weathered rock'. With these reservations in mind further consideration of the sites led to the rejection of Madisi due to excessive depths to water, while Dowa was given a low priority on the basis of the variable conditions and ephemeral yields found here previously; Nathenje was also thought to be unfavourable in view of its locally dissected topography. This left Ntcheu, Mponela and Chitedze as the first areas for detailed investigation. A fourth area of high priority - Chiwengo, near Kasungu - was added subsequently.

2.3.2 Chitedze

2.3.2.1 Background

This agricultural station and college was an expedient choice: its proximity to Lilongwe made it convenient logistically although the available information indicating a clay-rich regolith and relatively deep water-levels was not very encouraging. Increased demand at the station had led to a request for additional water supplies in 1980 when the Groundwater Section took the opportunity for testing their new designs for low-cost boreholes. The results of their investigations showed that the thickness and nature of the regolith varied considerably within short distances; the upper section was notably rich in clays and water levels, at 7-10m below surface, were relatively deep; rock types also varied and graphitic gneiss was reported in one borehole. Geophysical surveys were undertaken here, including the use of a variety of techniques not often available in Malawi (Carruthers, 1981). Resistivity traverses mainly reflected the presence of dry, superficial layers of variable thickness with some development of laterites. The bedrock did not show up as a clearly-defined rising segment on sounding curves taken to current electrode separations of at least 200m and its bulk resistivity appears to be reduced either by the presence of graphitic zones or by alteration to depths exceeding 50m in places. Anomalies in the total magnetic field - more correctly the flux density - brought out some interesting features and trends although it is difficult to define their origin given the widespread, but non-uniform dissemination of magnetite throughout the basement rocks. The one borehole drilled on the basis of the magnetic data gave a sustained yield of over 1l/s and proved successful enough to incorporate into the water-supply system: it was noticeable that the sequence penetrated here differed from that at the other boreholes. The seismic refraction method confirmed the absence of continuous bands of rock at shallow depth, but the lack of a sufficiently powerful energy source restricted its effectiveness.

2.3.2.2 Fieldwork

The area covered by the investigations in 1980 lay on the higher ground to the southwest of the college (see Fig 2). A shallower water-level of 5m recorded for borehole KK24 beside the dambo to the east was taken as an indication of conditions more suitable for a collector well. In fact, a site visit revealed that the location of the borehole had been misplotted and its results were not relevant to the present study. Nevertheless, the dambo seemed to warrant further consideration and resistivity, EM34-3 and magnetometer data were collected.

A north-south EM34-3 traverse crossing the dambo showed that the lowest ground was associated with conductive, superficial clays; away from this zone the vertical coil readings were much reduced though all values remained above 15mS/m (less than 70ohm.m) except with the 10m horizontal coil configuration. Resistivity soundings along the same line confirmed that a layer with a resistivity of about 5ohm.m and 2½m thickness overlies the central part of the dambo itself, while on the flanks there appear to be less conductive, but still clay-rich deposits close to surface. Apparent resistivity values tended to level off or even to decrease at the wider current-electrode separations of more than 160m, implying the presence of conductive layers at depth (see Appendix). EM34-3 values at 40m coil spacing placed a restriction of the occurrence of such layers and it seems likely that some of the resistivity curves were picking up lateral variations in the bedrock. It is difficult to identify the base of the regolith because of the absence of a strong resistivity contrast with the bedrock, and the lack of close agreement between EM34-3 values and the interpreted resistivity models. The clay-rich zone appears to extend to depths of 8-15m and it may overlie coarser regolith or more compact, weathered rock. The absence of a thick resistive cover may be due to a piezometric level at about 2m below surface though any aquifer will underlie the clays: the standing water observed to the east of the traverse lies above the level of the dambo and is presumably perched, after draining from the higher ground.

A west-east traverse to the south of the main dambo showed fluctuations in conductivity but the results did not highlight any marked change in conditions. Additional resistivity soundings confirmed the variability of both the superficial deposits - with conductive clays as well as sands and indurated material which inhibited the passage of current - and the underlying layers with no indication of high resistivities at depth. Magnetometer readings along both of the traverses showed the biggest variations on the west-east line: the western margin of the dambo was associated with a maximum and the eastern margin with a minimum in the total field values, covering an amplitude of 50nT. A more extensive coverage would be needed to define the extent and nature of these anomalies but a structural feature running along the centre of the dambo could be giving rise to a dipolar signature. Another likely cause of anomalies related to dambos is the occurrence of residual or placer deposits of magnetite.

2.3.2.3 Conclusions

Conditions to the east of Chitedze differ from those on the site investigated in 1980 in that the thickness of the resistive cover is reduced significantly: this suggests that water-levels are higher, as might be expected given the lower elevation. The absence of high resistivities at depth is taken to be characteristic of the bedrock locally and so the indications of higher values between the upper clays and the deepest layers might represent coarser, unconsolidated material or weathered rock at depths of 8-12m.

Further evidence was obtained of lateral variations in both the regolith and bedrock. While these changes could be delineated more pre-

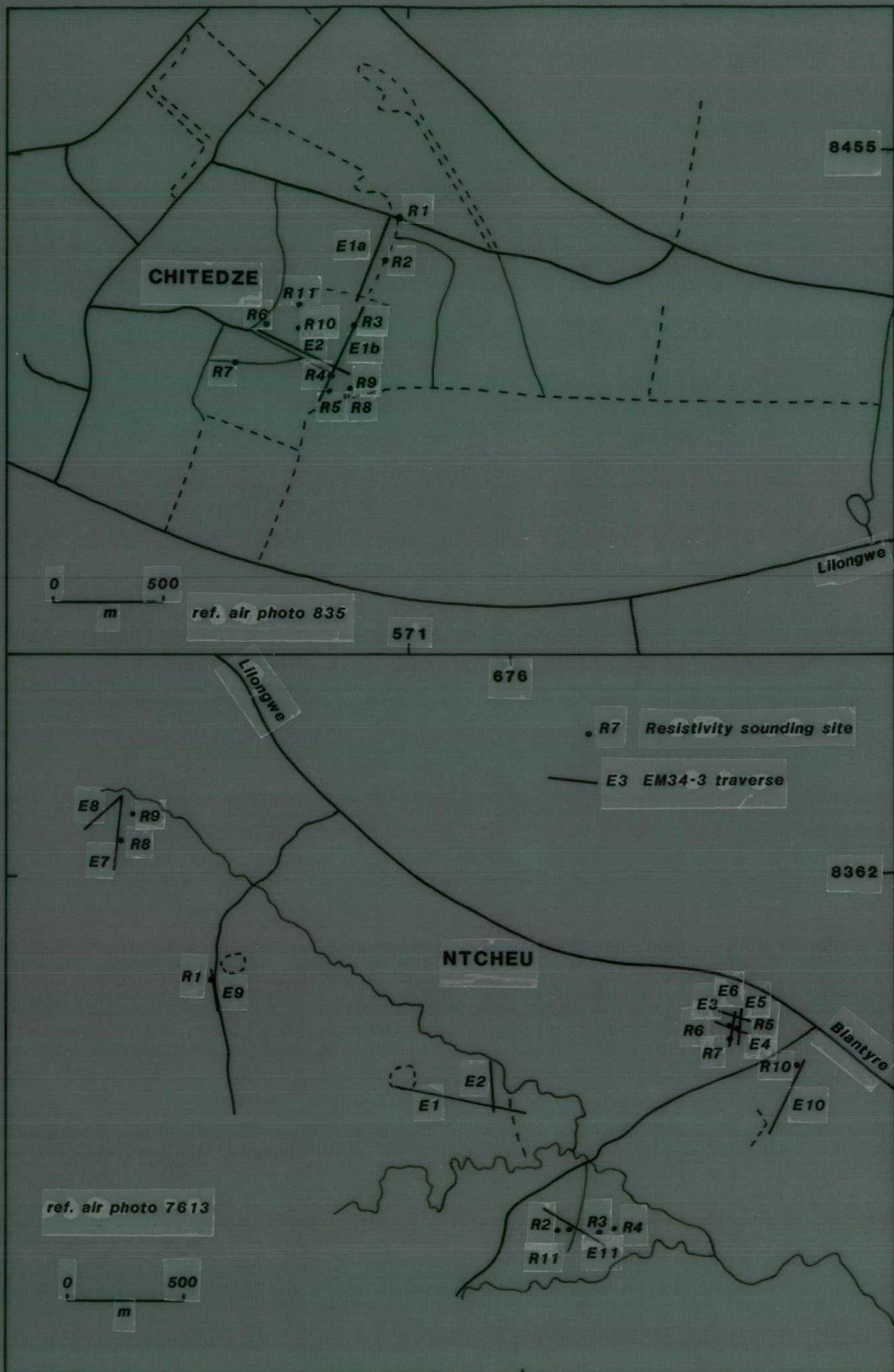

Fig 2. Geophysical site location diagrams for Chitedze and Ntcheu

cisely with detailed surveys it will not be possible to predict the nature of the succession with confidence from resistivity data. Three exploratory boreholes could be sited on the basis of the available results to test different responses and to give information on lithology, water-levels and yields. The results from these holes would determine whether more drilling, with or without additional geophysical surveys, should be undertaken. It should be noted that the area south of the dambo is subject to flooding and access will be difficult in the rainy season.

The area covered by the present survey was restricted to be within the college grounds. If only one site could be identified here there would be the possibility of investigating the next dambo to the northwest although this is nearly 2km away.

2.3.3 Ntcheu

2.3.3.1 Background

Ntcheu is stituated on a low ridge between mountains to the southwest and the Livulezi basin. Existing water supplies come from boreholes and the river, but these are inadequate even now: suggested alternatives have been to harvest water from the hill slopes; to pump water from a proposed dam; to take water from the lower ground to the northeast where test borehole yields of more than 5l/s were obtained. Two high-yielding boreholes could easily meet the required demand of $500m^3$/day or 5.8l/s, but the distances and more especially the lift involved in piping water from the known productive sites are considered excessive. A recent attempt to locate groundwater closer to the township used resistivity traversing in the valley to the southwest of Ntcheu but two boreholes drilled within about 200m of each other found shallow bedrock and little water.

2.3.3.2 Fieldwork

Surveys were undertaken at four locations to the southwest of the main Lilongwe-Blantyre road which runs through the town (see Fig 2). The first area was near the failed boreholes referred to above. No details of the drilling were available, but both holes were still open to depths of 17m and 10m respectively. Local residents reported that the water-level in the deeper hole remained high - it was 2.2m below ground at this time - and that shallow wells nearby provided water throughout the year: in contrast, the second hole in a small declivity at lower elevation drained nearly to its base - water-level was 0.5m below ground at this time. An EM34-3 traverse showed a marked variation in near-surface conditions crossing the depression which must be infilled with clays. The deeper borehole lies on the higher ground flanking this feature where the measured conductivity values of 10-20mS/m for the 10m and 20m coil spacings are more typical of a thin regolith. Orthogonal resistivity soundings here were surprisingly similar considering the irregular, bouldery nature of the ground and gave depths to bedrock of 12-13m: the resistivity of about 50ohm.m for the bulk of the regolith would usually be considered as favourable for groundwater given a thicker sequence. The values obtained some 700-1000m further northwest were indicative of superficial clays and bedrock at depths of no more than 10m. This interpretation was supported by the evidence of outcrop at surface, and in the main river-bed and deep gullies close to it.

Borehole Y212 to the south of the town by the old secondary school (and incorrectly marked on the 1:50000 map) was logged as penetrating 3m of top soil, weathered gneiss to 12m, broken granite to 20m and hard rock to 24m on basement gneiss. The yield was 0.5-0.61/s with water struck at 12m and rising to less than 4m. The interpretation of resistivity sounding R2 here gave bedrock at 13m for a regolith resistivity of 25-35ohm.m but additional sites to the east indicated that the regolith thinned out to 3m within 250m down the valley (see Appendix). A second sounding R11 near the borehole confirmed a bedrock depth of 12m for a somewhat higher regolith resistivity of 50-60ohm.m: these resistivities imply that the 'weathered rock' of the driller's log could be dug with little difficulty. An EM34-3 traverse showed some large variations in conductivity attributable to patches of clay overlying shallower bedrock.

The third location, below borehole L427 at the hospital, was selected mainly on the basis of surface features. The driller's log indicated superficial deposits to 11m and weathered rock to 43m; water was struck at 18m, rising to 6½m, and yielded 0.31/s. EM34-3 traverses defined a more conductive zone within the central part of a depression west of the borehole leading to a dambo. Resistivity soundings were affected by lateral variations relating to the localized clay infill and so neither the thickness nor the resistivity of the regolith were defined properly: depths to bedrock appear to be 10-16m with resistivities of 60-100ohm.m for the regolith. EM34-3 data from south of the borehole over a convex slope showed consistenly lower conductivity levels and sounding gave a depth to bedrock of 15m below resistivities of 75ohm.m. The higher resistivities for the regolith around this location may reflect a deeper water-level or a more silty matrix.

A fourth location was investigated to check on a linear feature which was apparent on the aerial photographs. This turned out to be an exposure of light-coloured, weathered rock and an EM34-3 traverse across it gave little response. The traverse was extended 500m to the west to join up with the earlier resistivity survey mentioned above. Measured conductivity values remained in the range 7-15mS/m at 10m and 20m coil spacings, which was a little lower than the level near the deeper borehole at the first location. In a clay-free environment such values could appear promising but in this area the occurrence of drier, compact clay over shallow bedrock seems more likely.

2.3.3.3 Conclusions

The choice of well sites around Ntcheu is constrained by the local topography, shallow bedrock and clays within the regolith. Resistivity interpretations give depths to bedrock in the 10-15m range which are, at best, marginal unless water-levels are high and the regolith is permeable. Given the lateral variations which are indicated it should be possible to find sites with depths to bedrock of 15m but it is less certain that conditions will be good enough for meeting the minimum demand target of at least 1½l/s continuous pumping from each of two wells.

Before any exploratory drilling is considered the results for the failed boreholes at the first location need checking. If necessary a pump test should be undertaken to see what yield can be sustained although in itself this is a poor guide to the likely performance of a collector well.

Resistivity interpretations by borehole Y212 were consistent with the lithological data. This gives some confidence in the results but if depths to bedrock are a critical factor in ensuring adequate saturated thickness then seismic refraction surveys would be needed to improve the lateral resolution and the precision of the interpretations. A site near Y212 might be feasible although the potential saturated thickness appears limited and much would depend on the permeability of the sequence: the location west of the borehole L427 offers similarly restricted prospects.

It seems unlikely that collector wells can provide a long-term solution to the water supply needs of Ntcheu, but they might be considered as a means of reducing the immediate problem. The exploration costs are likely to be relatively high in view of the shallow depths to bedrock indicated by the geophysical results.

2.3.4 Mponela

2.3.4.1 Background

Mponela is situated to the north of Lilongwe in the Dowa West region on the main road to Kasungu. The town is flanked on both sides by dambos and that to the west is currently being assessed for the extraction of gypsum. Higher ground lies to the south and regional drainage is to the northwest. There are about ten boreholes listed in the area of the town, two or three of which are pumped for the reticulated supply: again, several of the borehole locations as shown on the map are incorrect. Borehole yields vary but the results appear good in general. Of particular interest was site IR50 at the primary school for which a safe yield of 3l/s is quoted with a water-level of 2-2½m below surface. The formation log is unclear but it implies 3.6m of soil, gravel to 6.3m, weathered rock to 26m and gneiss to the final depth of 30m: water was met at 6m with the main inflows at 8½m, 17-19m and 22-24m. At present this well is fitted with a hand-pump although it appears capable of supplementing the town's supply. Borehole A41, by the west side of the road, also shows a shallow water-level, 2½-3m, and a good yield. Although water was struck at 6m the main supply was reported from 35m and the regolith appears to be much thicker here with decomposed gneiss extending to 30m over weathered gneiss to the bottom of the hole at 42½m. Borehole SM196 which is nearby had a rest level of 9m with water struck at 24m.

2.3.4.2 Fieldwork

IR50 was taken as the starting point for an EM34-3 traverse which crossed the dambo to the east of the school (see Fig 3). Measured conductivities were relatively high initially at 30-40mS/m except for the 40m horizontal coil configuration which maintained a level of about 15mS/m.

Values at the other spacings decreased steadily towards the dambo before increasing again sharply in response to the surficial clays. On the eastern side of the dambo conductivities at all spacings were close to 20mS/m, indicating a change in conditions from those near the school with a more resistive and probably thinner regolith at the lower elevations. A resistivity sounding some 70m west of the borehole showed a thin resistive cover to 1½m and a clay-rich zone extending to at least 7m and perhaps to 12m depth. There was some indication of an intermediate zone of 30ohm.m to 25m depth above the resistive bedrock and the inclusion of this results in the reduced thickness interpreted for the overlying clays. Additional soundings suggested that the area on the west side of the dambo extending 500m north and south from IR50 was generally favourable for collector well sites. Depths to resistive bedrock appear to be 15-35m with resistivities of 15-55ohm.m for the regolith, dependent to some extent on the existence of the poorly-defined intermediate zone referred to above. If these depths are confirmed by drilling it may be desireable to move downslope towards the dambo where the bedrock and water-levels should be shallower, so that the radials can be drilled within permeable material rather than the upper clays. Sounding R2 on the eastern flank of the dambo suggested there may be as little as 6m of conductive clays overlying more compact rock (see Appendix).

Further north the ground falls away beyond a break in slope to reveal outcrops of quartzite and graphitic gneiss. Soundings here picked up a highly conductive formation with resistivities of 1ohm.m and less which certainly represents the graphitic gneiss (see R3 in Appendix) at a depth of about 10m. EM34-3 traverses also gave a characteristic response as conductivities increased with depth and in the horizontal coil configuration went negative at the 40m coil spacing as would be expected for true conductivities in excess of about 600mS/m.

Near the head of the dambo to the south and east of Mponela the conductance of the clays was reduced and bedrock depths of 7-12m were interpreted for regolith resistivities of 15-20ohm.m: in consequence the typically high values recorded with the 10m coil spacing when crossing a dambo with the EM34-3 were muted here. The surface layer was much harder in this direction and there was direct evidence of lateritisation to depths of more than 2m. Measurements for two resistivity soundings on the margin of the larger dambo west of the road also suffered from problems with high electrode resistances although the results obtained appear reliable. They indicate depths to bedrock of 20-35m, the larger value being derived on the basis of sub-dividing the regolith into two main components with resistivities of 25-65ohm.m. The evidence for the deeper, more resistive component remains vague but a closer curve match is obtained by its inclusion. The base of the resistive surficial layers at 3m may represent the water-level as suggested by borehole A41, though as noted above SM196 raises doubts about this. The area west of the town was not investigated further at this time because of the possible association between the gypsum deposits in the dambo and sulphate contamination of groundwaters.

2.3.4.3 Conclusions

A zone of deeper bedrock was identified near the high-yielding borehole IR50 which appears suitable for collector wells. There is evidence of shallower bedrock near the dambo to the east and also downslope to the north where graphitic gneiss crops out. This allows some flexibility in site selection in that if the permeable zone is restricted to near the base of the regolith it should be possible to find bedrock at depths of 15-20m. If two sites are not available here then the area west of the road could be tested.

The rest water-levels recorded for the boreholes are not fully consistent and they may be subject to lithological or structural controls: the variability in yields also suggests there may be some steep, local hydraulic gradients. The exposed rocks indicate the potential for barriers to flow.

The projected demand of $500m^3$/day or 5.8l/s could be met in full by two high-capacity collector wells and on the evidence available it should certainly be possible to provide at least a half of this. Although the township has been accorded a low priority by the Water Department, sites here would be useful for assessing the performance of collector wells and provide a good comparison with boreholes in an environment where either technique would seem appropriate.

