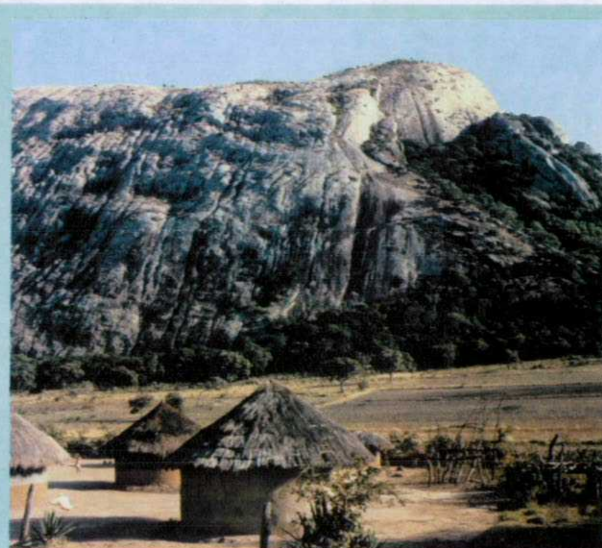
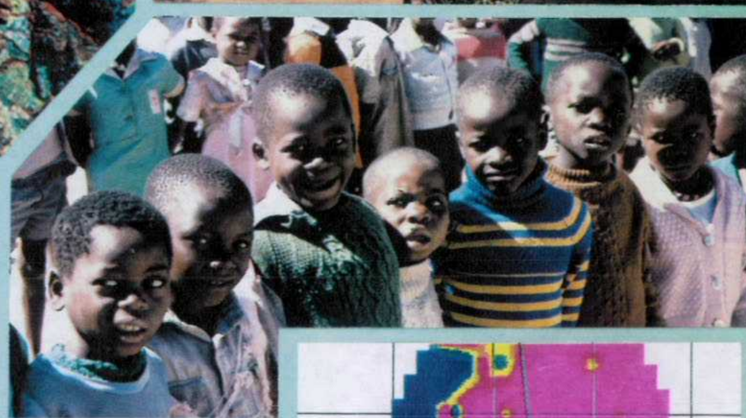
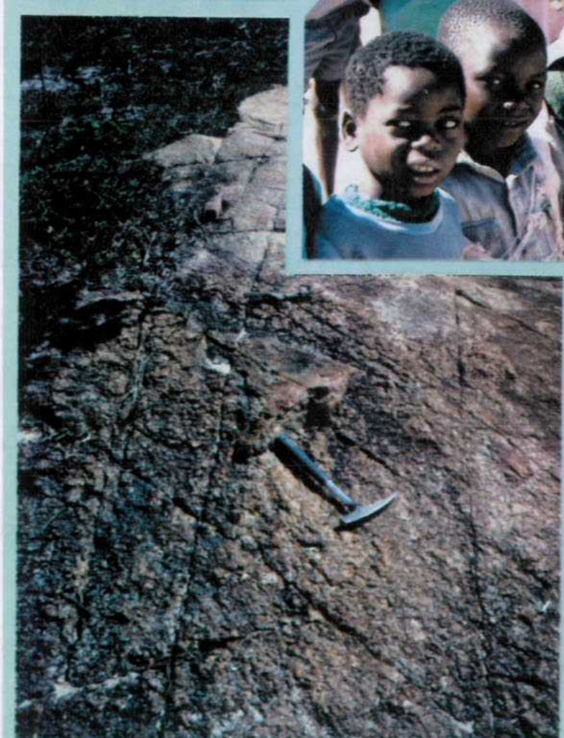
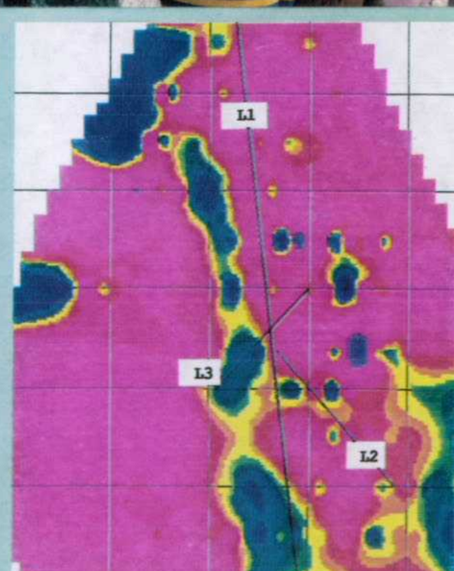
BRITISH GEOLOGICAL SURVEY
Technical Report WC/93/7
International Division

Natural Environment Research Council

Final Report

Geological and geophysical characterisation of lineaments in southeast Zimbabwe and implications for groundwater exploration

R M Carruthers, D Greenbaum, P D Jackson, S Mtetwa, R J Peart, and S L Shedlock

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BRITISH GEOLOGICAL SURVEY

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SUMMARY

Detailed studies have been undertaken relating to the geological significance of photolineaments, particularly those best seen at the scale of aerial photography, in crystalline basement terrain. These features are commonly thought to develop over fracture zones which form potential targets for siting water-supply boreholes in arid regions. The Masvingo Province of Zimbabwe was selected for site investigation as it represents an area subject to recurrent droughts where information is available from previous ODA supported projects. Close collaboration was maintained with the Ministry of Energy, Water Resources and Development of the Republic of Zimbabwe which provided counterpart staff and carried out the drilling operations.

Fieldwork was split into two parts. The first phase was devoted to geophysical surveys and geological 'ground-truth' mapping over four representative photolineaments and was reported on earlier (Greenbaum et al., 1991); the second phase reported on here followed completion of drilling (at three of the sites) and included core inspection, geophysical borehole logging, cross-hole seismic tomography and additional surface geophysics.

Geophysical surveys show the presence of anomalies coincident with, or offset parallel from, the lineaments and the drainage lines they tend to follow. These anomalies, being rarely of large amplitude, are distinguished mainly by their linearity and can be explained largely in terms of variations within the thin cover of weathered material. The drainage lines are typically associated with the development of a thin layer of grey conductive clays which show as darker tones on the photographs and generate the resistivity and electromagnetic anomalies. The lineaments themselves tend to coincide with local resistivity highs, or their margins, suggesting that quartz pegmatites and variations within the granite itself are significant. Quartz veining was certainly observed in outcrops whereas few open fissures were seen; in general, surface jointing followed a variety of directions with little preference for the lineament orientation. A distinctive magnetic anomaly low parallel to the lineament at one site was interpreted as due to a pegmatite-rich zone.

Core drilling did not confirm the existence of ***major*** *fracture zones, but at two sites there was clear evidence of enhanced fissuring to account for the photolineaments. There was some difficulty in distinguishing the change in weathering with depth from that attributable to steeply dipping fractures, and on the evidence of the geophysical logging it did seem that sub-horizontal features were important, at least in the upper part of the section. Such 'sheeting' is thought to be due to tensional unloading associated with erosion and provides the possibility of an interconnecting fractured aquifer along some lineaments. Despite this, the generally closed nature of the steep fissuring suggests that the groundwater potential of these zones is limited and productivity may depend on relatively small-scale variations within the rock mass. Certainly, the one site at which good yields were obtained gave no enhanced geophysical signature.*

Computer modelling techniques were developed to assess the type of geophysical response that could be expected. These confirmed the likely difficulty of resolving specific fracture-related anomalies from the geological background variation. In relation to siting collector wells, the seismic refraction technique should give the best results in following up favourable indications from reconnaissance electrical surveys.

The sites studied suggest that whereas photolineaments are an important element in borehole siting, they are not by themselves a wholly reliable guide but require supporting ground geophysical testing. A proposed strategy for groundwater development in low-rainfall areas underlain by basement rocks, such as southeast Zimbabwe, is to concentrate more effort on establishing a network of high-yielding wells at strategic points, rather than expecting to supply each village individually throughout periods of drought.

The study was carried out under the ODA/BGS Programme of Research and Development in Developing Countries, which forms part of the British Government overseas aid programme. Significant practical help was provided by the Ministry of Energy, Water Resources and Development of the Republic of Zimbabwe.

CONTENTS

CONTENTS (continued)

List of figures

List of figures (continued)

1. INTRODUCTION

1.1 Background

This report describes work undertaken in 1991/92, during the final year of ODA/BGS R & D Project No. 91/8 'Development of techniques for hydrogeological mapping and siting of boreholes and dug wells'. The project was concerned with the problems of locating groundwater resources in the crystalline basement terrain typical of much of southern Africa and many other parts of the developing world. The specific aspect of interest was the relationship between lineaments seen on aerial photographs and the occurrence of open fracture systems. Geological evidence provided by core drilling is presented from three sites studied previously (Greenbaum *et al.*, 1991), together with the results of additional geophysical fieldwork carried out during September-October 1991. The latter provided seismic data, obtained from both conventional refraction spreads and cross-hole tomography, as well as more detailed electromagnetic (EM) and resistivity surveys around the borehole sites. This report complements that by Greenbaum (1992) which addressed the application of remote sensing to assessments at a more regional scale.

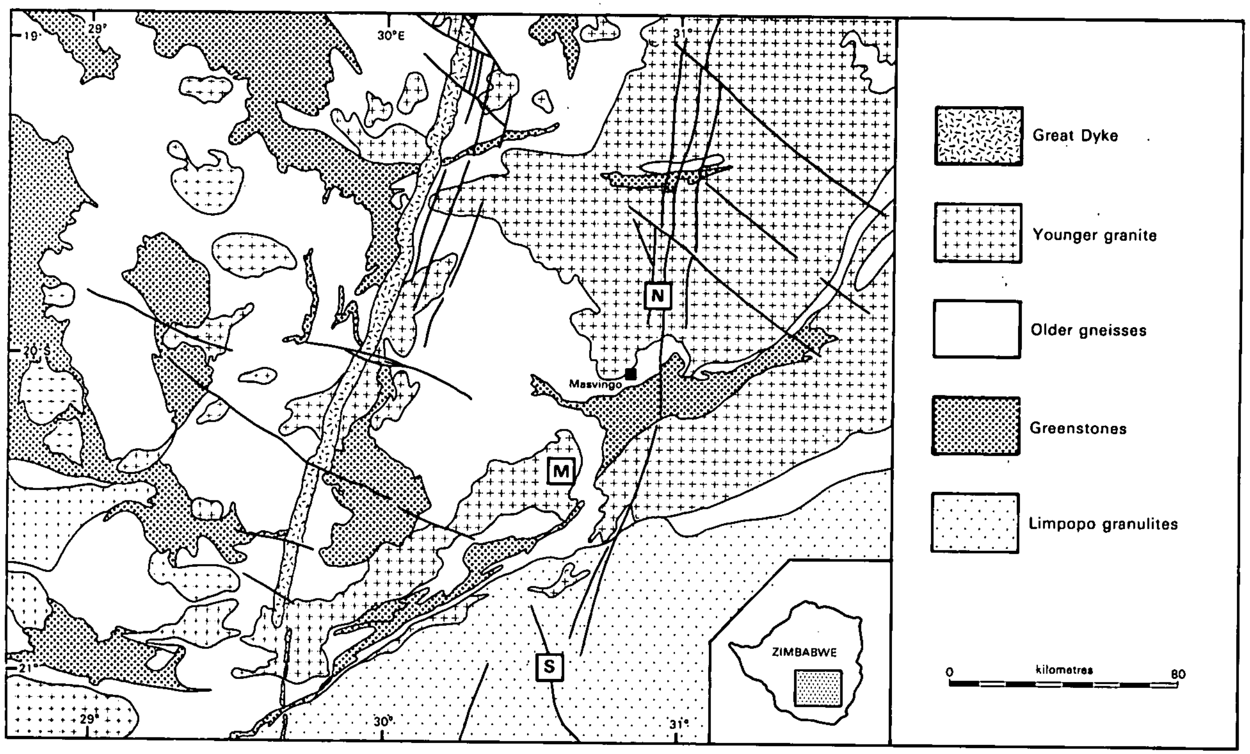
Previous investigations carried out under the Basement Aquifer Study (Wright, *ed.*, 1988) acknowledged the importance of geological (as opposed to production) drilling as a means of providing detailed information on the sub-surface geology, and holes were drilled at several sites in the Masvingo Province for this purpose. This approach was extended in the present project during which a concentrated programme of vertical and inclined drilling (the latter with core recovery) was carried out. Clearly, studies restricted to only three sites (referred to as Mhatiwa, Nanwi and Nemarundwe) cannot provide answers of general validity; however, they are a starting point, and the alternative approach (that of examining the statistics of a large number of existing borehole sites) had been tried with only limited success. The purpose of the drilling and down-hole geophysics was, therefore, to characterise as far as possible a few 'typical' lineaments in Masvingo Province, Zimbabwe, where the overall success rate for water-supply boreholes is relatively low.

1.2 Geological setting

The Zimbabwe Craton is a heterogenous assemblage of crystalline basement rocks of Archaean age comprising greenstones, mafic and ultramafic rocks, gneisses and migmatites, and late intrusive granites (Fig 1.1). The Archaean basement complex is intruded by the Great Dyke, overlain by supracrustal formations and margined on at least three sides by mobile belts. The sites studied and reported on here are located in the granites, gneisses and migmatites which make up by far the greater part of the lowland regions.

