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GEOPHYSICS AND HYDROGEOLOGY DIVISION

Report No 123

Report on a visit to Malawi (October–December 1980) to advise on the use of geophysics in groundwater development

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Report on a visit to Malawi (October–December 1980) to advise on the use of geophysics in groundwater developement

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CONTENTS

FIGURES

SUMMARY

The limitations of the resistivity survey methods used by the Groundwater Division for siting boreholes are discussed and better procedures are suggested, such as: adopting the Wenner or Schlumberger array configuration; a more appropriate choice of electrode spacings for constant separation traverses; generation of model curves by a calculator programme for matching against field data.

A review of existing data showed no consistent relation with drilling results and the interpretations did not reflect accurately either formation boundaries or aquifer yields. Better control is needed from borehole logs on lithology and aquifer thickness/depth in order to determine whether quantitative interpretations can be made more reliable. It is difficult to judge the qualitative success of resistivity surveys, but in plateau areas they have probably helped by discriminating against shallow bedrock: over alluvial deposits the depth of investigation has been too limited. In view of the heterogeneous nature of the environment it is essential that all the available information is readily accessible and used for reference in planning surveys and interpreting new data.

The results of fieldwork undertaken during the visit are described. These confirmed the difficulty inherent to trying to resolve details of interest. It seems unlikely that geophysical methods by themselves could be used to identify sites for high-yield boreholes, but attention is drawn to the value of magnetic and electromagnetic techniques for rapidly delineating trends within the bedrock.

1. INTRODUCTION

In response to a request submitted by the Department of Lands, Valuation and Water, Malawi, the UK Overseas Development Administration agreed to support a 3 month visit to Malawi by a geophysicist of the Institute of Geological Sciences, London, as part of a longer term technical cooperation project in groundwater studies (see references [1, 2]).

The terms of reference for the visit were: to advise on geophysical methods, data interpretation and equipment in groundwater development, to include

a. borehole siting in various geological environments

b. local and regional aquifer evaluation studies.

It was also understood that 2-4 weeks would be spent at the Geological Survey Department in Zomba to review existing data and to consider their possible requirements for geophysics in the future; this aspect of the visit is covered by a separate report [3].

Of the 10 weeks based in Lilongwe with the Groundwater Project about 6 weeks involved fieldwork, using equipment brought over from UK on a temporary basis, while the remainder were devoted to an assessment of current procedures and an analysis of some of the resistivity data collected over the previous 30 years.

1.1 Geological setting

Malawi lies along the southern part of the East African Rift System between longitudes 32°40'E and 35°55'E and latitudes 9°22'S and 17°08'S with inland waters covering 20% of its surface area (see Fig 1a). It can be divided into 4 physiographic regions: the low-lying area of Lake Malawi and the Shire Valley within the Rift System, at less than 500 m above sea level; a dissected escarpment zone; an extensive region of plateaux averaging about 1300 m; highland areas above 1500 m, reaching a maximum elevation of 3000 m in the Mulanje Mountains.

Most of the country is underlain by crystalline metamorphic rocks of the Mozambique Orogenic Belt (see Fig 1b). This Pre-Cambrian to Lower Palaeozoic Basement Complex is made up predominantly of gneisses and granulites, and includes a wide range of rocks of both igneous and sedimentary origin, with subsequent intrusives. The Karroo System is represented in the north and south of Malawi by sediments with a coal measures sequence, Stormberg Series basaltic lavas and dolerite intrusions. A characteristic suite of intrusive rocks, including syenites and carbonatites assigned to the Chilwa Alkaline Province of Upper Jurassic - Lower Cretaceous age, occurs in southern Malawi with sedimentary rocks such as the Lupata Series of a similar age. Lacustrine deposits of Tertiary age outcrop in narrow belts to the north-west of Lake Malawi together with more extensive developments of Quaternary sediments, which also occur around Lake Chilwa and in the Shire Valley. Colluvial deposits and in situ weathering products are extensively developed over the medium height plateaux, for example around Mzimba, Kasungu and Lilongwe and also around Mulanje Mountain.

The predominant structural trends seen in the Basement Complex and more recent formations tend to lie within a north-north-west to north-north-east direction, although there are numerous examples of divergences from this such as the north-west/south-east fault system along the Shire Valley, and west/east strike trends shown by some gneisses. The Malawi Rift, which remains seismically active, probably originated in late Tertiary times, although the extent to which it was influenced by pre-existing lines of weakness is not clear. The absence of contemporary volcanic activity, except in the extreme north, is characteristic of the western section of the Rift System.

For a more complete description of the geology of Malawi reference should be made to the publications of the Geological Survey Department, Zomba [4].

1.2 Organization

The exploitation of groundwater resources began with shallow dug-wells which were used to augment surface supplies during the dry season. These wells themselves were not always reliable, and, as the need for water grew in rural areas lacking perennial streams, the emphasis shifted towards deeper boreholes.

From the 1930's the Geological Survey Department became increasingly committed to borehole siting and a Groundwater Division was established to meet this demand and its associated construction and maintenance activities. More than 5000 holes have now been drilled, with an annual increment of about 250 (excluding any privately contracted sites) at present, compared to a maximum of over 400 in 1970-71. As might be expected, the distribution of boreholes is not uniform throughout the country - the greatest concentrations are in the central and southern regions near Lilongwe, Salima and in the Lower Shire Valley, while in the highland and escarpment areas few holes have been drilled because of the availability of surface water, and the low population density. In addition to the continuing requirement to provide rural supplies, present development tends to be associated with the agricultural sector - on new tobacco estates for example. Special studies are also being undertaken to meet particular requirements - such as those of the new international airport for Lilongwe and of urban supply for certain townships - and to obtain information on the potential of alluvial areas for providing irrigation water.

In 1980, following a World Health Organization recommendation [5], all aspects of water resource development were brought together in the Department of Lands, Valuation and Water, based in Lilongwe. As a part of this reorganization the Groundwater Division was transferred from the Geological Survey Department and now consists of 5 hydrogeologists with ancillary staff. Since 1950 electrical resistivity surveys have been used extensively for siting boreholes, an activity which occupied most of the time of the professional staff. It is now recognized that broader hydrogeological studies need to be undertaken together with the siting programme, and, in order to make the best use of the resources available, the role of geophysical methods has to be reconsidered in terms both of the effectiveness of present procedures and of future requirements.

2. GROUNDWATER OCCURRENCES

Up to the present time borehole siting by the Groundwater Division has proceeded on a more or less routine, ad hoc basis with little consideration of the hydrogeological context. As a result the available information has not been fully utilized: no attempt was made to establish a network of observation wells for monitoring fluctuations in water levels - measurements obtained since 1971 when handpumps have been removed for maintenance cannot be regarded as an entirely satisfactory substitute - while those reports which have been written over the years, relating the data on a regional basis, have had little influence on the siting procedure. The estimate of specific capacity which has been obtained from short-term (4-8 hours) pumping on completion of many holes provides a means of comparison between sites, though the extent to which the results reflect the properties of the aquifers themselves, as distinct from effects of borehole design and development, is less clear. Reliable information on transmissivities is restricted to a few specific localities such as around Blantyre /T59/, where detailed investigations have been undertaken, and more recent pump test data collected by the Urban Supply section; tests with observation wells have been conducted very rarely.

The nature of the aquifers in the plateau and escarpment areas remains unknown for the most part. The vertical sequence below the superficial, typically sandy soils is characterized by a transition from a more clay-rich, weathered zone of colluvium or saprolite, which may be overlain by laterites and tends to become more sandy with depth, to weathered, then fractured and finally hard, compact bedrock. Being mainly the result of in situ weathering, these changes are gradational and are influenced by the nature of the bedrock - its composition and the degree of jointing: additional zones of softer rock may occur at depth as a result of structure within the bedrock such as banding, dipping formations or fractures. In the dissected terrain of the escarpment, which is undergoing active erosion, the weathered mantle is not well developed, with hard rock typically less than 15 m below the surface, in comparison to the stable plateaux where the thickness of weathered material may exceed 50 m.

While zones of higher permeability evidently exist towards the base of the weathering profile, there is little information regarding the extent of hydraulic continuity throughout the weathered material as a whole; on the depths, thicknesses and lateral extent of the main aquifers; on the relative contribution of water from fracture zones within the harder rock; on recharge mechanism; or on the significance of dambo systems to groundwater occurrence. It seems likely that much of the storage occurs in the low-permeability weathered material, while the semi-confined aquifers which utilize it are more sandy or broken layers overlying fresh rock: these permeable zones need to have sufficient depth and thickness to avoid dewatering. Water quality is variable, but generally acceptable; a review of the hydrochemical data has been undertaken recently.

Aquifer characteristics within the alluvium of the lakeshore and Lower Shire Valley are likely to be more predictable than those in the weathered basement rocks, though borehole yields have not been significantly higher in general. The sediments are a sequence of silts, clays and sands - often poorly sorted or interdigatated - with few reported examples of thick gravels and sands: deeper drilling in these areas may reveal the presence of better aquifers than those utilized to date. Higher salinity values tend to be associated with the finer grained sediments and these may restrict the potential of any aquifers at depth. Poor quality water may also be derived from the Mesozoic sediments rising to higher levels along fault zones,but the basalts have yielded good supplies of fresh water at some sites.

3. BOREHOLE SITING

Electrical resistivity surveys have been used as the basis on which to select drilling sites ever since their introduction to Malawi and the consequent improvement in drilling results. The threshold for success was set at a yield of about 0.2 l/s which was taken to represent a minimum level acceptable for rural supply, and this criterion has been preserved up to the present. The principal benefit of the resistivity surveys appears to have been a reduction in the number of 'dry' holes as judged on this basis, and it is less clear that they provided a means of identifying sites where higher than average yields might be obtained. This, in turn, can be explained by the fact that while the resistivity data will usually discriminate against areas of shallow bedrock they do not specifically reflect the nature of the aquifer.

3.1 Equipment

Two types of instrument - the Megger and the ABEM Terrameter - are available for resistivity surveys and both of these measure the ratio of potential to current directly. The limited output power and sensitivity of this equipment restricts the effective depths of investigation which can be achieved, particularly in areas underlain by conductive formations, and where sandy soils give high contact resistances at the electrodes. It is adequate for detecting shallow bedrock in most circumstances, but cannot be expected to penetrate thick weathered, or alluvial, sequences.

Other geophysical equipment became available within the Geological Survey Department during the 1970's as a result of the mineral exploration programme. This included magnetometers, electromagnetic instruments (ABEM Turam and 35/88) and a frequency-domain induced polarization set with a 2.5 kW transmitter. Two or three surveys have been reported where these instruments were used in borehole siting: the detailed work near Blantyre [T530, T584] provides the only known example of a more comprehensive geophysical approach with magnetic, electromagnetic and resistivity data all being collected, while surveys in the Lower Shire Valley [T658, T663] illustrate the extra information which can be obtained with longer resistivity electrode arrays when more powerful equipment is available. Unfortunately, the potential of neither the equipment nor the survey techniques thus demonstrated were assimilated by the Groundwater Division, and routine borehole siting procedures continued unmodified, using only resistivity methods established in the 1950's [6].

Proposals have been put forward recently for the purchase of (Elsec) proton magnetometers and the (ABEM) Terrameter SAS 300 resistivity set with booster, which will provide a capability within the Division for undertaking more comprehensive surveys: the magnetic measurements are quickly and easily obtained and provide information on lithology and structure which can complement or support the resistivity data on detailed site investigations: the new Terrameter will significantly increase the range over which reliable resistivity data can be obtained.

3.2 Siting procedure

The array developed by Cooper has been employed almost exclusively by the Groundwater Division and attempts to introduce better procedures have met with no success to date, although the information has been available as noted above. While the shortcomings of this method are unlikely to have affected the overall success rate for rural boreholes, they could be significant in particular instances and for detailed surveys where a quantitative approach is required. A more serious problem over the years has probably been an inflexibility of approach to the siting procedure and a lack of appreciation of the principles underlying the field work and its interpretation. As the requirement grows for higher yielding boreholes to meet specific needs, and for locating supplies in less favourable areas, realizing the full potential of the available geophysical techniques will become a more important factor.

Sites have usually been selected by means of constant separation traverses (CST) - with equally spaced electrodes and so identical to a Wenner array - supported by expanding array data. In plateau terrain the expanding arrays are centred near lows brought out by the CST, while in areas of thick alluvium, zones of higher resistivity are thought to be more favourable as indicating a lower clay content. There has been a tendency to keep to standard electrode separations - 75 ft or 100 ft for CST and 100 ft for the fixed inner potential pair in expanding Cooper arrays. The amount of CST work undertaken at a particular site is variable but it is seldom extensive unless a detailed survey has been requested. Individual lines or a more random approach may be adopted to cover an area which is conveniently situated, and where the superficial features of vegetation and topography are most promising. It is not clear whether expanding array data were normally plotted in the field and an interpretation made by curve matching at that time or at a later stage:

the values themselves may have been used as sufficient evidence on which to accept or reject a site, as instructions to the drillers were not related to any interpreted interfaces in terms of maximum depths to be drilled.

The procedure for detailed surveys is essentially the same except that the CST are taken over a larger area on a grid pattern with lines 100 ft - 300 ft apart, and the results are contoured to indicate the trends and low resistivity zones on which to site the expanding arrays. The suitability of a site for drilling is assessed on the basis of there being a relatively thick layer of low-intermediate resistivity: in plateau terrain resistivities of about 25-60 ohm.m are usually taken to be indicative of water-bearing formations and sites with values in excess of 100 ohm.m would be avoided unless they suggested a significant change relative to their surroundings.

Interpretation of the expanding array data is based on the curve matching technique described by Cooper which is applicable to two-layer cases and to three-layer curves of the H type only ie those developing a minimum. The curves are plotted with a linear relative distance scale as abscissa and a logarithmic apparent resistivity scale as ordinate: sets of two-layer master curves have been plotted from computed points for different values of λ , the ratio of the thickness of the upper layer to the fixed distance between the inner pair of electrodes used in the array: curve matching with the field data is effected by fitting the apparent resistivity values while the distance scales remain coincident. For a three layer case Hummel's principle is adopted and the auxiliary point representing the combined upper layers determined by matching a two-layer master curve to the latter, ascending part of the field curve. As both outer electrode position and layer thickness are scaled in terms of the fixed inner electrode spacing 'a', the master curves can be matched independently of the system of units or the particular value of 'a' used to collect the field measurements.

Two problems arising from the limitations of the equipment affect the field data. First, it may be difficult or impossible to obtain reliable readings where the electrode contact resistances are high due to sandy or lateritic soils; second, in areas where conductive formations occur, signal strengths may be too small to be measured accurately. Both of these factors probably contribute to the erratic form of some of the field curves, though it is not clear to what extent the data could have been improved by choosing sites where high electrode contact resistances were avoided. One result of this in areas where laterites are developed extensively has been to reject potential sites on the basis of insufficient evidence, that is because the resistivity method was ineffective and not because the environment appeared unfavourable. Where thick alluvium is present resistivity values tend to be low: this limits the maximum electrode separation and hence the effective depth of investigation: it seems clear that in such circumstances boreholes have been sited on the basis of near-surface conductivity variations originating from above the level of the aquifers and bearing no obvious relation to them. Other points related to field procedures are discussed in the appendix.

3.3 Survey costs

A principal consideration for rural boreholes is that of keeping costs to a minimum. In comparison with shallow wells and gravity-fed water schemes, village boreholes, each supplying about 300 people, are expensive in terms of capital and, more particularly, maintenance: the taste of the borehole water tends to be different and regarded as inferior even though its quality may be good,and there has been a lack of communication at a local level on the advantages of borehole supplies, and on the need to avoid pollution and damage to the pumps. The question of borehole design is still being considered but it seems likely that the introduction of reduced diameter holes with non-metallic casing and properly designed gravel packs will result in significantly improved efficiencies at lower cost. In these circumstances the charges associated with the site survey are proportionately higher, while the need for a routine survey is less obvious.

It is difficult to obtain a reliable estimate for the real expenditure on a 'typical' survey as vehicle-related costs are the most important single item and the amount of travelling required is a very variable quantity. The figure of K250 used at present may be a realistic average but is probably an underestimate if account is taken of the range of circumstances it covers, overheads and other hidden charges. However, another important consideration in this respect concerns the extent to which a driller might be relied on to select a suitable site giving consideration to pollution hazards etc.: if a technical officer has to make a separate visit to fix sites the additional cost of combining this with a resistivity survey is likely to be marginal. Alternatively, if regional offices are established in the future, travel related charges could be reduced significantly.

3.4 Existing data

3.4.1 Filing system

Survey sites recommended for drilling are numbered sequentially with the initials of the officer who undertook the work, and it is this reference which has been used to define the site. The record sheets filed for each siting geologist contain information on the site location, with a tabulation of the expanding array data and any interpretation, and a plan showing the CST results, though this latter is not infrequently missing: the expanding array data are also plotted on tracing paper with the appropriate master curves drawn in. Subsequent drilling and borehole construction details are kept in separate files and the location of the boreholes plotted on 1:50,000 topographic bases.

This system suffers from several disadvantages: data for a set of boreholes from a particular area will be scattered throughout numerous different files which can only be identified by reference to the location map; at least two files must be accessed before the geophysical survey can be related to any drilling results; the files are not well designed physically and tend to come apart with handling; some files have been mislaid and the data lost; it is not possible to get a synoptic view of the data.

A card file system has now been introduced onto which the borehole information is being transferred in summary form. This is set up on an area basis defined in terms of major catchments, from 1 to 18, which are further subdivided into units designated by letters (see Fig 2): each site is then allocated a new, sequential number specifying the water resource unit and the relative time of drilling within it. Although the interpretations of the expanding array data are to be included on the cards so that they may be compared with the lithology, hydrochemistry and yield of the boreholes, these are not adequate for assessing the geophysical results - access to the original files is still necessary in order to check the reliability of the interpretation, the quality of the data and the range of CST values. There also remains the possibility of confusion in allocating site numbers as they are interdependent on this system, although the order in which the holes were drilled is of little significance in itself.

A new filing system is recommended - using grid coordinates as the primary reference - which would involve restructuring the files but would not introduce any new parameters. Thus, a new site investigation is assigned a sequential number according to the geologist's personal record even if no site is recommended as a result of the survey, and the kilometre grid reference noted together with the water resource unit code - the latter being expanded if the site is drilled to conform to the full reference number used to define the borehole for the card index system.

Each major catchment should have a separate file within which the geophysical data, including all expanding array and constant separation traverse results, are to be grouped in sets of 10 km grid squares and ordered sequentially in terms of grid reference values, with northings being subordinate to eastings. The 10 km squares should be tabulated to facilitate their location in the file. The possibility of confusion arising when there are several sites within any one kilometre square is avoided by reference to the unique, geologist's number.

The results of subsequent drilling at a site - to include lithology, aquifer properties and water conductivity if available - should be copied to the file with the geophysical siting information.

In addition, information should be presented on 1:50,000 scale map overlays in order to summarize the data and make it easier to establish any correlations between them. This could be done in the form of three coded lines of information such as:

AX 13 (M)	geologists site reference (yield)
QH (H)	resistivity curve type (final layer resistivity)
(*)45/20(32)	resistivity above the deepest interface/ depth of deepest interface (depth to bedrock as drilled)

The code for yield might be

D - dry	0 - 0.2 l/s
L - low	0.2 - 0.5 l/s
M - medium	0.5 - 1.0 l/s
H - high	1.0 - 2.0 l/s
X - very high	> 2.0 l/s

for plateau areas; different limits could be used in alluvium.
The code for final layer resistivity L - low, less than 100 ohm.m, I - intermediate, or H - high, more than 300 ohm.m.

The asterisk before the third line would be added where laterites or high contact resistances are found.

Results from detailed surveys are usually drawn up and contoured but there is no procedure for archiving the data or for writing reports describing the work and its outcome. The only formal record is that in the siting geologist's file, which refers to any specific site recommended for drilling.

3.4.2 Analysis of data from specific areas

In order to see whether any broad-scale patterns could be discerned within the data which had already been collected, use was made of the interpretations transferred onto the card-file system and not to the original data. They comprised 1285 boreholes covering parts of water resource units 1, 2, 3, 5, 9 and 17 which include both alluvial and plateau terrain. The unreliability and ambiguity inherent to the resistivity interpretations, borehole lithology descriptions and aquifer parameters preclude the possibility of establishing detailed correlations and the objective here was limited to categorizing the data and presenting them in a readily accessible form.

Interpreted layer resistivities were grouped as <10, 10-50, 50-100, 100-300, 300-1000 or >1000 ohm.m,and interface depths grouped as <5, 5-10, 10-15, 15-20 or >20 m; borehole yields and specific capacity were also listed, together with an indication of the lithology encountered and the depth at which water was struck. The total number of occurrences within each group of depth and resistivity were obtained for each sub-basin, together with borehole yields categorized as <0.5, 0.5-1.0, 1.0-1.5, or >1.5 l/s. The results are displayed in Fig 3 as circular, relative frequency plots - the length of arc being proportional to the number of occurrences for a group value indicated by the radial distance. Three limitations of this type of presentation should be borne in mind: first, it emphasizes groups at greater radii, as a larger area is enclosed for a given value; second, the group divisions are, to an extent, arbitrary and obviously affect the frequency distribution, particularly when data are concentrated close to a boundary; third, it is dimensionless, though the number of boreholes contributing to each set is noted by the plots.