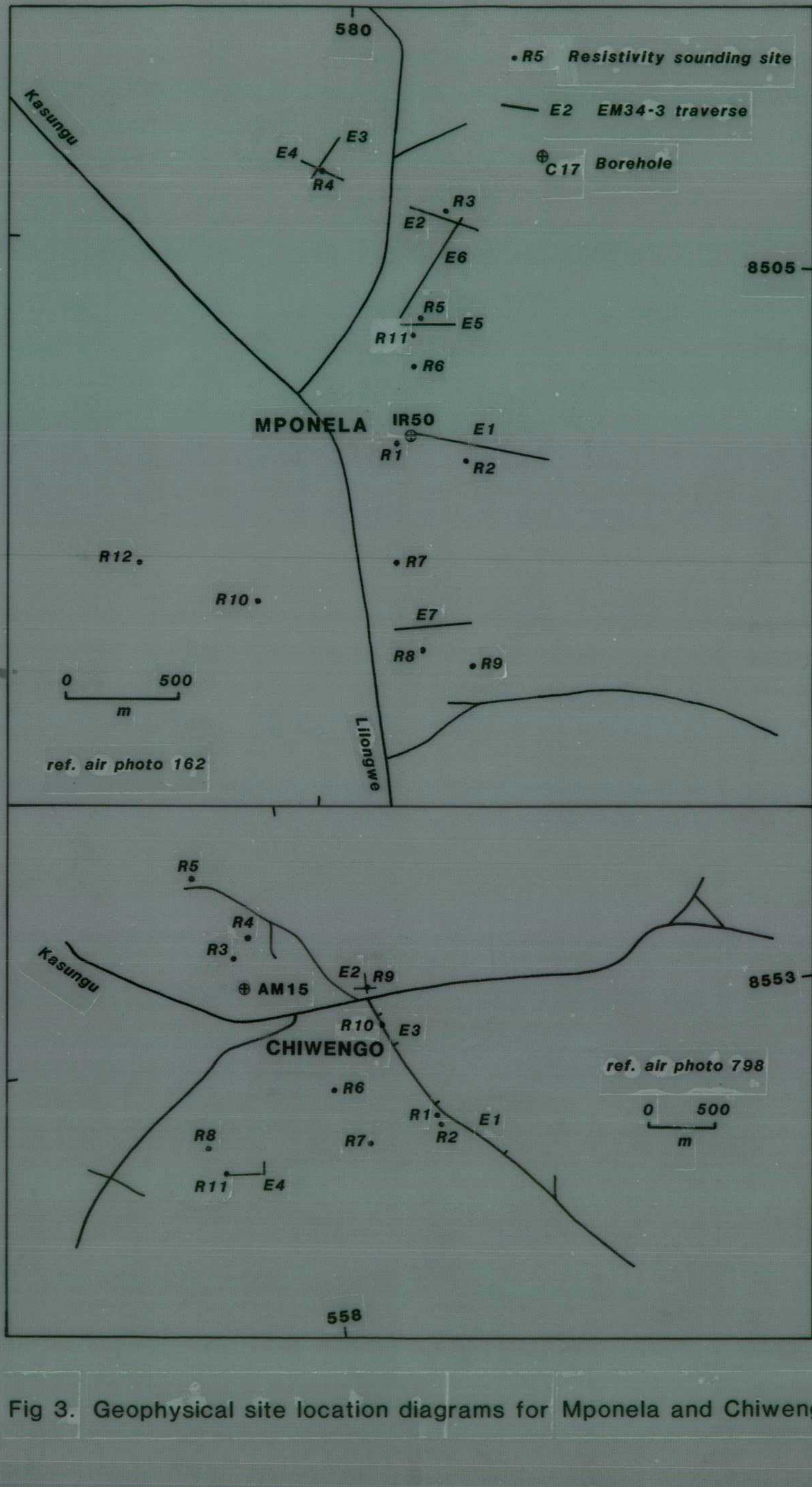

Fig 3. Geophysical site location diagrams for Mponela and Chiwengo

2.3.5 **Chiwengo**

2.3.5.1 Background

Kasungu is about 100km to the north-northwest of Lilongwe in an area of the plateau where borehole yields have been consistently lower than expected in this type of terrain. The village of Chiwengo lies within 10km east of Kasungu and is linked into the town's water supply by pipeline. Chiwengo is unusual in having a borehole, AM15, which can in principle more than meet the local demand of 70m^3/day. The 5 hour test run on completion of the hole in 1978 gave a constant yield of 4½ l/s for a drawdown which stabilized at only 8m after 15 minutes. Details of the current performance of the hole were not available but the safe yield is probably down to 1½ l/s for continuous pumping. The driller's log gives 6m of 'soil', weathered gneiss to 21½m and basement gneiss to the maximum depth of 61m; water was first struck at 9m, rising to 6m, but the main supply was reported at 30½m and 45½m depth. While the main supply is probably related to fractures within the hard rock and beyond the range of a collector well, the rest water-level and depth of weathering were encouraging enough to justify further investigation. A dug well, nearly 1km east of AM15 along the local watershed followed by the road, had water at a depth of 3m below ground and at the hand-pumped boreholes RM78 and RM79, a similar distance to the south, the water-levels after completion were 2m and 5½m respectively. These boreholes also went into gneiss but their specific capacities were two orders of magnitude less than for AM15. If collector wells did prove viable here then the water could be used to supplement the supply to Kasungu.

2.3.5.2 Fieldwork

Resistivity soundings at 11 sites around the village (see Fig 3) showed a range of response relating to a variety of near-surface material; there was also evidence of lateral changes within the regolith and bedrock although the curves could be attributed to horizontally-layered models. At site R3, 200m north of AM15, the ascending A-type curve was fitted more closely with a KH-model which put resistive bedrock at a depth of 13m, below a 2m thick conductive superficial layer and 11m of regolith; the upper 3m of regolith in this model were more resistive at 80-100ohm.m and taken to represent unsaturated material. The site was downslope from AM15, heading towards a dambo, and the regolith might well be thinner here; the simpler 3-layer model of soil, regolith of about 60ohm.m and bedrock still implies a depth of no more than 18m to bedrock. Site R9 near the dug well certainly showed a greater depth to the resistive substratum but the intermediate resistivities of 100-150ohm.m above it could also represent compact rock, leaving the base of the regolith at 8-13m rather than 25-35m. Drillers' logs for RM78 and RM79 imply that the regolith, described as decomposed gneiss, extends to 30-35m. The two soundings R6 and R7, respectively north and south of RM79 beside the dambo, show resistive material at the much shallower depths of 4-7m corresponding to the base of the 'soil' layer and if weathered/compact rather than 'decomposed' rock is not present then the zone is probably unsaturated; R1 and R2 by the subsidiary dambo joining from the northeast gave a similar type of response except that R2 did pick up a conductive zone either at intermediate depth of 13-26m or as a lateral change. An EM34-3 traverse across this dambo defined a sharp contact from the north between resistive, sand-covered regolith at 3-5mS/m and conductive dambo deposits giving apparent conductivities of more than 15mS/m: conductivities were invariably higher at the 10m coil spacing indicating a change in the near-surface deposits. The southern margin of the dambo was characterized by a narrow, very conductive zone with a gradual transition to lower values beyond. Although the effects are more obvious at shallow levels the resistivity results show that they relate to differences in the nature of the regolith and bedrock underlying the dambos. R10 was located on a zone of high EM34-3 values 250m along the same track leading south from the dug well. A layer of 75ohm.m was interpreted with a thickness of more than 20m below a conductive layer extending to 9m depth. The form of the curve is similar to R9 and the lower resistivity of the intermediate layer at R10 may reflect uncertainties in the field data and their interpretation; however, EM34-3 traverses show that broad-scale variations in conductivity are present, with the highest values around R10 and a trend to lower values to the south. The area including R9 and R10 offers some potential for a collector well site which would be best tested by a hole near R10. Information on the nature of the material at the bottom of the dug well would also be useful.

R4 had a similar form to R3 and again the more complex model with alternating resistive/conductive layers gave the better fit. A bedrock depth of 14-18m makes it acceptable for a collector well but the possibility of encountering hard rock or zones of low permeability within the regolith is significant. At R5, beside another dambo, the surface conductivity was high and the resistivity increased with depth from a level of 10ohm.m. The depth to resistive bedrock is over 20m and the evidence of hard bands is more tenuous here. In marked contrast, the surface resistivities southwest of the village were very high: values were about 5000ohm.m to a depth of 2½m at R8 and R11. Nevertheless the remainder of the sequence was little changed, with a conductive zone to 6-13m and intermediate resistivities of probably no more than 70-100ohm.m to at least 20m depth. EM34-3 data were relatively uniform over this area and the apparent conductivities of about 15mS/m maintained at the 20m coil separation are consistent with the resistivity interpretations. Whether the intermediate resistivity values originate from regolith rather than a conductive bedrock can be determined only by drilling or, perhaps, seismic refraction surveys.

2.3.5.3 Conclusions

The existence of a high-yielding borehole proves that groundwater supplies are available although their occurrence may be controlled mainly by fractures in the bedrock. The evidence of rest water-levels at depths of about 5m suggests that collector wells could be effective if the regolith is thick enough and two potential sites for exploratory drilling were identified, to the southwest and northeast of the village, from the resistivity survey. While the interpreted resistivity values to depths of 15-20m are in the range expected for regolith/highly weathered rock, there may be more coherent material retaining some of the structure of the parent rock below the upper conductive layer. In view of the projected difficulties in maintaining an adequate level of supply to Kasungu, testing of the Chiwengo sites for collector wells is considered justified on the available evidence.

2.3.6 Nathenje

No fieldwork was carried out at Nathenje for this project but resistivity surveys and drilling had been completed recently to locate a water supply for a new school site: the two boreholes were both abandoned in hard rock at shallow depth. As water-levels were close to surface it was suggested that a more rigorous pump test should be undertaken to see if a collector well would be viable: if so, further exploration could be undertaken to locate a second site to supplement the town supply for which the minimum requirement is about 2½l/s.

2.3.7 Recommendations

2.3.7.1 Collector well sites

Within the time available it was only possible to carry out a limited amount of fieldwork at four of the six sites proposed for collector wells. Of these, Mponela gave the most favourable results and it was suggested that preliminary test drilling should be undertaken at an early stage to confirm that conditions here are suitable for the construction of one pair of wells.

At Ntcheu a decision on whether to pursue the exploration programme has to be related to the long-term plans for supplying the township; a need for interim measures may justify collector wells even if they are unable to meet the initial specification. Depths to bedrock appear to be shallow where the water-levels are highest but some test drilling, in conjunction with further geophysical surveys if necessary, would be justified before rejecting the site.

An ability to extract groundwater from the district around Kasungu would be particularly valuable in view of the difficulty in locating good borehole sites. For this reason it is worth following-up the relatively favourable indications from Chiwengo in order to evaluate the potential of collector wells in this type of environment. If exploration holes in the two areas suggested from the resistivity surveys are unsuccessful there are no obvious alternatives for further work but the results would still provide useful control on the resistivity interpretations.

Geophysical results from Chitedze were inconclusive; on previous evidence the resistivity method may not be reliable in mapping the bedrock as there is no consistent contrast with the regolith and it is difficult to select the correct interface. Borehole data are needed within the area already covered to provide some control on bedrock depths, water-levels and yields before an extension of geophysical surveys is recommended. The required yields are relatively high and it will be necessary to penetrate a zone of good permeability if the wells are to be successful: the absence of short-wavelength magnetic anomalies suggests that low permeability is likely to prove more of a limitation than shallow bedrock.

If reconsideration of the borehole results for the Nathenje school site suggest that a collector well is suitable here then surveys will be needed to locate a second site for the town. Otherwise the suggested sequence of investigations on the evidence to date is Chitedze, Kasungu, Ntcheu. It is recommended that a limited amount of test drilling information be obtained from each of these sites before concentrating too much effort on any one of them. As the demand on these township sites will be relatively high it may be advisable to dig wells with the larger 3m diameter and to drill vertical or inclined rakers if necessary, as well as radially from them, in order to maximise yields.

2.3.7.2 General Considerations

A series of recommendations was included in the official report (Carruthers, 1981) which followed a previous visit in 1980 to advise the Groundwater Section of the Water Department on the use of geophysics. It became clear on this latest project that no action had been taken along these lines. This is perhaps not surprising in view of the pressures on staff time, including the prolonged absence of people on overseas courses, and the lack of a trained geophysicist in the section with an interest in seeing the changes made. The recommendations are still appropriate and some points are reiterated here.

The Cooper array method of resistivity sounding should be discontinued in favour of the Schlumberger array or in some circumstances the Wenner array. With the new resistivity equipment - ABEM SAS300 Terrameters with booster - acquired by the section, the practical limitations on the use of the Schlumberger array no longer apply. The main disadvantages of the Cooper array lie in the need to fix the separation of the inner electrodes and in the interpretation of the data. Standard procedures have been developed for modelling results from the Schlumberger and Wenner arrays which supercede the approximate curve matching methods as developed by Cooper for his array. A small micro-computer can now be used either to generate complete master curves from specific models to be tested against the field data, or to run one of the automatic curve-fitting programmes.

The availability of such a facility would greatly improve the reliability of interpretations and encourage a more quantitative approach: the computer would also run programmes for analysing hydrogeological data and storing information. While accurate, quantitative interpretations may be unnecessary for routine siting of handpump supply holes they would provide the background data on formation resistivities which are essential when more specific problems have to be addressed.

The SAS300 is a sophisticated piece of equipment but satisfactory results will only be obtained if its capabilities and limitations are properly understood and if correct field procedures are followed. Ancillary items such as the metal stakes, hammers, connecting clips, cables and measuring tapes must be in good condition and equal to the task required. Thus, where the surface layers are hard and dry the current electrodes in particular need to be both thick and long enough to ensure they can be driven well into the ground; containers with salted water should be carried so that electrode resistances can be reduced to acceptable levels for passing enough current and for keeping the impedance across the potential dipole low enough for the signal to be measured accurately. A separate multimeter is best suited to checking electrode resistances and circuit continuity.

The results of geophysical surveys should be interpreted and assessed in relation to subsequent drilling in order to reach a better understanding of the nature of the sequences and the factors which influence the interpretation. It is especially important to explain unsuccessful boreholes. The ambiguities and uncertainties associated with resistivity data mean that quantitative interpretations often prove unreliable unless some control is available. For this reason results need to be archived in a retrievable form so that they are available for reference when further work is required in the same area - if only to indicte that additional surveys are unlikely to assist in borehole siting.

3 BASEMENT AQUIFER PROJECT

3.1 ZIMBABWE

Discussions were held with Dr Swain of the Physics Department, University of Zimbabwe, who had initiated short-term student projects relating to groundwater exploration. A study undertaken in the previous year involved recording seismic refraction lines beside low-yielding boreholes which had been drilled as part of the drought relief programme in Victoria Province. The final report on this work was still awaited but the results had indicated the presence of lateral variations and suggested that better sites were available nearby. It was confirmed that similar surveys would be carried out near high-yielding wells for comparison in this summer's project. Dr Swain also supported the idea of surveys with the induced polarisation method to see if they would provide any useful information for discriminating between different parts of the regolith: he confirmed in principle that the department's equipment could be used on the BGS project if required.

No new proposals for additional geophysical work emerged and, as before, the intention remains that research-oriented work involving induced polarisation, electromagnetic and seismic methods should be related to following up indications of enhanced fracturing or zones of deeper weathering in Victoria Province derived from remote-sensing data. Survey areas will also be chosen on the basis of an analysis of the available hydrogeological information and on studies of the land-form. Another possibility for the project is to conduct more extensive surveys in areas covered by a recent Japanese aid programme where drilling results were poor. The object here would be to determine whether better sites can be located or if the groundwater potential is too restricted for local requirements to be met. A large amount of geophysical and drilling data is available from the recent projects and this could usefully be studied in greater detail before undertaking additional fieldwork.

3.2 MALAWI

It was possible to devote some time to two aspects of the basement aquifer project currently under investigation in Malawi. These concern the origin of high levels of sulphate ions in groundwater, and the nature of dambos in relation to the regolith and groundwater circulation.

3.2.1 Sulphate-rich waters

The Dowa West district has provided the focus of attention for studying the origin of high sulphate levels since a significant number of boreholes drilled here had to be abandoned as a result of the poor quality of the water. The geological maps and memoirs covering the region bring out the existence of pyrite-rich formations within the basement and it seemed possible that there could be a direct causal link between high-sulphate groundwater and subcropping bands of pyritic rock. The effects of water circulation may also be significant with some transport down the hydraulic gradient to be expected; the association of gypsum deposits with dambos is another feature requiring explanation in this context.

The detection of pyrite by geophysical means is usually relatively simple: the bulk resistivity of the host rock is often reduced sufficiently for it to be distinctive; where the pyrite occurs as veins or interconnected grains there should be a large electromagnetic response; if the pyrite is disseminated as discrete grains throughout the rock matrix then the induced polarisation should be high; where it occurs in conjunction with pyrrhotite a magnetic anomaly may be obtained. A complicating factor here is the widespread occurrence of graphite which has similar electrical properties. Any possibility of distinguishing the two on the basis of a magnetic response is remote because pyrrhotite is not commonly found while magnetite is ubiquitous as an accessory mineral within the basement rocks.

As more borehole data becomes available it seems that the occurrences of high sulphate levels tend to form localised groups. One such group to the east of Mponela is confined to the southeast side of a dambo while good quality water is obtained to the northwest. EM34-3 data from beside the abandoned borehole DW48 showed that the conductivity increased with depth, indicating that the bedrock here is conductive. Near

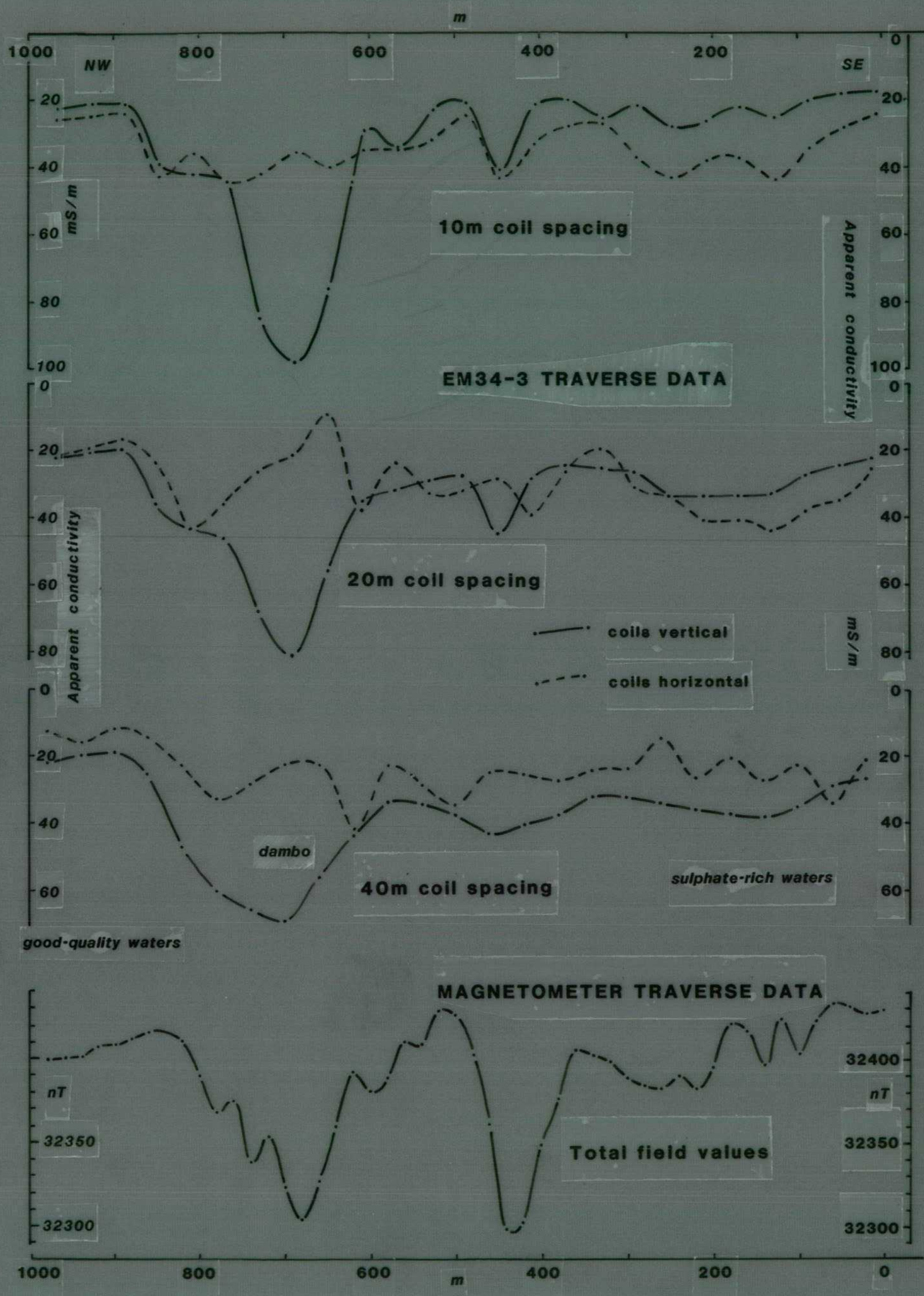

Fig 4. Traverse data related to sulphate-rich waters near Mponela

borehole DW25 where sulphate levels were lower, though the water quality was still poor, the conductivity again increased with depth but less markedly than at DW48 to give equivalent resistivities of 25-30ohm.m as against less than 20ohm.m. A traverse across the dambo from near DW25 to the vicinity of DW20 was notable for the high conductivity level maintained to the southeast of the dambo, particularly with the 40m vertical coil configuration (see Fig 4). Near-surface conductivities remained low except over the dambo itself where the surficial clays produced the biggest response. On the northwest side of the dambo by DW20 conductivities dropped to distinctly lower levels, except with the 10m vertical coil configuration for which values stayed about the same, and there is clearly a difference in the bedrock on either side of the dambo. Magnetometer readings also showed some interesting anomalies and there was a close correlation with the conductivity variations along the traverse. The coincidence of a magnetic low and a conductivity high on the relatively steep slope leading down to the dambo is probably characteristic of a specific unit within the bedrock.

While the results from a single traverse are not conclusive there is evidence that the difference in water quality here is associated with, if not necessarily caused by a change in the nature of the bedrock. Further work is needed to see if the relation between sulphate and bedrock conductivity levels is confirmed at other locations given that conductive graphitic rocks may occur in isolation from any sulphides.

3.2.2 Dambo studies

The mechanisms by which the shallow vegetated valleys known as dambos, or vleis in Zimbabwe, were formed are not well understood although these features cover a significant proportion of the land area in some regions of basement plateau terrain. Thus it is not clear whether they follow lines of weakness in the basement or reflect an earlier landform; whether the characteristic clays and sands associated with dambos are residual or laid down, partly at least, as channel deposits. Similarly, the contribution to the water balance from deep circulation as compared to shallow storage of seasonal rainfall is not known. The significance of dambos as lines of discharge of old groundwater has long been suspected but until recently few detailed studies of their interaction with the hydrogeological system have been attempted.

As part of the 1985 programme for this project the nature of the regolith and dambo deposits was investigated by cored boreholes supplemented with shallow and percussion drilling along two sections. Resistivity, EM34-3 and magnetic data were collected along these lines both as control on the geophysical interpretations and to provide an indication of the underlying formations. One of the dambos was located near Chikobwe, 13km north of Mponela, and the other, Chimimbe Dambo was near Magomero, 30km south of Nathenge. The borehole data had not been compiled at the time of preparing this report and so the geophysical interpretations are based on the preliminary assessment (Freshney and Hallam, personal communication).