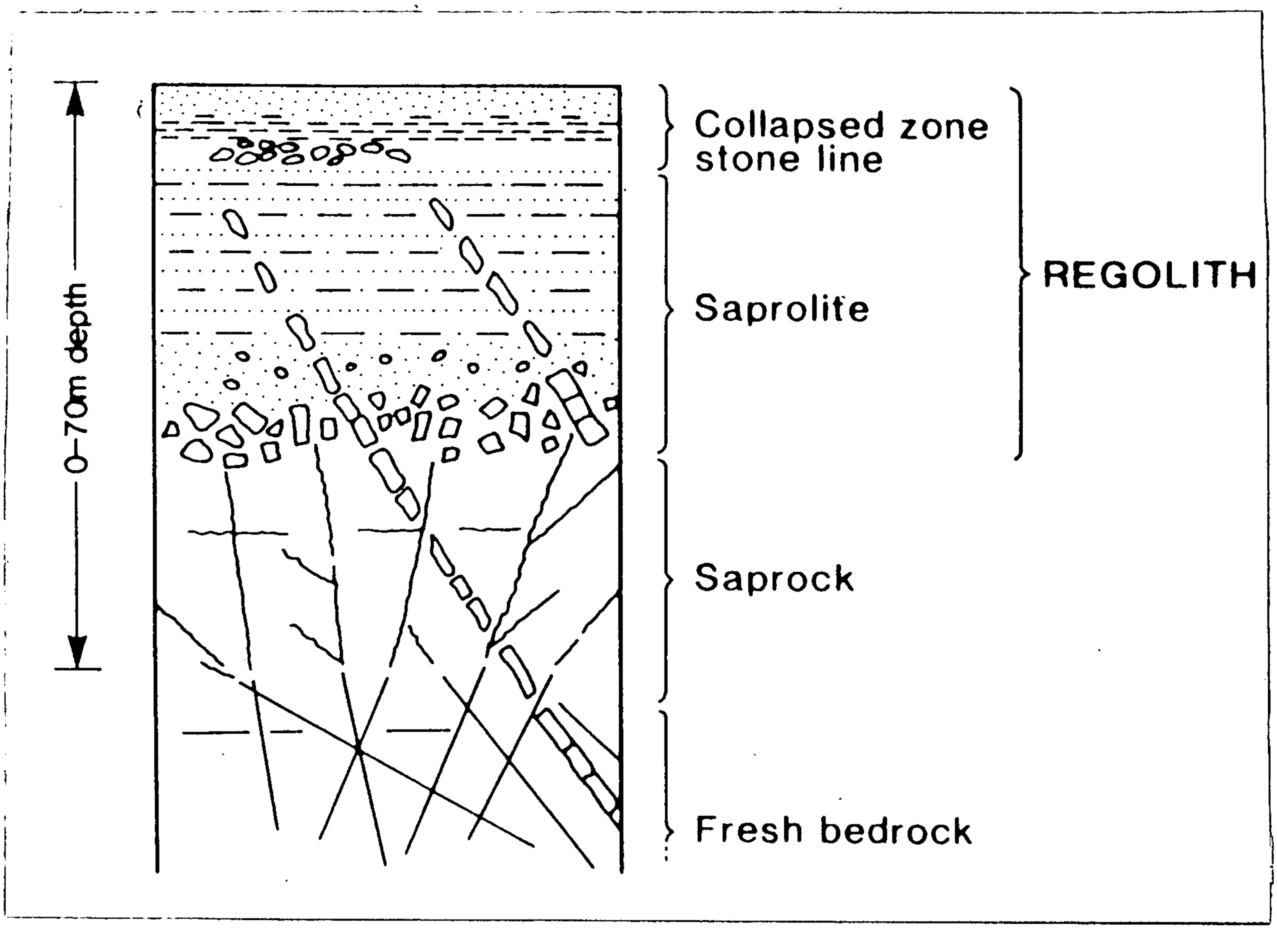
A reconstruction of igneous-tectonic events in the Zimbabwe Craton from the late Archaean through to the Phanerozoic, based on the analysis of imagery, aerial photographs, field studies and published mapping (Greenbaum, 1987) has shown that the geological development of the Craton was punctuated by repeated episodes of compressive tectonism involving at least four periods of important wrench type faulting separated by tension and dyke emplacement. According to these studies, most of the lineaments seen in the Masvingo region correspond to faults or joints of tectonic origin.

The crystalline rocks of cratonic areas in Africa and elsewhere possess little primary intergranular porosity or permeability and their hydrogeological properties are thus mainly determined by secondary effects such as brittle fracturing and weathering that give rise to secondary storativity and transmissivity (Clark, 1985). In arid areas, weathering etches out the lines of structural weakness, such as faults, joints and dykes, which are evident on satellite imagery and aerial photographs as 'lineaments'. These are often considered to be



N Nanwi/Nemarundwe M Mhatiwa S Sarahuru

Figure 1.1 Location map with regional geology



(1) Collapsed zone. This may show marked lateral variations but is generally sandy on watershed areas with illuviated clay near the base and sometimes a "stone" line; on valley slopes, colluvial material accumulates and in dambos, secondary clay materials predominate. Slope bottom laterites may also occur which can result in perched water tables. Permeabilities vary in accordance with lithology although on watersheds the collapsed zone normally occurs above the water table.

(2) Saprolite is derived by in-situ weathering from the bedrock but is disaggregated. Permeability commonly increases at lower levels due to paucity of secondary clay minerals.

(3) Saprock is weathered bedrock. Original features are likely to be more open than in the fresh bedrock and in the absence of secondary infilling, permeability could be high, but storativity low.

(taken from Wright ed 1988)

Figure 1.2 Description of weathering profile above crystalline basement

passageways for groundwater movement and therefore provide an important target for groundwater exploration.

In rural Zimbabwe, where the main effort is directed to the provision of numerous low-yielding boreholes (and dug wells) for village supplies, the identification of lineaments is most appropriately done at the scale of aerial photographs (1:25 000). At this scale, lineaments typically correspond to minor drainages and/or changes in soil colour, thought in most cases to be expressions of individual fracture traces. Basic dykes may form depressions or small ridges or have no relief expression at all, but are often characterised by dark soils, rubbly outcrop and dense vegetation.

Regolith is the term used to describe all in-situ products of weathering above the fresh, massive bedrock (Fig 1.2). It reaches a thickness up to about 50 m but averages much less than this and can show rapid variation on a local scale. The original volume of the bedrock is largely preserved until the final stage of the weathering process is reached, leaving the residual products confined to the uppermost few metres. Saprock refers to that part of the sequence which is weathered but retains its rock structure while the saprolite comprises the more advanced weathering products in which the original rock fabric is lost. The regolith is usually considered to be important as a water reservoir even if the primary target for drilling is fracturing in the underlying bedrock.

1.3 Nature of fracturing

Field evidence of fractures corresponding to lineaments is typically poor. Outcrops are scattered and few are located directly over the main lineaments which often correspond to weathered drainage lines. Even where exposures along lineaments *do* occur the evidence of fracturing is often equivocal. Some outcrops appear to be entirely unfractured whereas others show fractures sub-parallel to and/or cross-cutting the lineament trend. If it is accepted that lineaments are real geological phenomena then one must conclude that:

- the responsible fractures are not usually major open systems at the surface; and/or

- they are highly variable in development along their length (and depth).

A further possibility is that the present level of erosion has effectively reached the base of many of the fracture systems; this would explain the contrast between the strong regional pattern of fracturing and the poor evidence of major fractures seen in outcrops adjacent to lineaments.

Evidence from road cuts and quarry sections in many areas of SE Zimbabwe indicates that recent, open, near-horizontal (surface-parallel) joints are common in the near-surface zone but decrease in frequency downwards; they are considered to have formed by sheeting and erosional unloading (Ollier, 1984). Although the chance of intersecting a shallow-dipping fracture in a vertical borehole is high, the aquifer potential of such a fracture by itself is probably limited. If, however, several flat-lying fractures are cut by a vertical permeable zone, interconnections extending over a large area could result, providing the necessary storage and permeability to form an aquifer. This situation would result even if the vertical fracture zones (manifested as lineaments on imagery) were permeable only along very restricted channelways, since a flat-lying structure would virtually always make the necessary intersection.

1.4 Drilling information

The drilling programme comprised two components: (1) inclined holes across interpreted fracture zones (lineaments) drilled to provide core for geological logging; and (2) vertical deep and shallow air hammer holes for cross-hole tomography. Both the inclined and vertical holes were available for geophysical logging.

The Ministry of Energy, Water Resources and Development (MEWRD) provided drilling rigs and crews to undertake the drilling but, because this programme could not be directly supervised, delays were experienced in completing the work; the inclined core drilling in particular proceeded exceptionally slowly. The lack of on-site geological supervision further resulted in variable data quality and a virtual lack of drilling information for the vertical holes. As a result, the geological interpretation has proved difficult. Some of the specific problems relating to the interpretation of the geological logs are summarised below:

(1) Ideally, an inclined drill hole should be designed so that intersection occurs at a depth where the surface effects of weathering can be completely separated from weathering/oxidation due to water circulation in the fractures. The core should record the progression from regolith, saprock, weathered rock, and fresh rock, through a zone of core loss/oxidation/fracturing etc, passing finally into fresh rock once again. To achieve this, a drill hole should be sited some way from the lineament. In the present case, however, the very slow rate of coring meant that holes had to be collared quite close to the lineament in order to have a chance of hitting their target zones of fracturing (the location of which was anyway uncertain since the dip of fractures could only be assumed). As a consequence, the separation of depth-related weathering effects from the lateral effects associated with steep fracturing often proved difficult.

(2) The recognition of fracture zones in the core proved more difficult than expected, probably because such zones often appear to be poorly developed within the study area. Core losses (which can - but don't necessarily - indicate fracturing and shattered ground) occur, but the core fragments typically show rotation and abrasion so that clear evidence that tectonic fracturing was responsible is obscured. Undisturbed core sections are generally only recovered where the shears or fissure zones are filled and relatively unweathered, and these sections evidently do not represent conduits for water.

(3) The lack of detail in drillers' logs do not allow the location of water strikes or losses which could help with the interpretation of some of the zones encountered.

(4) It was not possible to orientate the cores; consequently, the dips of the observed fractures/fissures/veins could not be reliably determined. A fracture orientated 30° to the core axis in a hole inclined at 30° to the vertical could indicate a true dip of between 30° and 90°. Thus, many of the fractures could be interpreted as steep to vertical, whereas others making a more obtuse intersection with the core axis must be shallow-dipping. Intervals of unconsolidated material encountered below sections of solid core could represent either flat-lying or steep fractures, or could possibly indicate that the overlying solid material was a core stone. The hole diameter was insufficient for use of a televiewer to help in resolving some of these uncertainties.

(5) It was evident from the recovered core that during pulling-out operations, core sections were often left behind and retrieved as part of the next section: thus successive sections record, for example, 45% followed by 140% core recovery. This led to uncertainty in correlating between fractures observed in the core and downhole geophysical logs.

2. DESCRIPTION OF GEOPHYSICAL TECHNIQUES

2.1 Borehole geophysical logging

The present studies were undertaken using an OYO model 3030 borehole geophysical logging unit which included resistivity (differently spaced normal, micro-normal and normal-reverse arrays), borehole caliper and spontaneous potential tools. This unit could record formation resistivities up to 20,000 ohm.m with selectable scale sensitivity. All data obtained from this logging unit were recorded in digital format and transferred to a 3.5" floppy disk for permanent storage and subsequent processing.

Borehole geophysical logging aids in the identification of both the formations penetrated (giving details of bulk formation parameters) and any fractures/fissures intersected. Fracturing may be detected by a variety of logging techniques, and the most reliable indications are usually obtained from a combined approach. Figure 2.1 illustrates how low resistivities resulting from the increased fluid content of open fractures correspond to a decrease in the neutron count rate (i.e. an increase in the hydrogen index) as measured with a neutron-neutron tool. The latter reflects, mainly, the amount of hydrogen within the formation and so in this context it relates closely to the amount of water either in open pores or bound into clays.

Previous studies of the granitic terrains of Masvingo Province (Wright, 1988) had indicated that natural gamma and formation resistivity logging yield considerable information on the degree of weathering and also delineates fractures. The presence of these fractures does not of course indicate that they are of great areal extent, while the presence of a distinct fracture pattern observed in any one borehole may not be observed within any borehole drilled close by. In addition, these formations are extremely variable in their degree of weathering, with changes in the depth of weathering varying by as much as 5 m over a 10 m lateral displacement.

Fractures exhibit a distinctive response on the resistivity logs suggesting that weathering has occurred preferentially above the fracture, with a relatively small degree of weathering below. The reduced response on micro-resistivity logs is attributed to their relatively small depth of penetration. Due to the increased porosity of the weathered formations, the formation water dominates the resistivity log response, resulting in a progressive decrease in the indicated resistivity down to the fracture. The formation resistivity increases rapidly below the fracture, resulting in a saw-tooth type response which appears to be characteristic of permeable fractures. However, it must be noted that the geological logs of the cored holes provide no evidence to support these observations; indeed, the degree of weathering seen around fractures is often minimal.

Typically, formation changes may be obscured on resistivity logs by the fracture response. The neutron log shows porosity generally decreasing with depth but with local increases at fractures; the neutron log on its own does not distinguish the effects of weathering from changes in formation. Cross-plotting resistivity against neutron response with colour-coding of depths (Fig 2.2) distinguishes the response above and below the water table. Below the water table there is a steady increase in both resistivity and neutron count rate until a plateau is reached, indicating that the porosity as recorded by the neutron log is effectively zero (less than 1%). Resistivity continues to increase further with depth as more competent material is penetrated. Dips in the 'plateau' response represent the increase in porosity at discrete fractures, while the break in slope at the start of the plateau correlates with the base of weathering recorded by other methods such as drilling rate and surface resistivity.

The presence of fractures may also be deduced from changes in borehole diameter as recorded on the caliper log. However, not all fractures will be identified as the caliper arms