The Lower Shire Valley (unit 1) and Karonga Lakeshore (unit 17) data typify the lower-lying, alluvial areas. Their most obvious characteristics are the low proportion of 3-layer compared to 2-layer interpretations, the relatively high conductivities at all levels and the proportion of first interface depths exceeding 10 m. The high conductance - usually more than 1 ohm^{-1} of the second layer emphasizes the limitations of the instrumentation and of field procedures used for the surveys.

Around Lake Chirwa (unit 2) a 3-layer structure is clearly defined with few depth interpretations greater than 20 m. Resistivities for the intermediate layer tend to lie at the lower end of the 10-50 ohm.m range and this indication of a significant clay content may correlate with the lack of boreholes yielding over 1.5 l/s. However, this contrasts with the results from the south-west of Lake Malawi (unit 3) which show more higher-yielding wells where second layer resistivities are slightly less. This may be offset against a deeper, less resistive, third layer as it is not clear where the main water-producing horizins occur in relation to the resistivity layering.

Bua catchment (unit 5) is representative of plateau terrain and characterized by higher near-surface resistivities of 100-1000 ohm.m, second layer values of 25-50 ohm.m and third layer values over 100 ohm.m; the uppermost layer is up to 10 m, but typically less than 5 m thick, with the second interface below 15 m depth. Borehole yields given for sub-basin 5D are lower than for 5E or 5F, but apart from there being somewhat lower surface resistivities and higher third layer resistivities the other data appear similar. Results from Songwe/Lufira (unit 9) in the north of Malawi resemble those from Bua except for a higher proportion of second layer resistivities in the range 50-100 ohm.m.

Different ways are available for presenting this type of information such as by the more usual histogram, or by plotting two of the parameters against each other to show up any interrelation. The latter would be useful in comparing aquifer properties to layer resistivity when reliable data are obtained.

An inspection of the data from areas where borehole yields either varied markedly or were unusually low did not suggest any characteristics particular to the dry sites by which they might have been identified. This implies that the aquifers themselves do not influence the resistivity section beyond the range of variation typical of the weathered zone: the resistivity of the intermediate layer seems to depend more upon the effects of mineralogy and bedrock lithology on the whole sequence rather than on specific horizons within it. As the response due to an aquifer in itself will almost certainly be subtle, any minor perturbations from lateral changes or inaccuracies of measurement become significant. The borehole drilling logs do not suggest that the quantitative resistivity interpretations define interfaces of any physical reality in terms of lithological divisions or groundwater occurrence. In plateau terrain this can be attributed to the gradational nature of the weathering processes, while over alluvium also the sediments tend to be poorly sorted and the depth of investigation has been inadequate to encompass the main aquifers.

4. FIELDWORK

In view of the lack of geophysical equipment in Malawi and the need to evaluate the potential of different methods, seismic, resistivity, magnetic and electromagnetic instruments were brought over from UK for use during the visit. Six areas (see Fig 4) were chosen to provide data representative of the conditions which might be expected within the country as a whole and the results obtained are discussed below.

4.1 Methods and equipment

While low-power resistivity equipment has been used almost exclusively for siting boreholes the 1970's did see a limited number of surveys with a 2.5 kW McPhar induced polarization set and some combined resistivity, magnetic and electromagnetic surveying at a site near Blantyre, as noted earlier. The only technique employed during this visit which had not previously been used in Malawi was seismic refraction. The equipment comprised:

a. Huntec Mk 3, 160 W, battery-powered current transmitter producing square-waveform current pulses of alternate polarity, with a maximum amplitude of up to 1.5 A depending on the contact resistance at the electrodes and ground impedance: the pulses lasted 2s and were separated by 2s.

b. Scintrex IPR-8 : a remote-triggered receiver for voltage measurement in the range 150 μV to 40 V. This was used in conjunction with a. to provide a more powerful resistivity set than the Terrameters available within the Department.

c. Geonics EM16 : an electromagnetic receiver unit tuned to established, low-frequency (VLF), navigation transmitters operating at a frequency of 15-25 kHz; intended for detecting fracture zones in areas of shallow bedrock.

d. Elsec 770/Geometrics 816 proton magnetometers which measure the total magnetic field to an accuracy of 1 nT. Magnetite is commonly referred to as an accessory mineral present in varying degree within basement rocks, suggesting a means of mapping trends and structures within the bedrock.

e. Nimbus 1210F signal enhancement seismograph for recording seismic refraction data: a hammer and metal striker plate were used as the shot-point energy source to avoid the need for dynamite. This 12-channel system allowed a maximum geophone spread of 110 m. Analogue records are produced which provide a resolution of 0.5 ms for record lengths of up to 100 ms. Incoming signals are sampled digitally at 1024 points over the pre-set recording time - minimum 50 ms - for enhancement with repeated shots, and subsequent playback. It was intended for mapping the bedrock surface and for defining depths more rigorously.

In practice both electromagnetic and seismic techniques suffered due to weak signal strengths which greatly reduced their effectiveness. Southern Africa lies at the limits of the areas covered by VLF transmissions and although several stations were detectable in Malawi they did not allow accurate measurements to be made. For the seismic method; the hammer energy source proved inadequate for providing refractions from the bedrock: poor transmission properties, the thickness of the weathered material and difficulty in making good coupling with the ground meant that first arrivals could not be identified reliably for shot-point to geophone separations in excess of about 60 m despite the enhancement facility, although in some cases better results were obtained to 150 m.

4.2 Chitedze

This site was chosen for further investigation as it was being used by the Groundwater Project to develop techniques and designs for low-cost boreholes. Lying some 15 km west of Lilongwe, the area is towards the margin of the stable, mature, plateau forming the Lilongwe Plain: basement rocks are described as semi-pelitic - predominantly biotite and hornblende-gneisses, locally graphitic - which underlie a layer of weathered material - colluvium or saprolite with some laterites - of very variable thickness, up to about 40 m.

CST data were available from a grid of 400 m x 1000 m with a station interval and electrode spacing of 23 m and a line spacing of about 135 m, together with results from seven Cooper array sites. The borehole W118 which still yields a good supply of water had been sited some years earlier on the basis of a narrow, conductive zone located by a routine survey: the more recent CST failed to confirm this but as these results were erratic, and the expanding array curves were distorted, there may have been problems with electrode contact resistances or with non-uniformity of a thin, near-surface layer. It is difficult to make out any consistent trends within the data beyond the outline of two or three larger zones of high/low resistivity (see Fig 5).

In order to assess the value of the magnetic method in these circumstances measurements were taken along a traverse line which passed close to W118. Magnetic field values ranged over 170 nT and as the profile indicated some systematic variations it was decided that the coverage should be extended, maintaining a station interval of 10 m and a line spacing of 60 m. Because of instrumental problems the readings were less reliable than would be expected normally, while the presence of power lines, wire fencing and short wavelength anomalies of near-surface origin added to the noise level. A simple 4-point running average was taken in order to smooth the data and the contoured results are shown in Fig 5 together with the initial base-line profile. While the pattern is not simple there is evidence of a west-east trend through the central part of the area, and a subsidiary north-west trend - as represented most obviously by a relatively strong positive anomaly at the south-east of the grid. It is thought that the magnetic anomalies originate from near the top of the bedrock as a result of variations in depth and lithology. The influence of the overlying weathered layer is unclear: if little material transport has taken place then it should still reflect the mineralogy of the underlying bedrock, but differential rates of weathering, with possibilities for concentration or dissemination of residual magnetite, may be significant. As the basement itself is known to be heterogeneous there is little chance of distinguishing between variations in depth and composition - these may in fact be related - but a qualitative study of magnetic data may still be useful either in itself for preliminary reconnaissance, as a complement to electrical surveys or for extrapolating borehole information.

In the absence of an a priori understanding of the anomaly pattern a more experimental approach is needed by drilling on selected anomalies: as a corollary the results must be adequately reported and archived for future reference. On this basis borehole GP8 was sited on a narrow magnetic anomaly low in an area of poorly defined, intermediate CST resistivity values ie where the anomaly characteristics differed from those at the other sites. Beneath a 1-3 m thick superficial layer, of 0.3-0.4 km/s, seismic velocities were less than 1 km/s to a distance of at least 50 m. This implied that hard rock was more than 15 m below surface if its velocity is over 2 km/s, but as higher speed arrivals were not detected there was no positive indication of the depth to bedrock. Time-distance plots were similar to those by W118 except for a decrease in total travel times north of the baseline towards GP4. Measurements by site GP4, a hole which did encounter shallow bedrock, again failed to show a fast refractor, but it was noticeable that speeds within the upper layers were greater - at around 1.3 km/s - and that energy losses were higher. GP8 itself intersected a broken quartzitic formation with a high permeability at 10-15 m,which had not been found elsewhere. The aquifer was too thin and shallow for it to be pumped continuously at rates of more than 1.5 l/s but the hole was relatively successful: the best hole to date, GP7, yields over 2 l/s.

The other obvious magnetic feature, the positive anomaly at the eastern end of the grid, was covered by a seismic profile. The magnetic high was found to correlate with a change in the seismic velocities for the upper layers from about 0.7 km/s in the south to over 1 km/s in the north, with evidence of a discontinuity near 60 S on line 540 E. Energy transmission was better on this traverse as the soil was more compact, and indications were given of a third, faster layer at a depth of 14-20 m with a velocity of 1.5-2.3 km/s, taken to represent weathered rock, but too low for fresh basement. The magnetic profile shows a compound anomaly: values increase steadily from the north before an abrupt decrease beyond 50 S; a short-wavelength positive anomaly superimposed on the maximum suggests a dyke-like body along a contact zone near 55 S, with a unit of lower susceptibility to the south and west.

Expanding Schlumberger arrays at 11 sites were taken to maximum current electrode separations of 200 m. Upper layer resistivities of several hundreds of ohm.metres to depths of 4-15 m were invariably succeeded by lower values, typically about 70 ohm.m: the deepest interface as interpreted varies from 25-45 m but this is sensitive to uncertainties in the resistivity of the lowest layer. Graphite is found locally in the bedrock and this probably accounts for the absence of a strong contrast at depth in the basement. Lateral variations within the succession are apparent from both curve distortion and discrepancies between orthogonal array curves so that larger electrode separations do not define resistivities at depth. Curve distortion arises mainly from the inhomogeneity of the upper layers, but the systematic difference at larger spacings - apparent resistivities measured parallel to the baseline were lower than those taken orthogonal to it - indicate an anisotropic behaviour which almost certainly reflects the fabric of the bedrock. Such considerations mean that identification of the base of weathering and fixing its depth is very problematical.

One point of general interest was to consider if the areas of high resistivity outlined by CST were caused necessarily by shallow bedrock, rather than by variations within the weathered material: laterite occurring within the near-surface layers would not preclude the presence of good aquifers beneath it. At site 11 orthogonal sets of data confirmed that the CST values were attributable here to a relatively thin - less than 10 m - layer with a resistivity of several thousand ohm.metres which is assumed to be lateritic. Beneath this, apparent resistivities were reduced to no more than 50 ohm.m, and on the west-east line dropped to below 10 ohm.m at the widest electrode spacing of 320 m. These findings do not of course imply that high resistivities invariably indicate laterites but they do show that CST data above may be misleading unless results from at least two appropriate spacings are available.

Interpretations of the expanding array data are summarized diagramatically in Fig 6. They are presented as an indication of the simplest sets of values which fit the curves and are not to be regarded as representing the ground section reliably. The differences within the upper layers of the sequence suggest the lack of homogeneity in the weathered zone which is borne out by the drilling results. There are no criteria for defining aquifers in that, depending upon the lithology, a permeable layer might be represented by a more, or less, resistive zone within the section as, for example, a fractured quartzitic rock, or a more deeply weathered, graphitic rock. Sites 1, 2, 3, 6, 8, 11 gave relatively high longitudinal resistances, of more than 3000 ohm, for the upper layers and their spacial relation is consistent with a zoning in the bedrock parallel to the dominant magnetic trend: site 2 is an exception which may be influenced by cross-cutting features.

Spontaneous potential measurements along a short traverse by GP8 showed variations of up to 50 mV and which might have been related to the bedrock and its weathering products. Ideally a survey over a detailed grid would have been undertaken but shortage of time, combined with a difficulty - attributed to the dry, loose soil and vegetation - in obtaining reliable, repeatable data prevented this.

4.3 Kamuzu international airport site

The source of the water required to service the international airport being constructed 20 km north of Lilongwe has yet to be decided but it is hoped that groundwater will be able to meet all immediate needs - existing wells in the area suggest that high enough yields could be obtained from a series of properly constructed and maintained boreholes. Available data indicate characteristically varied properties for the bedrock and aquifers, and while a thin weathering profile usually corresponds with low yields it does not follow that deeper bedrock will be associated with the best aquifers; intermediate thicknesses tend to be more reliable.

Geologically the situation is similar to Chitedze with dambos - the local term describing the broad, shallow valley systems common in this type of plateau environment - being a more prominent feature. The possibility that the rectilinear drainage pattern apparent on aerial photographs might relate to fracture systems is obviously important in considering controls on groundwater occurrence, and geophysical surveys were undertaken to see if any specific responses were obtained over them.

A series of magnetic traverses, the baseline of which lay along the upper part of a well-defined drainage feature, showed a smoothly varying field with anomalies of about 150 nT in amplitude over an area of 400 x 500 m. While a clear, positive anomaly occurs by the grid origin near the centre of the valley the overall pattern is not topographically controlled, with the dominant trend of the contours appearing to be westerly, oblique to the valley. Sands bordering and within the dambro were quartzitic, blackened with ferro-magnesian minerals, and almost certainly contain disseminated magnetite, which may be concentrated locally. On a broader scale - as provided by aeromagnetic data - the anomalies may in fact be seen to group according to some structural control.

Resistivity CST using a Schlumberger array with current electrode spacings of 20 m and 120 m across the valley showed a correlation between the magnetic high and a central zone, 100 m wide, of more conductive near-surface material. At the 20 m electrode spacing apparent resistivities fell below 100 ohm.m compared to over 300 ohm.m elsewhere: the anomaly at the wider separation was ill-defined in comparison, indicating a superficial zone or one narrowing with depth - the ratio of apparent resistivities for the two spacings, 120 m/20 m, ranged from 0.08 to 1.4, with the more extreme differences to the south.

Expanding array data within the valley showed a dry, surface layer, 1-1.5 m thick, an intermediate zone of about 25 ohm.m and 6 m thickness, and an underlying, more resistive layer of 70-100 ohm.m. Away from the topographic depression the surface layers were thicker, with higher resistivities - giving values over 700 ohm.m to 5 m depth - probably indicating laterites especially to the south; intermediate layer values of more than 100 ohm.m to 15-30 m depth were succeeded by conductive, deeper layers which suggested the presence of graphitic bands within bedrock, with anisotropy again being apparent.

Most of the seismic first-arrival energy was propagated through the near-surface layers with a speed of 0.8-1.2 km/s. A poorly defined critical distance near 50 m suggested a deeper interface at about 15-20 m: total travel times over 75 m were around 60 ms. The faster velocities were associated with the slightly higher (more resistive) ground to the south where first arrivals were 'lost' beyond 30 m, but they were also evident as bands within the slower material of the valley. As it was not possible to map a bedrock refractor with the available energy source no conclusions could be reached regarding fracturing under the valley.

Measurements in a more mature dambo on the opposite, eastern side of the airfield differed in showing an ascending resistivity curve: a 3 m thick clay layer at 10-30 ohm.m was underlain by a sequence typical of weathered material, 40-70 ohm.m, 10-15 m thick, above bedrock at more than 200 ohm.m. It may be significant that these bedrock resistivities were greater than those indicated on the neighbouring higher ground, that is in suggesting a difference of lithology or a thinner zone of alteration. The contrasting surface material had a marked effect on the quality of the seismic refraction data with the dambo clays allowing arrivals to be detected over distances of 125 m - due presumably to more efficient energy coupling both at the source/detector level and through the near-surface layers as a whole. Higher speed arrivals at 1.6 km/s were readily observed to critical distances of 5-30 m, beyond which apparent velocities increased to as much as 4.5 km/s: the more compact material lay within about 8-15 m of the surface; total travel times over 125 m were only 50 ms. This evidence of shallower bedrock may be misleading in that elsewhere the equivalent arrivals may have been too weak to be detected.

4.4 Dowa

The area around Themba Dambo, within about 1½ km of Dowa township, was chosen as an example of the escarpment zone bordering the rift valley system, where the effects of uplift and active erosion result in a thin, weathered mantle over the bedrock. Groundwater supplies are usually attributed to fracture zones with bedrock, and unless these occur as relatively broad belts of shattering their precise location tends to be both critical and difficult.

A variety of rock types have been mapped near Dowa including biotite gneiss - commonly graphitic, pegmatic gneiss, calc-quartzite and quartz reefs: faults and fractures occur along a number of trends - west-north-west, north to north-north-west, east and north-east lineations can be picked out on aerial photographs.

Of seven boreholes drilled locally by the Groundwater Division, see Fig 7, CC15 beside Themba Dambo was abandoned as dry in a very graphitic formation, while L128 1½ km south of Dowa yielded over 4 l/s with less than 2 m drawdown. W120 which supplies the township at present has provided up to 2½ l/s and - like four of the other holes - was sited on the western side of the dambo, by the outlet of a subsidiary valley. The three holes RB24, Q15 and PM186 are now disused because of the large drawdown: yields of over 2 l/s and 1 l/s, and less than 0.5 l/s respectively, were reported. Pump test data for W120 gave a transmissivity of about 65 m^2/day, while for PM186 it was less than 2 m^2/day. Q15 showed a drawdown of 30 m when pumped at 0.4 l/s. In comparison, the holes G137 and SM227 sited on higher ground within the township gave up to ¾ l/s. Borehole depths range from 35½ m for W120 to 76 m for PM186 with depths to hard, compact bedrock being typically less than 15-20 m; rest water levels were 2-6 m.

These sites were chosen primarily on photogeological and topographic considerations and although some resistivity data were collected the results provided little relevant information as verified by borehole yields or lithology, except for indicating the presence of graphite-rich formations.

Prior to siting CC15, the latest hole, a detailed resistivity survey was undertaken with CST at 30 m intervals covering an area of about 1 km northwards from W120 by 300-600 m, including both sides of Themba Dambo. A narrow zone of low apparent resistivity, 20-30 ohm.m, at the extreme northern end of the grid was drilled and found to be caused by graphite. Elsewhere values ranged from intermediate levels of 50-100 ohm.m to relatively high values of over 200 ohm.m. These variations are thought to reflect differences in lithology - especially graphite/quartz content - and topographic effects, and no linear zones attributable to fracturing could be identified.

Seismic data acquired from the recent survey indicated only a two-layer situation on most spreads with an intermediate layer apparent rarely. Upper layer velocities of 0.3-0.6 km/s extended from 2 m to a maximum of 10 m, with underlying values in the range 2-4 km/s. The depth and range of coverage was inadequate to define fracturing by mapping the bedrock surface and velocity variations: certainly no obvious indications were observed and it is not clear that a simple bedrock refractor exists which might be delineated using a more powerful energy source - that is because changes are likely to be gradational and discontinuous laterally. It did appear that the superficial deposits were thicker on the higher ground away from the dambo.

Magnetometer traverses brought out some interesting anomalies, most consistently associated with the dambo area; variations along north-south lines were more subdued although there were isolated large anomalies. Insufficient time was available to cover the area in detail but it seems probable that the larger features reflect structural control as well as natural variations in magnetite concentration within the basement rocks. Anomalies of up to 1700 nT were recorded, positive, negative and dipolar in form, relative to background variations of about 200 nT.

Additional resistivity measurements were taken on the higher ground beside the dambo to see if better depth estimates for hard bedrock could be obtained. Expanding array data at seven sites were characterized by values in the range 100-400 ohm.m to electrode separations of over 100 m; larger spacings showed a rapid decrease which may have been caused by lateral effects from more conductive sediments in the dambo, as well as by graphitic horizons (see Fig 8a).

An attempt was made to obtain VLF electromagnetic readings despite the weak signal strengths. A few larger anomalies of up to 20% could be recognized: some related to narrow graphitic zones, others were associated with a surface conductor over the dambo, but they could not be traced between traverses 60 m apart. The accuracy of the measurements was no better than 3-5% so there was little chance of delineating any anomalies which might originate from open fractures: however, the occurrence of the anomalies observed does show that the method has a potential application which deserves fuller investigation with more suitable equipment - such as the ABEM 35/88 retained by the Geological Survey Department. While electromagnetic surveys may be no more definitive than resistivity data they will probably be at least as effective in mapping conductivity variations, and have the advantages of needing only two operators (for the systems envisaged with portable transmitter and receiver coils) and of using inductive coupling with the ground - which avoids the problems of high electrode resistance in dry or sandy conditions.

4.5 Kasungu area

While it had been noted that wells in the Kasungu area gave lower than average yields for plateau terrain, it was not clear whether the poor results reflected peculiarities of the local environment and weathering regime - which called for different siting criteria - or whether they were a consequence of a more general reduction in available groundwater.