Pairs of resistivity soundings were laid out near the two cored holes at Chikobwe Dambo. The survey was undertaken at the end of the dry season when the grey dambo clays were deeply cracked. Some of the electrodes were not well fixed into the ground but the surface clay layer had a resistivity of only 2-5ohm.m to a depth of 2m and the low contact resistances prevented undue distortion in the data even at close spacings. Resisitivities increased to about 15ohm.m within the second layer, extending for a thickness of 10m over a substratum of 100ohm.m; there was no evidence of a more resistive bedrock at the maximum current electrode separation of 240m. The borehole B1 reached hard rock - gneiss with common pyrite - at 13m, giving good agreement with the resistivity interpretation although the logged break at about 6m between dambo deposits and weathered rock was not expressed in the sounding curve and it would have been difficult to say a priori that a layer of 100ohm.m represented bedrock rather than weathered material. Results from the second site, 450m to the east-northeast on sloping ground flanking the dambo, were less satisfactory due to the dry sandy soils. Near-surface resistivities exceeding 1000ohm.m for several metres may reflect some development of indurated laterite: the underlying clay-rich regolith had a resistivity of 10-20ohm.m on average, though with indications that the sequence was actually banded with larger internal contrasts in resistivity. Again, the 'bedrock' resistivity was relativity low at no more than 100ohm.m. One of the curves implied a more conductive underlying layer which, if genuine, probably represents graphitic schist or more strongly pyritized rock. The second of the soundings was both shorter and 50m downslope from the first and so some difference in the character of the bedrock might be accommodated between the sites. The interpreted depth to bedrock of 35-40m is consistent with the absence of hard rock in the borehole which was completed at 30m.

EM34-3 data at coil separations of 10m and 20m brought out an interesting contrast in response crossing the margins of the dambo. The presence of the thin uppermost clays was characterized by high conductivities of over 100mS/m measured with the coils vertical and a marked decrease when the coils were oriented horizontally, more especially at the 20m spacing. Towards the southwest a steady reduction in conductivity occurred beyond a distance of 90m from B1 where pitting and shallow holes confirmed the transition from dambo deposits to colluvium or regolith. From 150m the conductivity section reversed, with more resistive material close to the surface and values of 20-25mS/m from the deeper regolith. Traversing to the northeast showed a less marked reduction in near-surface conductivity at the edge of the dambo deposits while horizontal coil values increased to more than 40mS/m. Thus there appears to be a distinct change in the nature of the bedrock and its weathering profile near the break in topographic slope. It may be significant that the presence of graphite was noted in the samples from one shallow hole, P20, at this end of the section. Further up the slope near B2, levels were suppressed somewhat by the resistive cover but a thick conductive sequence was still indicated.

Magnetometer readings were not taken on this line but susceptibility measurements on the core samples from B1 showed that the bedrock was only weakly magnetized, up to perhaps 0.5×10^{-3}SI, while the dambo clays gave no measureable response. At B2 however susceptibilities exceeded 2×10^{-3}SI within the uppermost 2m before falling back to less than 0.5×10^{-3}SI beyond 3m depth. There was a tendency for values to reduce further with depth but the variable mechanical state of the samples and their packaging made it difficult to obtain a genuine comparison.

The line at Chimimbe Dambo was located near the head of the valley. One set of geophysical data was collected before the drill sites had been finalized and additional results were obtained subsequently after their realignment. The EM34-3 profiles across the dambo clearly defined a zone of high surface conductivity corresponding to the grey clays although as they were thinner than at Chikobwe the maximum values were reduced here. Drilling did not extend across the northwest margin of the dambo but the change in EM34-3 values, with vertical coil values dropping below those with the coils horizontal for the 10m separations, suggests that the transition to more typical regolith is occurring at the end of the line. The

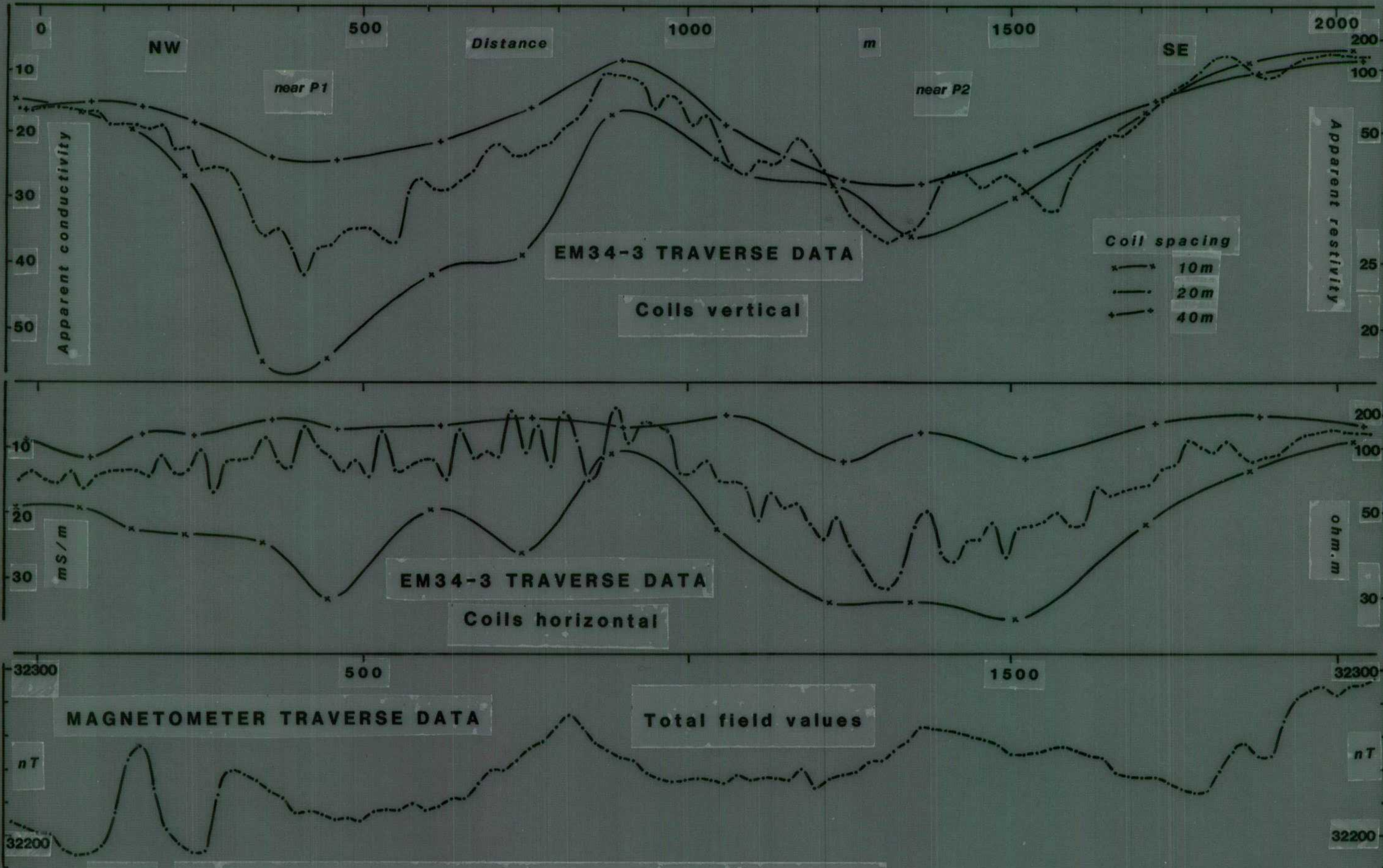

Fig 5. EM34-3 and magnetometer data across Chimimbe dambo, Malawi

limit of the grey clays to the southeast was best expressed in the 10m spacing vertical coil values which fell back to about 35mS/m but this does not mark the extent of the cover of dambo-type deposits. The first, longer traverse (see Fig 5) showed more clearly the change in the nature of the underlying weathered material and bedrock beyond this point, with an increase in the 20m horizontal coil values from a level of 10-15mS/m over the dambo clays to 25-30mS/m. A sandy cover underlain by indurated laterite reduced 10m vertical coil values to a similar level but only at 40m horizontal coil separations was the response subdued significantly. Further southeast, as the sands gave way to red soils of colluvium/regolith, all the values fell back to 10-15mS/m. This zone of higher conductivities is similar to that found at the edge of Chikobwe Dambo and the cause is thought to be the same, that is an increase in the depth of weathering associated with a change in the character of the bedrock near this margin of the dambo. Resistivity soundings (see Appendix) put the depth to hard rock at little more than 10m beneath the dambo clays at percussion hole P1, increasing to 15-20m further southeast near P2 though the values here are uncertain due to suppression and equivalence effects. The resistivity of the substratum is several hundreds of ohm.metres and perhaps more, with only a slight suggestion of a conductive layer at depth. Over the interfluve, however, there was clearer evidence of variations within the bedrock itself. At the site of cored borehole B3 two resistivity soundings both showed that a layer of about 60ohm.m, a typical average for regolith, extended below the depth of 17m at which hard rock was encountered. The curves were distorted by lateral variations and it was unclear whether the borehole was on a local high or if more conductive rock occurred at greater depth. Resistivity data from further east implied that bedrock of 60ohm.m extended from 18m to over 100m depth, while at percussion hole site P4 the whole sequence was resistive with measured values exceeding 300ohm.m throughout. Continuing southeast, by B4/P5, the regolith was again found to be conductive with a simple three-layer model underestimating by 6m the depth of 22m to hard resistive, rock. By Jenchelele Dambo the resistivity data showed an interface at 4m with a layer of 70-80ohm.m extending to a resistive substratum at 20m depth: unfortunately the shallow hole and pit here penetrated to only 3m in weathered gneiss and so the hardness or freshness of the intermediate layer was not established. Further northeast and 350m back upslope from the dambo, conductive bedrock was implied at a depth of about 30m beneath

15m of regolith and a similar thickness of resistive bedrock. EM34-3 traverse data were not consistent with a conductive substratum and the sounding curve was probably affected by lateral variations near the transition from regolith to dambo response. The conductivity of the upper dambo deposits was lower than at Chimimbe and the subdued response close to the centre of the valley implied a shallower, more resistive bedrock.

Magnetometer traverses also distinguished Chimimbe from Jenchelele dambo, showing more variation over the former. Anomalies of 60nT coincided with the margins of the zone of high superficial conductivity and the field again changed crossing the deeply-weathered section and passing onto the colluvium of the higher ground. Susceptibility values measured on cored samples from B3 and B4 were consistent in giving a weak response from the hard rock but relatively high values, decreasing from 10×10^{-3}SI, through the top 6m. The dambo clays themselves were not magnetic and only the marginal sands and upper colluvium seem to have a concentration of magnetite or related minerals. This is presumably derived from the local bedrock but the low, uniform level of magnetization at intermediate depth suggests that it has been transported rather than concentrated as a purely residual deposit. It is difficult to conclude from single profiles whether the anomalies do in fact originate from a near-surface source rather than from within the deeper bedrock.

3.2.3 Conclusions

The classic section through to bedrock has a resistive, hard rock with a high seismic velocity beneath the more conductive regolith; variations in these properties within the regolith then relate to the relative proportion of sand and clays, and within the bedrock to the degree of fracturing and weathering. In practice detailed surveys show a much greater variability in the electrical properties. Certain characteristics of the section, such as the difference between sands and clays in the near-surface layers or the presence of shallow resistive bedrock, are brought out but the wide overlap in the values given by the various types of weathered material and bedrock means that they cannot be differentiated uniquely. Without being able to fix some of the parameters of layer resistivity and thickness the interpretations are inherently ambiguous, often over a large range. Control provided by boreholes will be of limited value if the lateral variations restrict their range of application and in such circumstances it is necessary to use complementary geophysical techniques, particularly seismic refraction and perhaps magnetics, to monitor and compare the changes in different properties. Another methodology is to restrict the geophysics to rapid reconnaissance using for example EM34-3 and magnetics for mapping variations which can then be tested by boreholes: this approach is constrained by the efficiency of drilling operations in terms of both cost and time.

The extensive occurrence of graphite and pyrite within the basement rocks of central Malawi emphasizes the problems of differentiating regolith from basement; the long spreads necessary to establish the true resistivity of the substratum increase the likelihood that the assumption of uniform layering will be grossly incorrect. Where the bedrock is characteristically conductive however this may be associated with pyrite and water-quality problems due to high sulphate levels. If the analysis of existing hydrogeological data does not identify the main sources of contamination or if there are site-specific factors then further work is needed to prove that the geophysical response is diagnostic. Similarly, a decision on whether to extend geophysical investigations around dambos depends upon the requirements of other lines of research. Resistivity/conductivity results have consistently implied that dambos are associated with zones of shallower, resistive bedrock and not with enhanced weathering profiles relative to the present ground level. Distinctive variations occur across them which can be used for siting boreholes to the best advantage to test different aspects of the cross-section but seismic refraction data are needed for more precise control on the depths to bedrock.

4 SRI LANKA

4.1 DATA-BASE COMPILATION

4.1.1 General considerations

The availability of a large body of information within the Water Resources Board (WRB) including drillers' logs, geochemistry and geophysics provided an opportunity to test the advantages of having an easily accessible data-set. This has implications for establishing relationships between and within areas already studied, for monitoring current projects and for planning future work. It was agreed that a local member of staff would ba available to operate the computer system provided.

The data-base was structured into three categories of files covering lithology/hydrogeology/setting, geophysics and geochemistry. The geophysical section was further subdivided into a main file intended for each site investigated with resistivity soundings, and secondary files allowing specific examples of resistivity sounding curves and borehole logging to be stored for reference. Although cross-reference between files is possible some of the information on borehole lithology and yield was duplicated to maintain a format which could be used independently. Apart from archiving data there was a need to input some interpreted parameters as a basis for cross-correlation with drilling results. Most of the data have been assessed qualitatively and there are few formalized interpretations. The data-file was therefore restricted to a selection of key parameters which it was hoped could be documented in future surveys and picked relatively easily from the existing data.

The data-base software package sets a limit of 32 fields per record and so the input was kept to this number. The character string format used to combine some values into one field is an acceptable method of storing related data but it means that the potential of the system for plotting and cross-correlating parameters cannot be utilized easily. A questionnaire, as set out below, was designed during the course of the visit on the understanding that it would be modified and improved as necessary in the light of experience gained in operating the system. No results were available at the time of completing this report.

4.1.2 Geophysics file structure

Each field in the record is assigned a specific name, type - character, numeric or logic - and width, the description explains the information required. All numeric fields exclude a decimal point unless otherwise specified.

Main geophysics summary file: area name prefixed with GPS.......

FIELD		TYPE/WIDTH	DESCRIPTION
1	WELLREF	C/8	Borehole reference, name or number, identifying borehole site
2	RESREF	C/10	Resistivity sounding reference ending in (S) or (W) to indicate Schlumberger or Wenner array type
3	EAST	N/5	Grid coordinate easting to 10m
4	NORTH	N/5	Grid coordinate northing to 10m
5	ELEV	N/3	Elevation relative to datum (sea-level) in metres
6	SOIL	C/10	Thickness and type of soil formatted as X/C where X is in metres, / is a delimiter, C is a coded type reference
7	BASEREG	N/2	Depth to base of weathered rock in metres
8	ROCK	C/6	Code for type of bedrock
9	FRAC	C/25	Depth range of significant fissures and fracture zones: format as X1-Y1/X2-Y2/etc for depth to top and bottom with a maximum of 4 zones
10	RWL	N/2	Rest water level, depth below ground
11	STRUCK	N/2	Water 'first met' level depth
12	SUPPLY	N/2	Depth to main supply
13	YIELD	C/7	Well yield and drawdown as X/Y, yield in l/s
14	COND	N/5	Fluid conductivity, in Siemen per metre, x10000
15	RHO2	N/4	Apparent resistivity in ohm.m for: a = 2m
16	RHO5	N/4	a = 5m
17	RHO10	N/4	a = 10m
18	RHO20	N/4	a = 20m
19	RHO40	N/4	a = 40m use interpolated, adjusted values if necessary; 'a' is half the current electrode separation for Schlumberger, or a third for Wenner, array

FIELD		TYPE/WIDTH	DESCRIPTION
20	MAXSEP	C/8	Maximum 'a' spacing and apparent resistivity as X/Y
21	TYPE	C/3	Curve type eg H, KQ, AKH; use 2a or 2q for 2-layer case
22	QUALITY	N/1	Curve reliability factor: 1-3 for good - bad, smooth - erratic
23	SLOPE	N/1	End of curve slope: 1 if negative, 2 for 0-20°, 3 for 20-40°, 4 if over 40°
24	TC	N/3	Estimate of total conductance in Siemen (x100)
25	BREAKS	C/19	'a' range of significant curve discontinuities: format as field 9
26	REGTO	N/3	Interpreted depth to base of weathered rock: use negative to indicate uncertainty
27	AQU	N/3	Inferred depth to aquifer: use 999 if no aquifer expected
28	SURVEY	C/10	Number of ½ days spent on site survey/Number of other soundings/Length of traversing undertaken
29	TRAV	C/3	Traverse method: R(esistivity), E(M), S(eismic)
30	LOGTYPE	C/5	Type of borehole logging: R(esistivity), G(amma) etc
31	LOGINT	C/5	Range of useful log: from/to
32	INTERP	L/1	Quantitative interpretation: Y(es) or N(o)

Resistivity data file, name GPR------, designed to store a representative selection, about one in ten, of sounding curve data:

FIELD		TYPE/WIDTH	DESCRIPTION
1	RESREF	C/10	Resistivity sounding reference
2	EAST	N/5	Grid easting
3	NORTH	N/5	Grid northing
4	DATE	C/8	Date of sounding: dd/mm/yy
5	A1R1	C/8	Electrode separation ('a' value)/Apparent resistivity; for Schlumberger array list all observations for each potential dipole spacing consecutively
6	A2R2	C/8	
	"		
27	A23R23	C/8	
28	REM	C/40	Remarks, any special points relevant to inter-retation

Logging data file, name GPL ------, to store simplified coordinates, depths and parameter values, of log profiles

FIELD		TYPE/WIDTH	DESCRIPTION
1	WELLREF	C/10	Borehole reference
2	EAST	N/5	Grid easting
3	NORTH	N/5	Grid northing
4	LOG1	C/7	Type of log eg 16"NRML, TEMP, GAMMA etc
5	DPTHDAT1	C/119	Series of point values for log type 1 as X1:Y1/X2:Y2/X etc
6	DATUNIT1	C/10	Units of Y parameter values for log 1
7	LOG2	C/7	Type of log 2
8	DPTHDAT2	C/119	Coordinates for log 2
9	DATUNIT2	C/10	Units of log 2
	"		
18	DATUNIT5	C/10	Units of log 5

4.2 HAMBANTOTA DISTRICT

During the course of a brief visit to the regional office at Tangalle, borehole logging and trial seismic surveying were undertaken at a nearby saline well. It had been assumed that the high salinities measured in the groundwater from a number of wells in the coastal district of Hambantota originated from sea-water intrusion or transgression until geochemical and isotope data revealed characteristics more typical of prolonged water/rock interaction. This raises the possibility that prolonged pumping of 'saline' wells may allow recharge of the aquifer with fresh water in preference to less mobile water from depth. As a preliminary to any further investigations a test was conducted to see if geophysical logging could provide an indication of the salinity of water entering the holes. Temperature, fluid resistivity, short normal, long normal and lateral resistivity logs (see Fig. 6) were obtained from a rest water-level of -6m (depths measured relative to top of casing, about 0.6m above ground level) to the bottom of the hole at 40m and the exercise was repeated a week later from a depth of -16m after dewatering the hole three times. The initial temperature log in the undisturbed water showed a slight decrease with