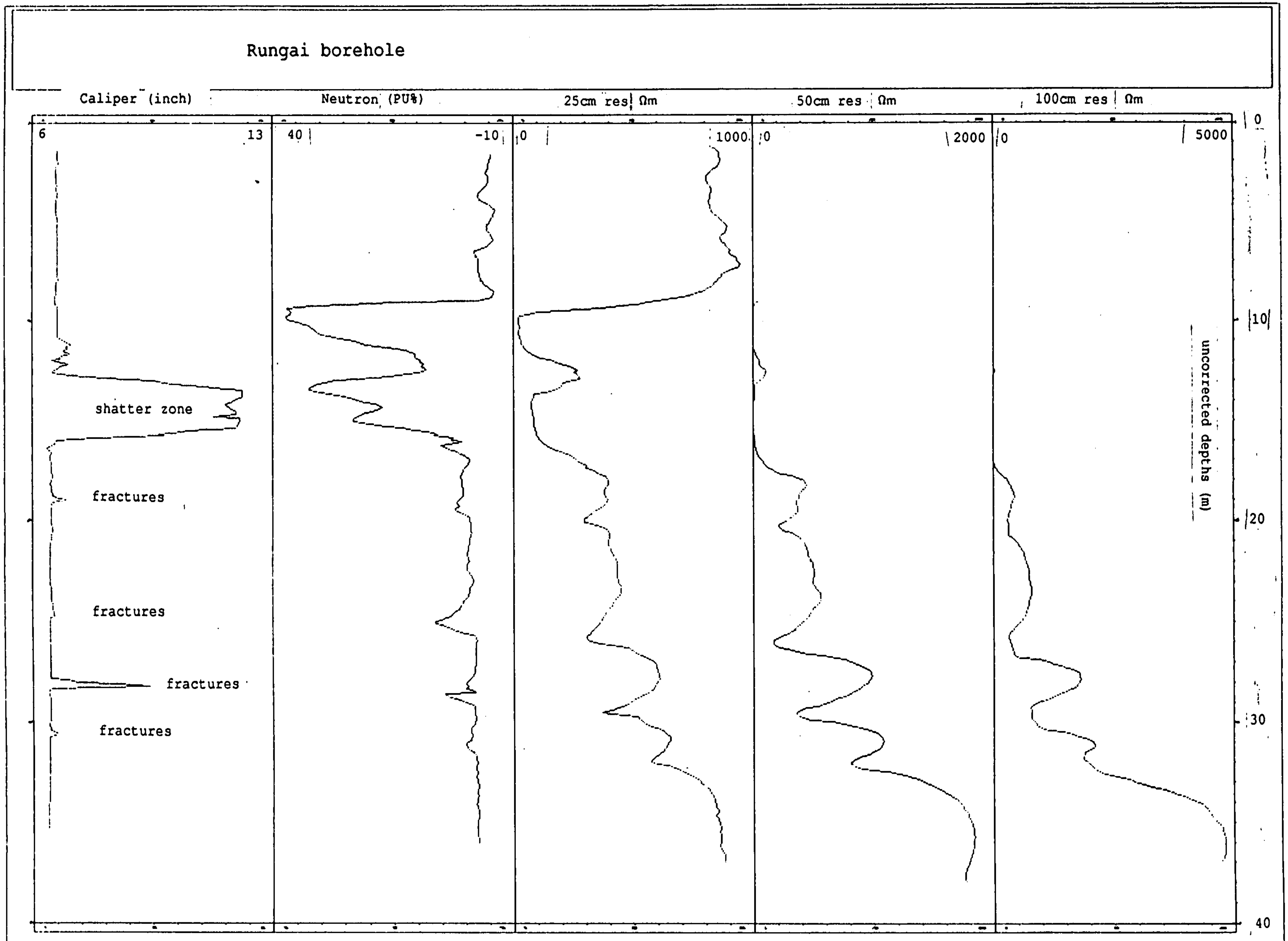


Figure 2.1 Example of geophysical borehole log response to fracturing

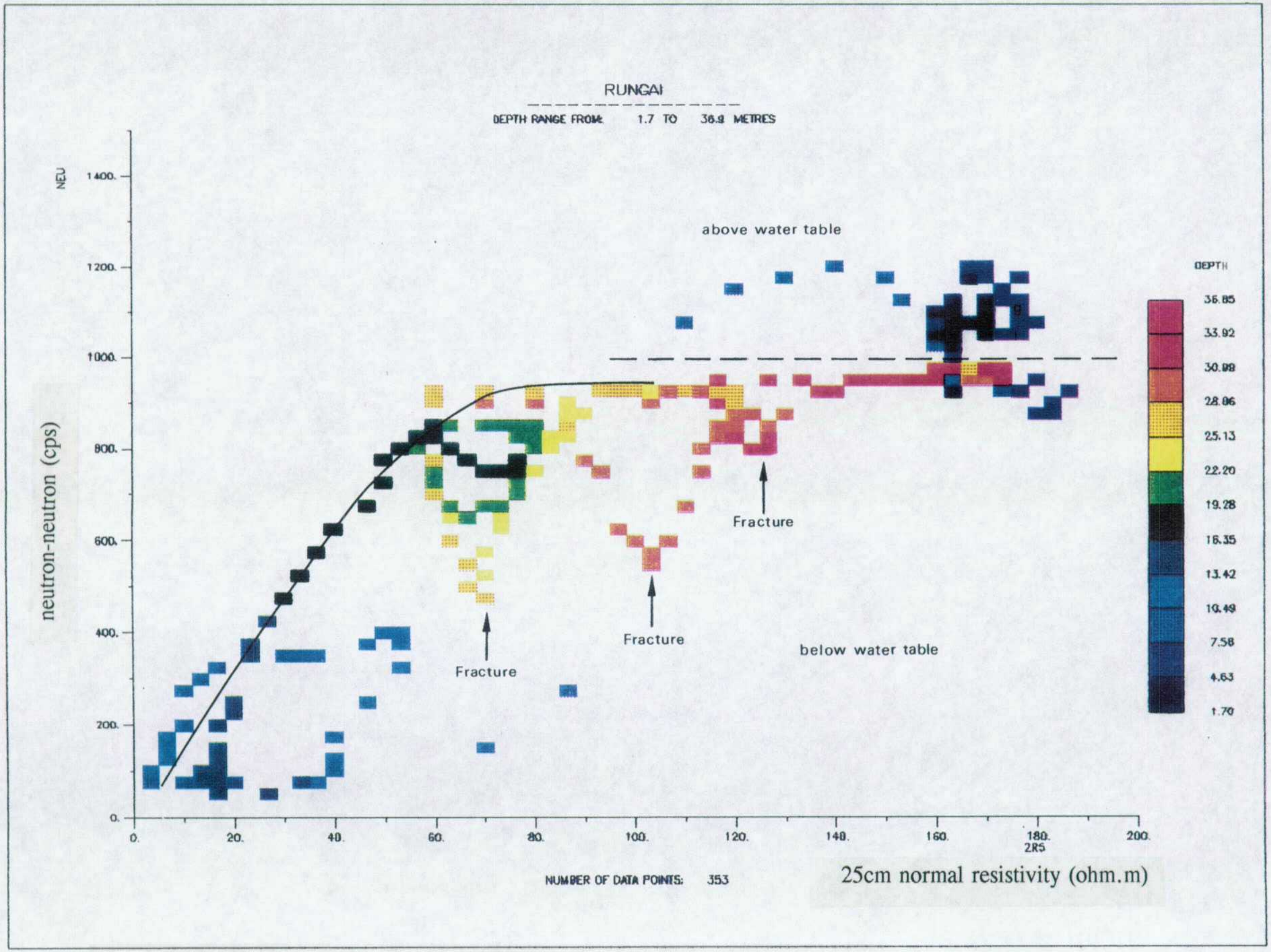


Figure 2.2 Cross-plot of resistivity and neutron-neutron borehole log data

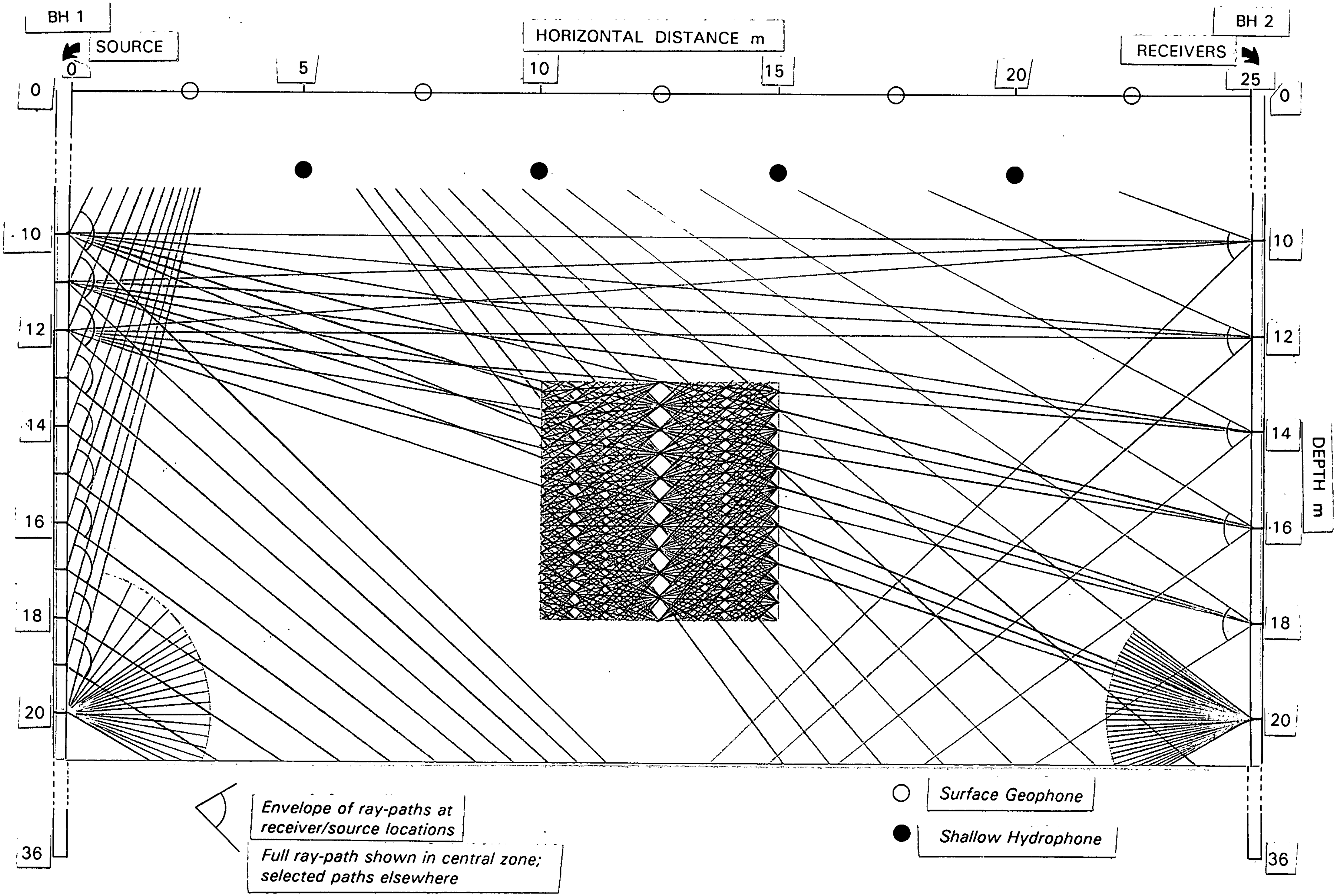


Figure 2.3 Example of ray-paths generated by seismic tomography method

may fail to penetrate some of the narrower fractures. In addition, drilling operations may enhance fractures where the formation has been shattered mechanically around the fracture aperture resulting in an apparently large fracture throat. Although the caliper log is useful for correlation, care must be taken in its interpretation to differentiate borehole rugosity effects that result from drilling operations.

Recent studies using the micro-resistivity sonde have resulted in a reassessment of fracturing as indicated on the normal resistivity logs. In zones of minor borehole rugosity, the micro-resistivity logs have indicated that the gross changes seen on normal resistivity logs comprise a number of minor fractures that are not resolved by the other logging techniques. Investigation of the normal and normal-reverse micro logs has shown that whereas drilling effects may dominate the normal [2.5 cm] micro log response, the deeper penetration of the normal-reverse log [5.0 cm] gives a truer indication of the existence of a fracture. Given the different depths of measurement available with the micro-resistivity sonde, the existence of a fracture may be verified by overlaying the two logs. Thus, if the 2.5 cm and 5 cm log traces have a similar form it is likely that a fracture exists. Where borehole rugosity dominates the micro-normal log response it is unlikely that drilling operations will cause a low resistivity response at the 5 cm spacing.

2.2 Cross-hole seismic tomography measurements

Cross-hole techniques are designed to assess the whole rock-mass between two boreholes, rather than the near-borehole zone as is the case with sonic logging tools. The simplest form of cross-hole seismic measurement is the parallel scan where observations are made between a seismic source in one borehole and a receiver at the same depth in an adjacent borehole. By measuring the travel time of the first arrival at each depth it is possible to plot the variation in the apparent compressional or shear wave velocity with depth. The term 'apparent velocity' is used to indicate that the true velocity in the horizontal direction is only obtained when the direct pulse between the source and receiver is timed through a homogeneous rock mass. In practice, the first arrival is often the refracted pulse from a lower interface along which the energy travels with a faster velocity. If the direct pulse through the rock mass is recognisable as a later arrival it can still be used to calculate the variation of velocity with depth, assuming a horizontally layered earth.

Cross-hole seismic tomography is the logical extension of the parallel cross-hole survey (e.g. McCann *et al.*, 1975, 1986; Grainger and McCann, 1977), and aims to provide one or more 2D images of seismic properties within the enclosed rock mass. Two or more boreholes, and possibly the ground surface, are used for the location of sources and detectors, and travel times are recorded between numerous combinations of source-receiver locations. The method has been shown to work in practice using both compressional and shear waves with, typically, up to 24 receiver channels being recorded simultaneously; time picks can be improved using high frequency sources utilising piezo-electric and, as in the present work, spark discharge methods (Meldrum *et al.*, 1991). The resulting multitude of ray paths can then be analysed in terms of the position, shape, and velocity contrast of any discontinuities or anomalous bodies which are intersected.

The benefits of the cross-borehole techniques are evident when we realise that undisturbed properties between boreholes can be assessed in-situ. This enables relatively large volumes of the rock-mass to be surveyed with a small number of boreholes whereas conventional drilling techniques would require a vast array of closely spaced boreholes to provide an acceptable assessment of spatially confined structures such as faults. Signal attenuation and the derived seismic velocity show a strong dependence on a number of factors - stress, weathering, pore fluid, porosity, permeability, temperature etc. - which are of interest in groundwater studies.

Equipment used for the present work included a high voltage (4.2 kV) sparker with control unit and 'active' (i.e. pre-amplified) hydrophones, all developed at BGS. Field data were collected with a hydrophone separation of 2 m and a sparker source spacing of 1 m. Additional geophones were used on the surface to compare their effectiveness with hydrophones suspended in shallow bores as required to resolve steeply dipping features (see below). The form of the ray-path coverage with the adopted source-receiver geometry means that the resolution changes across the tomogram. Figure 2.3 illustrates how the ray-paths build up (in homogeneous ground) to give the best coverage within the central zone while asymmetry is apparent at the edges. Velocity changes will,in practice,modify the ray-paths.

The algorithms for inverting or reconstructing a velocity image from travel time data are well documented in the literature, a good starting point being Dines and Lytle (1979), Hatton, Worthington and Makin (1986) or Dyer, Worthington and East (1986). Academic and commercial software is available, some of which include refinements to take account of practical difficulties such as hole deviations and grossly erroneous travel times. Seismic transmission tomography divides the rock-mass between two boreholes into a number of cells of constant velocity. The velocity of these cells is then assessed using a large number of rays with wide angular ray coverage. In a practical survey, the number of ray paths and the mathematical inversion procedure determines the number of cells in the velocity matrix. If the velocity distribution is very variable, curved ray analysis is often used (Cottin and others 1986) but in many cases straight ray reconstructions have been shown to suffice (Dyer, Worthington and Makin, 1986). Ray coverage is another concept with wide implications, for example horizontal bedding can be investigated by horizontal scans if ray bending can be discounted; however, a vertical 'dyke-like' velocity structure will not be identified even by a full scan (all possible ray paths) if only vertical boreholes are used. The results presented here have been interpreted using the VIBROVISION software package.

2.3 Seismic refraction surveys

The sonic velocities of subsurface formations can be deduced by measuring the time taken for signals to travel between a set of detectors (known as geophones) laid out on the ground. Where the formation velocities increase with depth, it is also possible to interpret the thicknesses of the different layers. For shallow investigations, to depths of 20-40 m, signals of sufficient energy can often be generated with a hammer and plate as the source, but more sophisticated weight-drop devices or explosives are needed if the signal attenuation is too high.

The equipment used for the survey work was a 24 channel ABEM Terraloc. This has the facility for signal enhancement, by adding (i.e. stacking) the results of a number of 'shots' at a given station so that weak signals are reinforced relative to the background noise (as caused, for example, by the wind). The gain setting can be adjusted independently on each geophone recording channel to allow for different distances from the source, and there are also a number of playback gain options for improving the definition of particular aspects of the records. Data can be transferred to a 3.5" floppy disk for permanent storage and results can be read back into the instrument for further processing subsequently.

A geophone separation of 2 m was adopted for the fieldwork to provide the necessary resolution of the small-scale lateral variations which were expected. The shotpoint interval was, typically, 15-25 m with a combination of 8 shot points for each spread (i.e. geophone set-up) being chosen to give good control on the arrivals from different refractors within 20 m of the surface. Shots were located at each end of the spread, 2 were internal to the spread and 2 shot points were offset beyond each end of it. Trials were also undertaken using a more detailed coverage in which the shot points replaced each geophone in turn. A stack of 5 shots was usually sufficient to produce adequate records.

In seismic refraction surveys it is the time at which energy first reaches each geophone that is required. As the distance between geophone and shot point increases, energy which travels in deeper layers (at higher velocities) overtakes the signals restricted to the slower, upper layers. This is readily seen by plotting the first-arrival times against geophone position. Refracted signals do not return to the surface from boundaries across which the velocity decreases with depth and any relatively low velocity layers within the sequence will usually be missed and cause errors in the interpretation. The seismic velocity is related to the density and rigidity of the medium and so it increases from dry soils and sands, to water-saturated sands, clays and more consolidated material, with massive rock giving the highest values. Thus, the type of in-situ weathering profile of interest here will generally show a progressive increase in velocity with depth as required.