A series of expanding Schlumberger arrays was sited from east of Kasungu, near the transition into the escarpment zone, to the mature plateau lands west of Kasungu, where dambos are particularly well developed, in an attempt to identify any factors which might be relevant to the interpretation of resistivity data. The most obvious and perhaps most significant feature of the curves is the consistently high resistivity shown by the bedrock here as compared to the other areas visited. This is apparent as a steeply rising segment at the wider electrode spacings which, in the absence of lateral variations, gives a reliable check on the total longitudinal conductance of the overlying formations. In these circumstances interpretation of depth of bedrock and the nature of the weathered zone should be more reliable, though it may still be difficult to resolve layers of intermediate resistivity near the base of the weathered section - as might be the situation with fractured bedrock - because of their suppression. An example of this is shown in Fig 8b where lateral effects are also evident, causing the curve to rise more steeply than the theoretical limit for uniform, horizontal layering. At several sites the curves failed to indicate weathered zone resistivities of less than 100 ohm.m; at others the more conductive intermediate layer extended to no more than about 10 m below surface, while the maximum interpreted depth to a high resistivity - more than 500 ohm.m - basement rock was 25 m. The occurrence of a more conductive weathered zone did not appear to correspond with higher borehole yields and it is assumed that it represents a greater clay content caused by differences in lithology and as such is not necessarily a favourable indication: the more relevant parameter is depth to the high resistivity interface. Fig 9 illustrates the difference in weathering profile and resistivity curves related to topography: curve 13 is from a site on a low ridge, and curves 12 and 14 were obtained in the adjacent, parallel dambos: also shown in Fig 10 are magnetic and VLF data along a traverse from the ridge of site 13 across the dambo of site 14 to the west, which suggest fault control or a change in lithology to the east of the dambo near 300NE and 500NE. Over the dambo itself the sequence appears less conductive than at its margins.

4.6 Salima area

Salima lies within the Rift Valley at the south-western side of Lake Malawi. The objectives of the resistivity surveys in this area were to obtain readings beside two recent holes - drilled into alluvial sands/silts/clays - which located good aquifers and at a third proposed site, and to investigate another, defined region where unusually low yields were obtained (see Fig 11a).

Results from two expanding Schlumberger arrays near each of the irrigation project test sites are shown in Figs 12 and 13. Interpreted depths to basement for the pairs of arrays are consistent within about 15% and they appear to be reasonable estimates in terms of known alluvial thickness. As might be expected, the upper part of the sequence can be differentiated but there is no resolution of layering from about 20 m depth to the high resistivity layer attributed to compact bedrock. This is consistent with the poor sorting of the sediments and it appears that the sands which constitute the aquifers are not sufficiently thick, laterally extensive or clean to be identified on the resistivity curves for depths of more than 20-30 m. On the basis of a limited amount of data from the alluvium of the Lower Shire Valley, an average value of over 10 ohm.m at depth gives a reasonable chance of there being permeable horizons: values of 5 ohm.m or less indicate a predominence of clays and saline water. Thus, by analogy, sites 1 and 2 are consistent with the presence of relatively fresh water, but at the proposed third site, where resistivity values of about 5 ohm.m are given, the prospects would appear less favourable: there is also the indication of shallower bedrock, at 50 m as compared to 75 m and more than 150 m for the holes drilled (bedrock was not proved by the drilling at these sites). Site 4, further west from site 3, confirmed the expected trend of bedrock being shallower in this direction, and also gave a resistivity of less than 10 ohm.m for the alluvial/colluvial cover.

The four arrays, 5-8 near low-yielding wells, were notable mainly for evidence of lateral discontinuities; the lack of consistency within the 4½ km covered by the sites was in marked contrast to the other data. These comments apply to the bedrock interface as well as to the superficial layers: two curves, 5 and 7, indicated a conductive basement, and none of them provided a reliable estimate of bedrock depth; curves 7 and 8 only, showed a conductive (? impermeable) layer within 5 m of the surface. No specific cause of the poor wells can be given but they may be near shallower bedrock or in an area of low recharge due to limited vertical permeability and lack of continuity of the weathered material.

4.7 Ngabu area

Along the south-west margin of the Lower Shire Valley are some of the most extensive developments of known Cretaceous and Karroo System rocks in Malawi, which include calcareous sandstones, mudstones, shales and basalt. Major faulting affects the disposition of these formations and the extent to which they underlie the thick alluvial cover towards the centre of the valley is unknown. As only the basalts are associated with good aquifers, mapping these units beneath drift by geophysical techniques may become important if deeper, high-yielding, boreholes are planned for irrigation purposes. Similarly, the tracing of faults below the alluvium would be needed as these may control the flow of groundwater and allow saline water from depth to circulate upwards and contaminate shallower aquifers.

Some airborne, ground magnetic, and gravity surveys have already been undertaken which indicate the value of these methods. Additional measurements, including seismics, were obtained during a brief visit to Ngabu in November 1980 to give more information on the physical properties of the rocks involved.

A magnetic traverse west of Ngabu clearly defined a faulted margin of the basalts with a positive anomaly of about 1000 nT in amplitude. The smoothness of the field to the north-east indicated a rapid thickening of the non-magnetic sediments: this was confirmed by Schlumberger array readings 175 m beyond the fault, which implied a depth to bedrock of over 150 m, and by the decrease in seismic velocity from 4 km/s to 2 km/s to the north east.

Resistivity measurements were taken by a proposed deep drilling site (1H304) in an attempt to estimate the thickness of alluvium near the centre of the valley, and to verify the basis on which the site was chosen - a channel of higher resistivity detected by an earlier CST grid survey. Orthogonal expanding arrays centred at the site were similar in form and showed a minimum of five layers in a KQH sequence: approximate interpreted values were 15 ohm.m to $1\frac{1}{2}$ m, 50 ohm.m to $5\frac{1}{2}$ m, 11 ohm.m to 19 m and $2\frac{1}{4}$ ohm.m to 230 m underlain by 20-25 ohm.m. A third array centred away from the higher CST values gave a lower intermediate layer resistivity but the sequence at depth was little different: 35 ohm.m to 5 m, 4 ohm.m to 20 m, $2\frac{3}{4}$ ohm.m to 230 m and a deepest layer of 25-30 ohm.m. The CST data are reflecting only variations in the upper 20 m of the sequence and cannot be related to any aquifers, the shallowest of which are usually found at greater depths. Resistivity values at 2-3 ohm.m for the alluvium as a whole are not favourable for the occurrence of good aquifers here and suggest instead a clay-rich sequence of low permeability in which any water is likely to be saline; an implication supported by the hydrochemistry of neighbouring wells. At the maximum current electrode separations of 1000 m apparent resistivity values were increasing, but not rapidly enough to define the true resistivity of the underlying formation as a hard compact bedrock such as basalt or basement, and more consistent with it being Mesozoic sedimentary rock.

Resistivity and seismic refraction data over supposed Lupata series sandstone suboutcrop did not detect any clear interface below a 1-4 m thick superficial layer. However, there was a transition to higher resistivity - from 6 to 12 ohm.m - and higher speed arrivals - from below 1 km/s to more than 2 km/s - for depths of 15-25 m: there were also lateral variations in velocity along the profile. Resistivity measurements at two nearby sites, one of which yielded significantly fresher water, showed differing near-surface values and the interpreted formation resistivity at depth by the less-saline site was slightly the higher at 7 ohm.m compared to 6 ohm.m.

Velocities recorded over near-surface basalt were about 4 km/s or more for fresh rock and 1.5-2.0 km/s for the weathered basalt. Energy transmission was variable but generally good,and first arrivals could be identified over distances of 100-150 m: the main problems lay in distinguishing specific refractors and matching them between spreads so that variations in depths and velocities could be monitored consistently. Velocities over quartzitic basement rock were of similar magnitude to those for the basalt: it is unlikely that the seismic method could differentiate between the two but their velocities should be significantly greater than those for the sedimentary rocks.

4.8 Summary of findings

The analysis of the data described in Section 3.4.2 was, almost certainly, too general to define any relationship between the aquifers and the resistivity interpretations, but it is probably as specific as the data warrent: more detailed studies could be undertaken on smaller areas when good quality results are available. As the sample is biassed to those sites picked out as lying within more conductive zones, the extent to which the results are representative of the areas as a whole is not clear; however, the interpreted resistivities are thought to be typical average values for the succession. The surveys described here support this view but it is clear that marked variations may occur near any site. Given that field procedures used by the Groundwater Division can be improved and better models derived from the data, the relevance of quantitative interpretations to the hydrogeology is still open to question. Two points need to be considered: first, whether the aquifers themselves can be resolved with the resistivity method - in consideration of the limits imposed by the accuracy of the measurements and by lateral variations; second, whether it is realistic to attempt interpretations in terms of a limited number of uniform layers, given the poor sorting within the succession - that is, the graditional nature of the weathering profile through the basement rocks, and the lack of distinction within the alluvial and colluvial deposits.

Borehole logging provides a means of measuring physical properties in situ and such values are, in general, preferable to determinations from core specimens. Unfortunately, resistivity logging is not practical over cased sections of a hole so that is rarely possible to obtain data from poorly consolidated formations: certainly the existing boreholes within Malawi would not be suitable for logging and special holes would be required. In the absence of such information some check is provided by matching interpretations of the surface data against boreholes where lithology and aquifer thickness and location are known: on this basis, previous surveys have not been successful in predicting depths to aquifers or recognizable lithological interfaces, though the drilling details themselves are questionable in many cases. Thus there is still a need for reliable information on the nature of the aquifers.

A more satisfactory approach to interpretation might be to invert the apparent resistivity curves by computer techniques [7] which generate a large number of layers - equal to the number of field data points : these would normally be smoothed to give an equivalent solution for fewer, thicker layers but in their original form they would correspond to a less formalized sequence. As the computing facilities needed to handle this are not available within Malawi such methods have no immediate application but some processing could be done at the Institute of Geological Sciences, UK, within the scope of the Groundwater Project to evaluate their potential.

Qualitatively, experience has suggested the resistivity surveys have reduced the number of 'dry' sites but a more rigorous proof of this is needed in particular areas. It would be expected that where bedrock may occur within 15 m of the surface resistivity highs are better avoided, but the results from Chitedze, for example, are equivocal. Care is needed to discriminate near-surface laterites or sandy layers from bedrock, and graphitic basement from a thick weathered zone. Good aquifers would be expected within fractured rock overlying basement and their effect on the resistivity curve is likely to be marginal, resulting in a less-rapidly rising 'hard-rock' segment and a higher total conductance. Where graphite is common, an aquifer might be expressed by relatively higher resistivities, while a high conductivity for the weathered zone indicating clay enrichment is not in itself favourable. Again it is stressed that the results need to be reassessed in the light of more hydrogeological control on the occurrence and extent of the aquifers.

Electromagnetic techniques have an application in relation to following up airborne survey indications, tracing significant fracture zones and conductivity mapping in lieu of CST. The VLF transmissions are inadequate for this purpose so that portable transmitter-receiver systems will be necessary - such as the Geonics EM31 and EM34, or Max-Min 3 equipment. It is recommended that trials using such methods should be undertaken in cooperation with the Geological Survey Department.

Seismic refraction results did not suggest a general application for the method except in relation to dambo studies for which a hammer source/enhancement seismograph combination should be adequate. More powerful energy sources, such as explosives or a 50 kg weight-drop device, would greatly extend its capabilities but the logistics of handling explosives or the lifting tripod would make the system more cumbersome. Interpretation of results from plateau regions will be hindered by the gradational nature of velocity variations both vertically and laterally.

Use of the magnetic method is to be encouraged on a routine basis for detailed surveys to complement conductivity information in delineating trends and structures within the bedrock.

The possibility of assessing alluvial thicknesses from gravity data has been suggested [8]. Available coverage is on a regional scale [3] which allows consideration of broad scale features, such as the minimum developed over the Lower Shire Valley; additional detailed surveys could be undertaken to define more localized bedrock depressions.

Particular aspects of the hydrogeology, such as the question of recharge mechanisms, have not been investigated. Thus, for example, the presence of laterites overlying permeable formations may prevent recharge to a potential aquifer. It has not been possible to differentiate grades of weathering on the basis of the resistivity data beyond the indications as to the nature of the near-surface material - more sandy, more clay rich - and of the sequence as a whole. By detailed surveys and the use of 2-D modelling techniques it may be practical to define the geometry of the aquifers in more detail if adequate borehole control is available. In these circumstances the induced polarization technique may help to discriminate variations in clay content. Such methods are beyond the capabilities of the Division as it is constituted at present and so they have not been investigated in detail for this report: their application in the future should not be discounted, with particular reference to the application of the new generation of mini-computers to data processing and interpretation.

5. CONCLUSIONS AND RECOMMENDATIONS

1. The resistivity method is the best geophysical technique available locally to assist in the routine siting of rural boreholes: its main advantages are simplicity of instrumentation and field procedures which provide a rapid means of obtaining qualitative and semi-quantitative information on the nature and thickness of near-surface layering to a depth of about 30 m with the equipment already available to the Groundwater Division. This is not to say that the results can be interpreted directly in terms of the location of aquifers but that they may indicate more or less favourable environments for their occurrence: nor does it imply that resistivity surveys are invariably a prerequisite for selecting borehole sites.

2. The objective of rural boreholes is to provide an adequate supply of good quality water at minimum cost. With regard to the siting procedure a more carefully controlled accounting system which kept track of days spent away from the official base, number of sites surveyed - differentiating time devoted to routine and detailed surveys, total mileage and vehicle maintenance for each field trip, would involve little administration while providing information on actual costs which might be used as a basis for improving efficiency and to decide for example on the 'cost effectiveness' of surveys in relation to the number of dry, shallow boreholes (that is those stopped of reaching hard bedrock) which could be drilled for the same outlay.

3. The programme for site surveys should be planned to minimize travelling and to allow for an appraisal of existing information before the fieldwork is undertaken; those surveys required at short notice which cannot be fitted conveniently into the schedule should be surcharged to cover additional costs incurred. Detailed surveys should be costed according to a nominal charge for overheads and office work, plus a daily rate and travelling expenses.

4. Every attempt should be made to ensure that borehole siting is based upon all the available information so that there is consideration of the overall water resources and regional context as well as of the results from neighbouring sites. This has an immediate bearing on the surveys in terms of the type of equipment and arrays required, the likelihood of problems associated with laterites or graphitic bedrock, whether any favourable geological conditions occur - fracture zones, dykes, quartzitic formations, whether previous results suggest that boreholes may not

be the best means of providing water, etc.

For this to be practical it will be necessary to have the information in a readily accessible form. The water resource unit reports should provide the regional picture including an assessment of the geophysical data while, as far as possible, the detailed results should be presented on map overlays.

5. In view of the difficulty of establishing a direct relationship between aquifer properties and geophysical results on theoretical grounds it is important to make the most of the data empirically, to bring out any trends and associations which might be extrapolated and applied more generally.

When considering the resistivity data in particular there is a danger of lapsing into a circular argument such that in plateau areas, for example, aquifers are always associated with zones of low resistivity outlined by CST simply because boreholes are always sited on this basis: it may be that equivalent, or at least adequate, yields could be obtained in other situations. The point is that without a degree of experimentation general conclusions cannot always be reached.

For these reasons it is suggested that a study area should be chosen within plateau terrain - such as sub-basin 5D in the Bua catchment - in order to evaluate the merits of different procedures. Present methods would be followed in a 'control' section while alternatives could be tested elsewhere. Initially the data would have to be compiled and a comprehensive review of the geological, hydrogeological and geophysical information undertaken to choose a representative control area, to decide whether any trends exist within the resistivity results, to delineate areas where resistivity surveys might be unnecessary.

Checks could then be made on: the practicality of selecting sites without previous surveys or on the basis of existing survey work; drilling on sites which would normally have been rejected in the course of a survey, for example because of laterites; drilling on zones of intermediate resistivity. Within this context the effects of relative topography - that is ridges/valleys, and the influence of dambos could also be considered: some previous work has been done in this respect but the results were not conclusive in themselves and were not combined with resistivity data.

6. The main value of the resistivity surveys lies in their ability to indicate the presence of shallow bedrock, within 15-20 m of the surface, thus reducing the risk of siting dry boreholes in plateau terrain and at the margins of thick alluvial deposits: there is little evidence that the surveys have lead to significantly higher borehole yields in areas of deeper bedrock. If districts can be outlined where the weathered zone is unlikely to be less than 15 m thick there is no obvious necessity for site surveys within them. This seems to apply even in areas where aquifers are difficult to locate although bedrock is not unduly shallow; that is, the resistivity method will not usually distinguish between a weathered layer with available water and one without, either because of a lack of discrimination, or the fact that the saturated thickness is small or confined to narrow zones.

Especial note should be taken of any circumstances particular to dry holes and an effort made to establish a reason for them, to distinguish failings in the siting procedure from the occurrence of generally barren environments.

7. A more flexible approach should be adopted to array dimensions in resistivity surveys. While a CST spacing of about 25 m is likely to be reasonable for many plateau areas it should be related to the average depth to bedrock and the form of the resistivity section indicated by previous surveys or expanding arrays at that time: if the spacing is too small the results will only reflect variations within the upper part of the weathered zone; if it is too large the resolution will be reduced unnecessarily and the data will be more susceptible to lateral effects.

As the resistivity curves usually indicate at least three distinct layers within the section any anomalous zones brought out by CST at a single separation may originate from one or several of a number of different causes. In order to distinguish variations in the thickness or resistivity of the upper zones from deeper causes which are likely to be more significant, it is necessary to use at least two spacings such as 5 m and 20 m, or 10 m and 30 m depending upon the circumstances. Where greater detail is required it is probably better to take measurements as a set of expanding arrays centred on a traverse line: the results can then be plotted on a pseudo-section of horizontal position against electrode separation and contoured. Such a presentation can be useful for highlighting anomalous zones and their relation to near-surface variations: it is not a substitute for a full interpretation in terms of depths.

8. Any interpretation of expanding array data will be limited by distortion due to lateral variations in layer thicknesses and resistivities for which corrections cannot be applied. There is no point in attempting detailed analysis of curves that do not conform to the criteria on which the interpretation is based. Some measures can be taken to estimate the magnitude and cause of these effects: by using two orthogonal arrays, or ideally, three arrays oriented at 120° to each other about a common central point, it should be possible to identify local inhomogeneities - which can be smoothed from particular curves - and larger scale variations caused by anisotropy in steeply dipping formations; by correlating interpretations against reliable borehole logs their validity can be checked and adjustments made to decide if, and how, a more realistic model could be set up on which to base interpretations in that locality; by undertaking detailed surveys, that is by increasing the number of sites in a given area, a more coherent pattern may emerge by identifying common factors and any less disturbed zones where interpretations can be given more weight. If the effects are too large only a qualitative assessment is justified, but it is important to ensure that the data themselves are reliable and that faulty field procedures are not causing or contributing to the difficulties.

9. The weathering profile and hence the resistivity data and aquifer properties in hard rock areas are strongly influenced by the bedrock lithology and jointing. It does not follow that the most conductive and deeply weathered sequences will contain the best aquifers; zones of a shallower, more resistive, quartzitic rock which produces few clays may represent a better target than a more deeply weathered graphite-rich rock. For this reason the practice of selecting sites simply in terms of resistivity lows or large depths to bedrock should be followed only with caution: the presence of zones of intermediate resistivity at sufficient depth may be more favourable. Any aquifers within the weathered zone will almost certainly be associated with intermediate resistivity values (the term intermediate is necessarily relative and depends upon the formations involved; it will normally imply a range of 50-300 ohm.m) where water quality is good, but the limited thickness will prevent their resolution from the expanding array data.

As mentioned above, definition of hard-bedrock resistivity values is often difficult, but in those cases where the expanding array curve rises steeply - at a maximum of 45° for a Schlumberger configuration - at depth beyond 100-200 ohm.m it can be assumed in general that the bedrock is compact, with few fractures and little chance of containing an aquifer: the converse does not follow, that low apparent resistivities preclude the possibility of a hard, compact, rock.

10. Detailed surveys should be based on obtaining the maximum amount of information even if some of it is redundant - this applies in particular to resistivity surveys - and in hardrock areas should comprise magnetic, expanding array, CST and perhaps self-potential methods. An orientation survey may be required initially to determine the direction for the traverses, which will usually be run across strike, and for the expanding arrays which should give better results along strike.

Measurement and line intervals need to be decided on the basis of the size of area to be covered and the wavelength and amplitude of the anomalies of interest relative to background levels. The grid should not be too detailed to start with as intermediate lines can be added when areas of interest have been located: a combination of 40 m/20 m/10 m or 60 m/30 m/15 m would be suitable in most circumstances. Station intervals should normally be less than the line separation unless a detailed uniform coverage is required.

Under favourable circumstances a gradient array might be used to map conductivity variations with good resolution and depth penetration: alternatively, a CST spacing can be chosen on the basis of expanding array data to be large enough to respond to variations near the bedrock interface. Together with magnetic data this will provide a basis for putting in extra lines to provide better definition,or for siting expanding arrays to give some depth control. Drilling sites would then be recommended in relation to the local geology and available hydrogeological information.