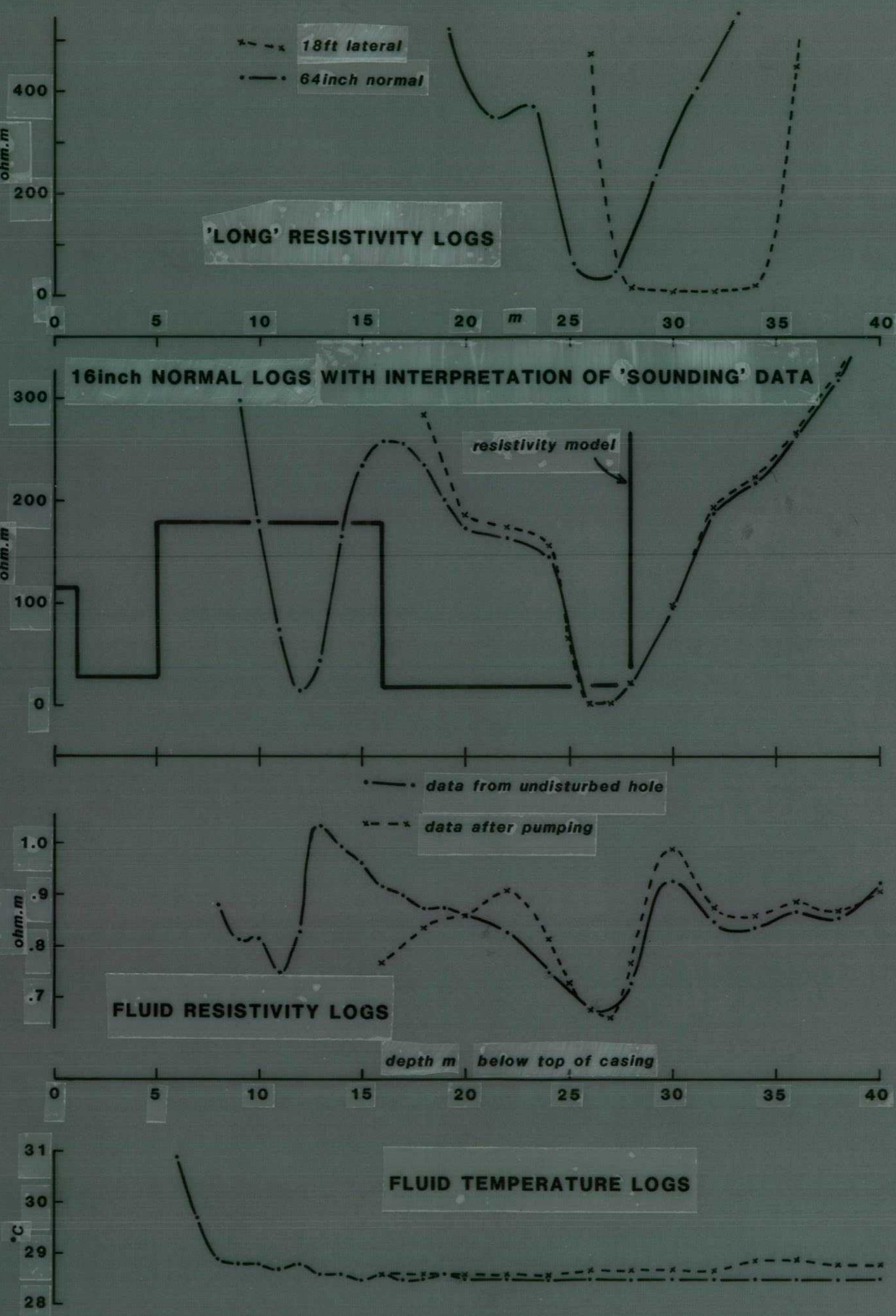

Fig 6. Geophysical logs from a saline well near Tangalle, Sri Lanka

depth to 15m before it stabilized at a value of 28.5°C: fluid resistivities were surprisingly variable over the range 0.7-1ohm.m with two conductive zones at 8-12m and 24-28m depth respectively. A layer of fresh water at the top of the column can be attributed to the direct infiltration of rain-water around the outside of the casing, with the conductive zone below it representing a seepage of older groundwater at the base of the colluvium in which salts leached from the soil and weathering zone have accumulated. The sharp discontinuity at 13m suggests a change to hard, impermeable rock containing fractures such as the one at 26m through which more saline water enters the hole, and it seems that fresher water must also have access in order to account for the higher resistivities through the intervening zone. After pumping the well the water temperature showed a small positive gradient with depth between 16m and 34m to reach nearly 29°C. Fluid resistivities were little changed near the bottom of the hole but values at 23m were nearly 10% higher before falling back below those recorded earlier from 20m to 16m, the limit of recovery at the time of taking the measurements. This pattern is consistent with some fresher water entering the hole at 23-24m, above a clay-filled fracture of low permeability, while saline water from the more productive upper zone fills the hole: if the fresher water is slightly confined it will then tend to flush the column upwards. The resistivity logs showed the same conductive layers at 12m and 27m with a marked increase in resistivity below 31m. Modelling the original resistivity sounding curve for this site (see Appendix) required a 5-layer HKH sequence: a 1m thick surface layer of 100ohm.m underlain by 4m of colluvium at 25ohm.m rested on a more resistive zone to about 16m depth; this was succeeded by a conductive layer of 20ohm.m to the resistive sub-stratum at 30m. The basic features of this interpretation are in good agreement with the borehole logs, particularly in defining the resistive base, and although the intermediate zone has been simplified the presence of the deeper conductive layer is indicated.

Seismic refraction data were collected using the signal enhancement OYO seismograph belonging to the WRB in conjunction with a weight-drop energy source. Two short lines of two spreads were sited across and along the valley near the borehole. The plots of first-arrival times against distance were very irregular but despite some difficulties in obtaining good quality data this almost certainly reflects the variability in the nature of the sequence. Only two layers were positively identified, representing an overburden velocity of 0.4-0.6m/ms above compact rock of about 4m/ms. The overburden itself appears inhomogeneous, due perhaps to the presence of boulders within it, and thickness estimates using a simple delay-time analysis put its thickness at 4-8m, consistent with the resistivity interpretation. The bedrock interface may be approximately horizontal as the variation in depth is largely accommodated by the change in geophone elevation.

4.3 CONCLUSIONS

It was intended that the format devised for putting information onto the computer data-base would provide a summary of the geophysical data collected at each well site together with several parameters relating to their interpretation, on the assumption that resistivity sounding would be the method most commonly employed. The immediate objective is to assess existing data. Most of the necessary details can be abstracted from the records but the interpreted values will have to be assigned by qualified staff as the success of the system depends upon the quality of the data put in. It will obviously be easier to establish a system for collecting information in a suitable form for direct input in future.

Field trials in Hambantota district showed that useful information can be obtained from borehole logging and futher such work is justified in any investigation of the aquifer system and the problems of high salinity. The seismic method was seen to work despite a combination of adverse factors including poor energy transmission, high wind noise, an inadequate energy source, difficult local topography and access. In areas of such shallow hard rock the application to siting boreholes appears limited, but for dug wells it could prove very useful.

Proposals were submitted and accepted in principle for additional fieldwork in 1986 to study two aspects of the basement aquifer system. The first, in relation to borehole siting, is concerned with establishing the relation between fracture zones and 'breaks' identified on resistivity sounding curves; the second is to determine the most efficient techniques for mapping the bedrock surface, in order to site collector wells to the best advantage.

5 ACKNOWLEDGEMENTS

All the assistance provided by staff of the Water Departments in Malawi, Sri Lanka and Zimbabwe is gratefully acknowledged: this included making field crews and transport available, often at short notice. The British High Commissions also helped with transport and with clearance of equipment through customs. The projects are funded by the Overseas Development Administration.

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APPENDIX: Selected resistivity sounding data with interpretations

A representative set of resistivity sounding curves are included to illustrate the type of data obtained during the fieldwork. The data were collected using standard techniques with a Schlumberger array configuration and the curves were adjusted to compensate for any discontinuities associated with changes in potential dipole length. Model curves were generated using the linear filter method of Ghosh (1971) as developed by O'Neill (1975), and then matched directly against the field points on a microcomputer. Adjustments were made to the model by inspection rather than by one of the semi-automatic curve-fitting routines. The interpretations presented are subject to the usual ambiguity due to the limitations of a one-dimensional model with equivalence and suppression effects and they are not put forward as being definitive.

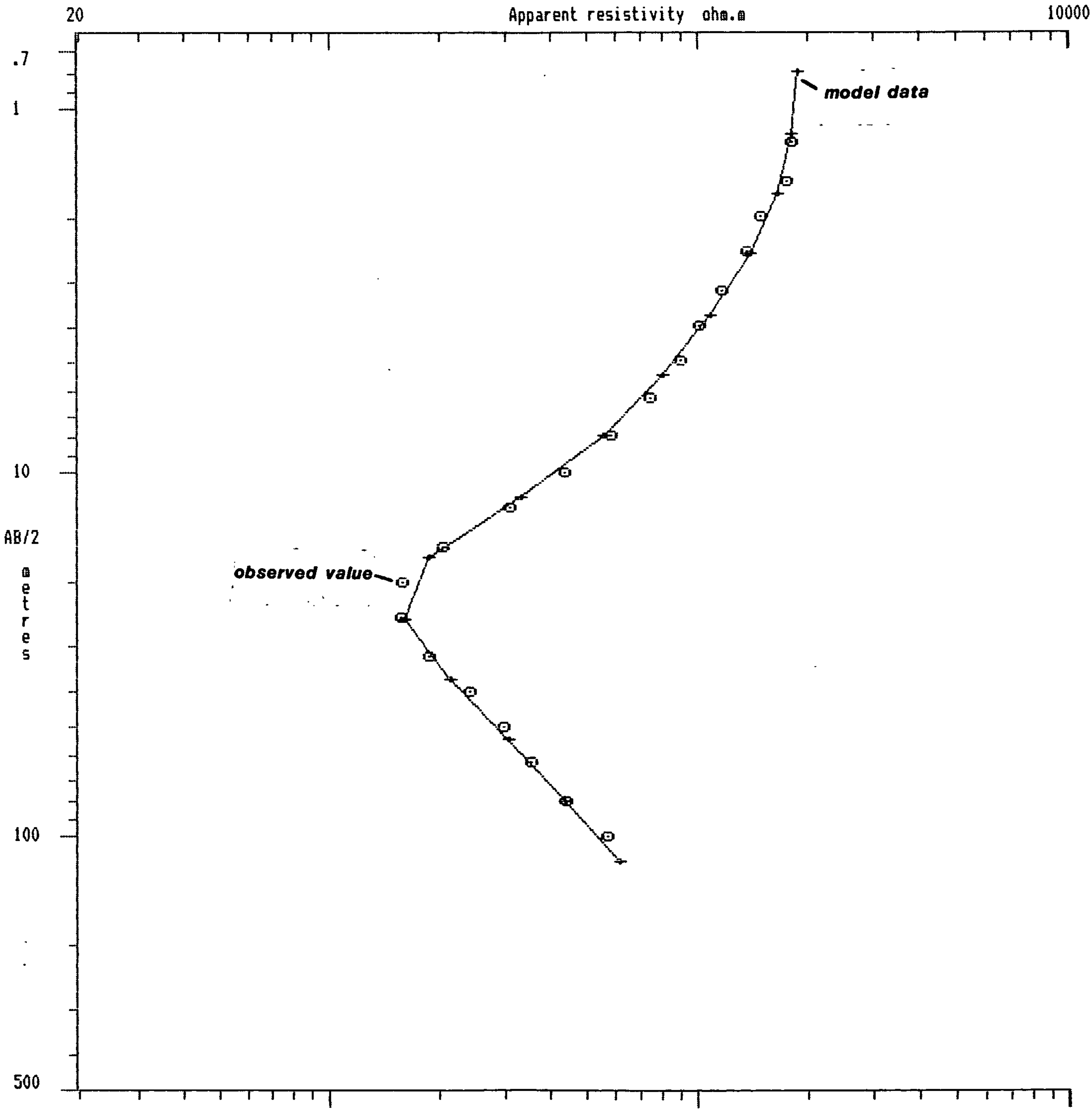
The sites illustrated are:

St Lioba's School, Wedza; GP72/R1(x2) and R2
Mukumba School, Chiota; GP35, GP301(x2) and b/h9 (x2), GP228
Chitedze, Malawi; R3 and R10
Ntcheu, Malawi; R2 and R4
Mponela, Malawi; R2, R3 and R5
Chimimbe dambo traverse; R1 to R6, by percussion hole sites
Tangalle, Sri Lanka; MRA12

Resistivity 'sounding' results.

Site: Z/Wed/StL1b(S)

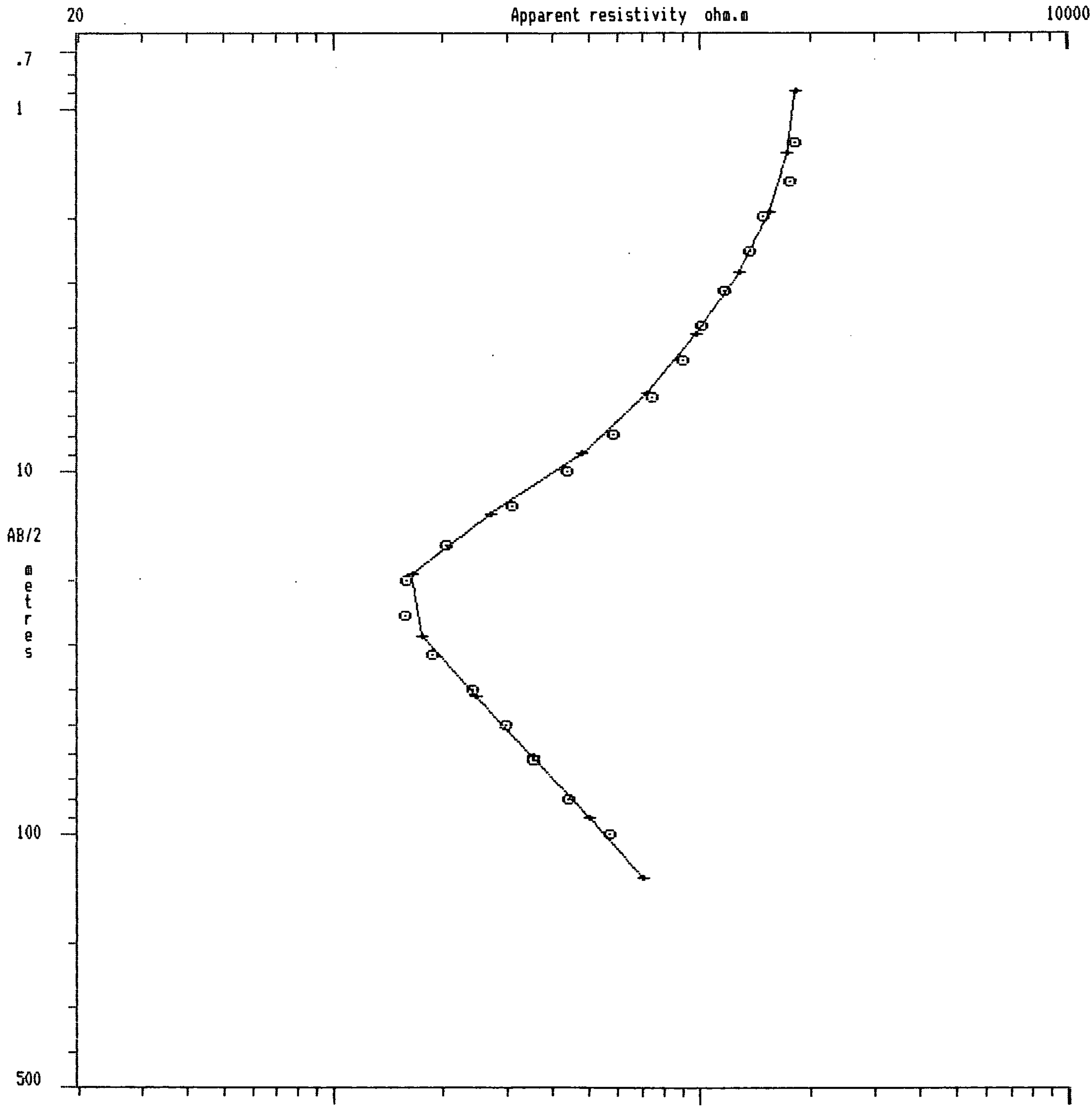
MODEL: layer	res		depth
(1)	1900.0	to	1.3
(2)	760.0	to	5.5
(3)	70.0	to	17.0
(4)	5000.0	to	))



Resistivity 'sounding' results.

Site: Z/Wed/StLib(S)

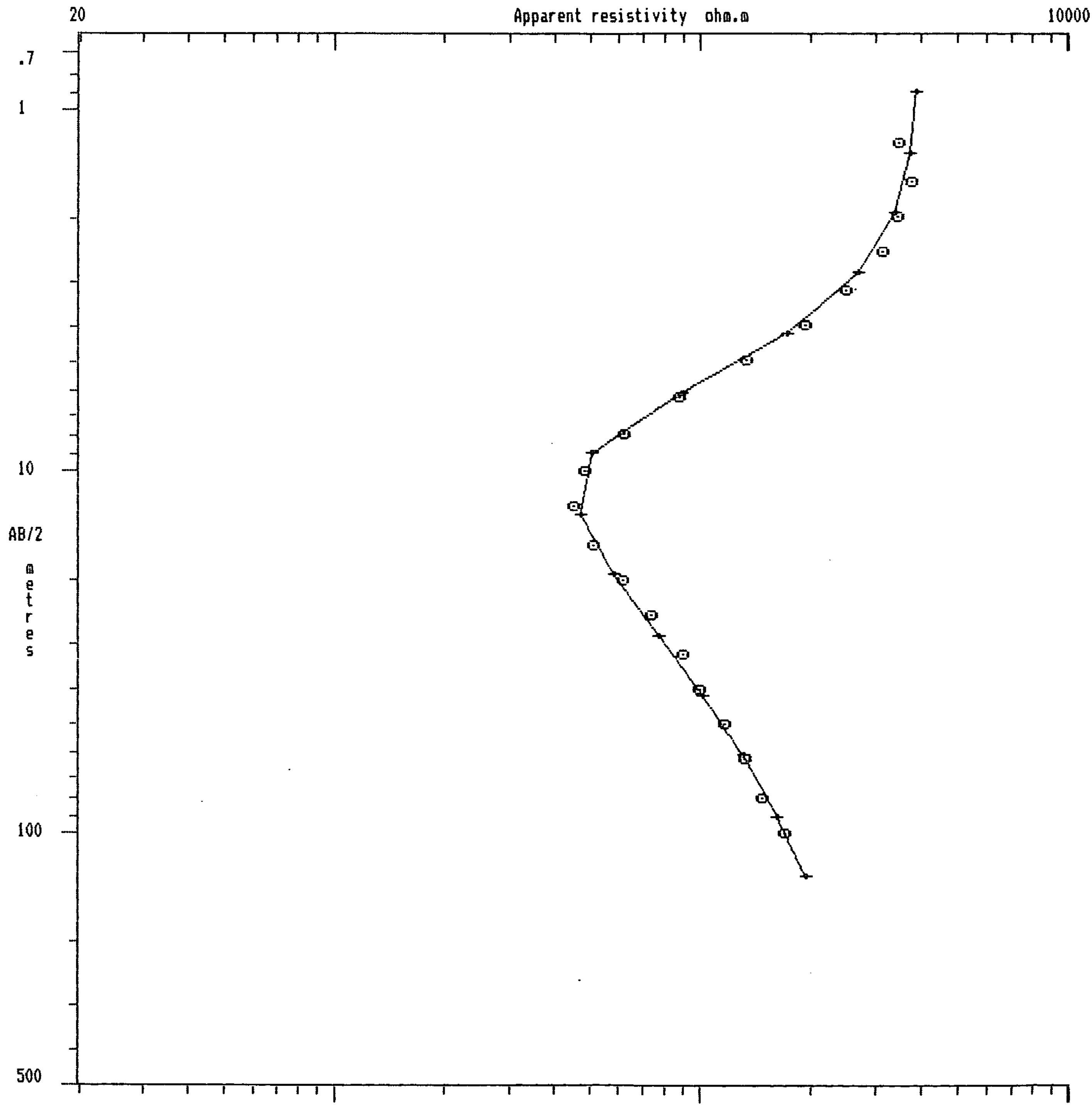
MODEL: layer	res		depth
(1)	1850.0	to	1.3
(2)	750.0	to	5.8
(3)	24.0	to	9.5
(4)	4500.0	to	>>



Resistivity 'sounding' results.

Site: Z/Wed/StL2a(S)

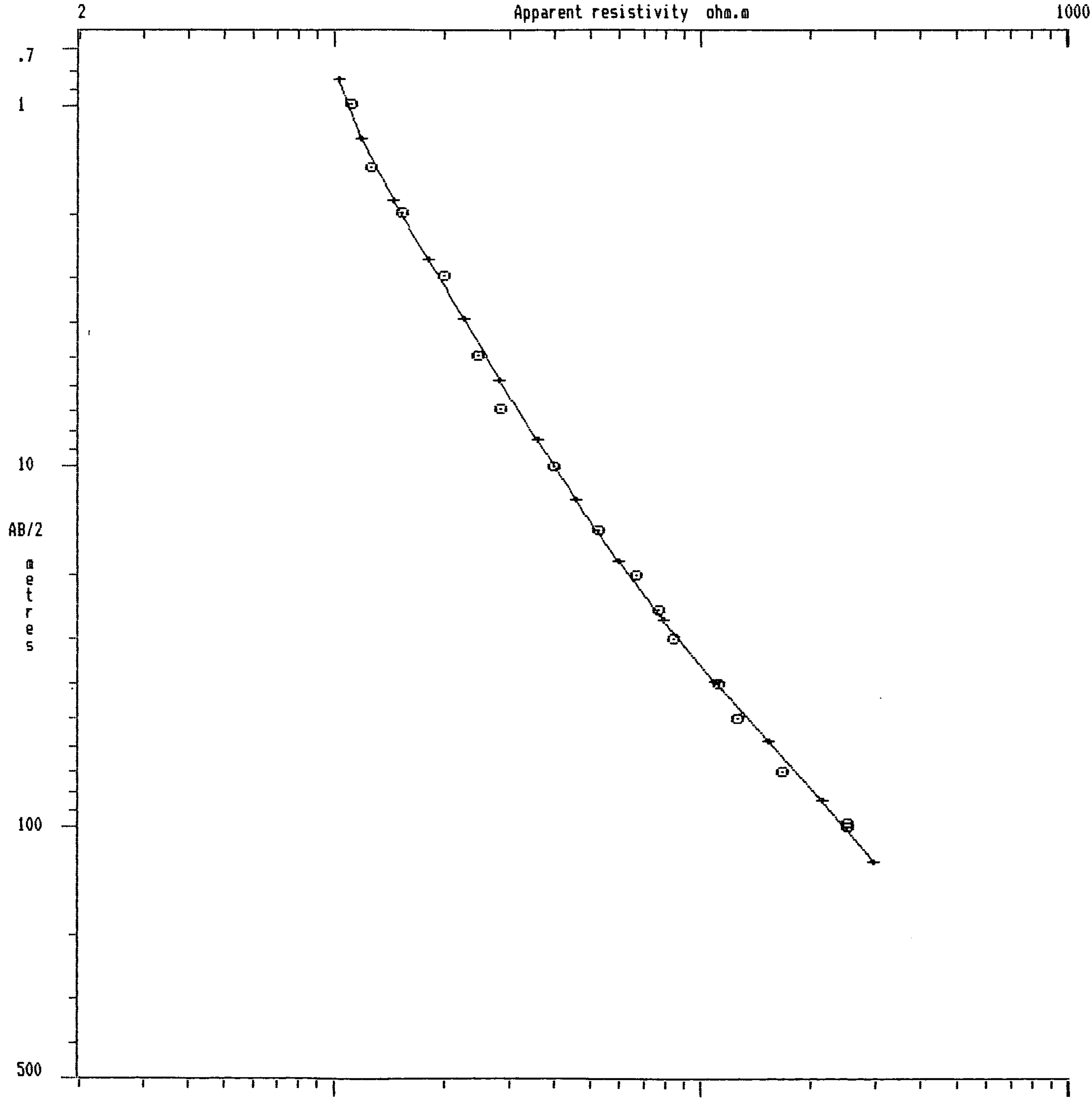
MODEL: layer	res		depth
(1)	3900.0	to	1.9
(2)	320.0	to	11.0
(3)	2800.0	to	))



Resistivity 'sounding' results.