An important limitation in shallow investigations is the accuracy with which the first-arrival times can be picked, as errors of as little as 1 ms become significant. The equipment itself has the necessary resolution but two extraneous factors have to be considered. Recognition of the true first arrival is limited by the strength of the energy source and the degree of signal attenuation through the ground. In the work reported here, excessive wind and cultural noise at the sites reduced the maximum gain settings that could be used for the more distant geophones. This meant that the first breaks recorded at these geophones were less distinctive than might have been expected. There was insufficient time to reduce wind vibration by burying or covering the geophones and an unduly large number of additional stacks would have been needed to counteract the low gain setting.

The second constraint concerns definition of the zero time, that is when the shot is 'fired'. The measurement cycle was initiated by a trigger geophone placed close to the hammer impact plate and some problems were experienced in setting the gain of this geophone so that it was sensitive enough to pick up the shot instant accurately, without causing mistriggers due to routine movements near the shot point. There will be a small delay between the actual shot instant and the arrival at the trigger geophone and this will vary according to the precise distance between them, the speed of sound in unconsolidated materials being about 0.4 m/ms. Further delay will result if the triggering threshold is not passed by the first energy arrivals.

Simple interpretation procedures assume that each layer has a constant velocity and that the refracting boundaries are horizontal or dipping at a constant angle. The layer velocities and the interface depths can then be calculated beneath the shot points and interpolated between them. Irregular interfaces can be mapped in some detail providing there is sufficient shot point coverage and the arrivals can be correctly assigned to the different refractors. This type of delay-time analysis allows lateral changes in both velocity and depth to be mapped. A more sophisticated approach to the interpretation of refraction data over non-uniform ground was developed by Palmer (1980) and a computer program based on his 'reciprocal time method' was used to process the results obtained in Zimbabwe. While this technique relies on relatively few assumptions, it still depends upon an ability to recognise the number of layers present beneath each geophone and to assign the arrivals to the correct layer.

Sonic velocities in this report are generally given in units of metres per millisecond (m/ms) as these relate directly to the scale at which the measurements are taken. However, the use of metres per second is retained in some of the diagrams produced from commercial software, where 1 m/ms = 1000 m/s = 1 km/s.

2.4 Direct current electrical methods

In the direct current (DC) electrical method, the traditional approach of the groundwater geophysicist, electric current is introduced into the ground through one pair of electrodes and the resulting potential difference established between a neighbouring pair of electrodes is measured. The value of apparent resistivity of the volume of ground influencing the current flow is obtained by a calculation involving the measured current and potential drop, and a geometrical factor that varies with the electrode pattern and spacings used. In the rather rare case of homogeneous ground, this value of apparent resistivity is equal to the actual or specific resistivity of that ground; more often, however, it represents a weighted average of all the influencing lithologies.

The electrical resistivity of rock is determined principally by its water content, other influencing factors being the quality (or saltiness) of this water, the clay content or state of weathering and, rarely, the presence of minerals of metallic lustre. The objective of resistivity surveying for fracture zones is thus to locate near-vertical zones of low resistivity, enclosed laterally by a highly resistive host (i.e. the non porous crystalline rock). The main source of geological 'noise' is likely to be the clay derived from preferential weathering within the fractures; this will both enhance the resistivity response and yet reduce the effective porosity of the secondary aquifers. Variations in the conductance (i.e. thickness and resistivity) of the overburden can also produce false anomalies in this context.

During this project, resistivity measurements were obtained using the battery powered ABEM SAS300 Terrameter with auxiliary booster. This equipment includes a signal averaging system whereby a continuously averaged value of resistance is displayed, to be accepted when it appears stable. The transmitted pulse is switched DC at about 0.2 Hz; this waveform facilitates rejection of tellurics, spontaneous potentials and electrode polarisation effects (thereby allowing the use of metal stakes for both current and potential electrodes). Reliable measurements may be obtained with current as low as 0.2 mA but for most of the present work it was possible to maintain current output in the range 2-50 mA.

For the resistivity surveys undertaken in 1991 the dipole-dipole electrode array configuration was used, yielding information simultaneously on both lateral and vertical resistivity variations. The current and potential electrode dipoles were 5 m long and the station separation was also 5 m. Measurements were made at each station with potential pairs at successively greater separation (from 5 m to 40 m) from the current electrodes, thereby achieving greater depths of investigation. The measuring or plotting point is taken to be at the intersection of lines drawn at 45° from the midpoint of the electrode pairs involved. In this manner the results, usually contoured, are presented as a pseudo-section which, in a very generalised way, indicates both lateral and vertical resistivity variations. This array has been shown to respond relatively well to narrow, steeply dipping conductors while it also yields some information on depth of burial and depth extent of the anomaly sources.

Brief mention of the gradient array, an electrode pattern used extensively in the previous year's work, should also be included here because recent modelling of some gradient array responses is described in this report. With this array, the current electrodes are set a relatively large distance apart and the potential electrodes are traversed within the central 3/5 of this separation where, in homogeneous ground, the electric field can be considered as uniform. The use of fixed current electrodes is especially beneficial in areas of high contact resistance (dry sands, shallow rock etc) since special effort can be made to prepare current electrode sites (digging of slurry pits etc). The current electrode separation controls the depth of investigation and the potential electrode separation is kept as small as possible to enhance the resolution. In addition to logistical advantages, this array is best able to indicate the lateral position and dip of a target.

A variety of techniques was used in modelling different aspects of the resistivity data. The well-established linear filter approach to the interpretation of 'depth-sounding' curves produces rapid solutions for a 1D layered earth model. This can either be applied interactively, to generate theoretical curves which are assessed by the operator in relation to a set of field data, or in a (semi-)automatic mode to derive a model which reproduces the field data within a specified tolerance.

The dipole-dipole pseudo-sections were modelled in 2D using a finite element approach in which the subsurface is represented by a series of triangular elements to which specific resistivities are assigned. A matrix equation defining the behaviour of a potential field within this mesh is derived and solved for a given set of source and receiver locations. The calculated apparent resistivity values can then be plotted and compared with the observed section. Examples of the results obtained with this approach are included below (see e.g. figures 3.13, 3.14 and 4.9). This type of program was also adapted to look at the effect of lateral variations on resistivity (Schlumberger array) sounding data.

Although 3D numerical resistivity modelling is not in common use, there are examples in the literature outlining the approaches used, such as Finite Element (FE) (Dey and Morrison, 1979) or Finite Difference (FD) (Scriba, 1981) numerical schemes. An FD scheme has been developed (Reece, 1986; Jackson *et al*, 1989) which can accommodate both 2D and 3D resistivity modelling. In common with many other techniques it incorporates a three dimensional grid of nodes at which the potential is calculated. However, each node may have a different current and resistivity associated with it, enabling the technique to handle arbitrary electrode arrays.

Several observed gradient array anomalies have also been modelled using alternative BGS software, the RES3D program. This allows forward interactive modelling of multiple 3D bodies of uniform resistivity and strike extent within a 2-layered earth (overburden plus host) using an integral equation approach. In addition to the modelling of observed profiles, some predictive modelling was undertaken in connection with the allied topic of geophysical siting of collector wells. Some results of 3D modelling are described in Section 7.

As with geophysical modelling techniques in nearly all situations, it should be remembered that a close match between observed and calculated responses in no way guarantees the correctness of the model.

2.5 Electromagnetic (EM) methods

EM techniques are becoming increasingly popular in groundwater investigations because they do not require electrode contact with the ground and are therefore relatively rapid. These techniques are based on the use of continuous fixed frequency signals, typically in the range 100-8000 Hz. The receiver picks up the combined effects of the directly transmitted field and any secondary fields generated by conductors within the ground and variations in this received field give information on conductors present. The distance between transmitter and receiver coils, the transmitter frequency, coil orientation and ground conductivities are all factors which control the effective depth of investigation.

A configuration commonly adopted with such equipment is moving source-receiver; here the transmitter and receiver coils are in the form of moulded, portable loops which can be easily moved together, a fixed distance apart, along the traverse. The received field is measured relative to the primary signal as transferred directly through a reference cable. The coils are aligned to be co-planar either in the horizontal or vertical sense, with the measurement being referred to the point midway between them. The conductivity which can be deduced directly from the readings will be valid if the ground is homogeneous. Variation in the values with coil spacing provides some indication of the type of layering that is present. A characteristic response is also given when the system crosses a steeply dipping conductor; this has the form of a minimum over the conductor with flanking highs of lower amplitude, and contains information on the width, dip, depth and conductivity of the body. The relative amplitudes of the in-phase (real) component and out-of-phase (or imaginary) component responses relates to the conductivity of the source; the presence of conductive overburden also affects the responses differently.

The Geonics EM-34 moving source-receiver ground conductivity meter was used during the present survey. This instrument displays the out-of-phase response converted to a scale of (apparent) conductivity and uses the in-phase response to indicate when the coil spacing is near its correct value of 10 m, 20 m or 40 m. By switching the transmitter frequency automatically from 6400 Hz, through 1600 Hz to 400 Hz according to the coil separation, the induction number is kept about the same and low enough for the linear conversion to conductivity to be a reasonable approximation, given that the corrections become progressively larger as the conductivity increases above 50 mS/m. Readings are easily obtained with the coils horizontal or vertical as determined by visual reference. Values tend to be less reliable in the horizontal coil configuration due to orientation errors but the effective depth of investigation is significantly increased (by a factor of about 2). In the present work the use of level bubbles attached to each coil resulted in more consistent horizontal coil measurements. Data quality also tends to deteriorate at lower conductivity levels when the sensitivity of the receiver is at a maximum and the effects of atmospheric EM noise or coil movement become more significant.

Two types of EM34 response are generally considered to be significant with respect to borehole siting in basement terrain. In one case, the horizontal coil response at the wider separations increases relative to that given with the coils vertical. This suggests a thickening of the weathered zone in what is essentially a layered situation which can be approximated by a 1D 'sounding' model. In practice, these zones can be narrow relative to the coil separation and so a 2D model should result in better depth estimates though without necessarily leading to any significant refinement in the most favourable local drilling site.

The second case is characterised by a maximum in the vertical coil response coinciding with the type of horizontal coil anomaly characteristic of a thin, steeply dipping conductor (i.e. a central minimum flanked by positive shoulders relative to the background level). This can be interpreted as representing a zone of enhanced weathering and thus greater conductance, overlying a fractured rock which is itself a conductor. However, in the absence of poor quality water or the development of clay minerals within the fractures, it is difficult to account for the horizontal coil signature. An alternative explanation assumes that superficial clays account for the high in vertical coil readings while a notch-like feature in the bedrock profile, associated with the fracturing, causes the horizontal coil response. Drilling evidence is equivocal and modelling techniques are needed to discriminate between these two possibilities, the significant difference being that in the second case there is no response attributable directly to the presence of open fractures at depth.

2.6 Magnetic susceptibility

The magnetic susceptibility of rocks, a measure of how strongly magnetised they become in the earth's inducing field, is determined almost entirely by their content of ferrimagnetic minerals, principally magnetite and ilmenite. Quite subtle changes in the content of these auxiliary minerals result in the very large susceptibility variations displayed by rocks. In addition quartz, a very common mineral, is diamagnetic (i.e. it possesses a small, negative magnetic susceptibility) and in sufficient concentration will be characterised by a low magnetic field intensity. This means that magnetometry, among the most cost effective of geophysical techniques, can be a very sensitive tool of geological mapping.

Susceptibility measurements were made in situ using a Brno Kappameter at apparently anomalous sites at both Mhatiwa and Nemarundwe as indicated by the previous year's magnetic (total field) traverses. Measurements were also made on a variety of granitic-pegmatitic phases, at both Nanwi and Nemarundwe, and several rock samples displaying a wide range of susceptibility were subsequently submitted for analyses of opaque mineral content; further information on magnetic susceptibility was obtained from measurements on core samples from the inclined boreholes. These field susceptibility values have been incorporated in modelling the total field magnetic responses using GRAVMAG, an in-house interactive 2.5D forward modelling programme. All these results are discussed below in the relevant sections.