Preliminary interpretations need to be revised in the light of drilling results, and further work undertaken if necessary to select new sites. The person responsible for the geophysical surveys should be kept informed of results from holes drilled subsequently - this applies also to routine siting when the delay might be of several months - and an assessment made of the original work, in terms of its usefulness, the reliability of the interpretation and whether it could be improved or refined, and any more general conclusions which might be reached.

11. For rural borehole sites more emphasis than at present might be placed on expanding arrays. A single array at a site chosen by inspection on general considerations could be sufficient to eliminate the possibility of shallow bedrock: two orthogonal arrays would allow a more

reliable assessment to be made. If shallow bedrock is present a series of short CST, preferably across strike, would help to indicate any zones of deeper weathering, but these should be expressed on at least two lines 20 m - 30 m apart and confirmed with expanding array data.

12. Where interpretation of expanding array data is difficult or ambiguous the conductance of the layers (that is the ratio of thickness to resistivity) detected should be estimated. This parameter is likely to be more reliable and there is evidence from other studies that it is a good diagnostic parameter in relation to aquifer properties and the nature of the weathered material; in alluvial areas the transverse resistance (the product of layer thickness and resistivity) will be significant. Total conductance can be obtained directly from the field curve where the final layer has a relatively high resistivity.

13. The electromagnetic method would allow the equivalent of CST to be undertaken more quickly while avoiding any problem of making ground contact. Some indication can also be obtained on the changes in conductivity with depth. Such equipment would be useful for mapping shallow bedrock and for checking proposed expanding array resistivity sites for lateral variations.

14. A close liaison should be maintained with the Geological Survey Department (which still retains information directly related to the Groundwater Division, that is reports - listed in the reference section - and CST contoured maps). Apart from the interchange of geological information there is the possibility that more geophysics will be undertaken from the Department within the next few years; it has electromagnetic equipment which could be applied to hydrogeological problems, though their 2½ kW induced polarization/resistivity set is probably beyond immediate repair. Airborne geophysical surveys have already been undertaken over several areas of Malawi and it would be interesting to relate the electromagnetic anomalies to borehole records: many anomalies were attributed to ionic conductors and some of these might be associated with fracture zones or particular formations within the bedrock which, in turn, control or influence groundwater occurrence. Aeromagnetic maps would provide a setting for any detailed ground surveys and suggest lithological trends and structural features.

The setting up of a geophysical section within the Geological Survey would provide the equipment and expertise necessary for undertaking more specialized surveys, such as: investigations using induced polarization; interpretation of airborne electromagnetic data in terms of groundwater potential, and ground follow-up work; to assess structural controls and total thickness of sediments in the Lower Shire Valley; application of seismic refraction and gravity methods eg to dambo sites or locating buried channels. As such work is likely to form only a minor part of the activities of the Groundwater Division the capacity for doing it would have to be established within a broader context of geophysics in Malawi.

5.1 Specific recommendations

1. SI units should be adopted for all physical measurements.

2. A revised filing system should be introduced for routine borehole siting data into which existing information would be incorporated if possible.

3. A separate 'dry holes' file should be opened onto which all relevant siting and lithological details will be copied.

4. A summary of expanding array and borehole data should be plotted on 1:50,000 overlays to the topographic maps.

5. A 'clerical' officer should be appointed with responsibility for: organizing and maintaining the filing system, transferring and copying information between files and onto maps, storing maps and overlays, abstracting information as required by the professional and technical officers.

6. Two people are required to take over responsibility for routine field work, including geophysical surveys and collection of hydrogeological data. These posts need to be defined - preferably at Technical Officer standard - and filled as soon as possible so that training can be completed within the duration of the Groundwater Project. It is important that the possibility of professional staff being obliged to take up this work again is avoided.

7. The results of all detailed surveys should be written up as brief reports which describe the hydrogeological setting, the fieldwork and its interpretation and the outcome of any drilling; all the relevant data and diagrams should be included and borehole site information copied onto the main file.

All field note books should be properly annotated and stored for future reference.

8. Use of the Cooper array in resistivity surveys should be discontinued and the Wenner configuration adopted for the routine expanding

array sites: where conditions permit the Schlumberger array is to be preferred.

9. Routine surveys should not usually be undertaken where thick - greater than say 25 m - recent deposits are known to exist. Specific projects using longer resistivity arrays might be considered when more powerful instruments become available; for example, to delineate the extent of clay-rich, saline zones in such areas.

10. Detailed surveys should be fully integrated with hydrogeological, geological and drilling studies.

11. It is not practical to set out a rigid procedure to be followed in applying geophysics to borehole siting: to a large extent its value can only be assessed empirically and it is essential that results and field techniques are kept under review, and that a flexible approach is maintained. The type of considerations involved are summarized in the accompanying flow-chart, Fig 14.

12. The immediate requirements for new geophysical equipment within the Division - for the ABEM Terrameter SAS 300 with booster SAS 2000, and the Elsec 770 proton magnetometer - are covered by proposals which have already been put forward. Ancillary items which should be acquired are porous pots for use with resistivity equipment (the Terrameter SAS can also measure self-potentials for which non-polarizing electrodes are essential) and simple multimeters for checking battery voltages, electrode contact resistances, continuity of wires etc.

The most suitable electromagnetic equipment available at present is the Geonics EM31 - single operator, depth of investigation typically about 6 m, price £3350 - and the Geonics EM34-3 - two operators, depth of investigation up to about 50 m, price £5500. Both instruments give a direct read-out of apparent conductivity.

6. ACKNOWLEDGEMENTS

The assistance provided by all members of the Groundwater Project is gratefully acknowledged, with particular reference to Mr R Kafundu, Mr P J Chilton, Mr D R C Grey and Miss C Carr who attended to most of the logistical problems and assisted in the fieldwork at various times.

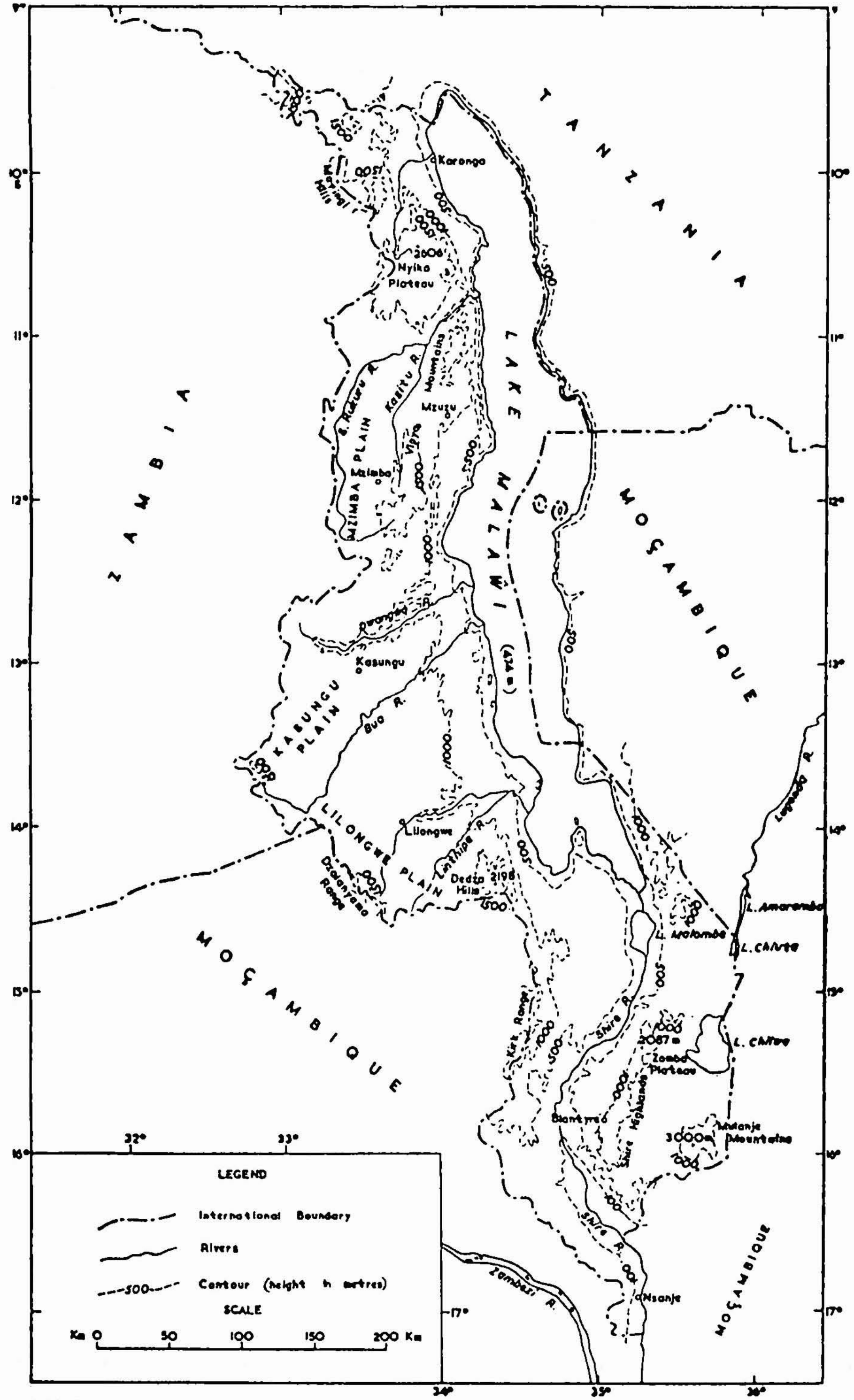


FIG 1a. Malawi : topography and drainage

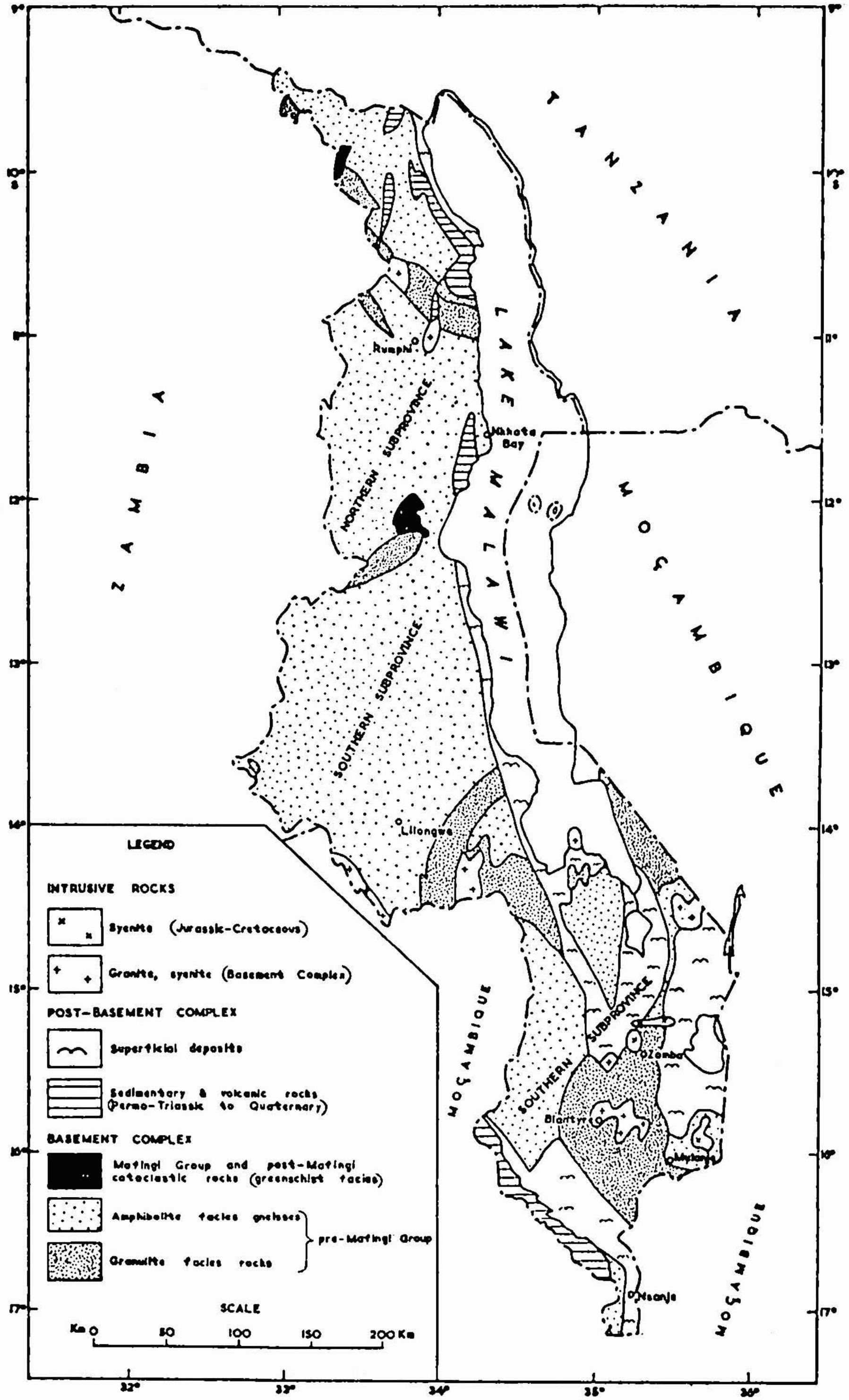


FIG 1b. Malawi : major geological units

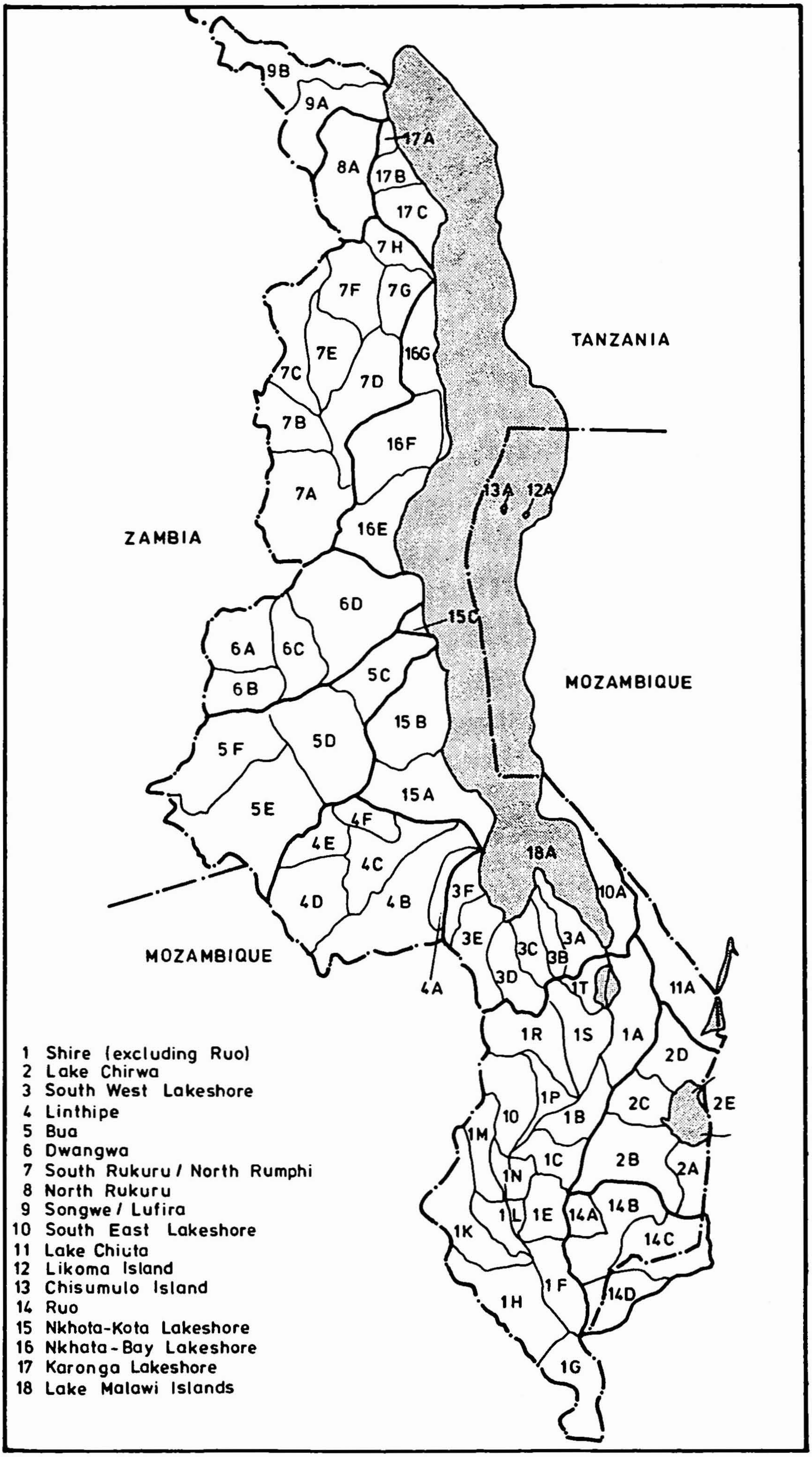


FIG 2. LOCATION OF WATER RESOURCE UNITS

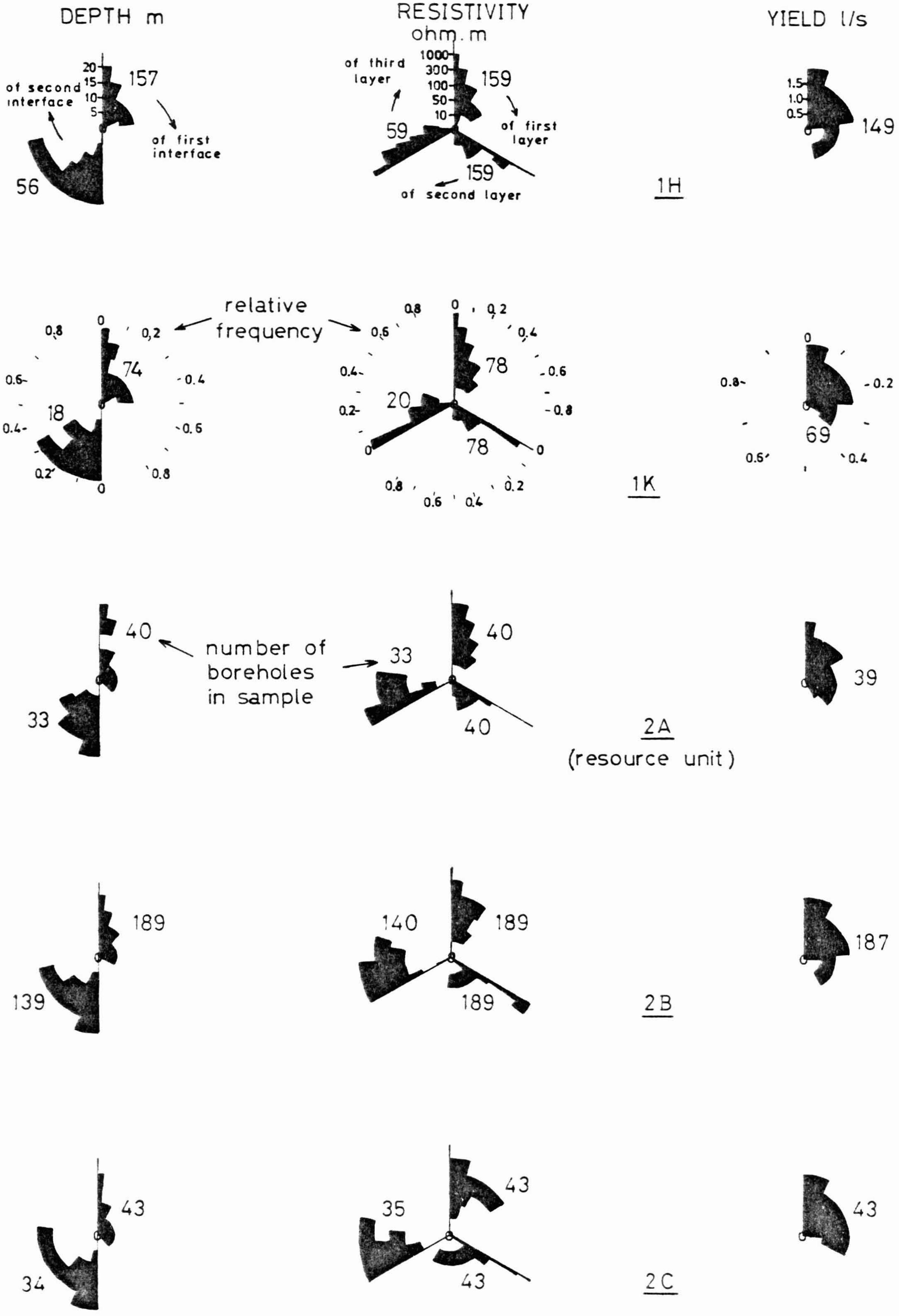
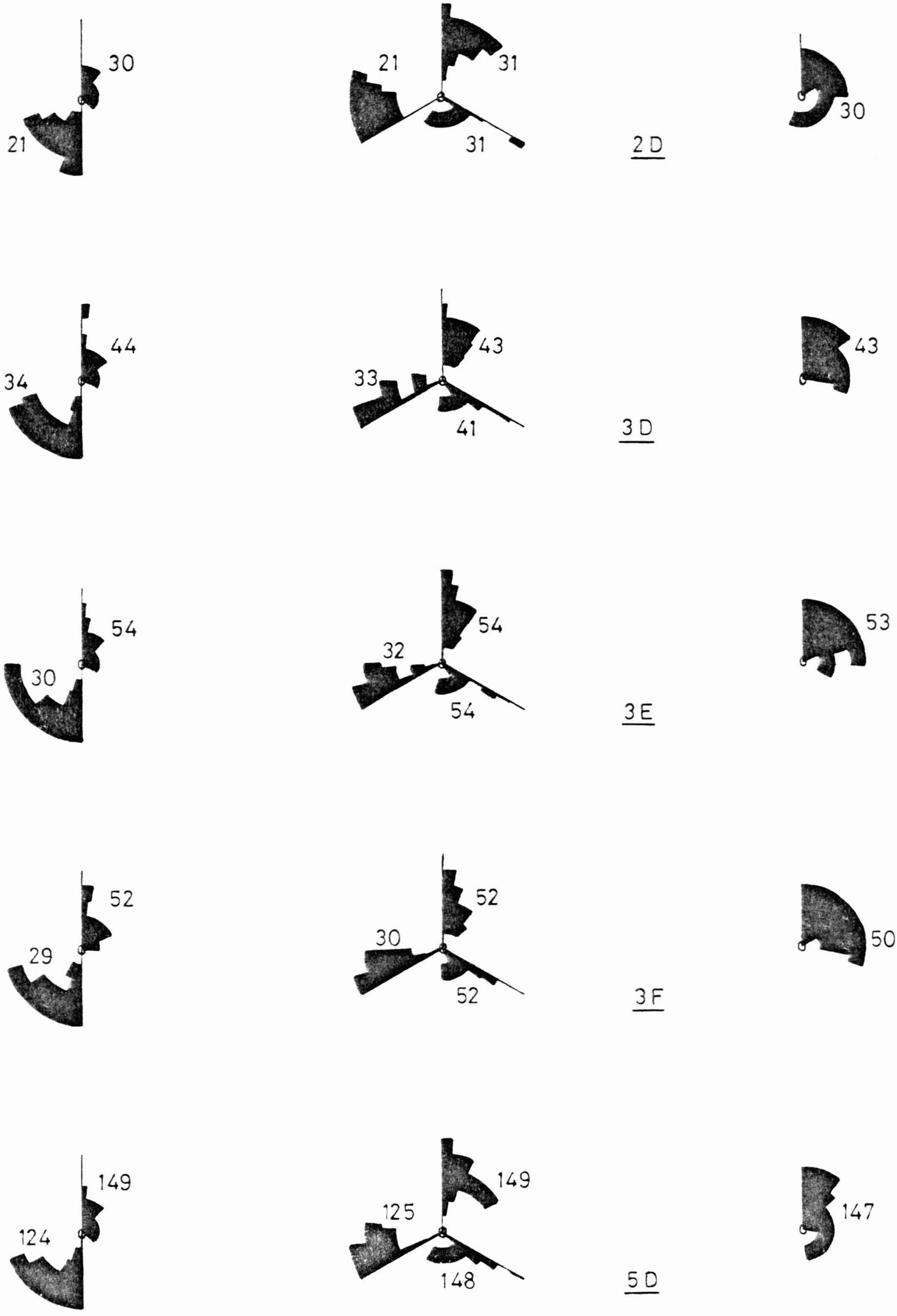