Site: Z/Ch/Muk35(S)

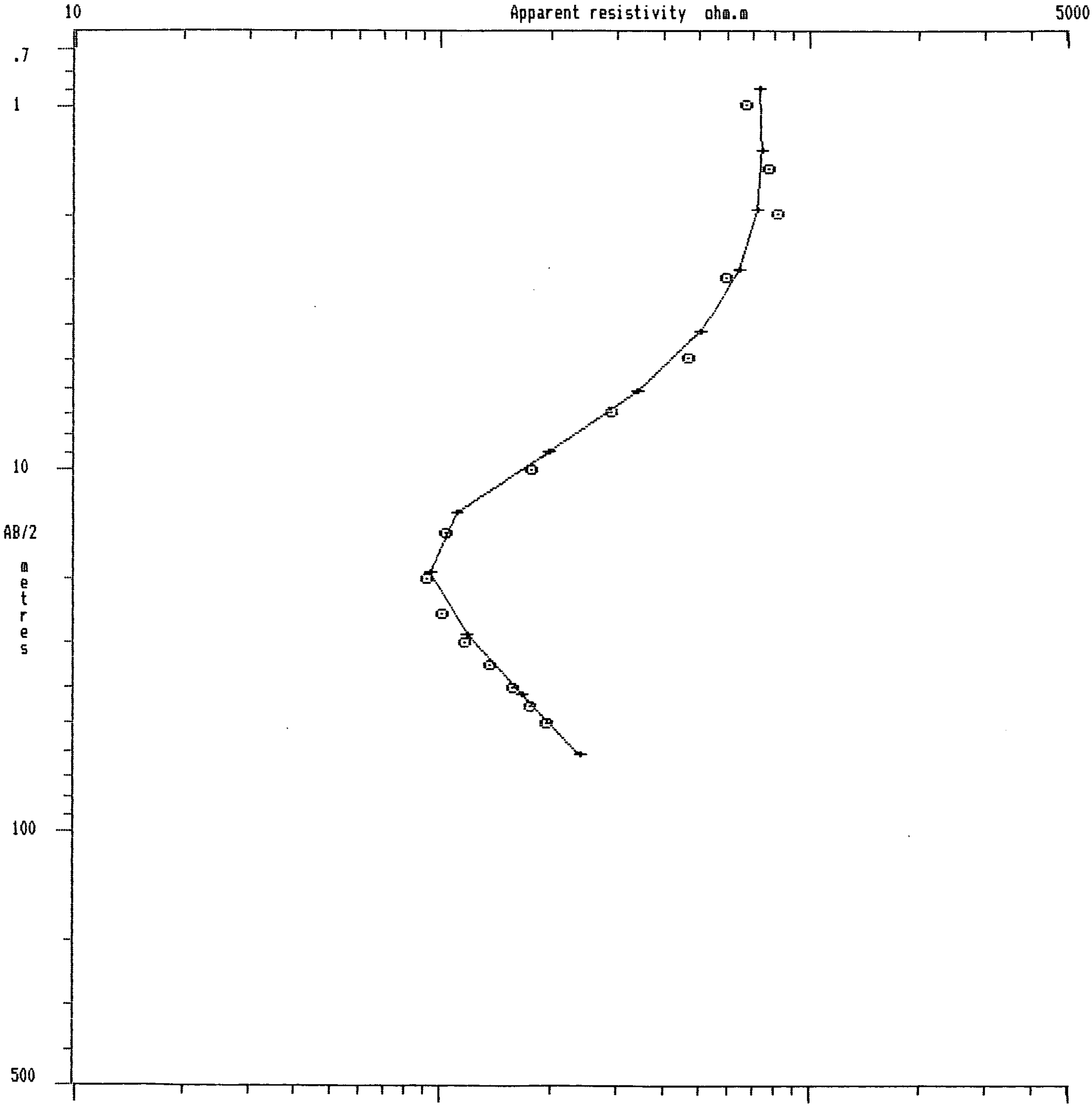
MODEL: layer	res		depth
(1)	9.0	to	0.8
(2)	32.0	to	4.0
(3)	93.0	to	19.0
(4)	1500.0	to	))



Resistivity 'sounding' results.

Site: Z/Ch/Muk301n(S)

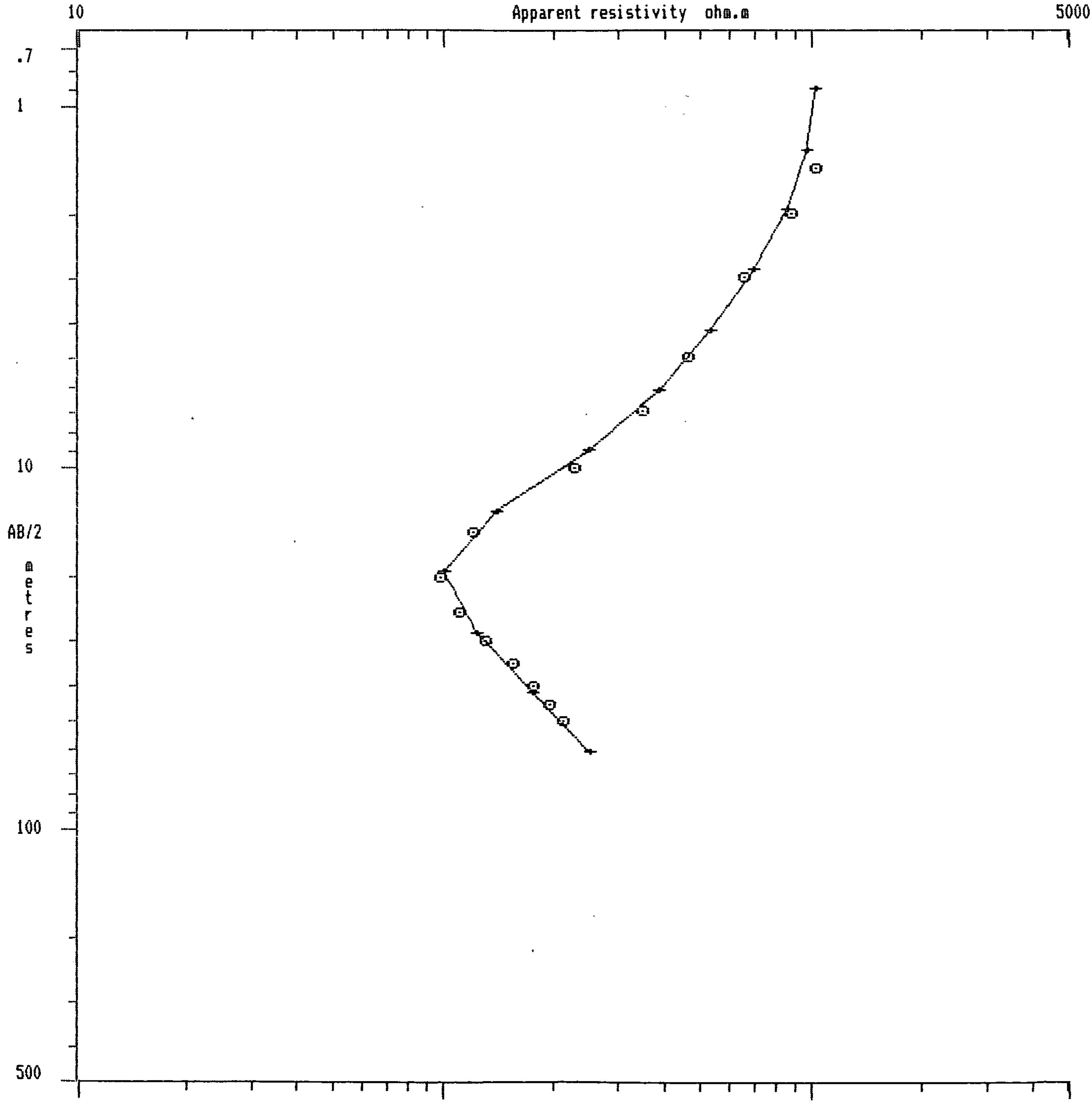
MODEL: layer	res		depth
(1)	700.0	to	0.6
(2)	900.0	to	1.5
(3)	400.0	to	4.0
(4)	56.0	to	17.0
(5)	3000.0	to	>>



Resistivity 'sounding' results.

Site: Z/Ch/Muk301w(S)

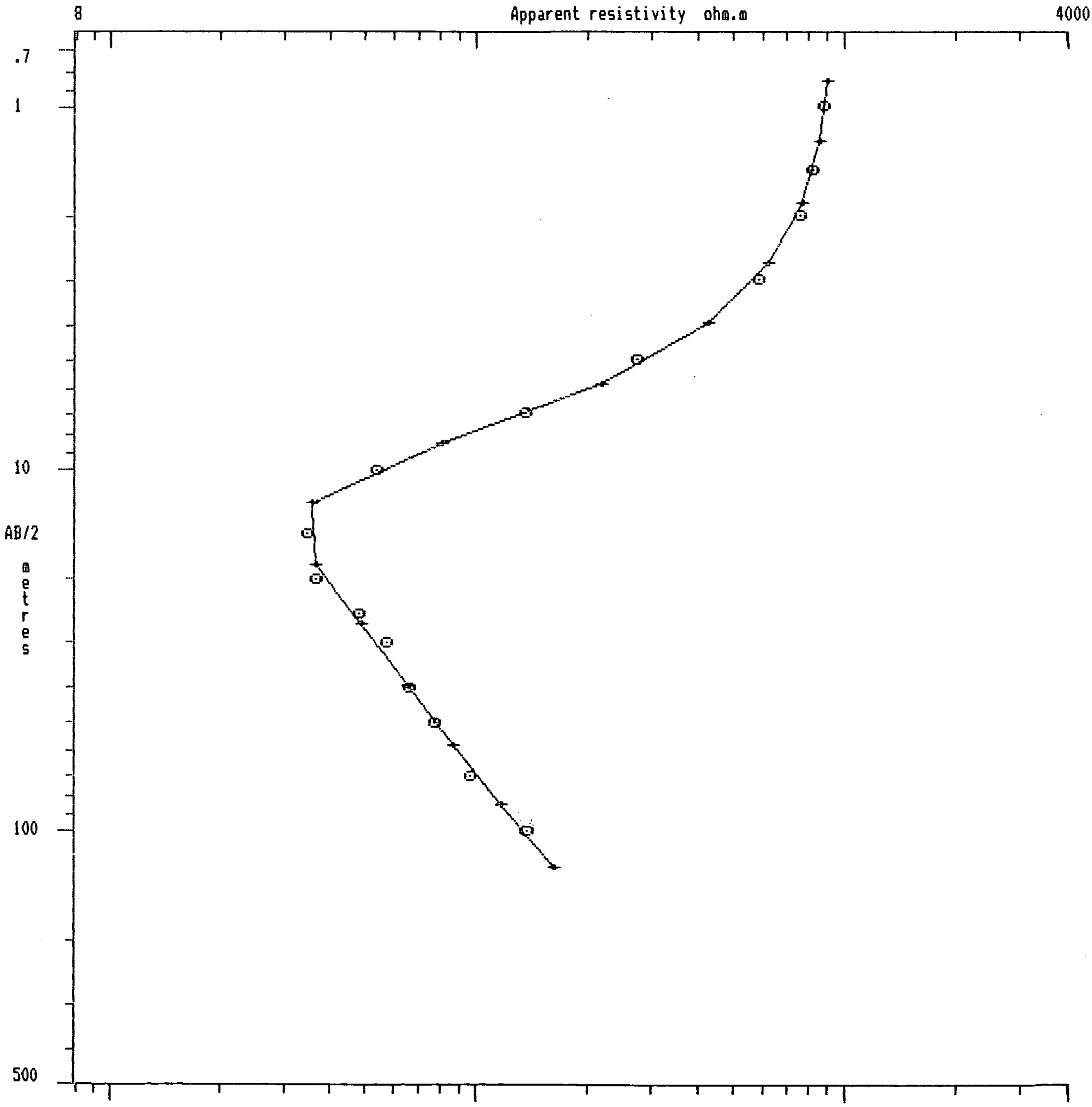
MODEL: layer	res		depth
(1)	1050.0	to	1.2
(2)	440.0	to	5.2
(3)	13.0	to	7.8
(4)	120.0	to	10.0
(5)	3000.0	to	))



Resistivity 'sounding' results.

Site: Z/Ch/Muk-bh9(S)

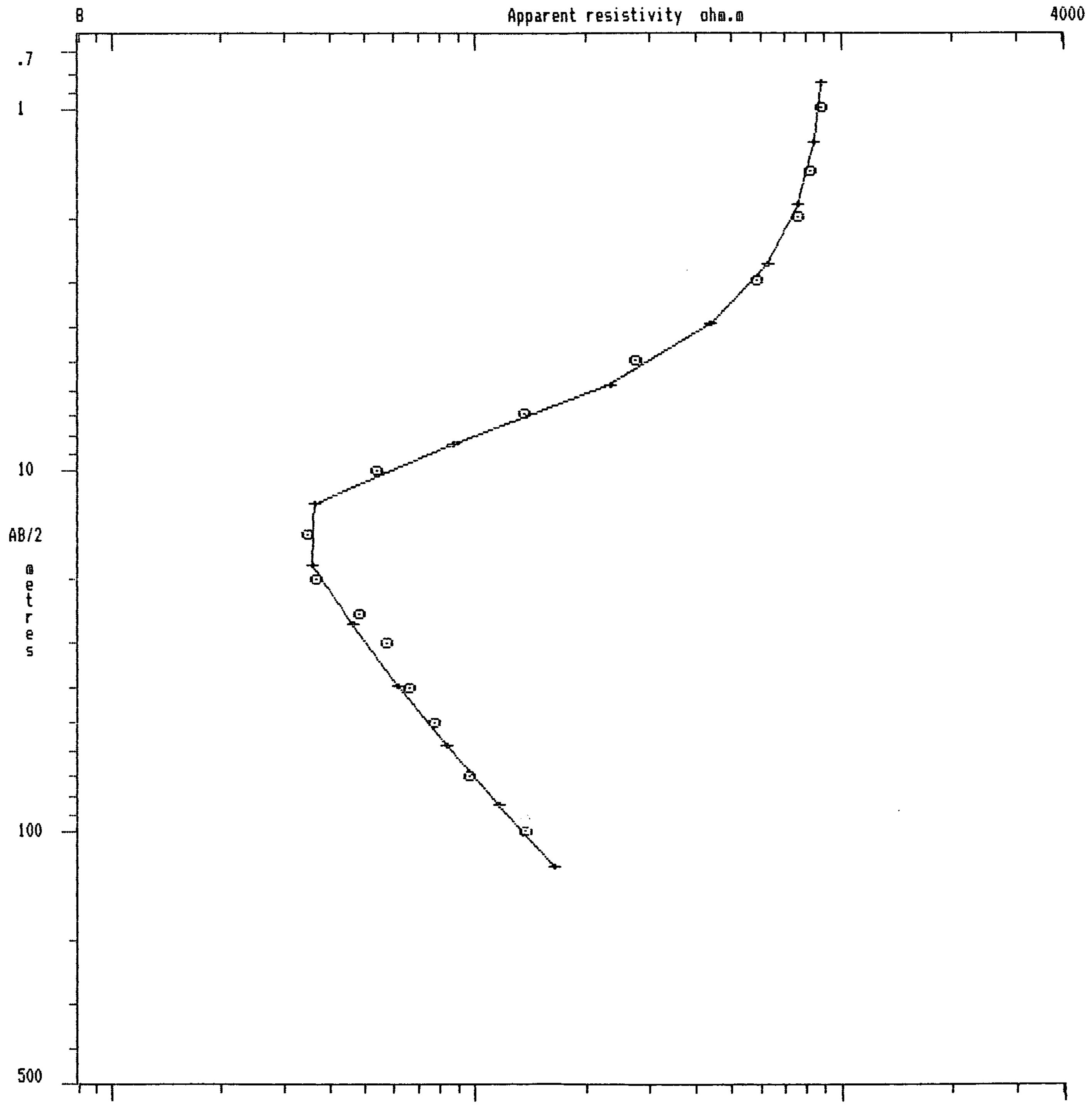
MODEL: layer	res		depth
(1)	920.0	to	1.0
(2)	600.0	to	2.6
(3)	18.0	to	11.0
(4)	800.0	to	15.0
(5)	40.0	to	26.0
(6)	3000.0	to	))



Resistivity 'sounding' results.

Site: Z/Ch/Muk-bh9(S)

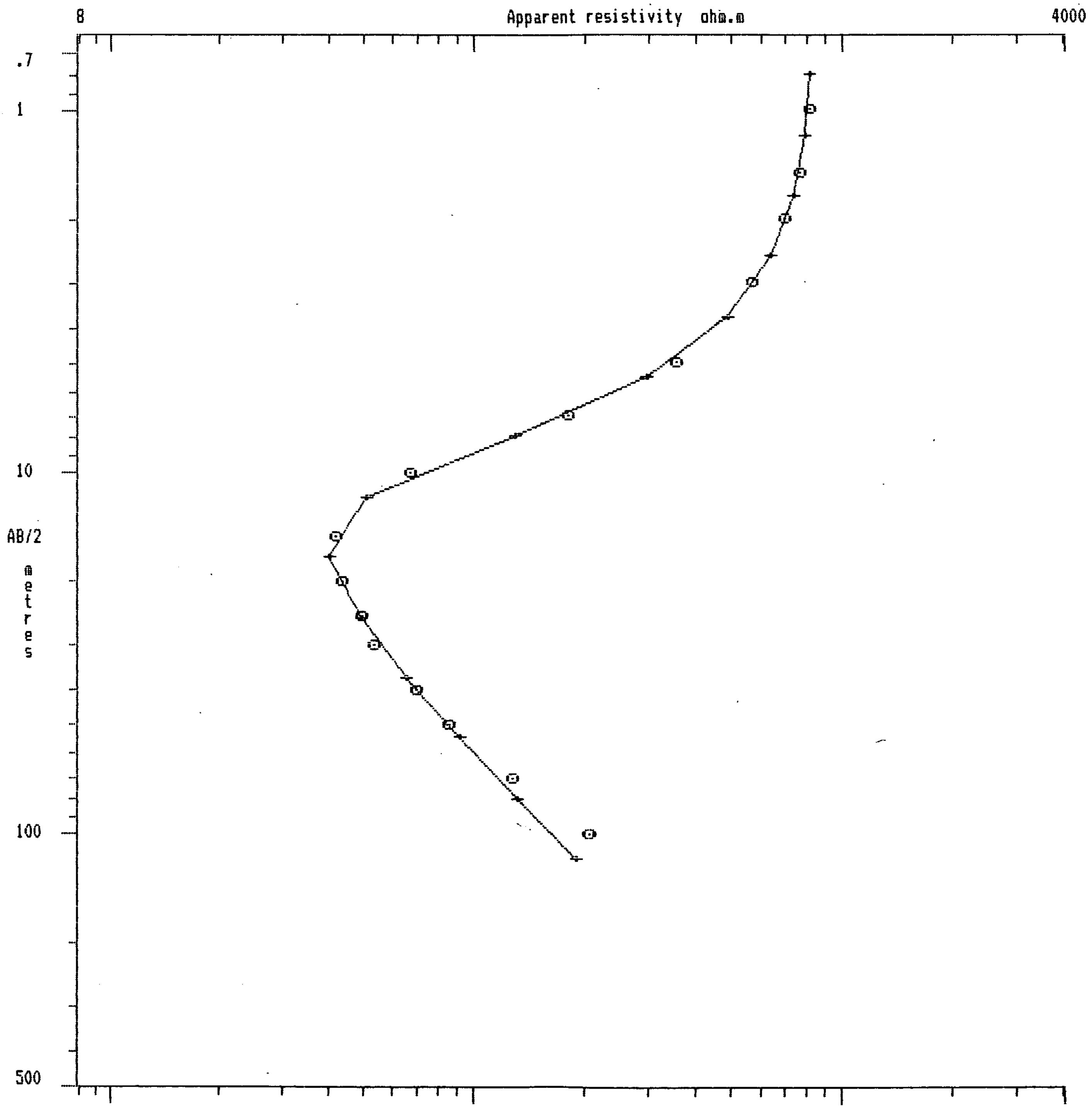
MODEL: layer	res		depth
(1)	900.0	to	1.0
(2)	600.0	to	2.7
(3)	13.0	to	7.5
(4)	85.0	to	35.0
(5)	1500.0	to	))



Resistivity 'sounding' results.