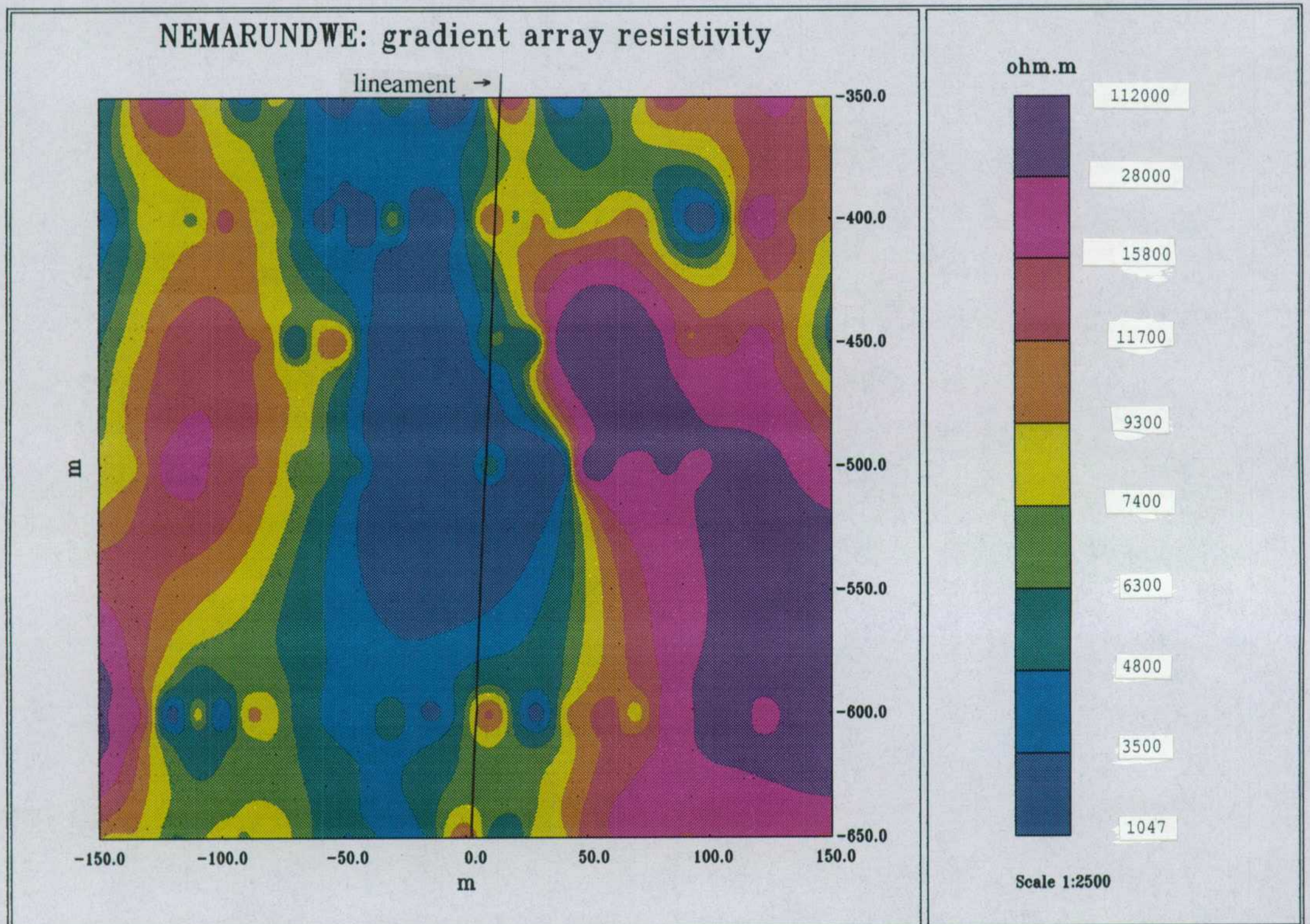


Figure 3.1 Nemarundwe: gradient array resistivity data covering Bh sites

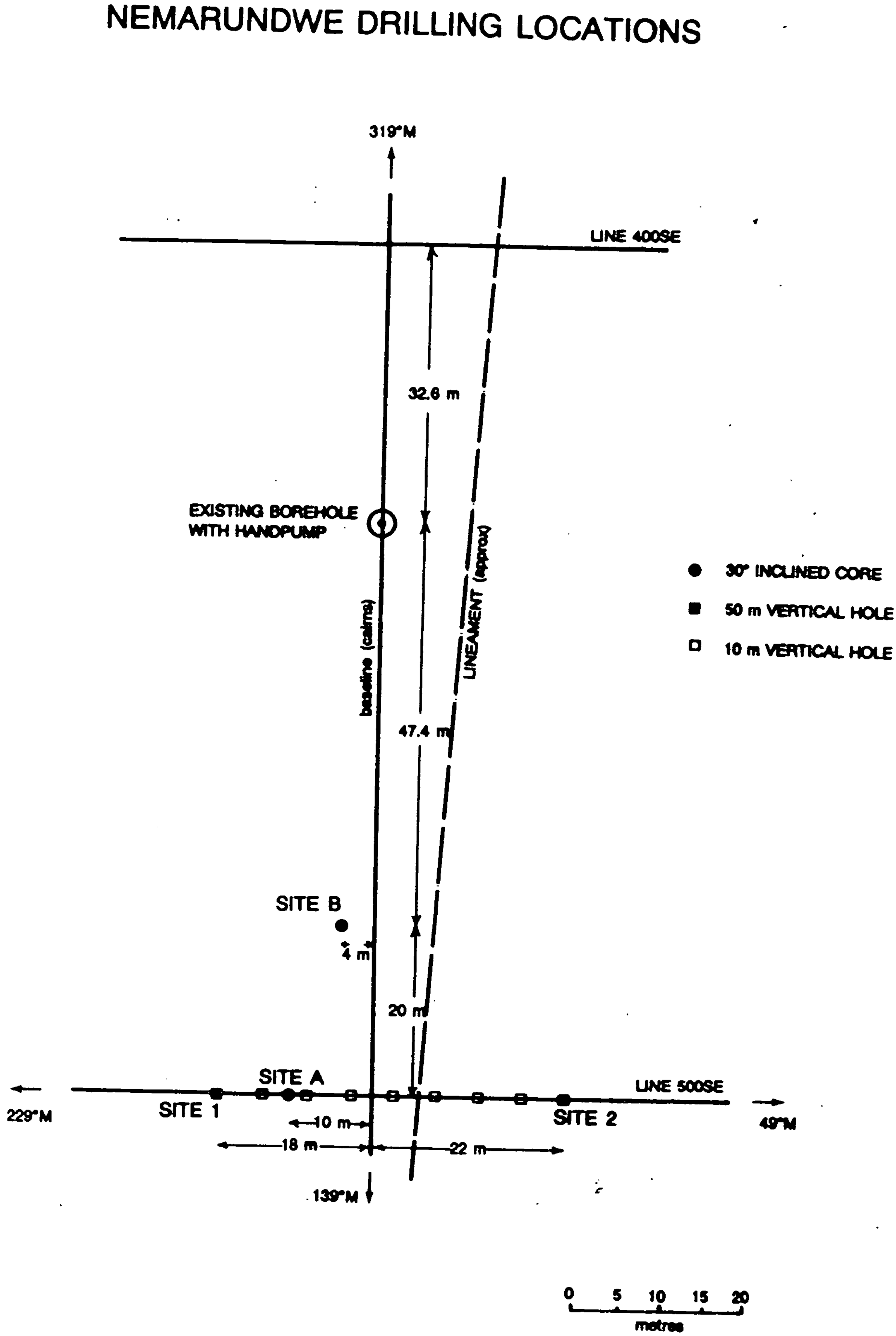


Figure 3.2 Nemarundwe: drilling site plan

BH/1 NEMARUNDWE INCLINED (SITE B)
SUMMARY GEOLOGICAL LOG

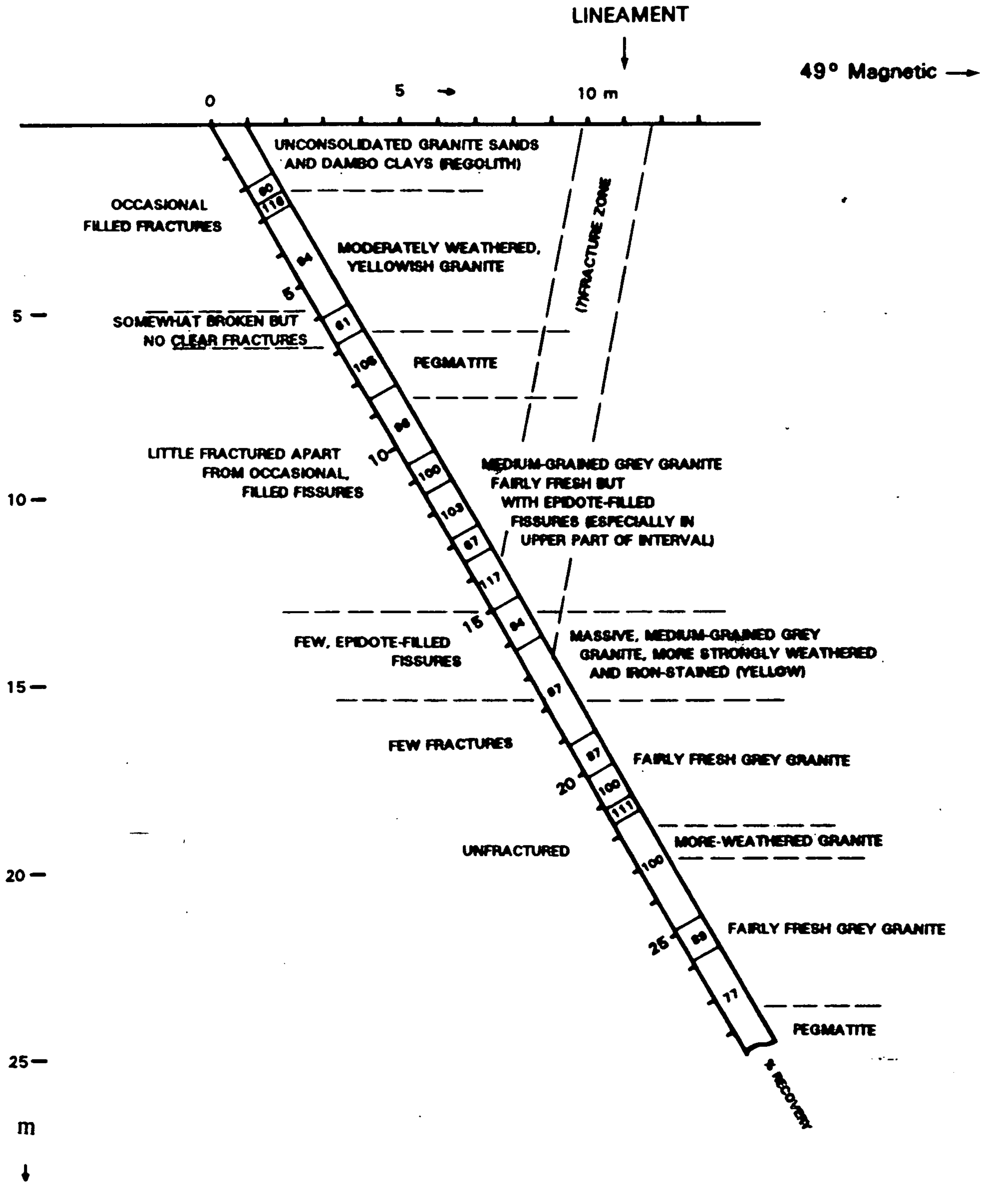


Figure 3.3 Diagrammatic geological summary log of Site B

15.00 to (?)17.75 m:	massive, grey, medium-grained granite appearing more weathered and iron-stained (yellow). Good recovery (this is apparent from the completeness of the core). Only a few epidote-filled hairline fissures.
(?)17.75 to 27.16 m:	virtually unfractured, fairly fresh grey granite. Some increase in yellow staining from 21.55 m for about 1 m. The rocks are essentially unfractured over this interval.
(?)27.16 to end:	coarse pegmatite. Core a little broken but no clear fractures.

Interpretation:

Despite the presence of the occasional prominent steep fracture, the upper weathered zone probably correlates with surface weathering processes. The only other possible fracture zone occurs between 15 m and (?)17.75 m but other than the slightly increased weathering here, there is little to suggest a fracture zone. Such a zone, if linked to the surface position of the lineament, would, however, correlate with a similar interpretation that could be made for Site A and would indicate a fracture zone with a similar hade of 12.5° to the SW. The evidence for such a structure is, however, rather suspect.

BH/2 (Site A) - inclined

Location

This borehole was sited 15 m to the SW of the lineament and drilled at an inclination of 30° to the vertical towards 49°. It was completed at a down-hole depth of 37.20 m (approx 32 m true depth).

Description

The log is summarised in Figure 3.4. Unconsolidated material, corresponding to regolith, was penetrated to 5.81 m (about 5 m true depth), followed by a further 1 m of very weathered, yellowish granite (saprock). This gave way to fresher pink and grey, medium-grained granite which continued to the bottom of the hole. Variations in the geology include pegmatitic injection and grain size differences from fine to coarse. Epidotisation also varied somewhat.

An increase in hairline, epidote-filled fissures occurs at around 8.50 to 9.50 m. Core loss occurred at between 10 and 11 m and may correspond to fracturing but this cannot be observed directly and there is no evidence for it in the resistivity log. Overall, in the interval from 10.11 to 13.63 m, recovery averaged only 52%. Several fractures are seen in the recovered core and others may be present. For this to represent the lineament at depth, the fracture zone would have to be very shallow-dipping, which is considered unlikely. It is more probable that this represents a shallow-dipping fracture zone unrelated to the lineament. Recovery below this point is generally high with a few exceptions. Between about 19 and 23 m there is an increase in the number of epidote-filled, closed hairline fractures, many of which are steep, but weathering in this zone shows no increase.

Interpretation and correlation with Site B

The indications of fracturing from about 8.50 m to 13.63 m could be due either to shallow-dipping or steep fractures, but if the latter then these could not be an expression of the interpreted photolineament. Alternatively, if the zone of increased fracturing noted between 19 and 23 m *is* related to the photolineament it would suggest a structure hading around 15° to the SW, correlating with a similarly uncertain interpretation in B/H 1 (Site B). If this interpretation is correct (which is by no means certain) then at a true depth of only 16 to 20 m, the fissures comprising this fracture are closed and unweathered, and therefore of little significance in terms of groundwater movement.

3.3.2 *Geophysical logs*

Borehole geophysical logging was undertaken at Site 1, Site 2, inclined borehole site A and the 7 shallow hydrophone boreholes. Each vertical borehole was logged with micro-resistivity, and the two deep boreholes additionally with caliper and normal resistivity. Due to access difficulties associated with its small diameter, only normal resistivity logging was possible in the inclined borehole. (Inclined borehole B, located some 20 m to the NW) could not be logged due to collapse.

Water levels were generally encountered at a depth of about 5 m, with the exception of the borehole at Site 1 where the water was at 38 m. To enable seismic tomography studies to be run, this borehole had first to be filled with imported water and it was notable that after a period of five days the water level had not dropped by more than one metre. In marked contrast, the borehole at Site 2 produced a high yield during drilling operations, the water coming mainly from a series of discrete fractures at 32 m below surface.

Inspection of the micro-resistivity responses in the shallow vertical boreholes showed that the formation to the northeast of the lineament exhibited a higher background resistivity but with clear indications of fracturing (Fig 3.5). Thus, the lineament appears to separate a more weathered formation (in which fracturing is not expressed) to the southwest, from a more resistive, yet fractured, formation to the northeast.

The existing borehole, fitted with a hand pump, is located 67 m to the northwest of survey line 500SE (along the baseline of the grid), and some 10 m to the SW of the lineament. This had been logged previously with a complete suite of geophysical techniques which showed that weathering extended down to a depth of 11 m (Fig 3.6). Micro-normal resistivities within this top section were less than 100 ohm.m; these can be linked with the lower resistivities measured in the hydrophone boreholes to the southwest of the lineament during the present study.

The geophysical logs of Site A (Fig 3.7) show good correlation between changes in normal resistivity and the lithological boundaries observed in the core. Core recovery was good below 13.6 m and the change from low to high resistivity occurs approximately at this depth; background formation resistivities generally reflect the degree of weathering.