FIG 3. SUMMARY OF RESISTIVITY INTERPRETATIONS ON AN AREAL BASIS


30
21
21
31
31
2D
30
44
34
43
33
41
3D
43
54
30
54
32
54
3E
53
52
29
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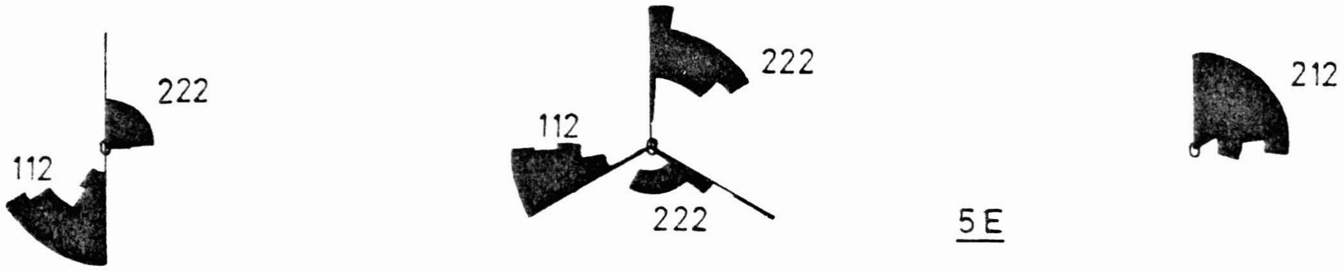
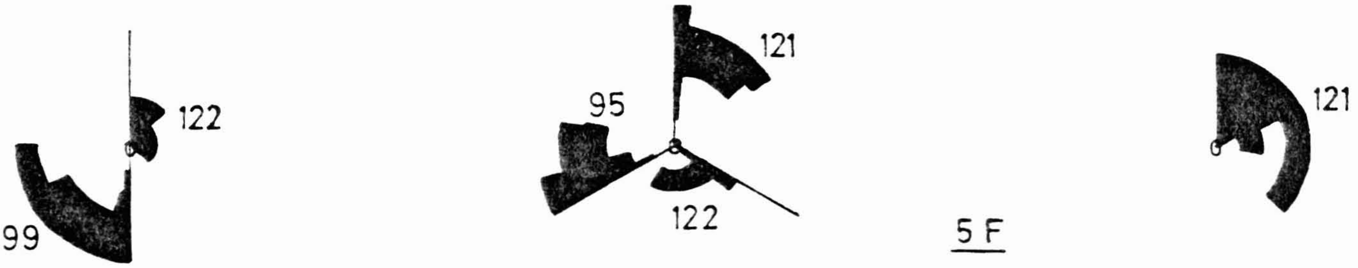
30
52
3F
50
149
124
149
125
148
5D
147

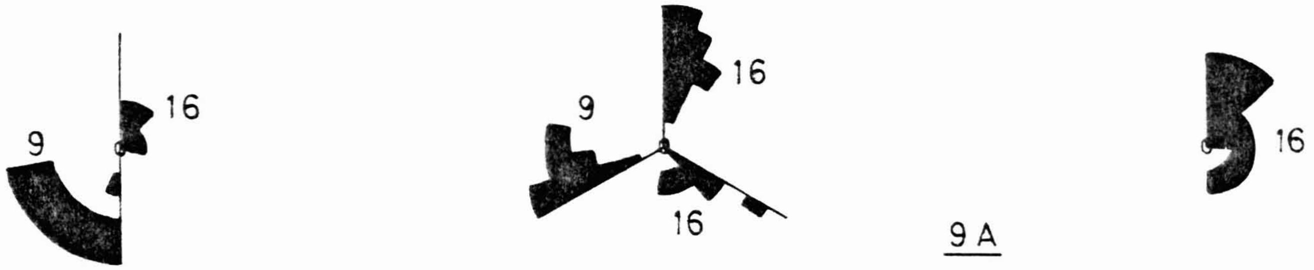
FIG 3. (cont)



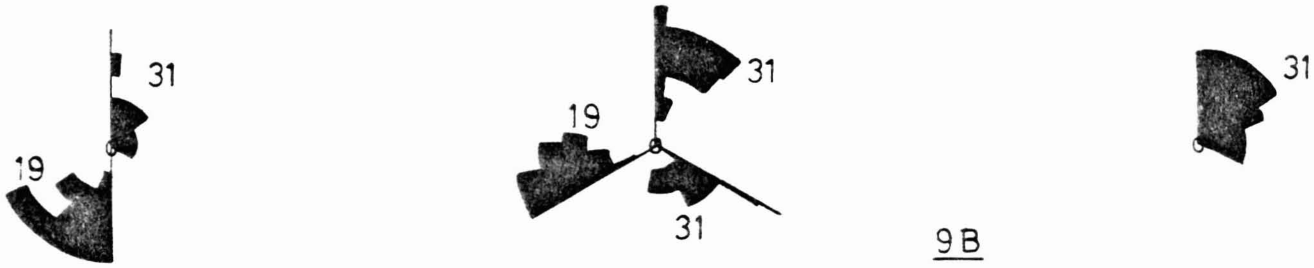
5 E



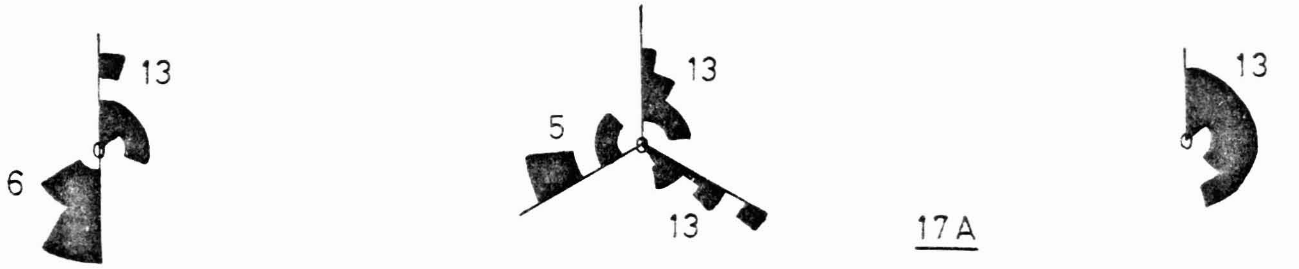
5 F



9 A

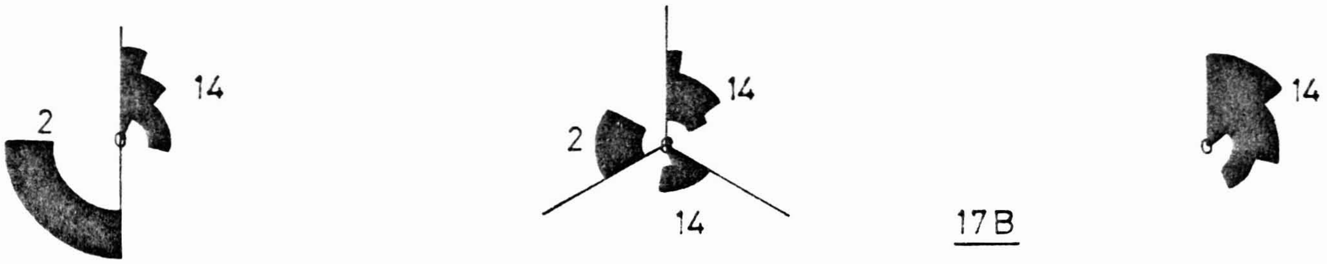


9 B

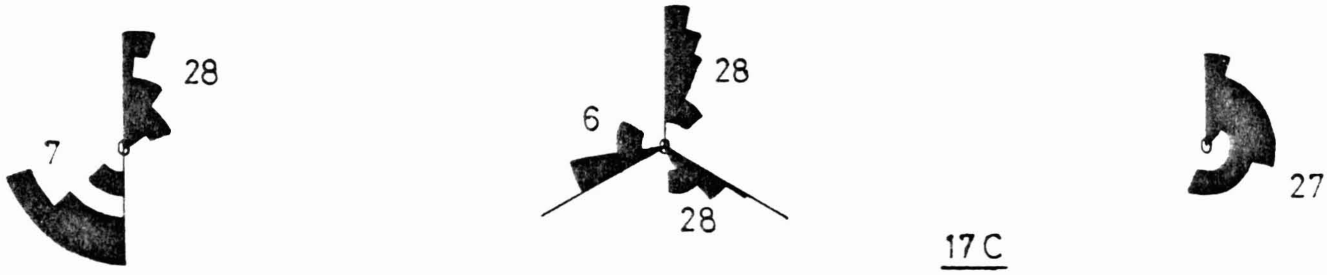


17 A

FIG 3. (cont)



17B



17C

Resource units

1 Shire (excluding Ruo)
2 Lake Chirwa
3 South-west Lakeshore
5 Bua
9 Songwe / Lufira
17 Karonga Lakeshore

FIG 3. (cont)

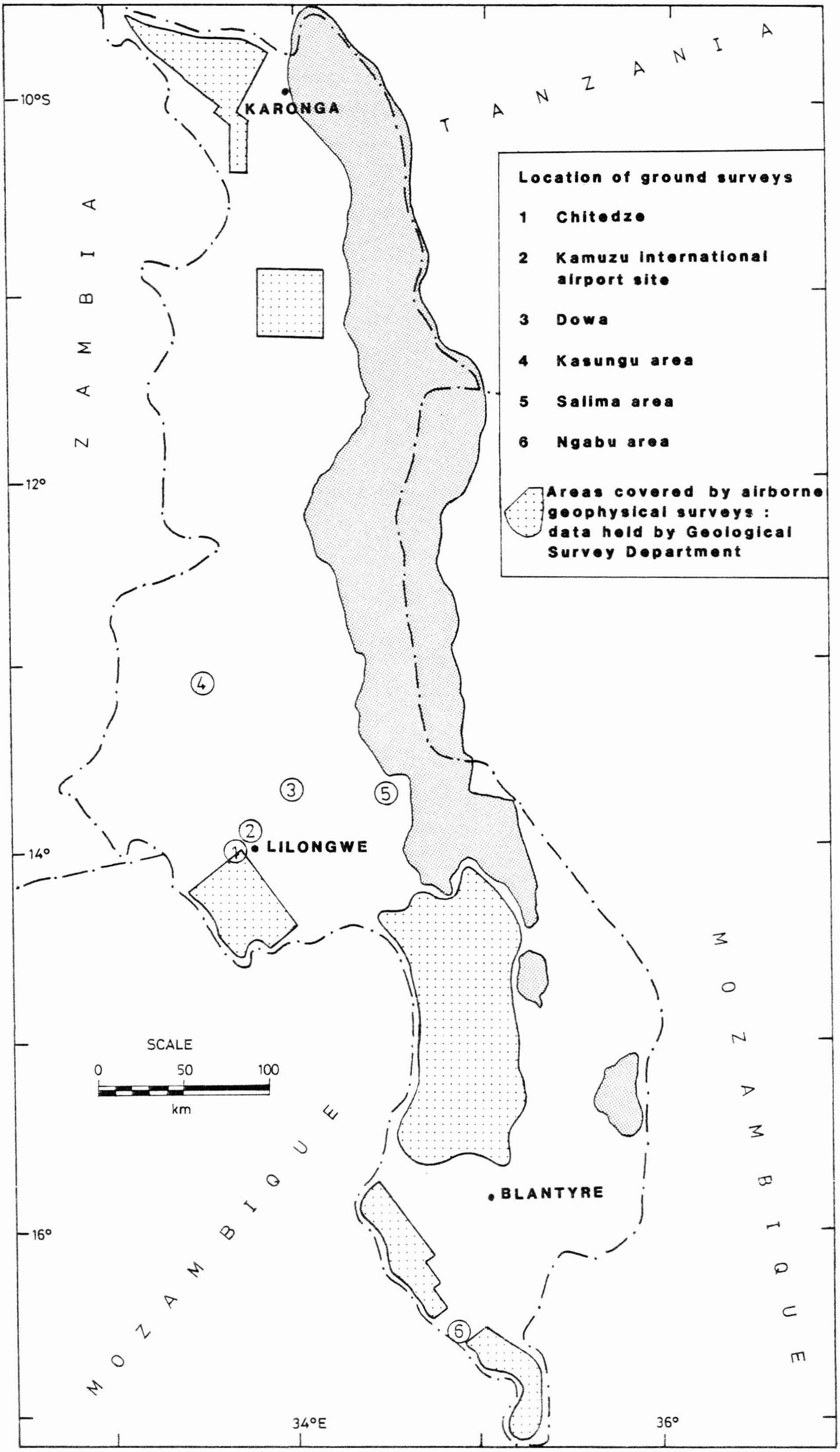
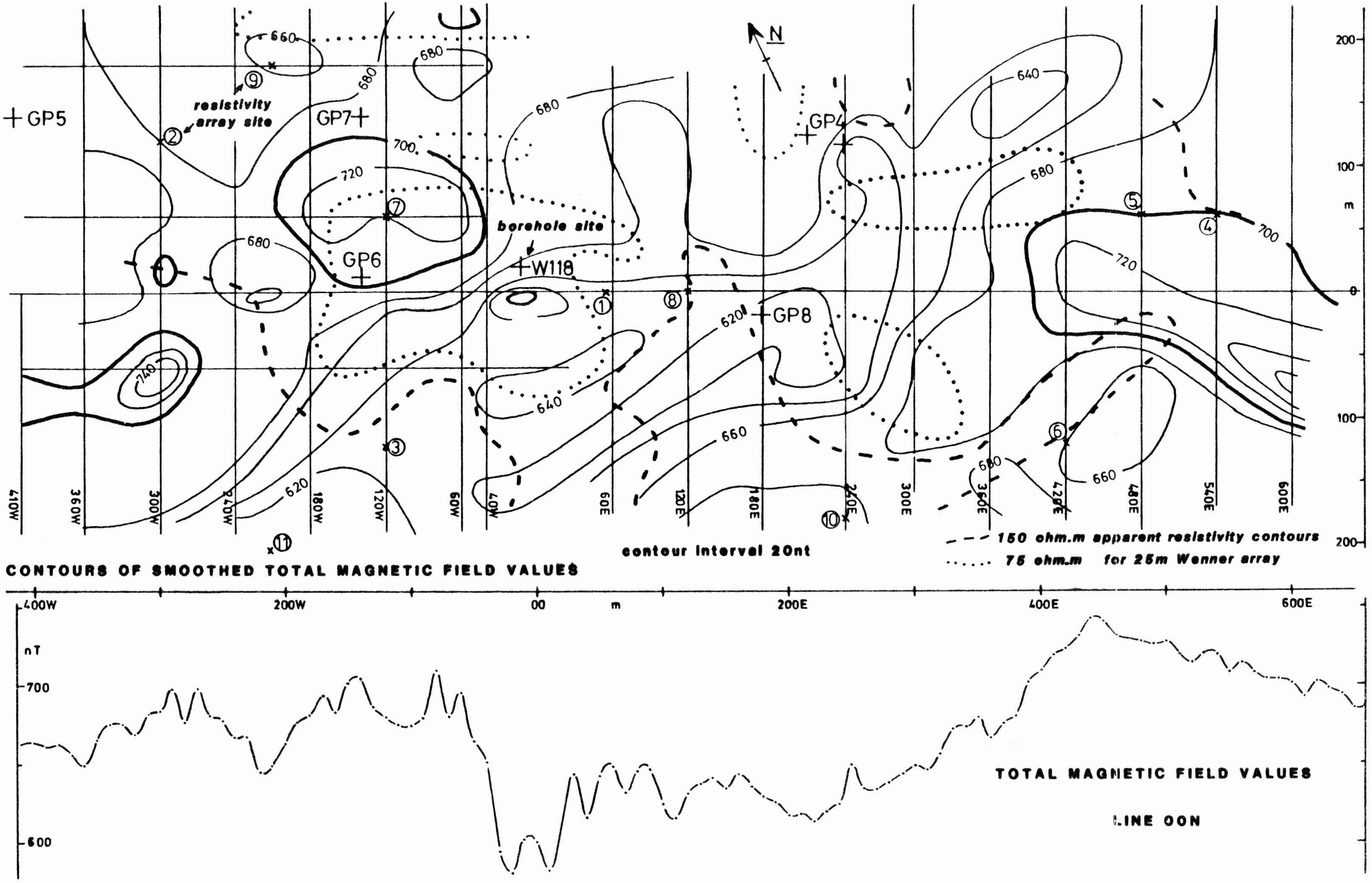