Site: Z/Ch/Muk228(S)

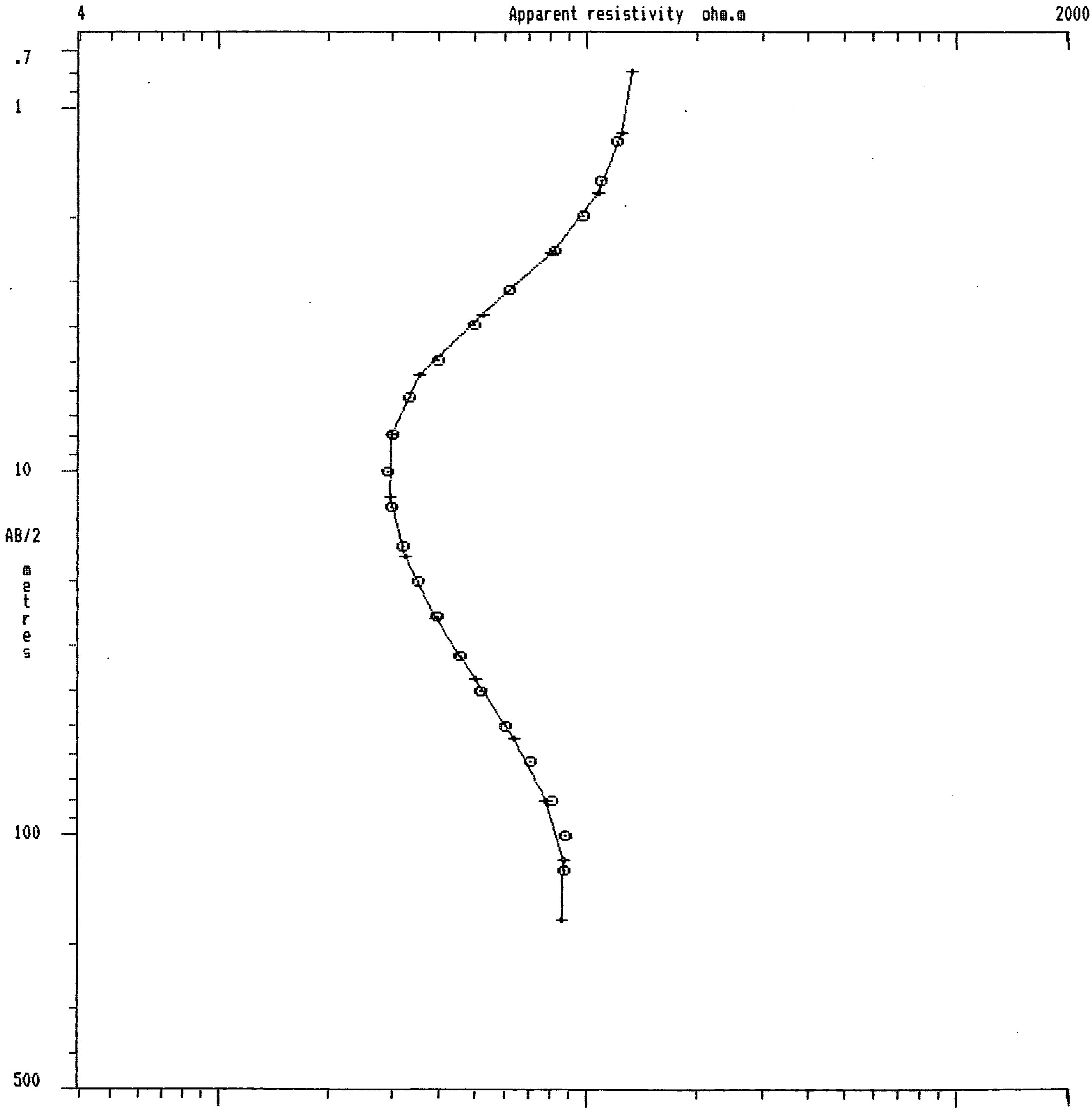
MODEL: layer	res		depth
(1)	820.0	to	1.0
(2)	620.0	to	2.8
(3)	18.0	to	7.5
(4)	57.0	to	26.0
(5)	3000.0	to	>>



Resistivity 'sounding' results.

Site: M/Chit/R3(S)

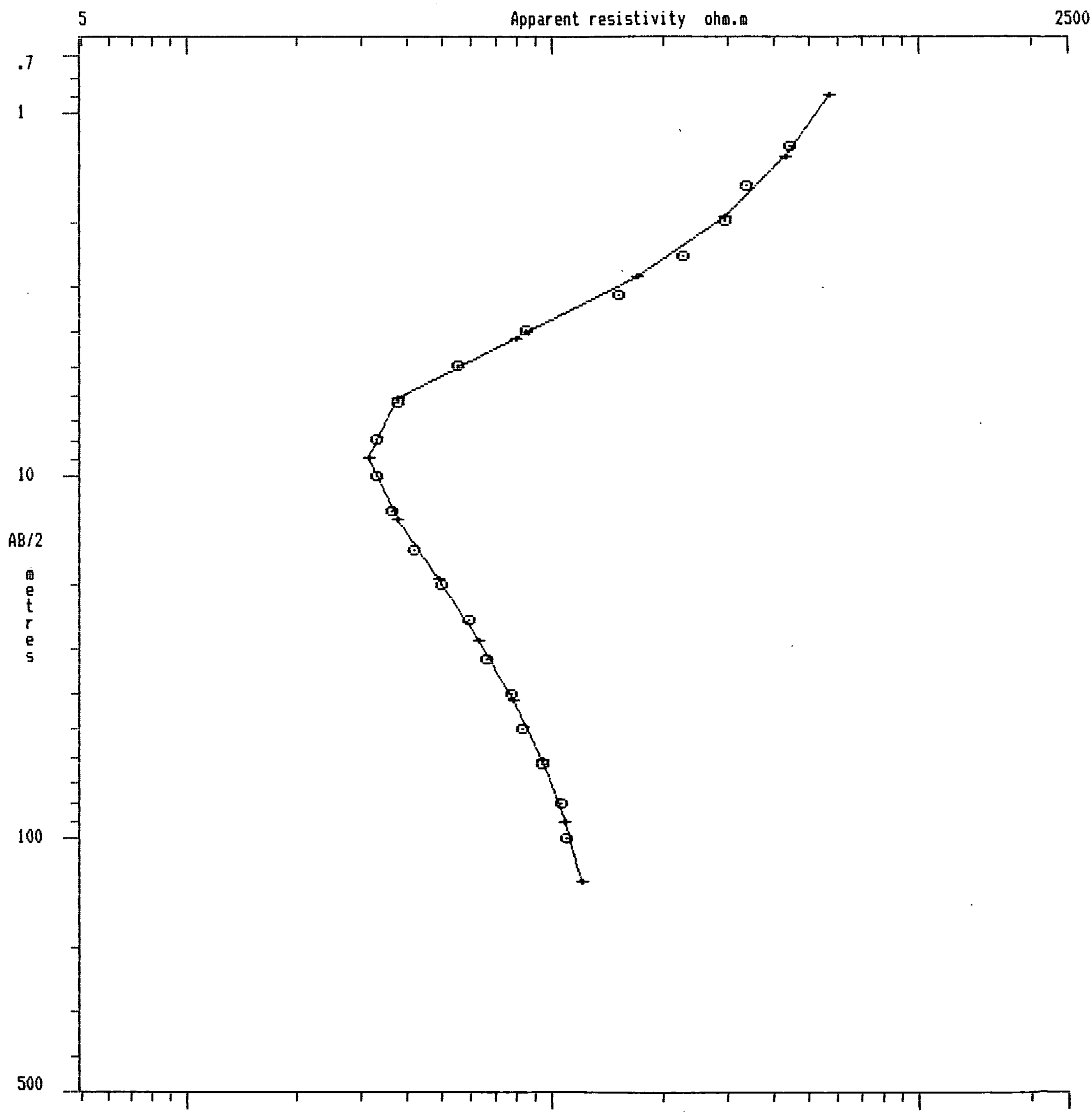
MODEL: layer	res		depth
(1)	137.0	to	1.3
(2)	26.0	to	12.5
(3)	45.0	to	20.0
(4)	200.0	to	70.0
(5)	33.0	to	))



Resistivity 'sounding' results.

Site: M/Chit/R10(S)

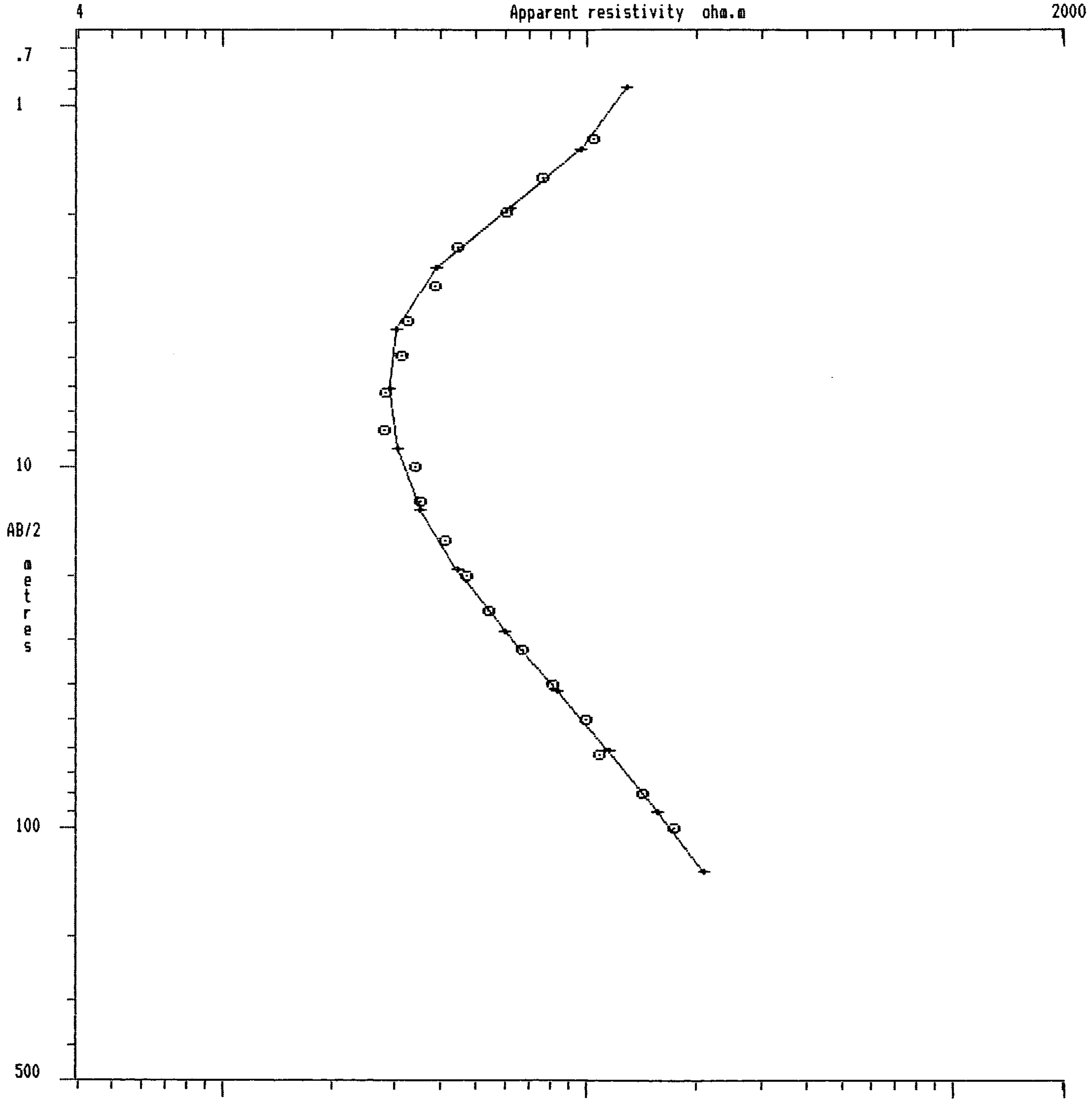
MODEL: layer	res		depth
(1)	750.0	to	0.5
(2)	300.0	to	1.6
(3)	21.0	to	7.6
(4)	140.0	to	>>



Resistivity 'sounding' results.

Site: M/Ntch/R2(S)

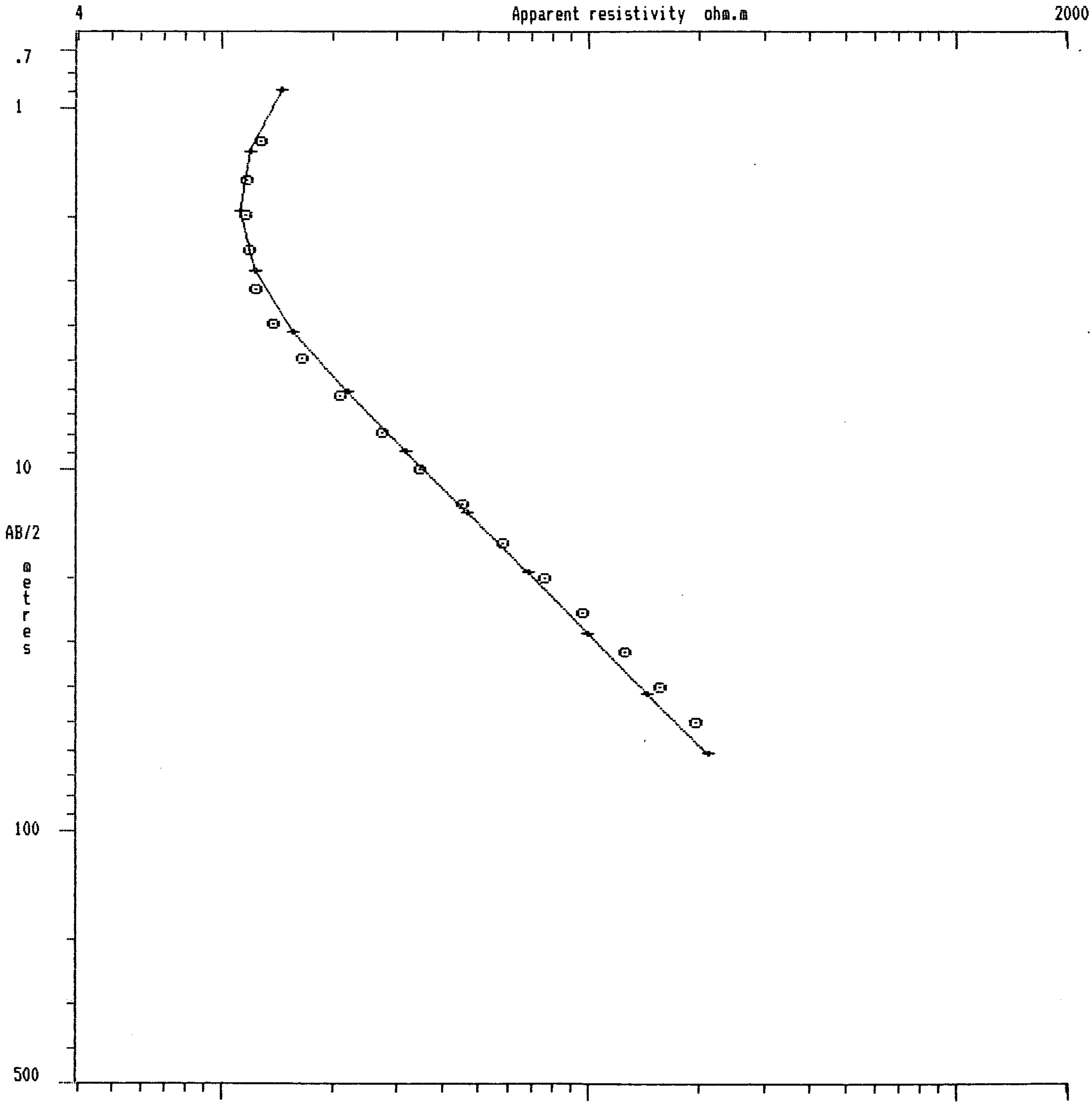
MODEL: layer	res		depth
(1)	160.0	to	0.7
(2)	26.0	to	7.0
(3)	40.0	to	15.0
(4)	600.0	to	>>



Resistivity 'sounding' results.

Site: M/Ntch/R4(S)

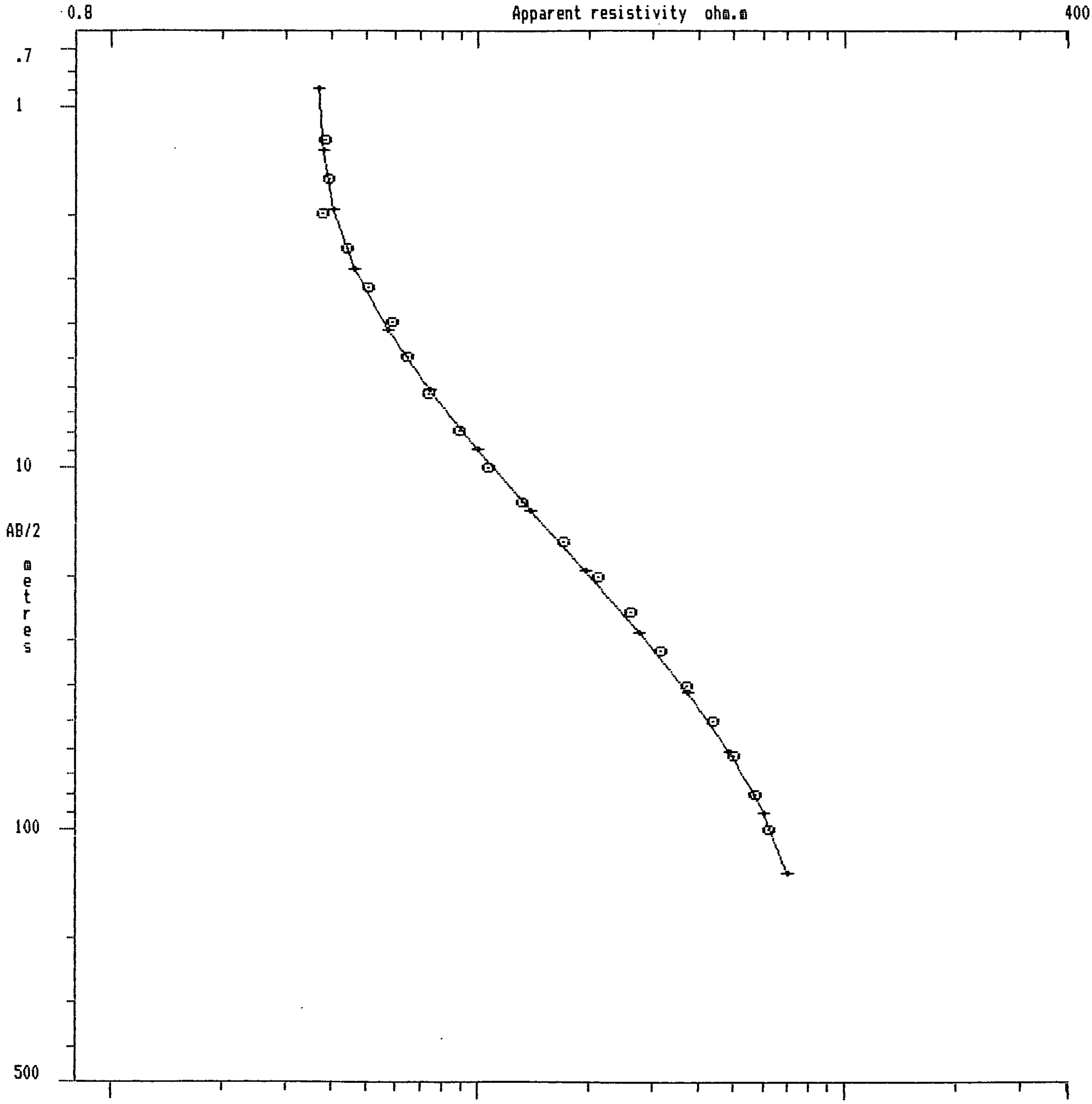
MODEL: layer	res		depth
(1)	27.0	to	0.3
(2)	9.5	to	2.9
(3)	8000.0	to	))



Resistivity 'sounding' results.