Grain densities determined from core samples from the inclined boreholes (Fig 3.8) showed some small variations about a mean near 2.62 Mg/m^3, attributable perhaps to incipient weathering, but no systematic change across the lineament. Magnetic susceptibility measurements (Fig 3.9) did show a distinct increase for the rocks below about 14 m at Site A and 8 m at Site B. At the former, average values for samples to the southwest were 0.27×10^{-3} SI as opposed to 1.18×10^{-3} SI to the northeast: an intervening set of low values (19-25 m) may be associated with the lineament but this zone was not apparent at Site B. While such variations may reflect a change in mineralogy across the lineament, as suggested

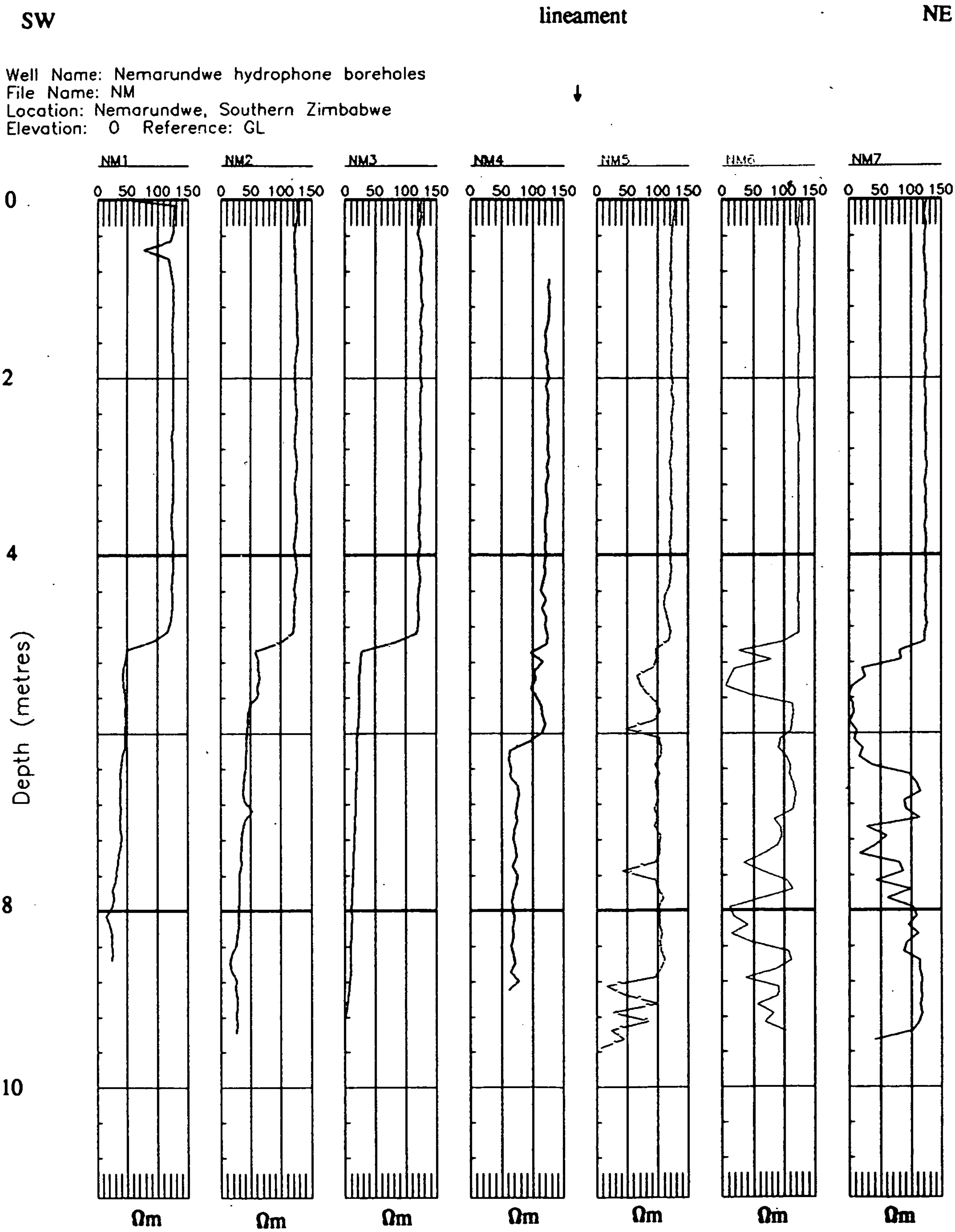


Figure 3.5 Comparison of micro-resistivity logs from hydrophone boreholes

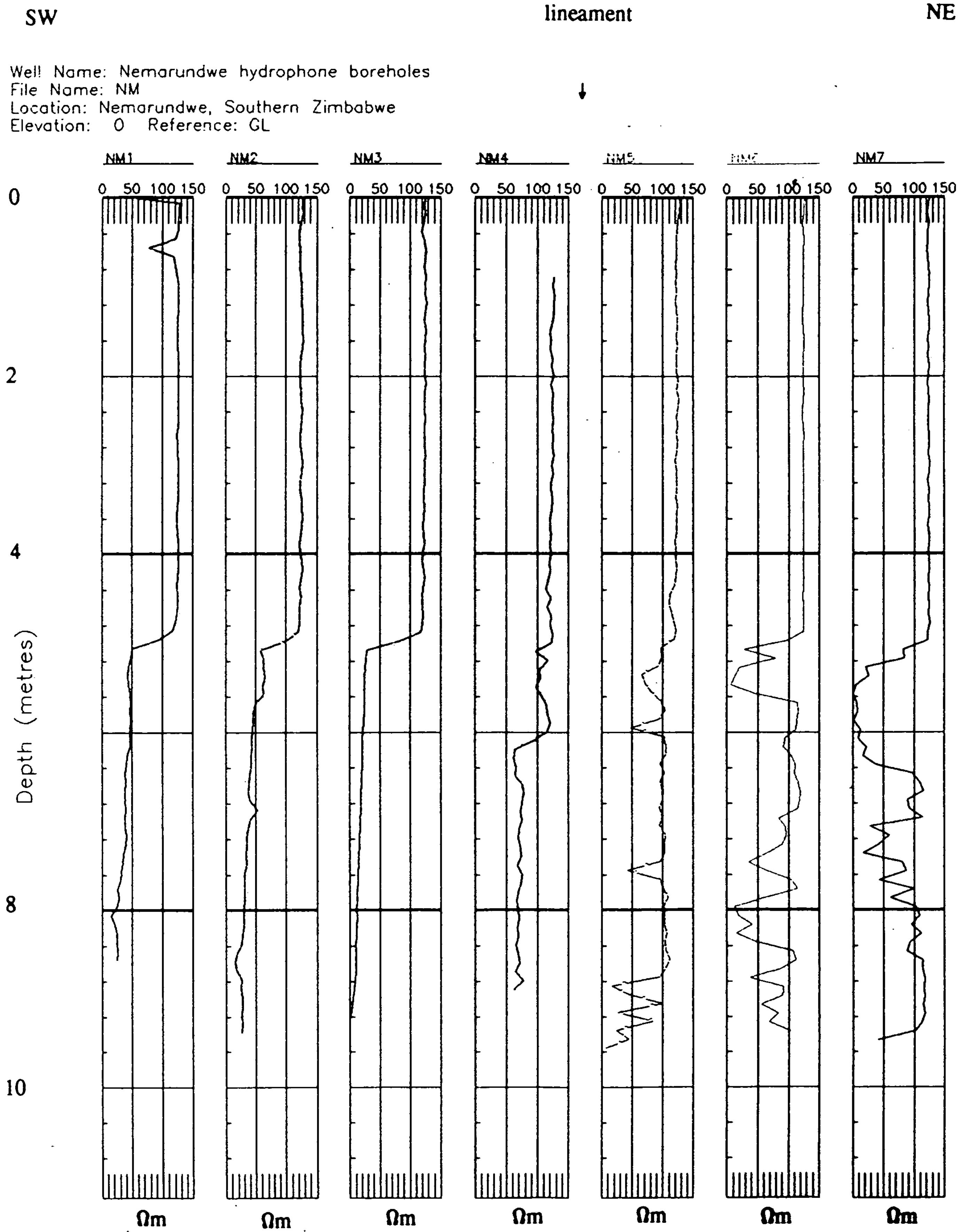


Figure 3.5 Comparison of micro-resistivity logs from hydrophone boreholes

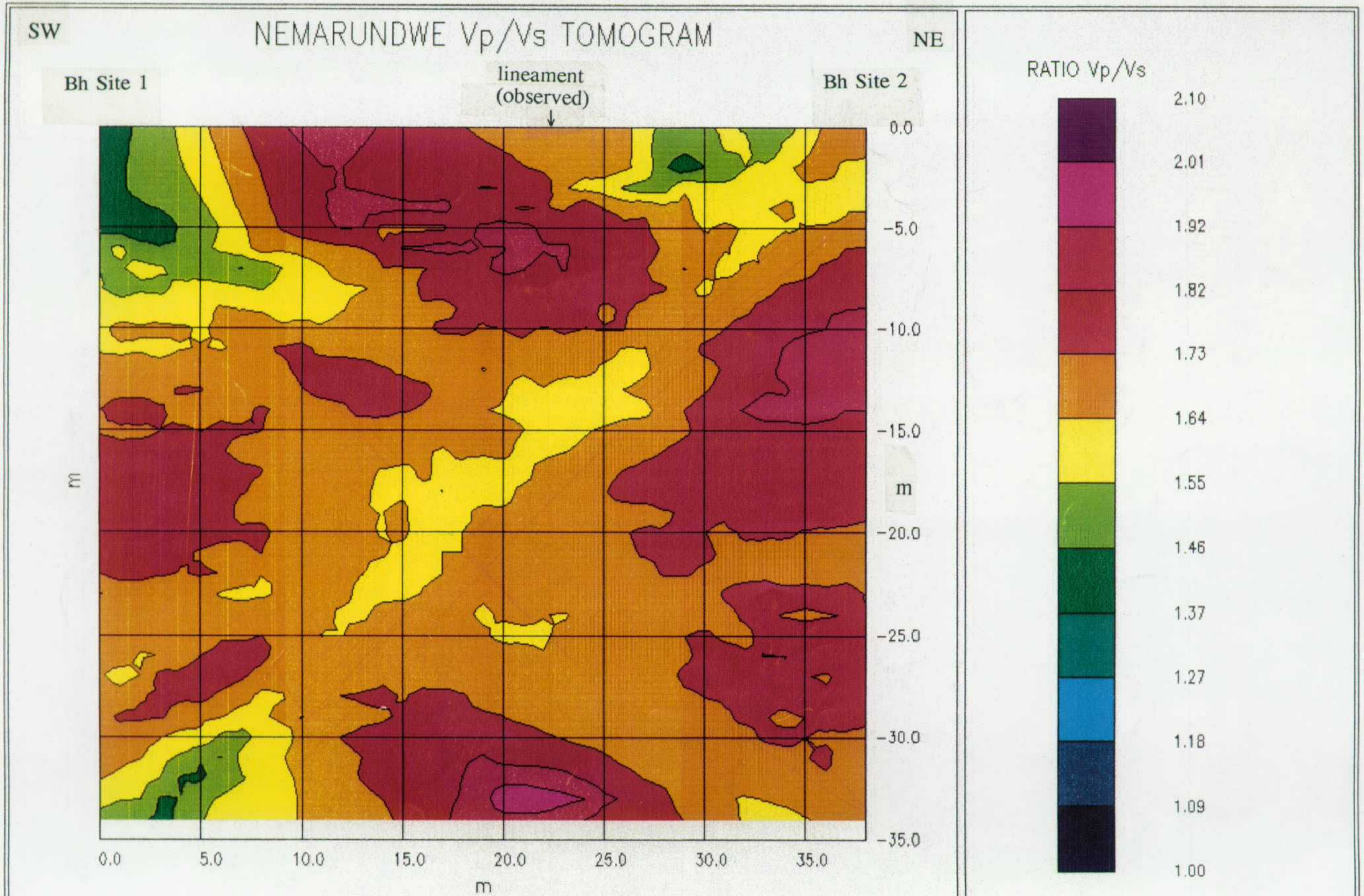


Figure 3.11 P:S-wave ratio tomogram between Sites 1 and 2

BH/2 NEMARUNDWE INCLINED (SITE A)
SUMMARY GEOLOGICAL LOG

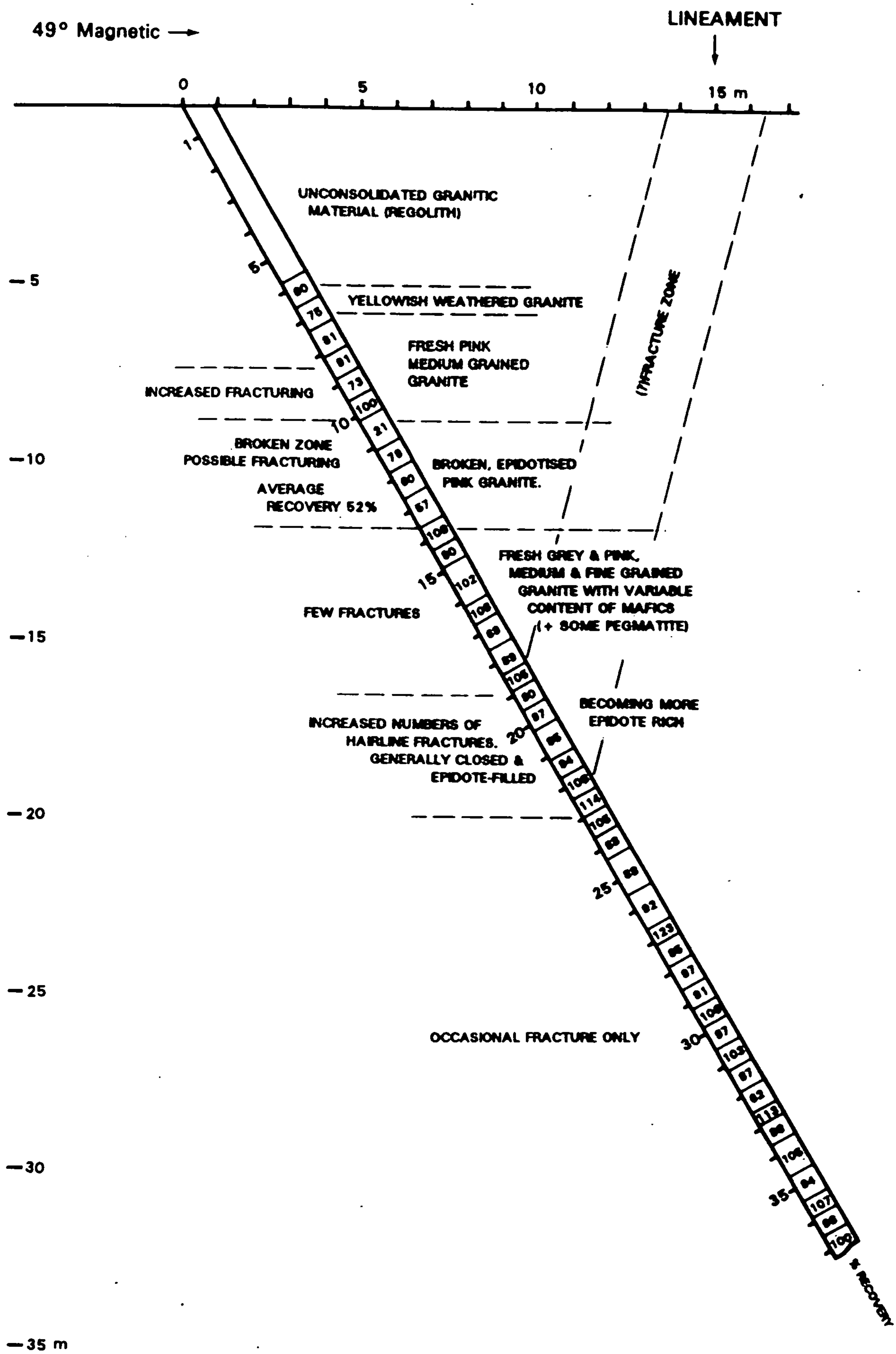


Figure 3.4 Diagrammatic geological summary log of Site A