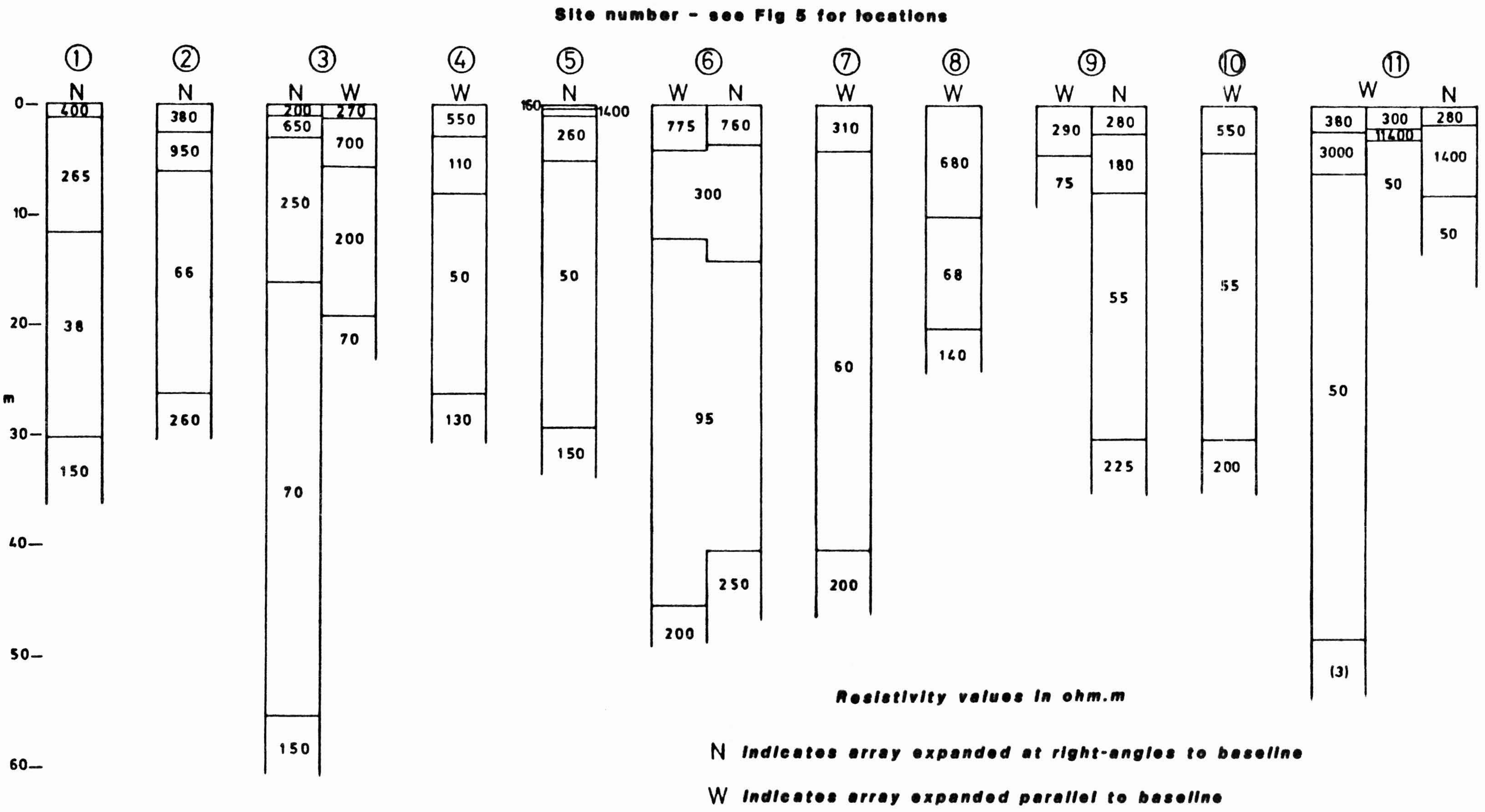
FIG 4. LOCATION MAP SHOWING FIELDWORK AREAS AND AIRBORNE GEOPHYSICS