Site: M/Mpon/R2(S)

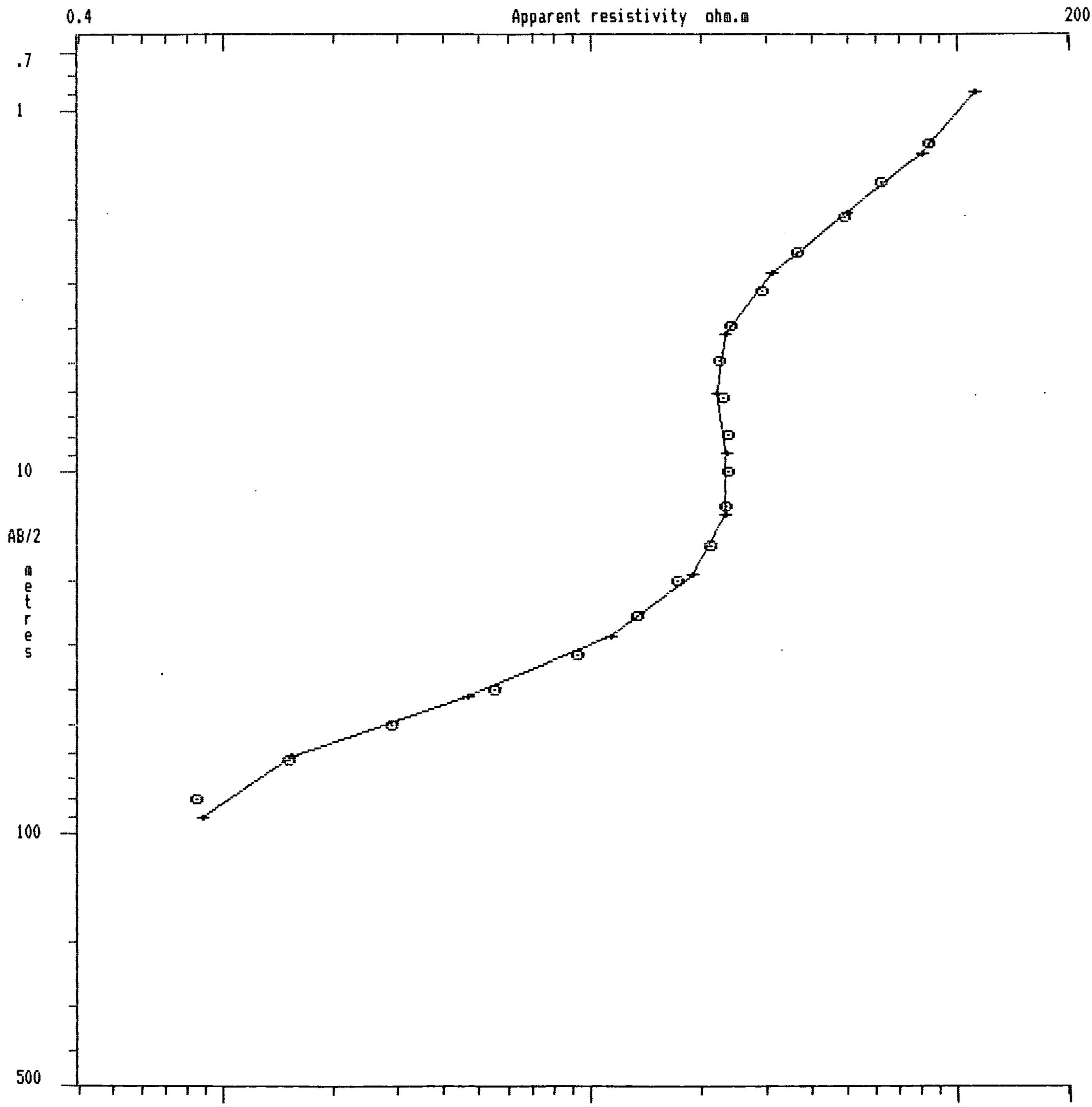
MODEL: layer	res		depth
(1)	3.6	to	1.9
(2)	11.0	to	6.3
(3)	350.0	to	20.0
(4)	70.0	to	))



Resistivity 'sounding' results.

Site: M/Mpon/R3(S)

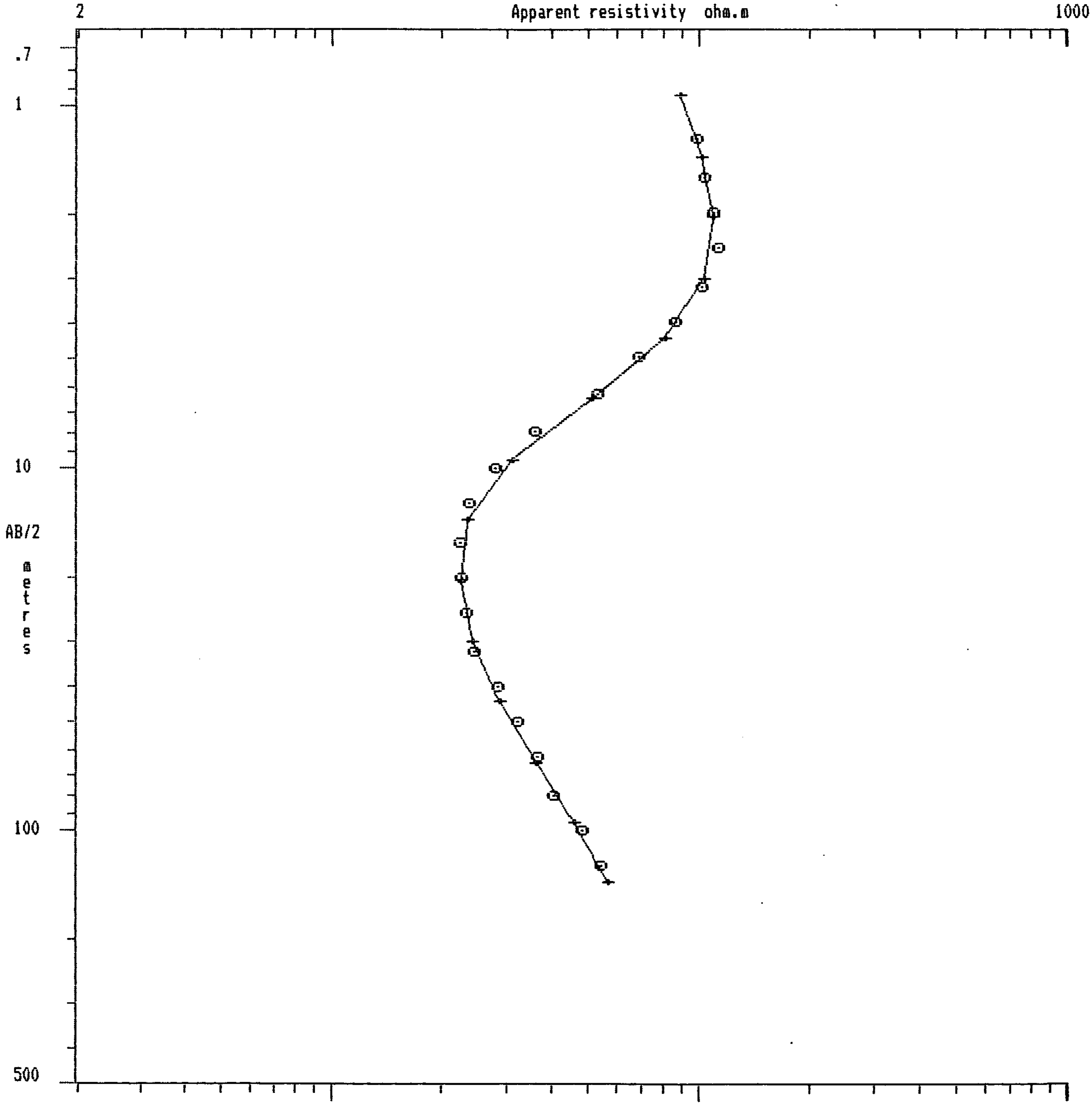
MODEL: layer	res		depth
(1)	150.0	to	0.6
(2)	30.0	to	1.7
(3)	14.0	to	4.0
(4)	50.0	to	9.5
(5)	0.8	to	>>



Resistivity 'sounding' results.

Site: M/Mpon/RS(S)

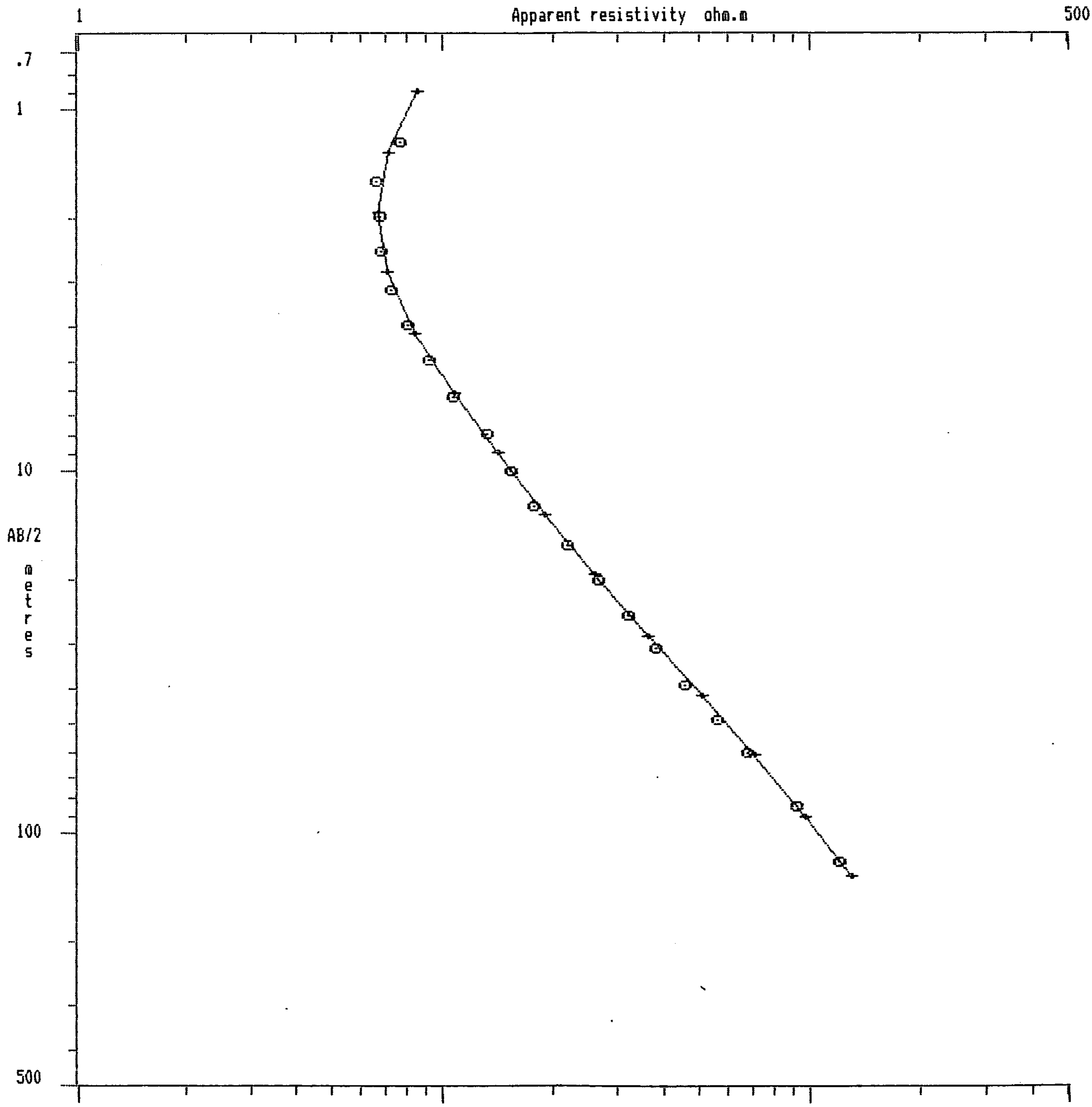
MODEL: layer	res		depth
(1)	70.0	to	0.6
(2)	200.0	to	1.7
(3)	20.0	to	28.0
(4)	100.0	to	))



Resistivity 'sounding' results.

Site: M/Mag/bh1(S)

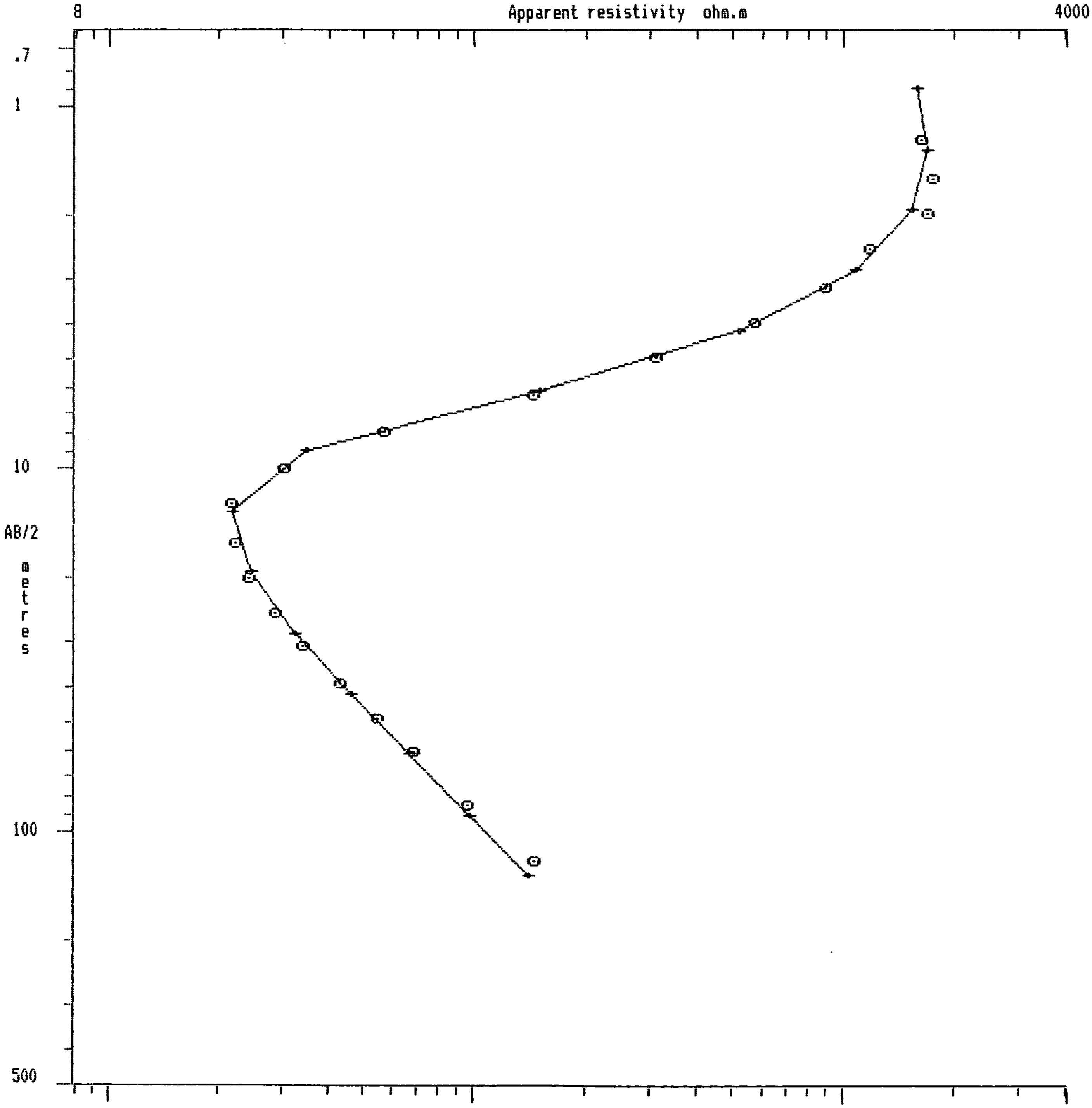
MODEL: layer	res		depth
(1)	15.0	to	0.3
(2)	5.8	to	2.7
(3)	28.0	to	11.0
(4)	380.0	to	))



Resistivity 'sounding' results.

Site: M/Mag/bh2a(S)

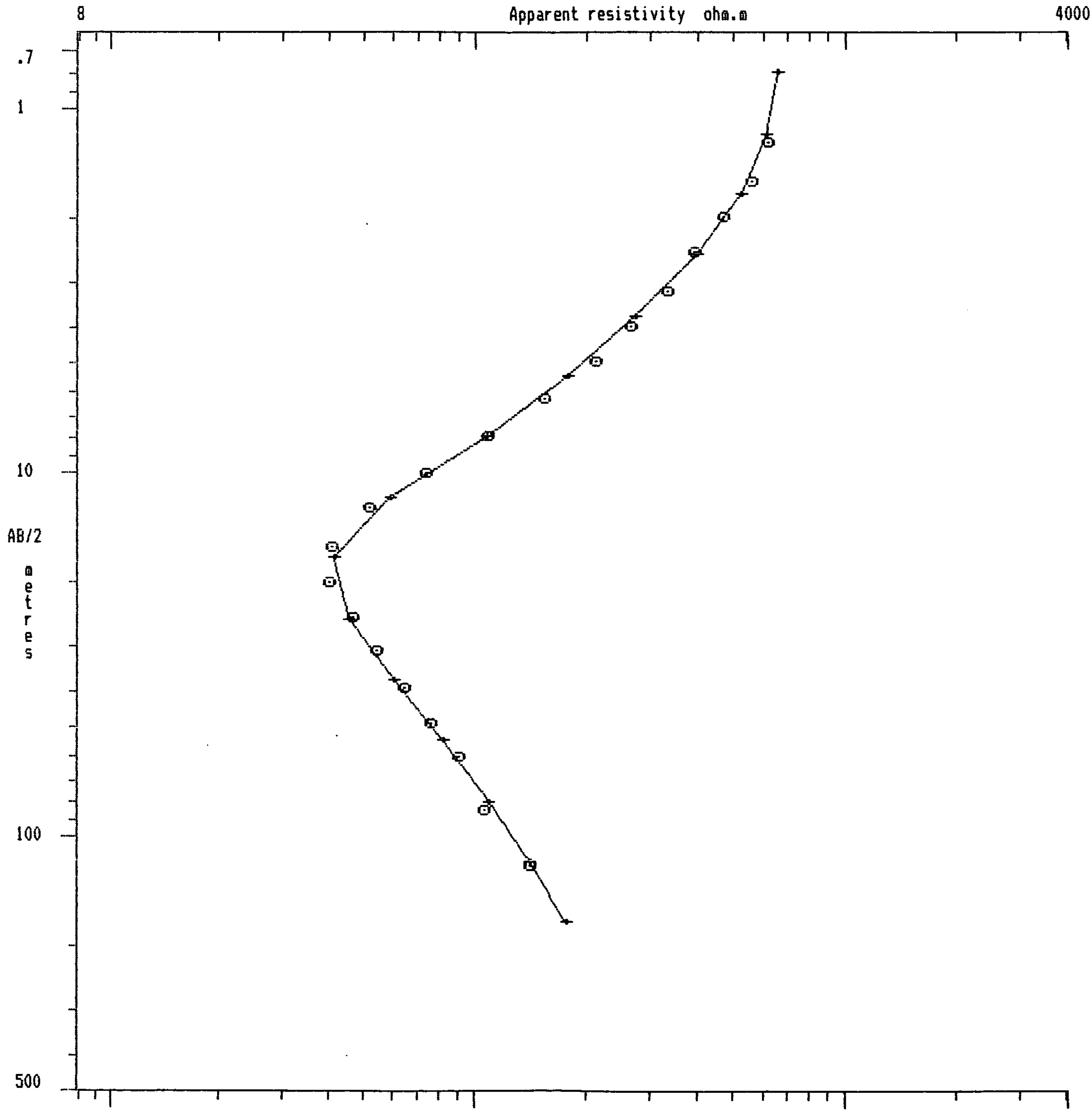
MODEL: layer	res		depth
(1)	1000.0	to	0.3
(2)	3000.0	to	1.2
(3)	18.0	to	17.5
(4)	3000.0	to	))



Resistivity 'sounding' results.

Site: M/Mag/bh2b(S)

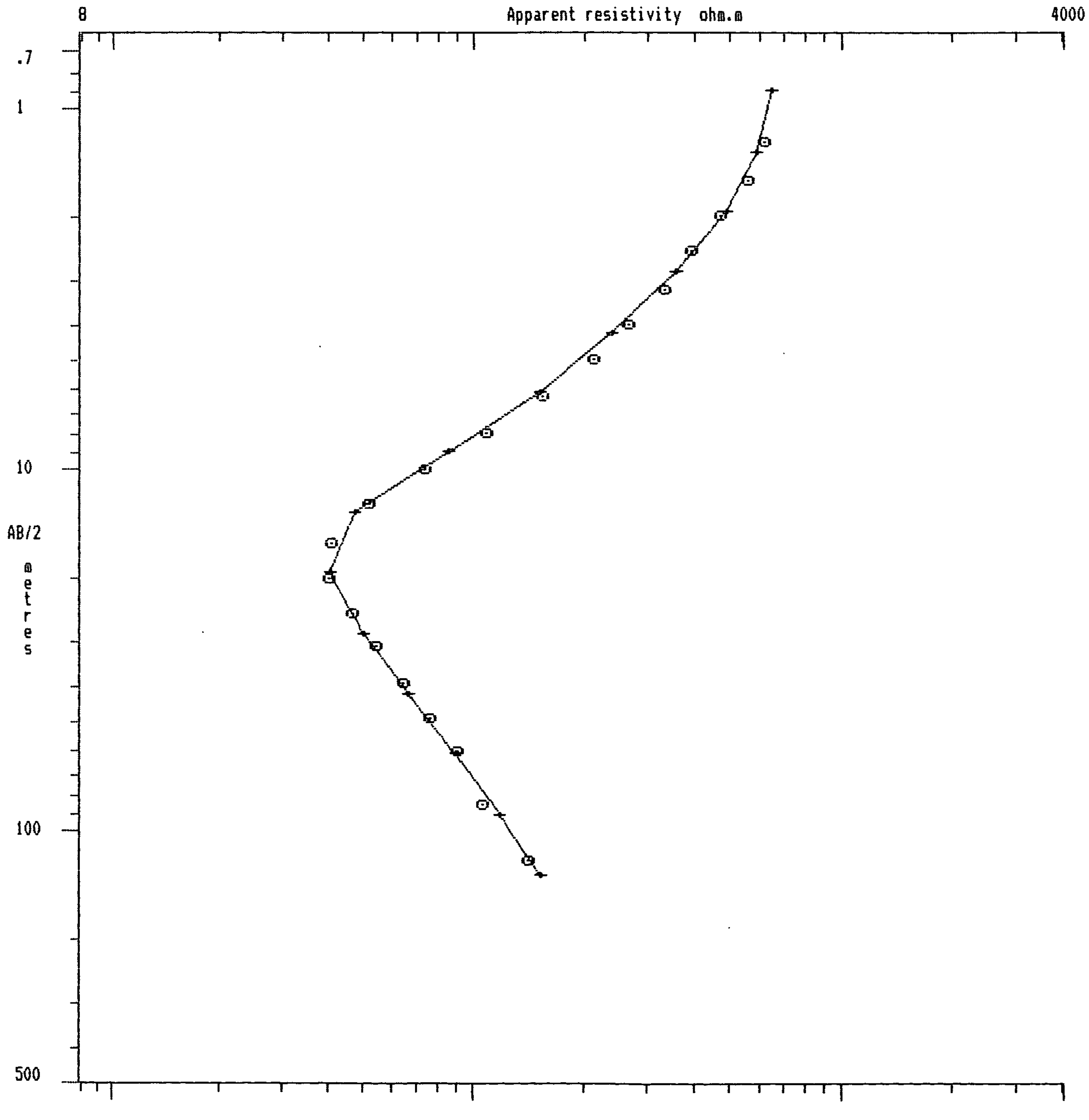
MODEL: layer	res		depth
(1)	680.0	to	1.1
(2)	200.0	to	4.2
(3)	25.0	to	17.0
(4)	320.0	to	))



Resistivity 'sounding' results.