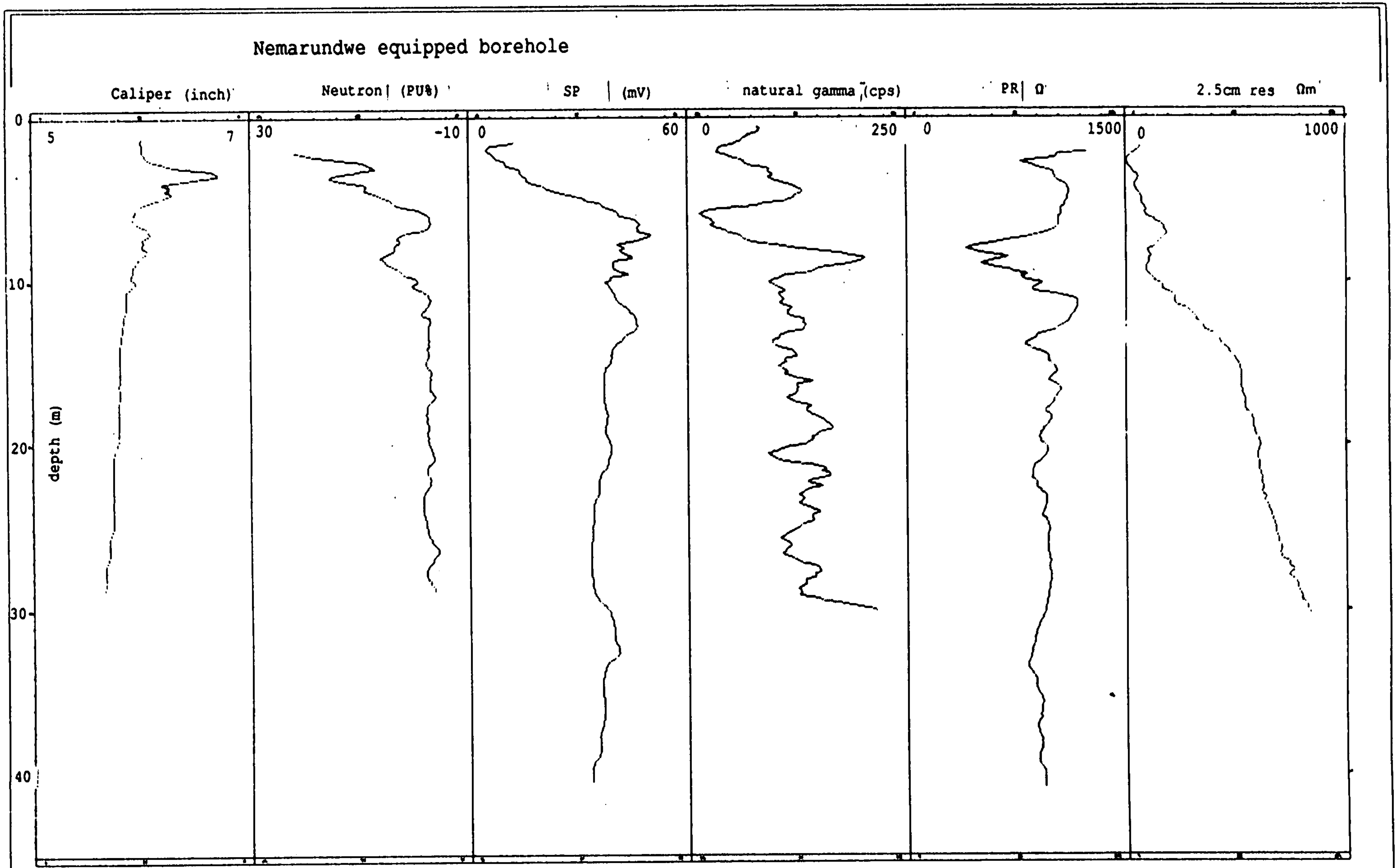


Figure 3.6 Comparison of geophysical logs from equipped borehole site

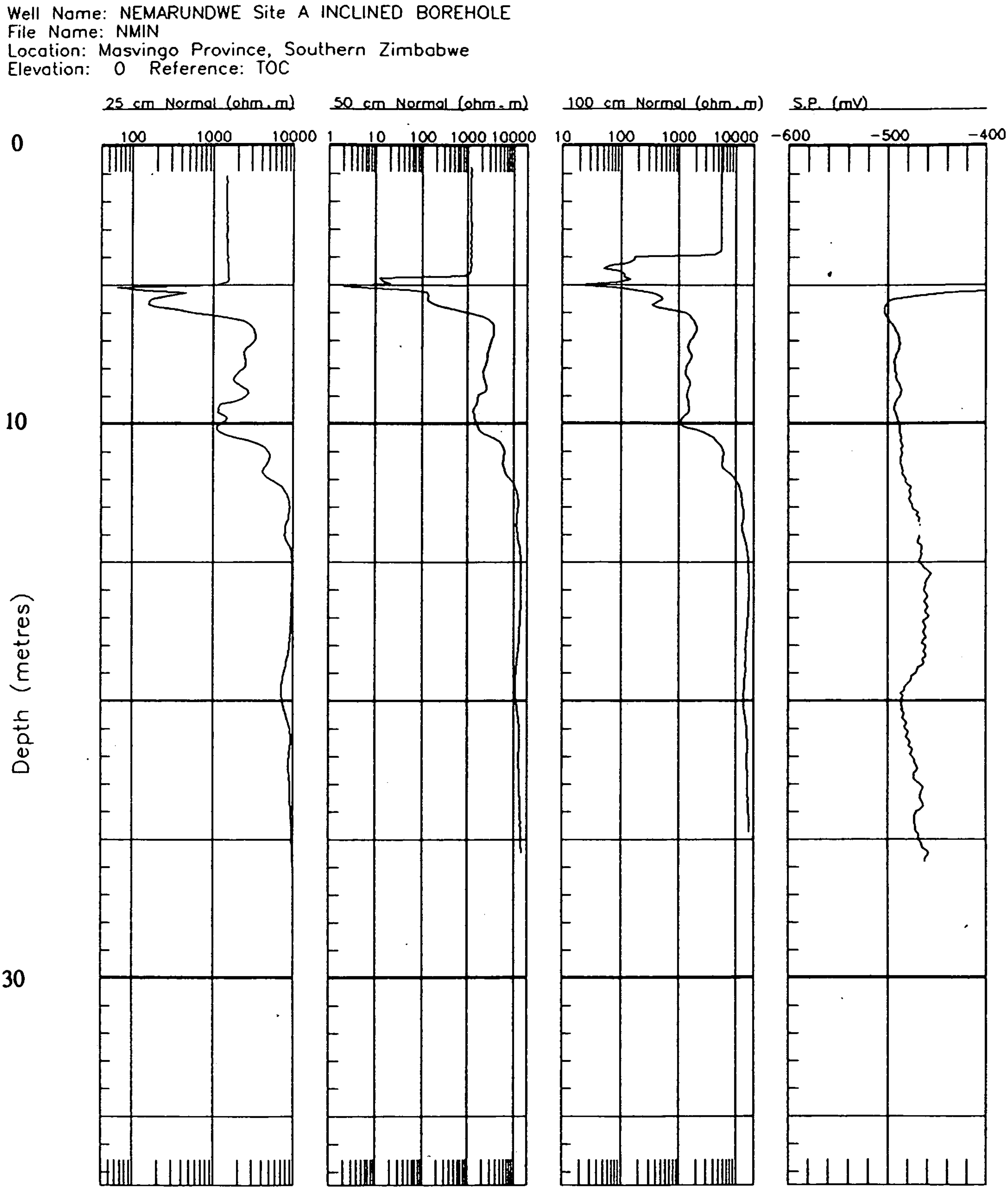


Figure 3.7 Geophysical logs from Site A

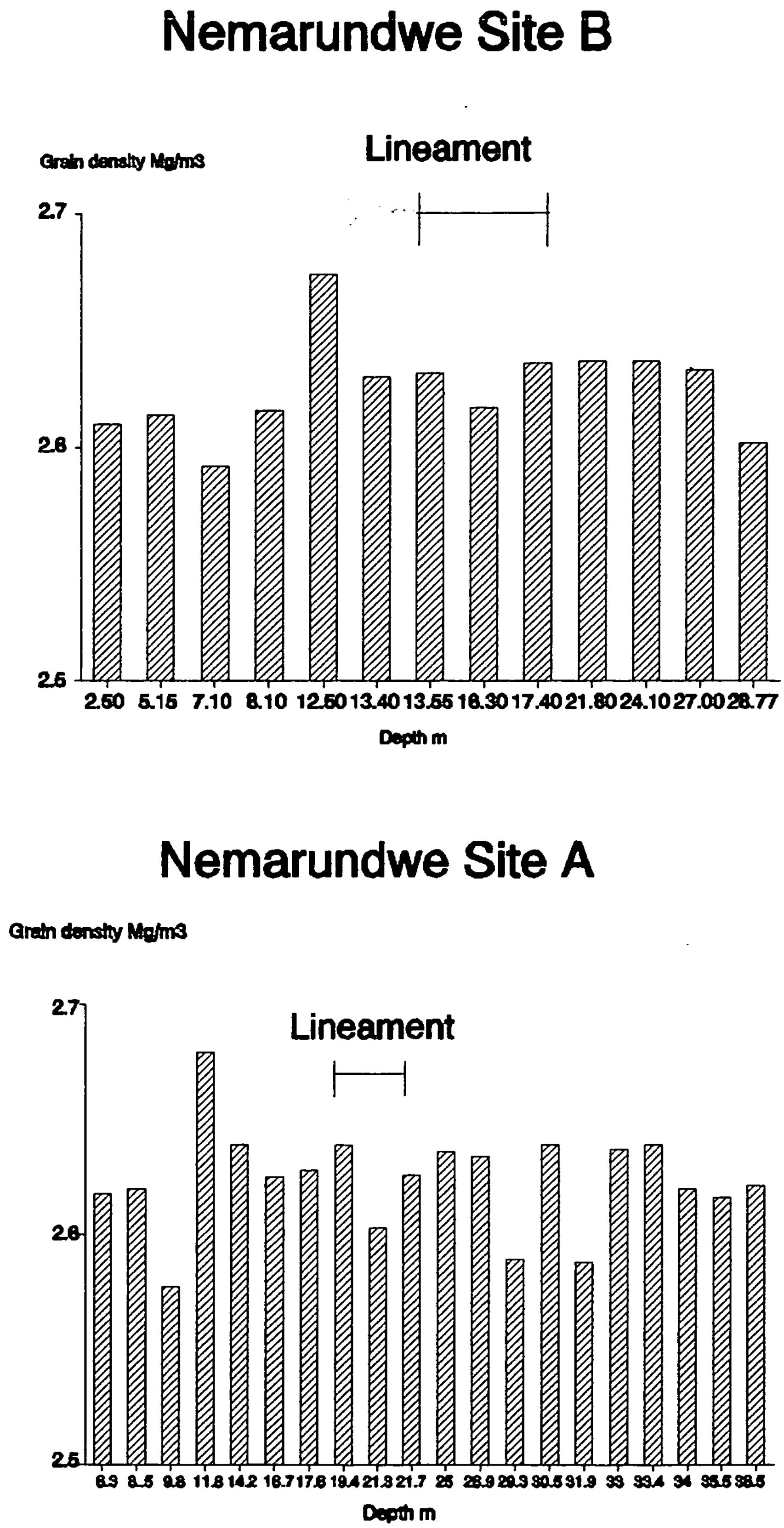


Figure 3.8 Densities of core samples from Sites A and B

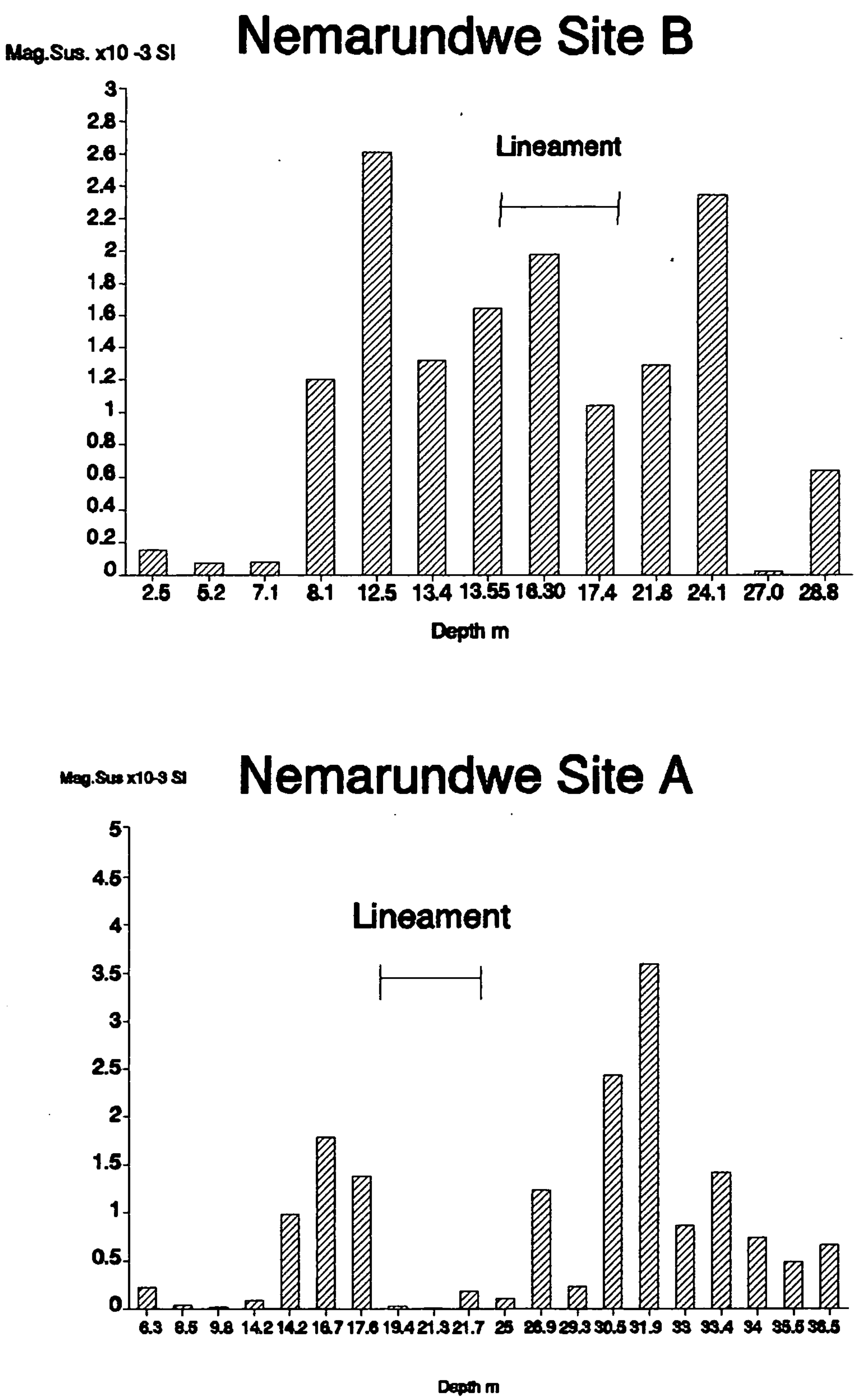


Figure 3.9 Magnetic susceptibilities of core samples from Sites A and B

3. RESULTS FROM NEMARUNDWE

3.1 Background

Nemarundwe is located within the mapped outcrop of the Younger Granites. The geomorphology of the region is of occasional rounded bornhardts separated by large expanses of regolith. The granites are gneissic to migmatitic in texture and show fracturing and pegmatite veining along various directions. Pegmatite veins cross-cut one another in a complex manner; planar fracturing of recent origin within these pegmatite veins is common, and all exposed pegmatites show preferential weathering. The Popoteke Fault passes close to Nemarundwe, where it forms a ridge indicating that it is filled/intruded. Although lineaments are common in this area, most are of moderate length only (generally less than 1 km) and show a considerable range of directions about the dominant NNW and ESE trends.