CONTOURS OF SMOOTHED TOTAL MAGNETIC FIELD VALUES

TOTAL MAGNETIC FIELD VALUES

LINE OON

FIG 5. MAGNETIC AND RESISTIVITY DATA FROM CHITEDZE


Site number - see Fig 5 for locations

Resistivity values in ohm.m

N ***Indicates array expanded at right-angles to baseline***

W ***Indicates array expanded parallel to baseline***

FIG 6. RESISTIVITY INTERPRETATIONS FROM CHITEDZE

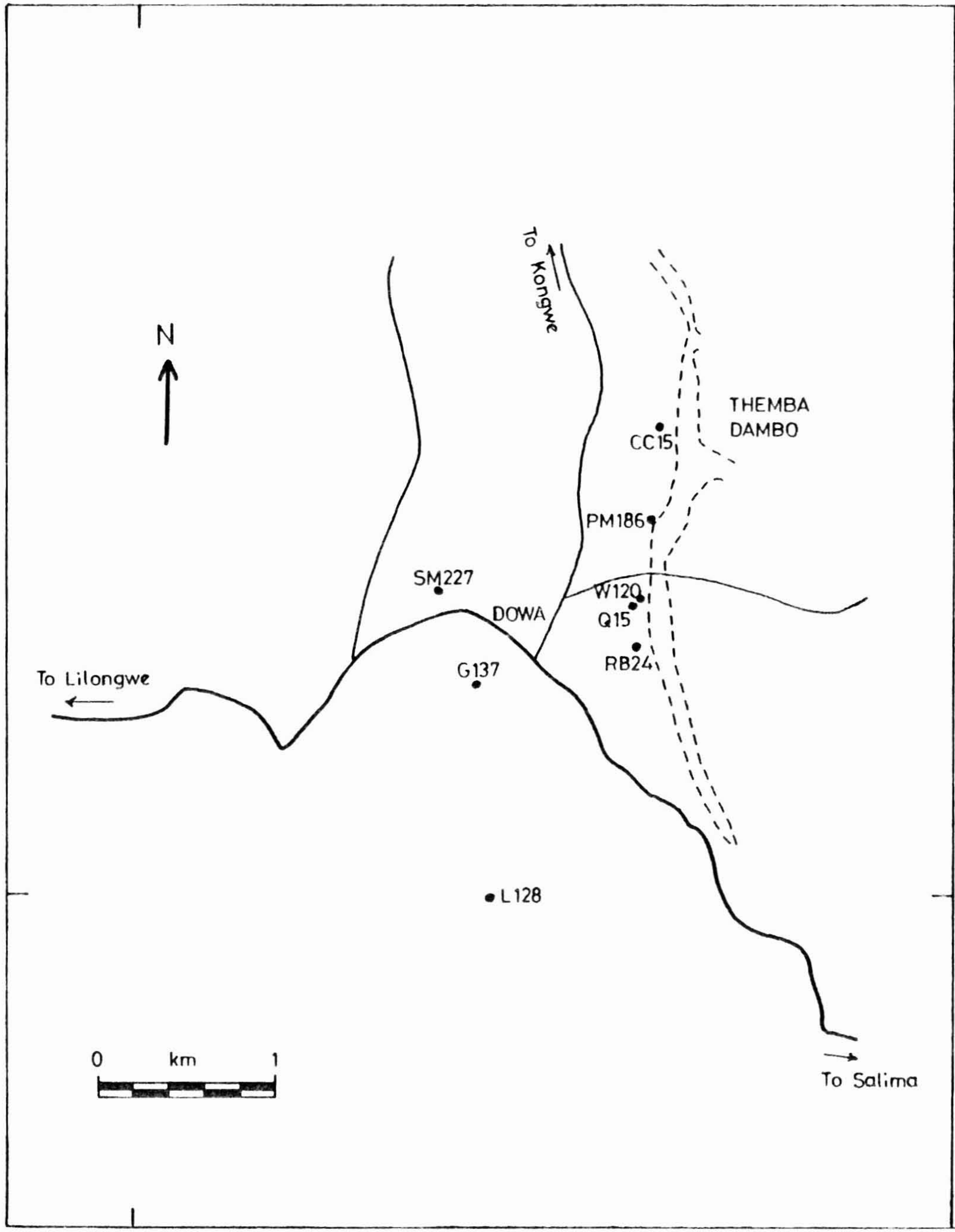


FIG 7. DOWA AREA BOREHOLE LOCATION MAP

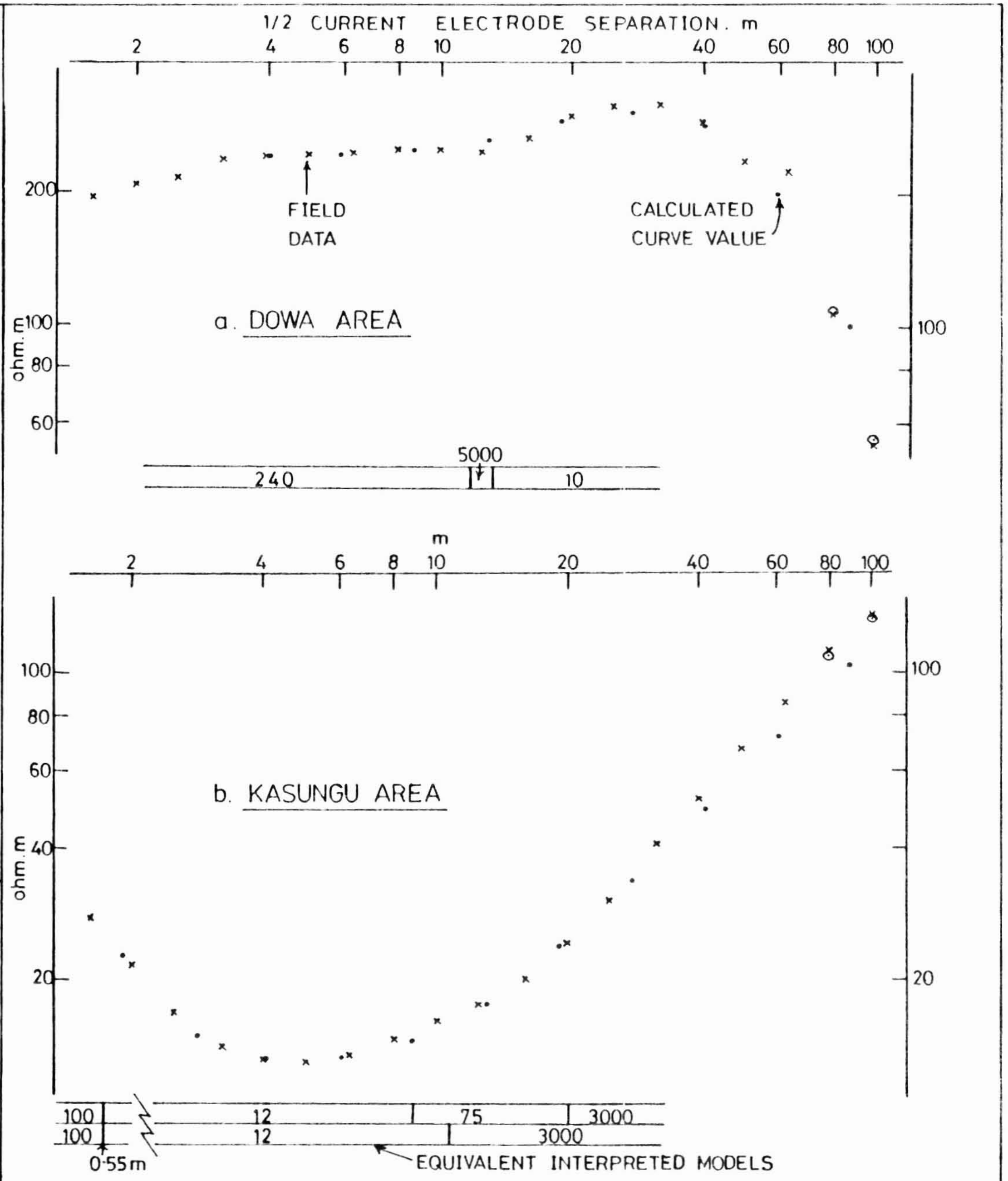


FIG 8. RESISTIVITY DATA AND INTERPRETATIONS

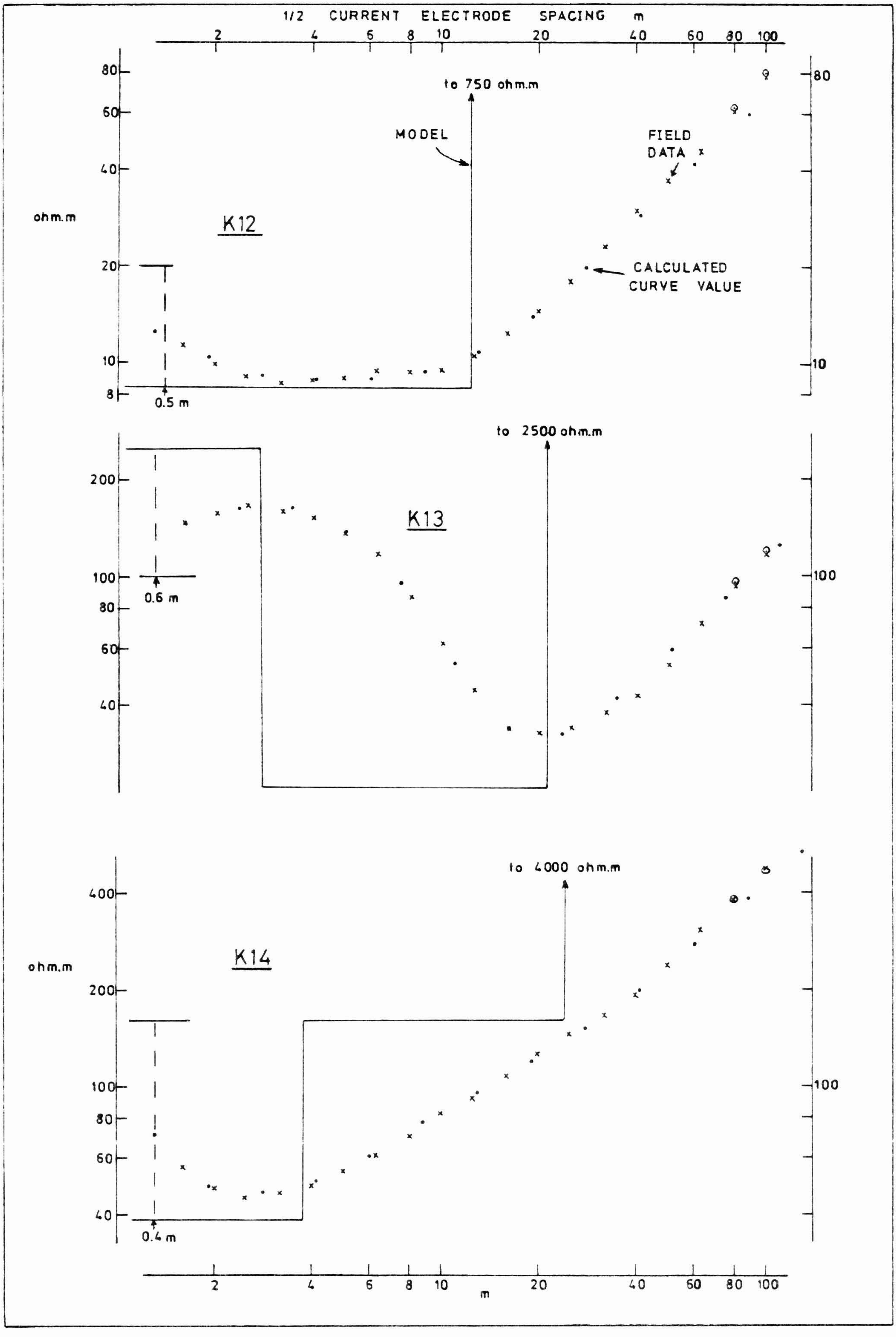


FIG 9. KASUNGU AREA : RESISTIVITY DATA AND INTERPRETATIONS

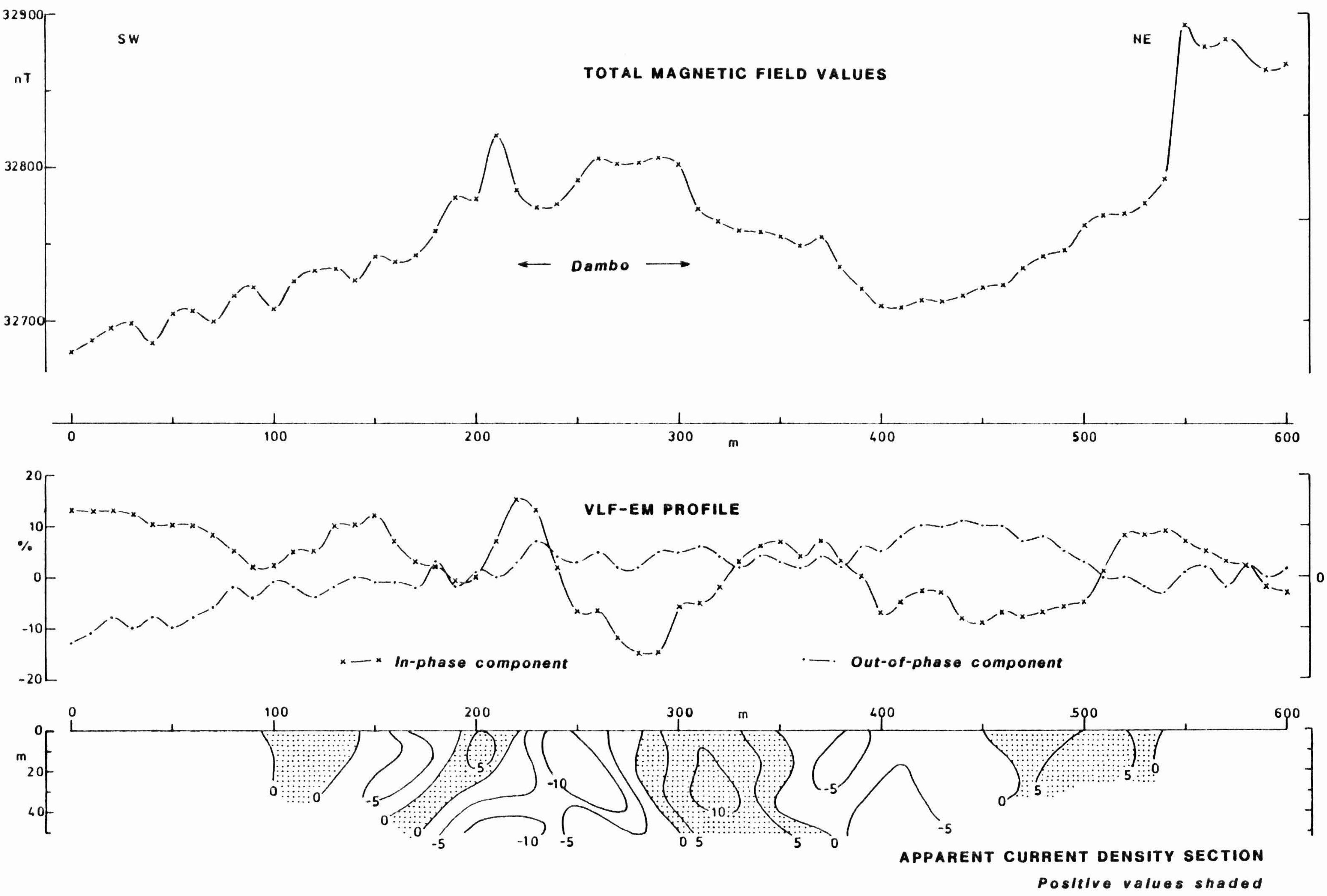


FIG 10. KASUNGU AREA : MAGNETIC AND VLF ELECTROMAGNETIC TRAVERSE DATA

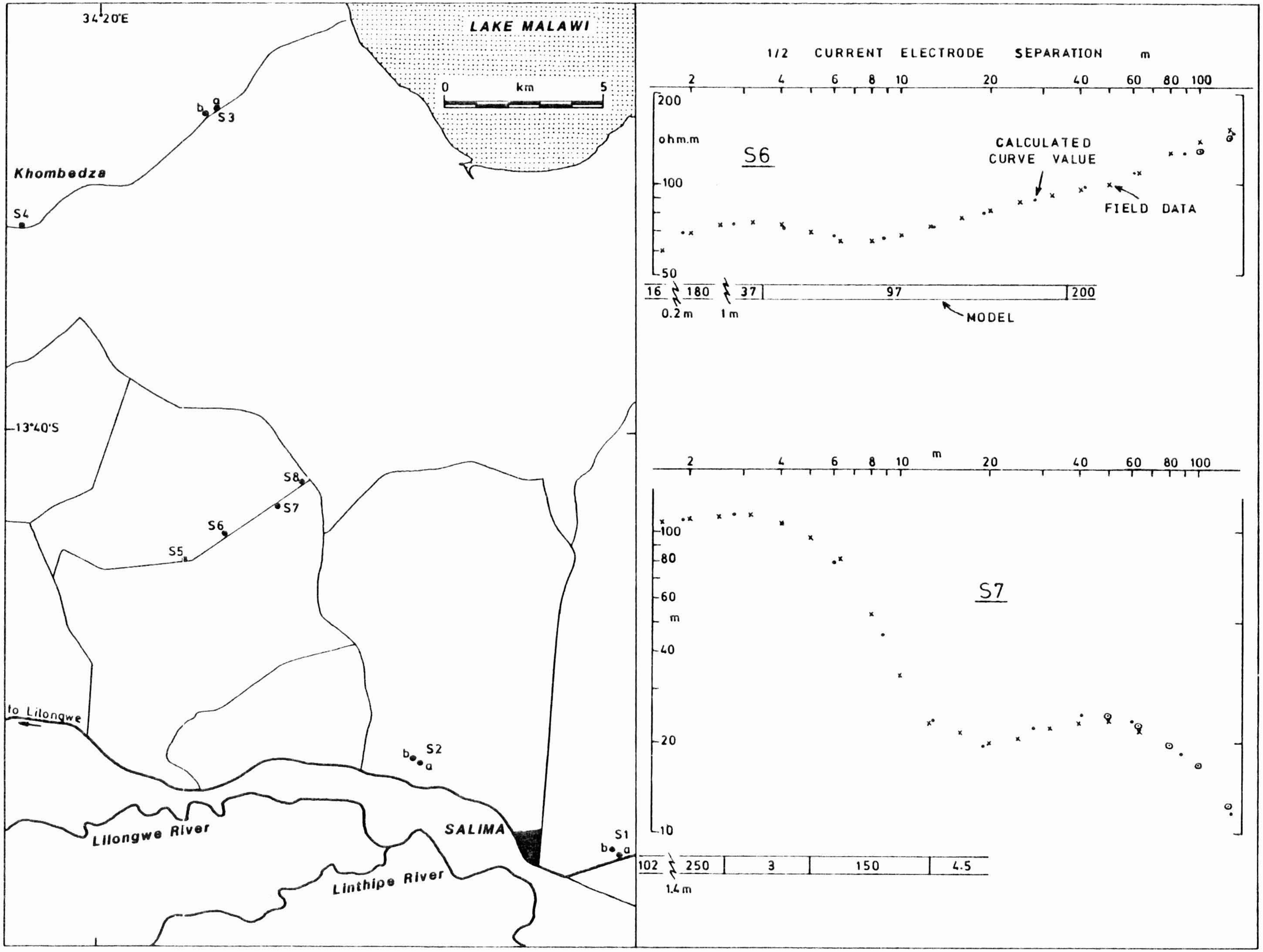


FIG 11. SALIMA AREA : a. SITE LOCATION MAP b. RESISTIVITY DATA AND INTERPRETATIONS

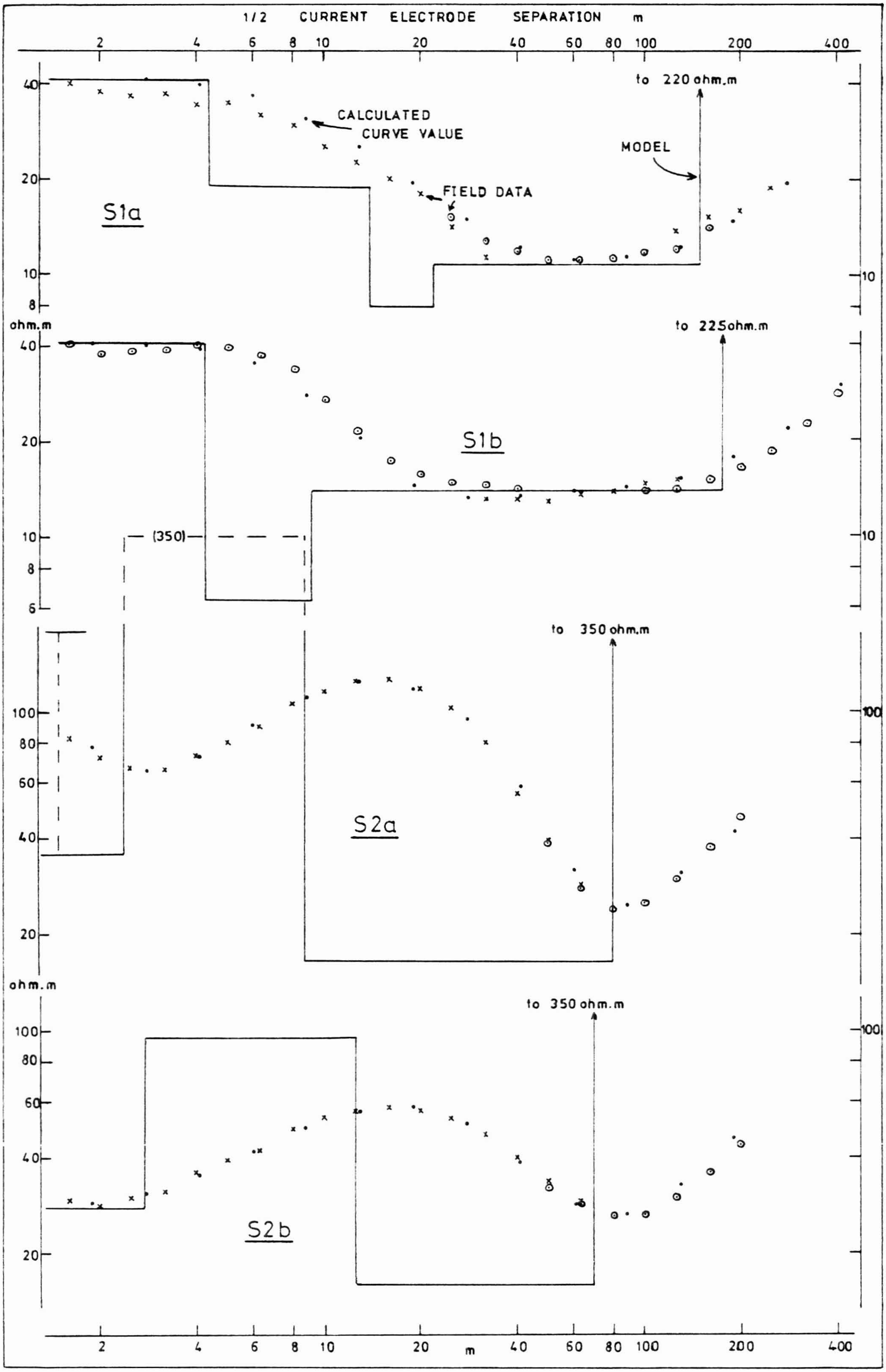


FIG 12. RESISTIVITY DATA AND INTERPRETATIONS FROM SALIMA

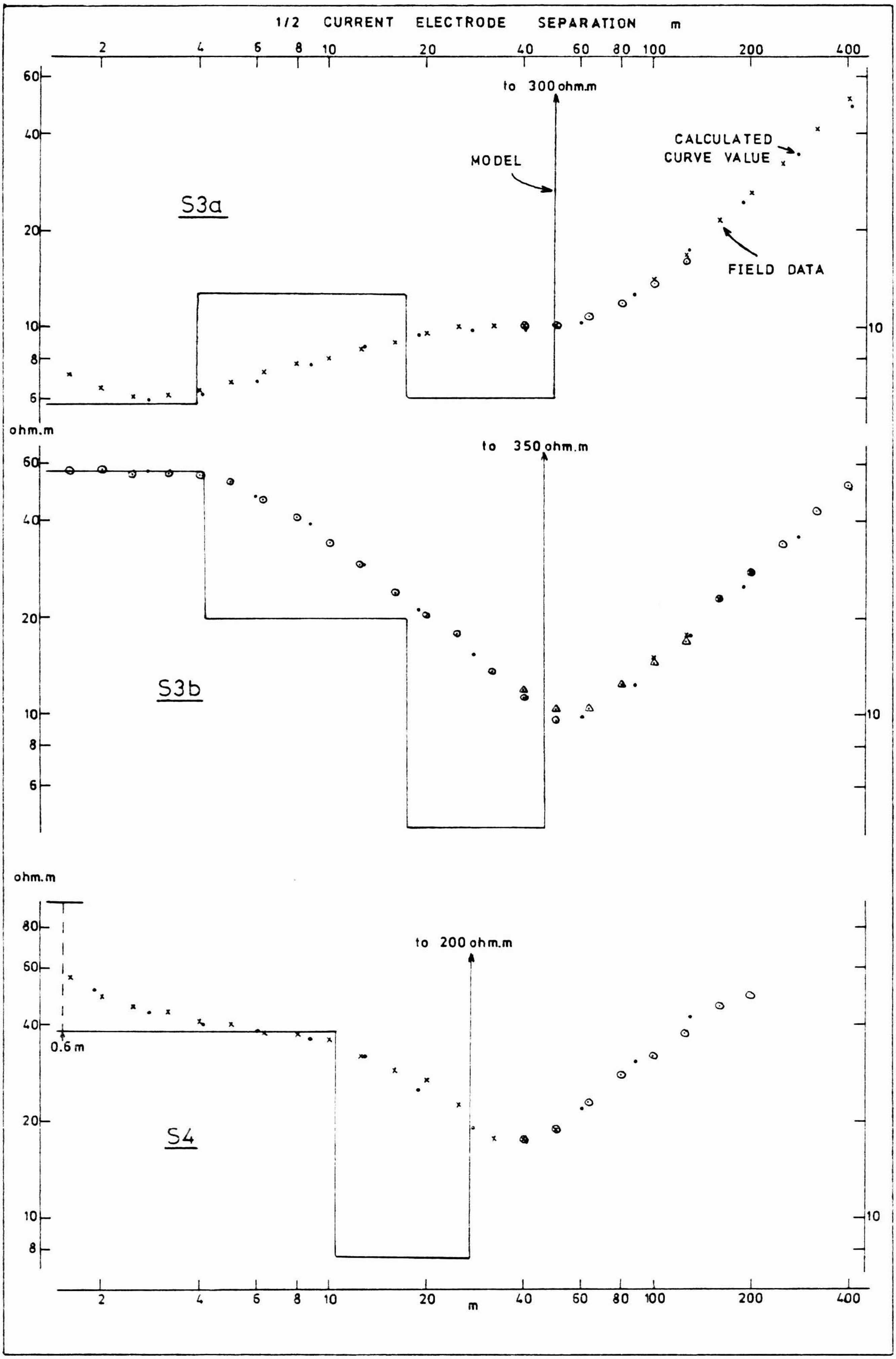
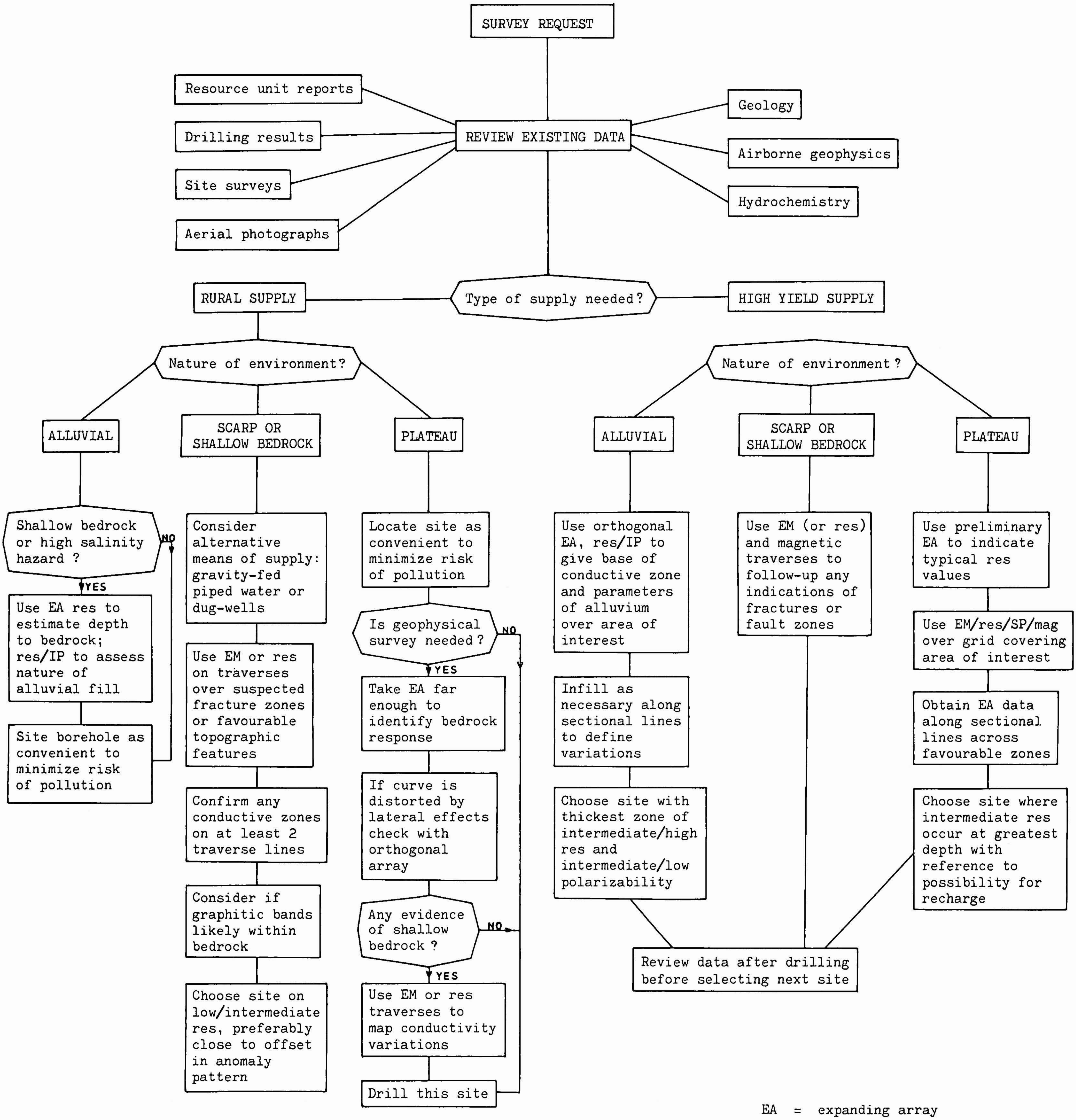


FIG 13. RESISTIVITY DATA AND INTERPRETATIONS FROM SALIMA



EA = expanding array
res = resistivity
EM = electro-magnetic
IP = induced polarization

FIG 14. FLOW DIAGRAM SUMMARIZING APPROACH TO BOREHOLE SITING

APPENDIX. SURVEY TECHNIQUES

What follows is a summary of some of the basic principles relating to the collection and interpretation of field data: it is not intended as an exhaustive guide but includes some practical details thought to be of relevance in the context of the Groundwater Division; for further information see [1668], [9].

The SI system of units is used throughout unless otherwise stated: for example potential differences as measured in volts, currents in amperes, resistivities in ohm.metres, distances in metres, magnetic induction-nanotesla

A. Resistivity methods

A1 Elementary theory

In uniform ground - defined as a semi-infinite, homogeneous, isotropic medium overlain by a medium (i.e. air) with a conductivity of zero - the potential V measured at a distance r from a point source of current I at the surface is given from Ohm's law by

$$V = \frac{I}{2\pi} \times \rho \times \frac{1}{r}$$

where ρ is the resistivity of the ground

Consideration of the return current electrode drawing a current -I gives the potential at a point P_1 as:

$$V = \frac{I}{2\pi} \times \rho \left[\frac{1}{r_1} - \frac{1}{r_2}\right]$$

where r_1 and r_2 are the distances of the current electrodes from P_1.

In the practical situation a potential difference is measured between two electrodes at P_1 and P_2 on the surface (as shown in Fig A) and is given by:

$$\Delta V = \frac{I\rho}{2\pi} \times \left[\left[\frac{1}{r_1} - \frac{1}{r_2}\right] - \left[\frac{1}{r_3} - \frac{1}{r_4}\right]\right]$$

where r_3 and r_4 are the distances of the current electrodes from the second potential electrode at P_2.

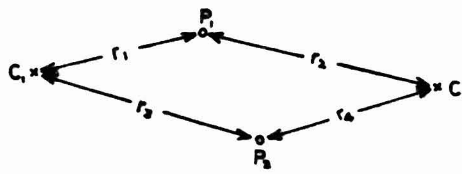
This is the basic formula applicable to all the different array configurations adopted for electrical resistivity surveying and it is used to define an apparent resistivity ρ_A which is evaluated from the field measurements. This apparent resistivity is not simply related to the actual distribution of sub-surface resistivities but it represents the value which would be measured in uniform ground as defined above: it serves as the basis for subsequent interpretation of field data in terms of a sequence of horizontally disposed layers each having a constant resistivity or for modelling specific, usually two-dimensional resistivity distributions.

A2 Electrode configurations

Of the many types of electrode array which have been suggested only a limited number are commonly adopted and, of these, two - the Schlumberger and Wenner - have a general application to groundwater surveys. The electrode disposition for these arrays and the formulae for calculating apparent resistivities are shown in Fig. A: the array developed by Cooper and used by him locally in the 1950's is included as this is still employed by the Groundwater Section in borehole siting, while the dipole-dipole and equatorial-dipole arrays are also shown although their application in this context is restricted to mapping deeper structures, such as those associated with geothermal reservoirs or major fracture zones.

The best choice of array is determined by practical considerations in relation to the objectives of the survey: for quantitative interpretation the electrodes are almost invariably co-linear to avoid undue complications in mathematical modelling, while for qualitative mapping purposes a more flexible approach can be adopted. Signal strengths - a function of the output power of the transmitter, electrode separations, ground conductivities and contact resistances - have to be significant when compared against the sensitivity of the receiver, background noise levels and electrical coupling effects, and the required depth of investigation, bearing in mind that logistical problems in moving electrodes and handling long lengths of wire should be kept to a minimum.

A particular survey will usually be directed towards either estimating depths and resistivies within an approximately horizontally layered sequence, or to mapping lateral variations and discontinuities. In the former case the technique is to progressively increase the array dimensions about a fixed central point, while to detect lateral changes the whole array is moved along a traverse with a constant electrode spacing: using the dipole-dipole these two methods are often combined to produce a vertical pseudo-section of conductivity variations.



$$\rho_A = 2\pi \frac{\Delta V}{I} \frac{1}{\left(\frac{1}{r_1} - \frac{1}{r_2}\right) - \left(\frac{1}{r_3} - \frac{1}{r_4}\right)}$$

×C marks current electrode position

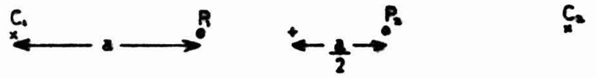
∘P marks potential electrode position

(i) General case for arbitrary electrode arrangement

$$\rho_A = \pi\left(\frac{a^2}{b} - \frac{b}{4}\right) \frac{\Delta V}{I} \quad ; \quad b < \frac{a}{2}$$

+ marks assumed 'point' of measurement

(ii) Schlumberger array

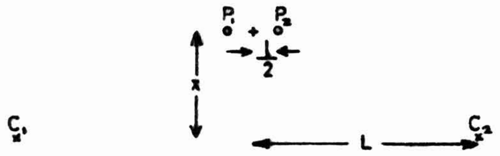


$$\rho_A = 2\pi a \frac{\Delta V}{I}$$

(iii) Wenner array

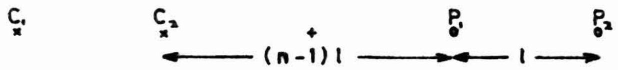
$$\rho_A = \pi a f(f+1) \frac{\Delta V}{I}$$

(iv) Cooper array



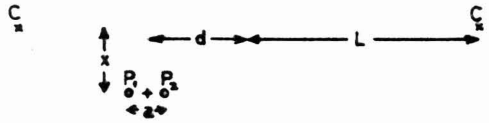
$$\rho_A = \pi \frac{(x^2 - L^2)^{3/2}}{l\,L} \frac{\Delta V}{I} \quad ; \quad x + L \gg l$$

(v) Equatorial dipole array



$$\rho_A = \pi n l (n^2 - 1) \frac{\Delta V}{I}$$

(vi) Dipole-dipole array



$$o = 2\pi \frac{D^2}{a} \frac{1}{\frac{1-D}{(Z^2+(1-D)^2)^{3/2}} + \frac{1+D}{(Z^2+(1+D)^2)^{3/2}}} \frac{\Delta V}{I}$$

$$Z = \frac{x}{L} < 0.6 \quad ; \quad D = \frac{d}{L} < 0.6 \quad ; \quad \frac{a}{L} < 0.1$$

(vii) Gradient (modified Schlumberger) array

FIG A. ELECTRODE ARRAYS FOR USE IN GROUNDWATER SURVEYS

Of the Schlumberger and Wenner arrays the former would be preferred for most applications except where signal strengths are low. Its principal advantages for determining depths lie in its lower sensitivity to unknown near-surface inhomogeneities and telluric noise, the availability of better interpretation techniques and the fact that only two electrodes have to be moved between readings. The current electrode spacing is increased logarithmically, reflecting the reduction in resolution at greater distances: the inner potential electrode dipole separation is fixed at a small value, nominally less than 20% of that between the current electrodes, until the signal level becomes too low for accurate measurement. By repeating at least two measurements when the potential dipole size has to be increased the magnitude of any discontinuity due to lateral variations near the potential electrodes can be determined reliably and an adjustment made to the field data to give a smooth curve for interpretation. Propertional errors in the apparent resistivities due to incorrect electrode positioning and localized inhomogeneities will tend to be greater for the smaller dipole separations and so these points are shifted vertically when adjusting the curve so that the best estimate of the deeper formation resistivities is obtained.

With the Wenner array the separation between the four electrodes is maintained equal so that as the array is expanded, again in equal logarithmic steps, all the electrodes are moved. Apart from smoothing the field curve to remove the effects of any minor near-surface distortions no adjustments have to be made to the data before interpretation.

For constant separation traverses the Schlumberger array again has certain theoretical advantages in that it gives a better response to anomalous zones which are narrow compared to the current electrode spacing. The modified Schlumberger - or gradient - array is particularly useful for mapping limited areas, up to about $\frac{1}{2}$ km square; this is because the two current electrodes are fixed, the depth of investigation is large, and traversing with the potential dipole can be done quickly. Again the main limitation is that of signal strength: relatively high transmitted currents or high apparent resistivities are necessary if this array is to be used successfully.