Site: M/Mag/bh2b(S)

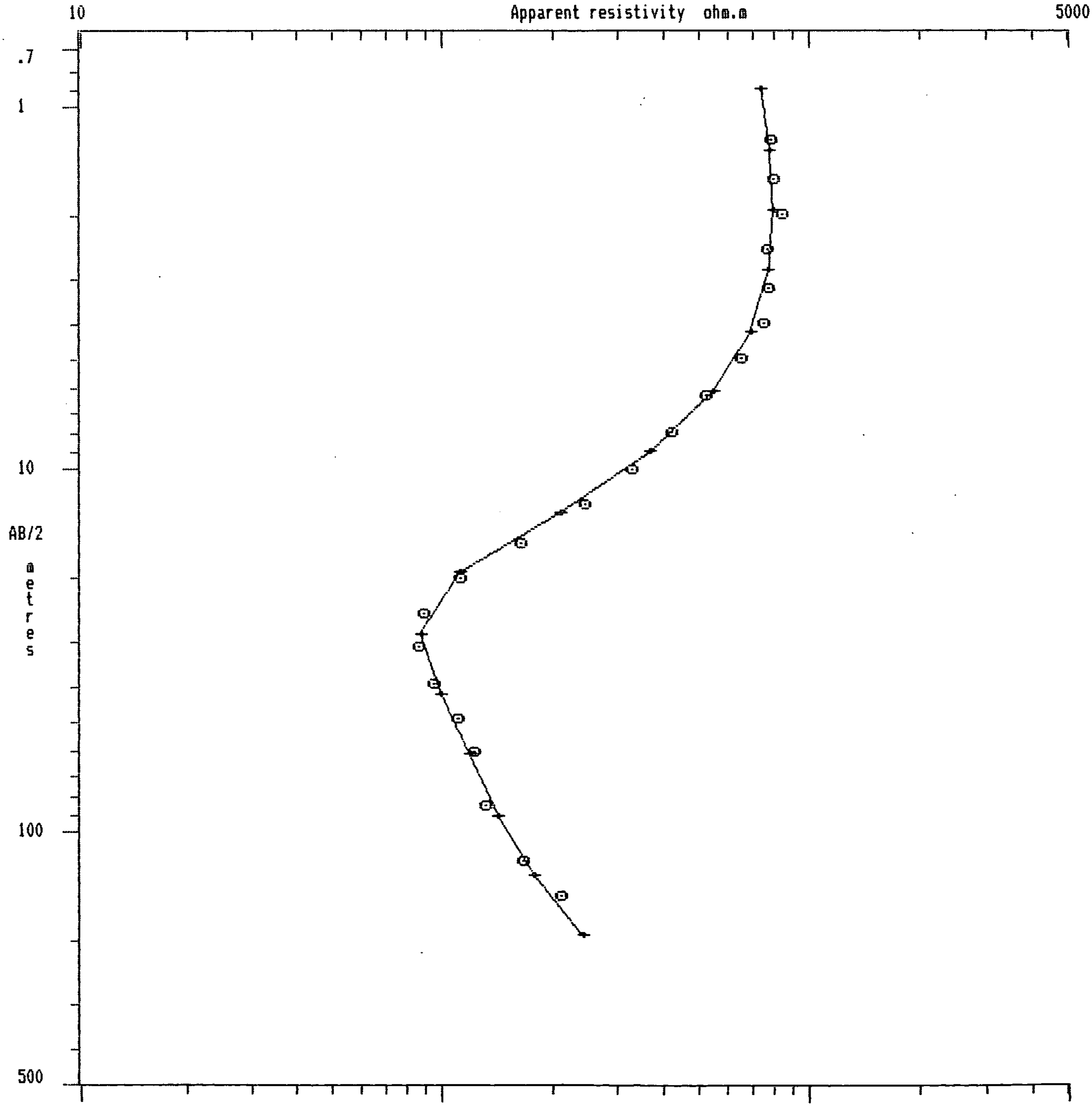
MODEL: layer	res		depth
(1)	680.0	to	1.1
(2)	200.0	to	4.2
(3)	20.0	to	12.0
(4)	95.0	to	27.0
(5)	350.0	to	))



Resistivity 'sounding' results.

Site: M/Mag/bh3a(S)

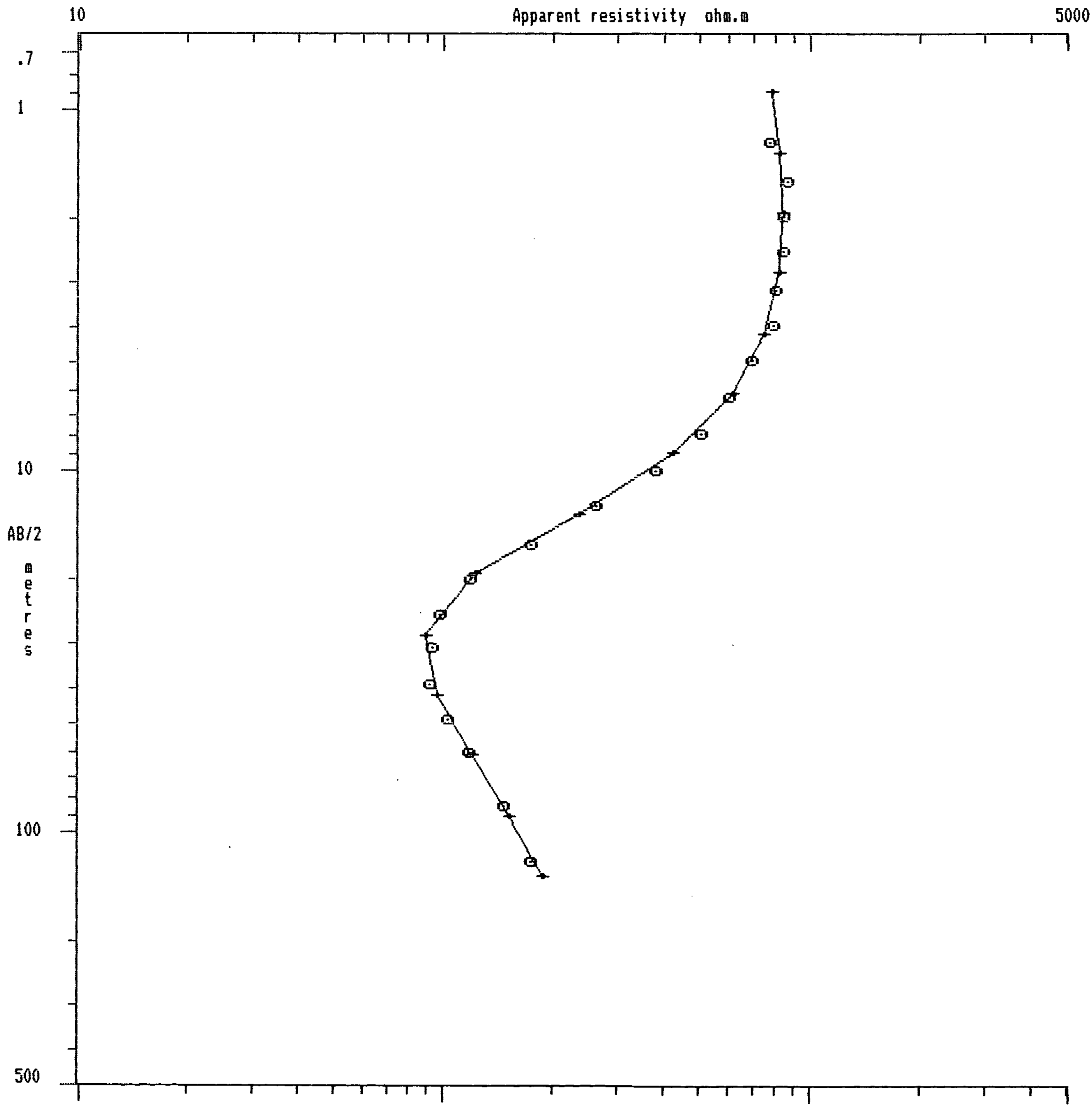
MODEL: layer	res		depth
(1)	650.0	to	0.4
(2)	880.0	to	2.5
(3)	380.0	to	6.5
(4)	40.0	to	17.0
(5)	350.0	to	30.0
(6)	50.0	to	52.0
(7)	2500.0	to	))



Resistivity 'sounding' results.

Site: M/Mag/bh3b(S)

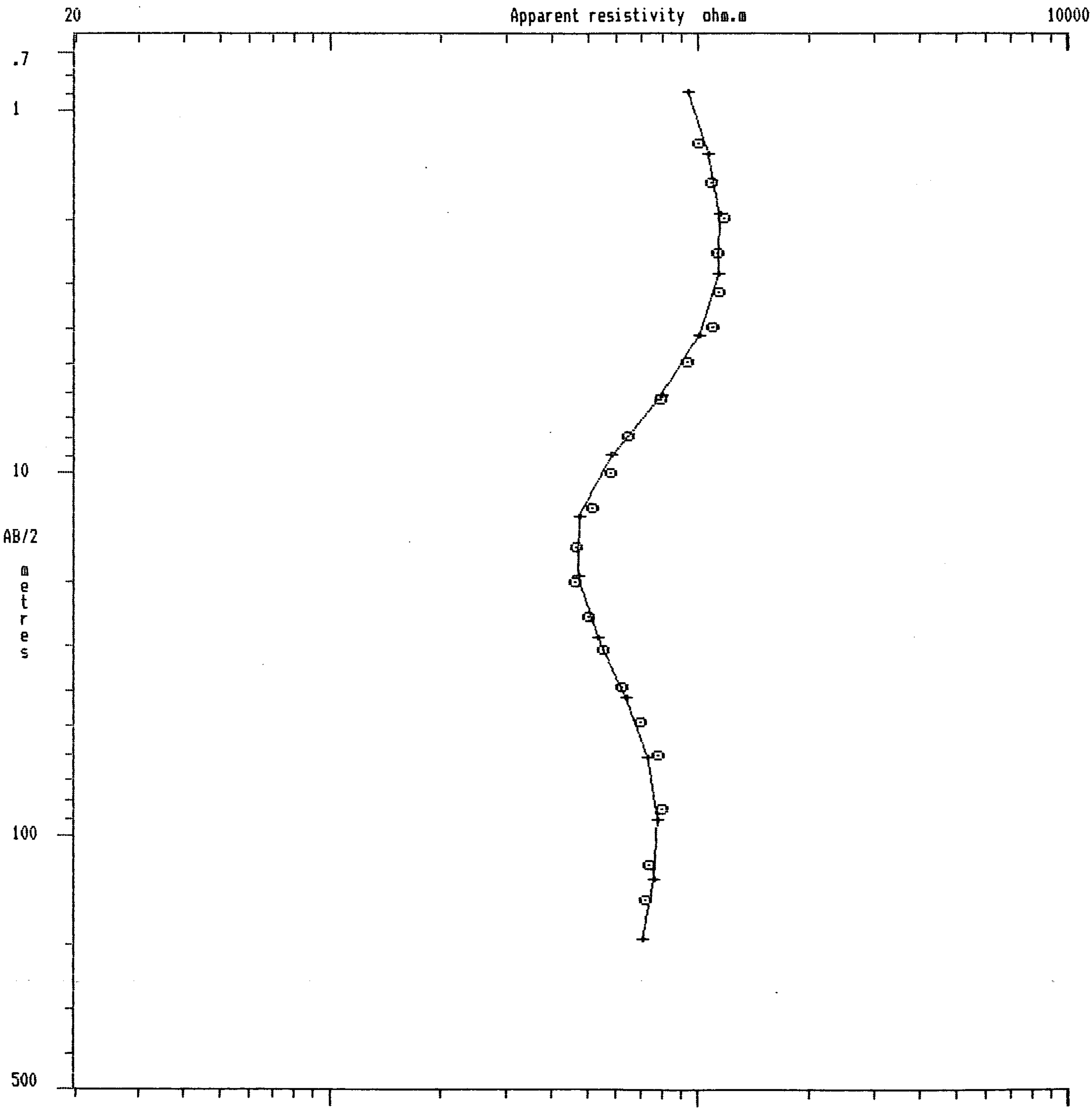
MODEL: layer	res		depth
(1)	650.0	to	0.3
(2)	900.0	to	2.2
(3)	630.0	to	5.2
(4)	66.0	to	30.0
(5)	330.0	to	))



Resistivity 'sounding' results.

Site: M/Mag/bh4a(S)

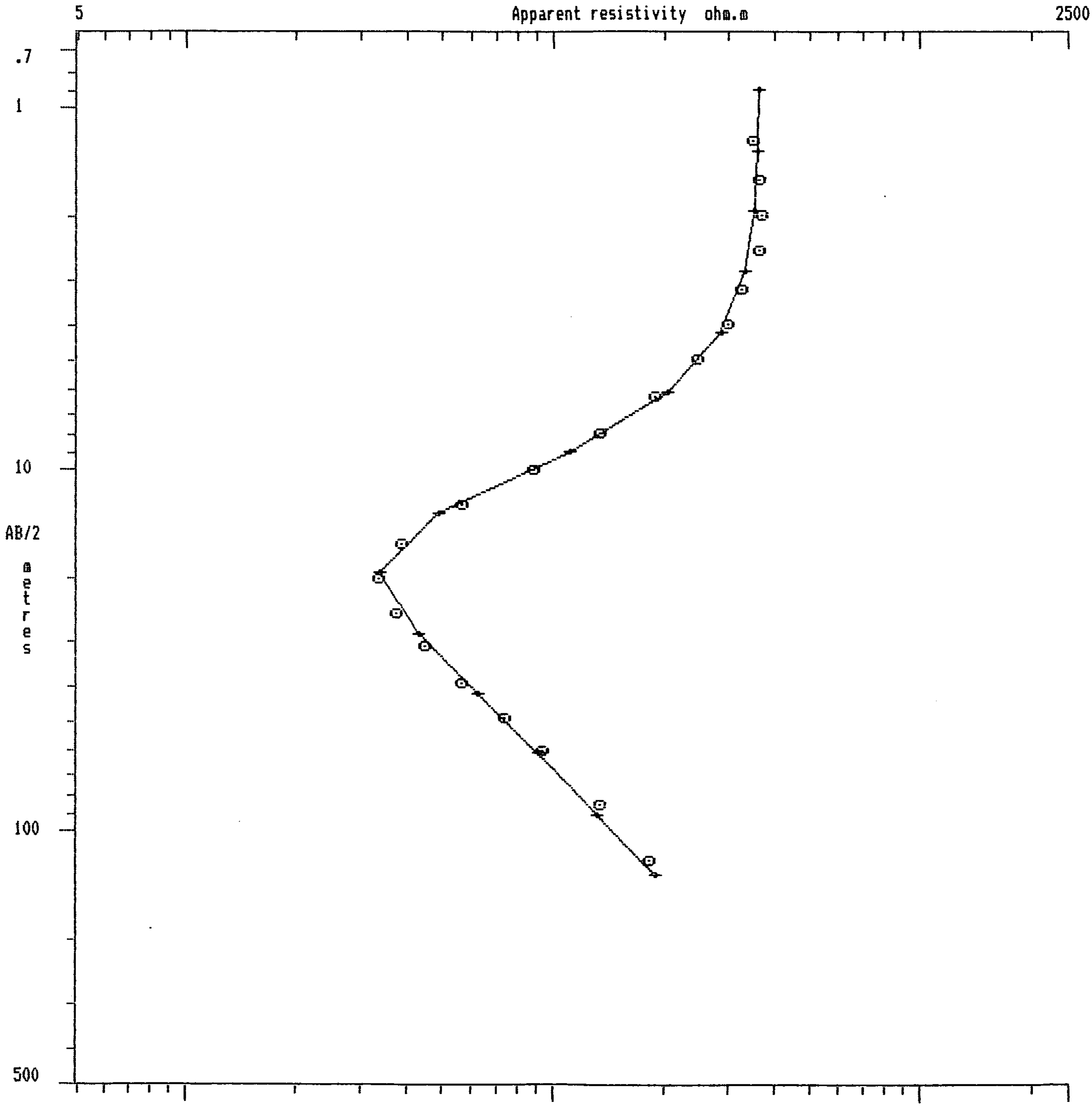
MODEL: layer	res		depth
(1)	540.0	to	0.3
(2)	1400.0	to	2.4
(3)	370.0	to	18.0
(4)	2500.0	to	30.0
(5)	600.0	to	))



Resistivity 'sounding' results.

Site: M/Mag/bh5(S)

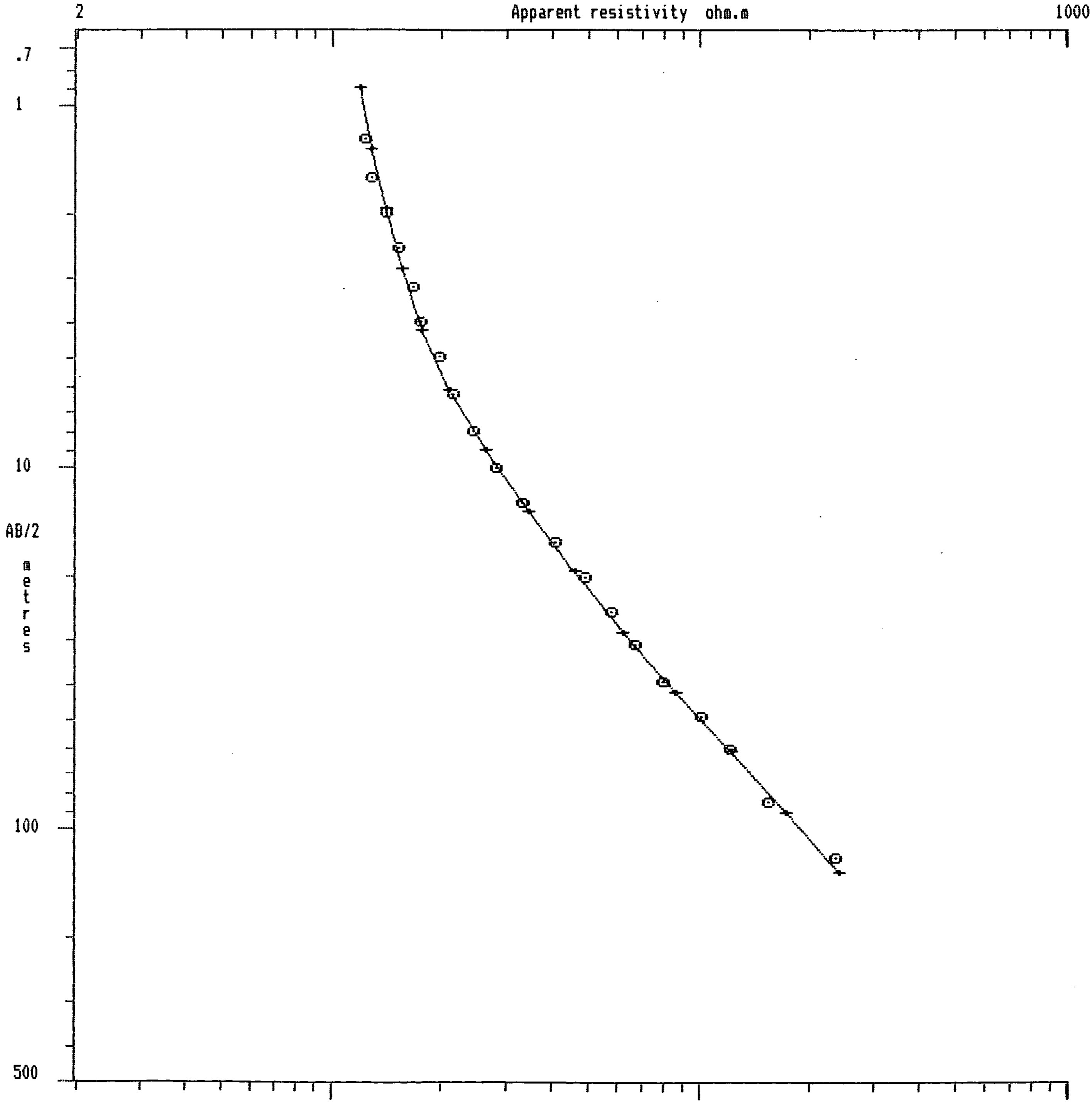
MODEL: layer	res	depth
(1)	360.0 to	3.5
(2)	16.0 to	14.0
(3)	3500.0 to	))



Resistivity 'sounding' results.

Site: M/Mag/bh6(S)

MODEL: layer	res		depth
(1)	11.0	to	0.7
(2)	17.0	to	4.3
(3)	80.0	to	20.0
(4)	1500.0	to	))



Resistivity 'sounding' results.

Site: SL/Tan/MRA12(S)

MODEL: layer	res		depth
(1)	115.0	to	1.2
(2)	26.0	to	5.0
(3)	180.0	to	16.0
(4)	17.0	to	28.0
(5)	5000.0	to	))