A3 Field procedure

The main prerequisites for collecting good quality field data are matters of common sense and should be self evident but a few instances are cited here to illustrate the point.

1. The people responsible for the field measurements must either be conscientious themselves or be adequately supervised.

2. If the equipment is to be used to its maximum efficiency there must be an appreciation both of its potential and of its limitations: this, in turn, requires either complete familiarity with the instruments or an ability to find and understand the relevant operating manuals.

For example, considering the old-style Terrameter:

a. the V and G boxes should be separated by at least 1 m to avoid interference;

b. the output power should be matched against operating conditions, which is why voltage and current selectors are provided on the G-box - where near-surface resistivities are higher increasing the voltage should allow more current to be passed and produce a more stable output, while use of the current relating selector determines whether all or half of the batteries are utilized (this switch will also limit the battery voltage check) so that the output current can be increased when signal strengths are low, because of large electrode spacings or high conductivities;

c. excessive humidity levels should be avoided - hence the provision of moisture - absorbing crystals which are meant to be dried when they have turned red - and high temperatures may also be detrimental;

d. the cause of undue sensitivity of the V-box gain control should be investigated.

3. Precautions should be taken against electromagnetic and capacitative coupling effects by separating current and potential cables by several metres and keeping them away from other electrodes.

4. If the reliability of a reading is suspect it can be repeated at a different current setting, with the current and potential electrodes interchanged, or after displacing the electrodes slightly.

5. A check should be made on contact resistances with a separate meter if there is no provision for doing so on the instrument itself. Limiting values depend upon the particular equipment being used: up to 20 kilo.ohm will usually be acceptable at the potential dipole while resistances at the current electrodes should be kept below 500-1000 ohm by means of water, salt, additional stakes, aluminium foil buried in pits (only convenient for fixed or re-useable sites), or relocating electrodes if possible.

6. The accuracy of the measurements should be monitored in the field to avoid errors due to mis-reading, incorrect positioning of electrodes or instrumental difficulties. This applies especially whilst obtaining expanding array data when spurious results are easily detected as departures from a smooth curve: erratic results at large separations cannot be attributed to sub-surface conductivity variations and will usually indicate that the signal strengths are too low in relation to the receiver sensitivity.

7. Notes should be kept on the field record of any factors which might influence the results or assist their interpretation, for example changes in vegetation, soil type or contact resistance; the occurrence of outcrop, surface water or artificial sources of interference; the nature of the topography, climate etc.

8. The separation of the potential electrodes should be kept to a minimum to reduce the effects of noise across the receiver ie the current electrodes should be outermost for both expanding arrays and CST. Where noise is still a problem or signal strengths are low, better results may be obtained with porous pots for the potential electrodes.

9. The number of points needed to define the field curve depends upon the smoothness of the curve, that is the amount of interference from near-surface effects, and from 6 to 12 points per logarithmic decade may be necessary. In Malawi the higher number is preferable as the curves tend to be irregular, especially in the dry season.

A4 Data interpretation

The type of interpretation required will obviously depend upon the particular problem and can vary from a qualitative assessment of the field data to detailed correlation and curve matching.

For routine surveys, where a rapid evaluation is needed, it should still be possible to plot the results of expanding Wenner or Schlumberger array data and make an interpretation by matching against 2- and 3- layer master curves - using auxiliary curve methods if necessary - in the field: the total conductance of the weathered zone should also be estimated from the field curve and checked against the interpreted values. An interpretation is especially important where the near-surface layers have an unusually high or low resistivity as in such cases the shape of the field curve will not obviously reflect the depth to bedrock. The curve matching procedures are fully explained in their accompanying descriptions. Resistivity and electrode separation data are plotted on a log-log scale and a match obtained with the coordinate axes parallel: master curve parameters and the position of the origin of the master curve on the field data plot provide the required information. The curves are arranged systematically according to type, resistivity and thickness ratios, with auxiliary curves for each type. Curve type is denoted by a letter, as defined on the Russian system whereby resistivity contrasts are considered in groups of three:

H denotes a curve with $\rho_{n-1} > \rho_n < \rho_{n+1}$
K " " " " $\rho_{n-1} < \rho_n > \rho_{n+1}$
Q " " " " $\rho_{n-1} > \rho_n > \rho_{n+1}$
A " " " " $\rho_{n-1} < \rho_n < \rho_{n+1}$

A curve originating from a 4-layer case is designated by two letters, so that HA represents $\rho_1 > \rho_2 < \rho_3 < \rho_4$; a 5-layer case would need three letters and so on. Some combinations such as KA are not allowable by definition.

Auxiliary curve methods are not rigorous and tend to be less reliable where larger contrasts occur. For this reason it is advisable to check such interpretations by generating a curve from the layer parameters derived, and comparing the results with the field data; any adjustments can then be made as necessary to obtain a better fit. The calculations can be performed using a calculator with a capacity for about 80 memory registers and 320 programme instructions: a programme suitable for a Texas Instrument T159 calculator is listed in the next section. As in most geophysical techniques an interpretation of resistivity data will not be unique, even if the layering is uniform and a good fit is obtained to the field data. This arises from the finite precision of the field measurements - usually no better than 3% - and the similarity of curves derived from different models, that is the effect known as equivalence. The range of equivalent solutions should be checked, particularly in detailed surveys and for correlating results against drilling: it influences the number of layers that can be resolved as well as the values assigned to individual layers. A problem with the Malawi data tends to arise in fixing the resistivity of the bedrock, which produces a corresponding uncertainty in the depth to its upper surface. By using larger electrode separations the definition of that part of the curve could be improved but this is offset by increased interference from lateral variations. Existing data indicate that the upper section of 'hard' bedrock is not characterized by very high average resistivities and usually appears to be less than 500 ohm.m: where graphitic/pyrite-rich bedrock occurs its resistivity may be lower than that of the overlying weathered material.

Detailed CST data can be related to 2-dimensional models, for which pseudo-sections have been obtained analytically. These can be useful for showing the influence of near-surface features and the patterns produced by particular configurations, but they would not have a general application. The main objective of the CST is to bring out trends and structures related to the weathered layer/bedrock contact which can be done qualitatively and in association with expanding array and drilling data. A point to remember in contouring resistivity data is that proportional changes tend to be more significant than absolute values, and it is normal practice to choose contours on a logarithmic, rather than a linear, scale to avoid undue bias towards high values and so maintain the definition of conductive areas.

B. TI 59 calculator programmes

B1 Apparent resistivities for Schlumberger array data model

The programme calculates the apparent resistivities which would be measured with a Schlumberger array configuration at the surface for a set of different electrode spacings above a horizontally-layered earth with specified resistivities and interface depths.

To operate the programme proceed as follows, using a print cradle if available:

1. enter 8 Op 17 to partition calculator space correctly to accept the programme;

2. enter programme from magnetic cards or through the keyboard; if using the keyboard the 'filter' values will have to be entered in STO 10-29, EXP [(In 10)/6] (or 1.467799) in STO 03;

3. enter initial 'a' ($\frac{1}{2}$ current electrode spacing) value in STO 30;
4. enter 515151 Op 02 - optional for printing;
5. press RST, R/S: display should show 38.00;
6. the programme expects model layers to be specified by depths but by entering St flg 2 it will expect the thickness of each layer, for the current model only;
7. enter: resistivity of uppermost layer, R/S
   depth to the first interface (or layer thickness), R/S
   resistivity of second layer, R/S
   depth to second interface (or layer thickness), R/S
   etc.
   resistivity of deepest layer;
8. if the printer is being used, model parameters - resistivities, depths and thicknesses - will be printed during step 7, the unspecified thickness or depth being calculated automatically;
9. enter any negative number, R/S, to signify end of model data;
10. after about 5-10 minutes, depending upon the complexity of the model, the calculator will print (or display, see note a.) successive values of half current electrode spacing and apparent resistivity over three logarithmic decades - 19 points;
11. when calculations are complete, memory stores are reset by the programme and the next model can be entered, from step 6 above.

TI 59 Calculator programme : to calculate apparent resistivity values ......

```
000  03   3
001  05   5
002  69  OP
003  04   04
004  69  OP
005  05   05
006  08   8
007  00   0
008  42  STO
009  08   08
010  58  FIX
011  02   02
012  25  CLR
013  42  STO
014  02   02
015  42  STO
016  50   50
017  32  X:T
018  03   3
019  00   0
020  42  STO
021  00   00
022  03   3
023  06   6
024  42  STO
025  01   01
026  03   3
027  08   8
028  42  STO
029  04   04
030  91  R/S
031  69  OP
032  06   06
033  69  OP
034  20   20
035  72  ST*
036  00   00
037  91  R/S
038  22  INV
039  77   GE
040  00   00
041  90   90
042  69  OP
043  21   21
044  99  PRT
045  87  IFF
046  02   02
047  00   00
048  61   61
049  75   -
050  32  X:T
051  95   =
052  72  ST*
053  01   01
054  99  PRT
055  98  ADV
056  69  OP
057  22   22
058  61  GTO
059  00   00
060  30   30
061  72  ST*
062  01   01
063  44  SUM
064  50   50
065  43  RCL
066  50   50
067  99  PRT
068  98  ADV
069  69  OP
070  22   22
071  61  GTO
072  00   00
073  30   30
074  76  LBL
075  49  PRD
076  85   +
077  42  STO
078  06   06
079  01   1
080  95   =
081  55   ÷
082  53   (
083  01   1
084  75   -
085  43  RCL
086  06   06
087  54   )
088  65   ×
089  92  RTN
090  69  OP
091  05   05
092  98  ADV
093  73  RC*
094  00   00
095  69  OP
096  30   30
097  75   -
098  73  RC*
099  00   00
100  95   =
101  55   ÷
102  53   (
103  73  RC*
104  00   00
105  69  OP
106  20   20
107  85   +
108  73  RC*
109  00   00
110  54   )
111  95   =
112  42  STO
113  42   42
114  01   1
115  08   8
116  00   0
117  32  X:T
118  22  INV
119  86  STF
120  01   01
121  43  RCL
122  02   02
123  75   -
124  01   1
125  95   =
126  42  STO
127  09   09
128  69  OP
129  38   38
130  43  RCL
131  30   30
132  65   ×
133  93   .
134  08   8
135  07   7
136  07   7
137  05   5
138  65   ×
139  43  RCL
140  03   03
141  45  YX
142  53   (
143  43  RCL
144  04   04
145  75   -
146  01   1
147  05   5
148  54   )
149  55   ÷
150  42  STO
151  05   05
152  02   2
153  55   ÷
154  73  RC*
155  01   01
156  95   =
157  35  1/X
158  22  INV
159  77   GE
160  01   01
161  67   67
162  86  STF
163  01   01
164  61  GTO
165  01   01
166  75   75
167  94  +/-
168  22  INV
169  23  LNX
170  65   ×
171  43  RCL
172  42   42
173  71  SBR
174  49  PRD
175  69  OP
176  30   30
177  73  RC*
178  00   00
179  95   =
```

......for the Schlumberger array electrode configuration.

```
180  42  STO
181  07   07
182  22  INV
183  87  IFF
184  01   01
185  01   01
186  93   93
187  01   1
188  42  STO
189  06   06
190  61  GTO
191  02   02
192  11   11
193  02   2
194  94  +/-
195  65   ×
196  69  OP
197  31   31
198  73  RC*
199  01   01
200  55   ÷
201  43  RCL
202  05   05
203  95   =
204  22  INV
205  23  LNX
206  94  +/-
207  71  SBR
208  49  PRD
209  42  STO
210  06   06
211  69  OP
212  30   30
213  73  RC*
214  00   00
215  85   +
216  43  RCL
217  07   07
218  95   =
219  55   ÷
220  53   (
221  43  RCL
222  06   06
223  65   ×
224  43  RCL
225  07   07
226  55   ÷
227  73  RC*
228  00   00
229  85   +
230  01   1
231  54   )
232  95   =
233  42  STO
234  07   07
235  97  DSZ
236  09   09
237  01   01
238  82   82
239  72  ST*
```

```
240  08   08
241  43  RCL
242  02   02
243  44  SUM
244  00   00
245  85   +
246  03   3
247  06   6
248  95   =
249  42  STO
250  01   01
251  97  DSZ
252  04   04
253  01   01
254  14   14
255  00   0
256  42  STO
257  06   06
258  08   8
259  00   0
260  32  X:T
261  98  ADV
262  43  RCL
263  09   09
264  67   EQ
265  00   00
266  04   04
267  43  RCL
268  08   08
269  42  STO
270  09   09
271  00   0
272  42  STO
273  04   04
274  02   2
275  00   0
276  42  STO
277  07   07
278  02   2
279  09   9
280  42  STO
281  05   05
282  43  RCL
283  30   30
284  65   ×
285  43  RCL
286  03   03
287  45  Y×
288  43  RCL
289  06   06
290  95   =
291  99  PRT
292  69  OP
293  26   26
294  73  RC*
295  09   09
296  65   ×
297  73  RC*
298  05   05
299  95   =
```

```
300  44  SUM
301  04   04
302  69  OP
303  29   29
304  69  OP
305  35   35
306  97  DSZ
307  07   07
308  02   02
309  94   94
310  69  OP
311  28   28
312  43  RCL
313  04   04
314  69  OP
315  06   06
316  98  ADV
317  61  GTO
318  02   02
319  62   62
```

```
         30.     00
         36.     01
          0.     02
 1.467799268     03
         38.     04
          0.     05
          0.     06
          0.     07
         80.     08
          0.     09
    0.003042     10
   -0.001198     11
     0.01284     12
      0.0235     13
     0.08688     14
      0.2374     15
      0.6194     16
      1.1817     17
      0.4248     18
     -3.4507     19
      2.7044     20
     -1.1324     21
       0.393     22
     -0.1436     23
     0.05812     24
    -0.02521     25
     0.01125     26
   -0.004978     27
    0.002072     28
   -0.000318     29
```

NOTES

a. if a printer is not available the programme can still be used if locations 285 and 310 are changed to R/S ie instruction/key code 91; programme operation will then halt to display the $\frac{1}{2}$ current electrode spacing and apparent resistivity values - to continue calculation press R/S;

b. the programme as written will accept models with up to six layers (ie 5 interfaces below ground level) and calculates 19 points from the initial 'a' value;

c. STO 04, set to 38, defines the number of transform function values calculated (= 19 + number of 'a' values required); this can be changed between 20 and 46 by entering desired the number in STO 04 between steps 5 and 6; fewer points will mean reduced calculation time, but if set to more than 38 then storage space allocated to model parameters will be overwritten and the number of layers allowed must be reduced pro rata (NB layer thicknesses stored from STO 37 onwards, transform function values from STO 79 downwards).

d. in certain circumstances of high depth or resistivity ratios the filter is inadequate and calculated values will be incorrect; this will be indicated by negative or 'oscillating' values of apparent resistivity and can only be corrected by simplifying the model or reducing the contrasts;

e. in rare cases with high resistivities an error condition may result from the INV lnx function; this can be avoided by decreasing the T-register value at programme locations 114-116, though the results should not differ significantly.

B.2 Apparent resistivities for the gradient array configuration

```
000  76 LBL          041  42 STO
001  15  E           042  07  07
002  43 RCL          043  02   2
003  04  04          044  42 STO
004  94 +/-          045  08  08
005  42 STO          046  42 STO
006  04  04          047  09  09
007  85  +           048  25 CLR
008  73 RC*          049  42 STO
009  07  07          050  05  05
010  95  =           051  15  E
011  33 X²           052  44 SUM
012  85  +           053  05  05
013  43 RCL          054  97 DSZ
014  03  03          055  08  08
015  33 X²           056  00  00
016  95  =           057  51  51
017  34 ΓX           058  69 OP
018  35 1/X          059  27  27
019  92 RTN          060  15  E
020  76 LBL          061  22 INV
021  12  B           062  44 SUM
022  91 R/S          063  05  05
023  75  -           064  97 DSZ
024  91 R/S          065  09  09
025  42 STO          066  00  00
026  00  00          067  60  60
027  55  ÷           068  91 R/S
028  02  2           069  65  X
029  95  =           070  02  2
030  42 STO          071  65  X
031  01  01          072  89  π
032  85  +           073  55  ÷
033  43 RCL          074  43 RCL
034  00  00          075  05  05
035  95  =           076  95  =
036  42 STO          077  91 R/S
037  02  02          078  43 RCL
038  76 LBL          07   06  06
039  14  D           080  44 SUM
040  01  1           081  04  04
                     082  14  D
```

To run programme (with reference to Fig A(vii)) :

1. enter station interval into STO 06
2. enter x into STO 03
3. enter d into STO 04
4. press B
5. enter X, press R/S
6. enter a, press R/S
7. enter observed resistance, press R/S
8. read apparent resistivity from display
9. for next reading along traverse return to step 5 - to check station position read STO 04 - and continue
10. for next reading out of sequence, enter appropriate value in STO 04, and press D, return to step 7 and continue
11. for reading on new traverse line return to step 2 and continue.

C. Magnetic survey methods

C 1 Instruments

There are two basic types of instrument commonly used for field surveys - the fluxgate and the proton-precession magnetometers. The fluxgate magnetometer consists of a core of magnetic material with a very high permeability which can be magnetized to saturation by the maximum current of a low frequency internal source: in the presence of an external steady magnetic field the point at which saturation occurs within the current cycle is altered depending on the orientation of the field relative to the core. This effect can be monitored and calibrated in terms of the strength of the biassing field. The instrument gives a direct readout, it is small and lightweight; its main disadvantages are a limited sensitivity due to inherent noise and instrumental drift. For most field applications these instruments are quite adequate though where small anomalies, less than about 20-30 nT, have to be defined a proton magnetometer would be preferred. As it is only that component of the external field parallel to the core which affects the reading, a particular direction has to be defined for the measurements: normally this would be the vertical.

The proton magnetometer gives the absolute value of the total magnetic field to better than 1 nT free from instrumental drift. A liquid rich in protons is polarized in a direction approximately normal to the external field by passing current through a coil around it. On removing the polarizing field the protons effectively precess about the external field at a frequency which depends only on the field strength and a physical constant. This frequency is detected in a pick-up coil from the voltage induced by the moving protons and converted into a readout of the field value. The instrument uses more power and is bulkier than the fluxgate, it only measures total field values and there are limitations to the magnetic gradient which it can tolerate, but its reliability and sensitivity can be advantageous.

C 2 Fieldwork

The earth's magnetic field shows a diurnal variation with an amplitude typically 20-30 nT on which may be superimposed much larger, erratic changes due to transient disturbances known as magnetic storms. In order to monitor these fluctations during a field survey it is normal practice to repeat readings at selected points where the magnetic gradients are low, every two or three hours. Depending upon the magnitude of these variations (which will include instrumental drift in the case of a fluxgate magnetometer) relative to the anomalies of interest the survey data can be adjusted using a correction curve or by linear interpolation of the change between base station readings - this will usually be necessary for detailed surveys with measurements taken on different days - or the corrections may be thought negligible, particularly for isolated traverses: if a severe magnetic storm occurs it may be necessary to discontinue the survey for one or two days if reliable readings are to be obtained.

The magnetometers will respond to any magnetic objects carried by the operator and are also sensitive to interference from their battery power-pack, movement of the detector, external artificial (ie non-geological) sources such as fences, vehicles, buildings etc., and near-surface 'noise' from isolated rocks and pebbles. Many of these problems can be reduced or avoided with a little care in field operations and the siting of traverse lines and measurement points to keep the detector away from sources of interference. It is also good practice to maintain the same orientation when taking readings so that any anomaly associated with the instrument and the operator remains constant. Any factors which might influence a measurement should be noted in the field record.

Station intervals and traverse line separations have to be related to the particular problem - the size of area to be covered and the wavelength of the anomalies: where magnetized rocks lie close to the surface, ie in plateau areas, a spacing of 10 m will probably be required, with additional points if necessary. In order to contour the magnetic data the line separation may need to be as small as 20 m, but it may be more efficient to start with a coarser grid and only infill as required.

C 3 Interpretation of results

The corrected field data are presented as profiles or in the form of contoured maps which can be used qualitatively to identify magnetic bodies, structures and trends: numerous techniques are also described in the literature for deducing the geometry and magnetization of source bodies from suitably definitive anomalies.

Only a limited number of minerals are responsible for rock magnetism, the principal of which is magnetite with other oxides of iron and titanium, and pyrrhotite, constituting most of the remainder.

Because of this association with magnetite, basic rocks tend to be more magnetic than sedimentary, metamorphic or granitic rocks but this is not axiomatic, particularly in the context of Malawi. While much of rock magnetism is induced under the influence of the earth's present magnetic field, remanent magnetization acquired during the history of the rock may be of equal or greater magnitude and have quite a different orientation.

The inducing magnetic field is directed at about 45°-50° above the horizon (reducing northwards) within Malawi so that the characteristic profile across a thin, steeply-dipping body should be obviously dipolar in form, with the maximum developed on the northerly flank. At these magnetic latitudes the vertical field component is significant and interfaces with a north-south strike can be expected to generate anomalies with an amplitude of at least 50% of their equivalent from a west-east orientation.

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