Nemarundwe is the site of a broad, open vlei along the centre of which a minor drainage, associated with dark soils, marks the line of a lineament over a distance of about 1 km. The vlei appears to be covered by a thin layer of regolith; scattered and more continuous outcrops occur throughout, and dug pits show the presence of sap-rock at a depth of about 1 metre. Outcrops occurring close to, or overlying, the lineament indicate that fresh bedrock is present at very shallow depth near the centre of the vlei. The lineament trends approximately N134°E.

Outcrops show strong fracturing along various directions, some of which are sub-parallel to the main lineament trend. At one location, 15 m away from the lineament, a zone of fractures is exposed up to 2 m wide and more than 50 m long, composed of 1 mm to 10 cm wide quartz-filled fractures. For the most part these fractures dip steeply to the east (about 80°). The zone trends approximately N127°E but there is an associated (conjugate?) set of similar quartz-filled fractures trending N161°E. The few outcrops that occur directly along the line of the lineament appear to be unfractured; if the lineament does represent a fracture then it must be discontinuous or deviate around these outcrops.

3.2 Previous work

Very high resistivities measured with the gradient array reflect the presence both of shallow bedrock and of dry, quartz-rich overburden. A distinctive conductive zone, up to 100 m wide, was also detected, with resistivities of 50-100 ohm m being recorded in the upper part of the sequence using the EM34 equipment. This zone was parallel to the vlei but its axis was offset about 30 m southwest from the lineament, which coincided with the lowest part of the topographic profiles.

The magnetic response was characterised by a set of incoherent, large amplitude anomalies superimposed on a more typically subdued background variation. These short wavelength anomalies could only rarely be correlated between traverses and they were attributed to narrow, intermittent bands of darker minerals within the bedrock. No association was seen between the magnetic response and either the resistivity data or the lineation itself.

VLF data obtained using a portable transmitter proved very effective in detecting the conductivity variations using both the E- and M-field modes of operation, and the results were comparable with those from the gradient array resistivity survey. The EM34 results also picked out the conductive zones and they were especially useful in indicating clearly that much of the response originated from within the uppermost 5 m of the sequence.

The area selected for more detailed investigation and drilling was near line 500SE, 67 m from the existing borehole which had been sited as part of the Basement Aquifer Project.

The geophysical responses were well defined here and the lineament was clearly linked to the margin of a resistive band which lay within the more conductive zone (Fig 3.1). Outcrop occurred about 50 m to the northeast. The centre of the vlei was essentially flat over a distance of 30 m to either side of the baseline and beyond this the ground rose gently, by about 2 m in the next 100 m.

3.3 Borehole results

The drilling plan for Nemarundwe is shown in Fig 3.2. The Nemarundwe site is located on map sheet Makaholi 1930 D4 at approximately [28320 780100]. The fixed ground reference is the existing borehole drilled earlier by BGS and fitted with a handpump.

One cored hole (Site A) is located 10 m to the SW of the grid baseline along line 500SE; it is inclined 30° from the vertical towards 49°M and was designed to pass through the fracture zone. A second inclined, cored hole (Site B) is situated 20 m northwestwards of line 500SE along the baseline and 4 m southwestward of it.

Two 50 m deep vertical air-hammer holes are located 18 m SW (Site 1) and 22 m NE (Site 2) from the baseline on line 500SE. Seven shallow (10 m) vertical holes at 5 m spacing were drilled between Site 1 and Site 2, primarily as detector sites for the seismic tomography work, to assist definition of any steeply dipping anomalies.

3.3.1 *Geological logs*

BH/1 (Site B) - inclined

Location

This hole was sited 11 m to the SW of the lineament and drilled at 30° to the vertical on an azimuth of 49°. The hole was finally abandoned at a down-hole (inclined) depth of 28.77 m (25 m true depth) due to a stuck bit. Though less than the target depth, this should have been sufficient to have intersected a vertical fracture zone corresponding to the photolineament. The log is summarised in Figure 3.3.

Description

0.00 to 2.00 m:	unconsolidated sands and dambo clays (regolith).
2.00 to c.6.50 m:	moderately weathered, yellowish-stained granite with some pegmatite. Recovery generally good and core complete. One or two prominent steep fractures.
c.6.50 to c. 8.50 m:	pegmatite. Generally massive and fresh with only a few fractures.
c. 8.50 to 15.00 m:	medium-grained grey granite. Fairly fresh but with epidote along fissures especially in the upper part of this interval. Rocks essentially unfractured (apart from infrequent epidote-filled, hairline fissures, some steep) and recovery generally high.

by the resistivity data, the effects of weathering must also be considered, particularly in the upper part of the sequence. Unfortunately, because the holes were sited near the lineament it is not possible to completely separate surface weathering effects from primary effects.

3.3.3 *Seismic tomography*

Seismic tomography investigations were undertaken at Nemarundwe with the sparker source in the borehole at Site 1 and with an active hydrophone array in Site 2 borehole. Hydrophones were also located near the bottom of the intervening shallow boreholes and geophones placed on the surface between them. A complete survey was run using a 1 m interval between source locations and a 2 m receiver separation giving the ray-path coverage shown in Figure 2.3.

The tomogram (Fig 3.10) indicated a greater depth of weathering to the southwest of the lineament, with formation velocities generally less than 4.5 m/ms being measured down to about 15 m. To the northeast of the lineament a more competent rock was indicated with seismic velocities exceeding 5.0 m/ms extending from the surface and dipping to the southwest at 40°. This zone is truncated at a depth of 5-10 m, close to the postulated position of the lineament, and appeared to be downthrown by as much as 7 m before continuing to the southwest with the same dip.

Observed velocity variations at Site 2 correspond with fracture indications as observed on the borehole geophysical logs. The main zone of fracturing was over the depth range 15-25 m. The tomogram suggests that these fractures are close to horizontal. No pronounced fracturing is indicated below about 10 m at Site 1, confirming the resistivity log interpretation. No strong, near-vertical feature was imaged between the boreholes, and only the discontinuities in shallow-dipping events provided any indication of the existence of a lineament.

Further analysis of the seismic data was undertaken using the shear (S) wave arrival times. Compressional and shear waves respond to different rock properties and thus complement each other, with the S-wave velocity being particularly sensitive to the presence of fluids. The S-wave data produced a similar image to that of the P-wave tomogram and again suggested a near-vertical discontinuity at about 23.5 m to the southeast of Site 1, with an apparent hade of 3° to the southwest.

A tomogram of Vp/Vs ratios was generated (Fig 3.11) to emphasise variations which might relate to fluid-filled, weathered granite. Typical compressional and shear wave velocities of massive granite (as obtained from a literature search) are 5.75 m/ms and 3.25 m/ms respectively, giving a Vp/Vs ratio of about 1.75-1.8; ratios determined in the present work were generally in the range 1.55-1.64, mainly resulting from S-wave velocities reaching 4 m/ms. Higher ratios occur with increasing porosity (and weathering) while lower values may be caused by quartz.

The Vp/Vs tomogram showed the more weathered granite to occur on the southwest side of the lineament where values were about 1.75; the higher values indicative of fluid-filled fractures correlate with fracture indications in the borehole logs. The shallow, competent bedrock to the northeast of the lineament showed lower values which might represent a higher quartz content. The formation boundaries noted from the individual Vp and Vs tomograms were also apparent.

3.3.4 *Discussion and general implications*

The photolineament at Nemarundwe is typical of many in the region. Its principal expression is as a quasi-linear feature over a distance of about 1 km marked by a minor drainage. Surface evidence of fracturing along the lineament is lacking; where fractures are seen on outcrops in *general proximity* to the lineament, they are mostly planar and are either tightly closed or infilled and sealed by quartz and epidote.

The geological logs for the inclined boreholes (sites A and B) do not convincingly support the existence of a vertical or steep fracture zone, although a 2-3 m wide zone of increased fissuring could be postulated composed of sealed epidote-filled hairline fractures with an apparent hade of 13.5° to 15° to the SW. This is marked by a small reduction in the normal resistivity in the Site A log. There is also a reduction in magnetic susceptibility in core samples from Site A that more-or-less corresponds to the interpreted position of the fracture zone, although this is less evident in the data for Site B. As a potential water-bearing fracture zone it is unimpressive. Nevertheless, in seeking a geological explanation for this lineament, there is perhaps no alternative but to conclude that *where penetrated by the drilling* the related fracture consists of closed, hairline fissures. Whether in other parts of the fracture plane these correspond to open passageways weathered by passage of water can only be surmised.

The northeast increase in resistivity values in boreholes drilled along line 500SE, accompanied by indications of increased fracturing, and the change in magnetic susceptibility down the inclined borehole at Site A, are consistent with a change in rock type more-or-less coincident with the lineament. One possibility is, therefore, that the fracture is actually a fault, juxtaposing granites of slightly different composition. No evidence for such a change in lithology was observed either in outcrop or in the core but it is possible that a minor difference in composition would go unnoticed, particularly where the rocks are weathered. Alternatively, the lower magnetic susceptibility in the upper part of the inclined hole could be explained as a result of the oxidation of magnetite within a uniform rock type. This ambiguity emphasises the problem referred to earlier (Section 1.4) of separating the surface effects of weathering from lateral changes across the lineament in inclined holes.

Despite these uncertainties, the inferred lateral variation in amount of fracturing is important in confirming a structural change across the lineament, at least along this section. Interestingly, the rest water level was consistently at around 5 m in all the vertical holes except Site 1 which was effectively dry. The extremely slow dispersion of the water added to this hole (1 m in 5 days) indicates very low porosity/permeability here; of the three deep holes drilled (Sites 1, 2 and A), only Site 2 in the apparently more massive, fractured rocks to the NE was a good water producer. The tomogram suggests that the zone of fracturing dips to the southwest with a projected intersection at Site 1 of 45-55 m, and it may be, therefore, that the borehole at Site 1 terminated above the zone of productive fracturing.

3.4 Additional geophysical surveys

3.4.1 *Seismic refraction*

Measurements were recorded from three spreads on line 502SE, from 63SW to 75NE, with a constant geophone separation of 2 m. Detailed shot point coverage, also at 2 m intervals, was obtained from the central spread.

Only one refractor is readily identified over the line as a whole, with a velocity of 4.5-6 m/ms. While the higher values are typical of massive, granitic bedrock, velocities of <5 m/ms suggest that some fracturing is present. The interpretation (see Fig 3.12) shows

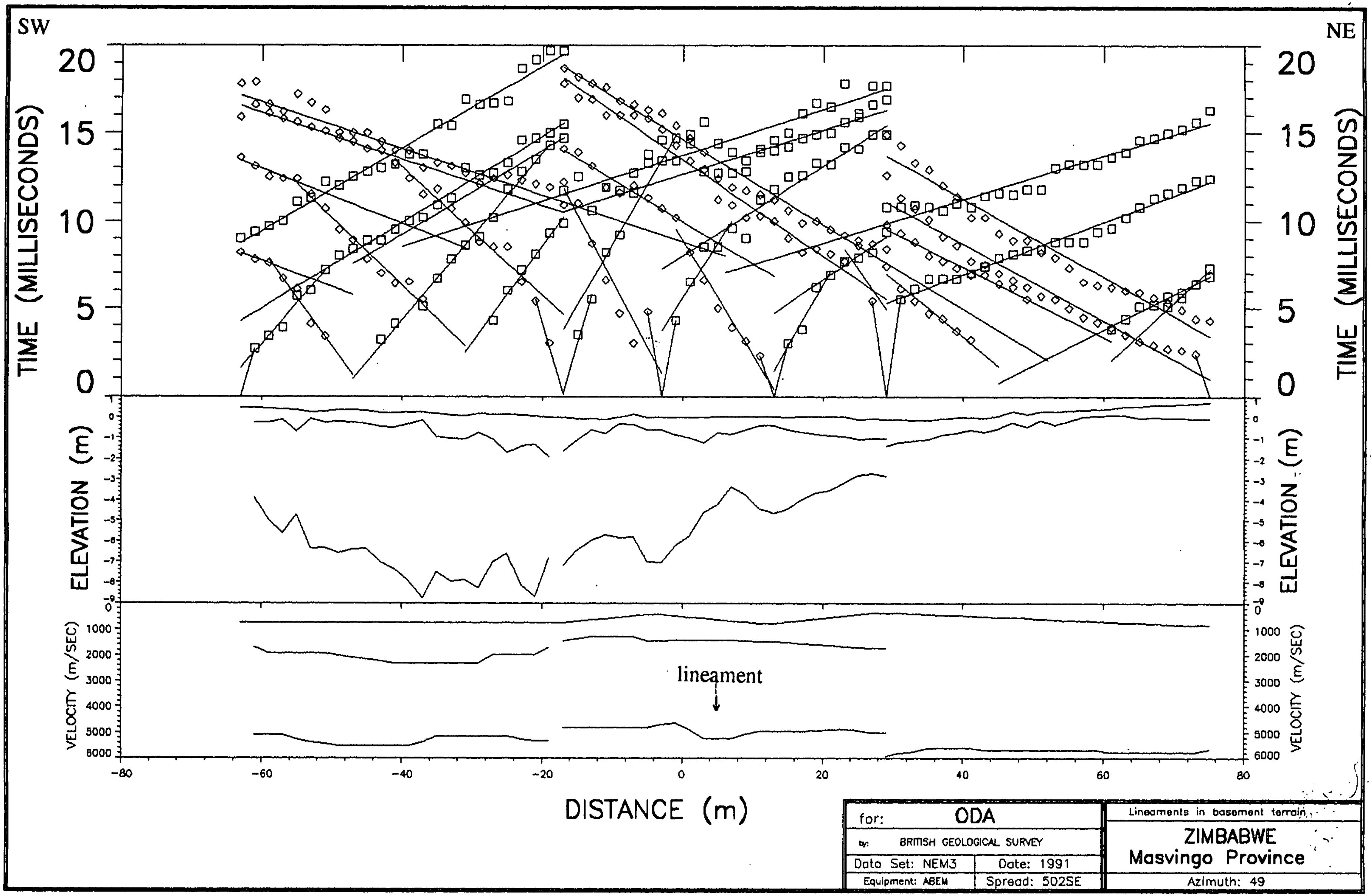


Figure 3.12 Seismic refraction data and model from Line 502SE

the depth to bedrock increasing from 0.5-1 m over most of the northeastern spread, to average about 5 m beneath the central spread. It remains near this level to the southwest with undulations of +/-1 m. Velocities within the overburden were 0.3-1.2 m/ms although uncertainties in the zero time will affect these values and they will tend to be systematically too low.

It was possible to identify an intermediate layer over most of the southwestern spread and the interpreted velocities of around 2 m/ms are compatible with saprolite. Its presence was more speculative on the central spread but it seems likely that the layer does continues to the northeast before becoming too thin to be resolved; the apparent disappearance of this layer at the join of two spreads is largely coincidental, given that the shot point coverage is less good here. The existence of thin bands of more compact material within the overburden is suggested by phase reversals in the first arrivals and impersistent indications of high velocity layers, leading to ambiguity in picking the correct times.

While the overall form of the bedrock surface is consistent with the resistivity interpretation (see below), there is little obvious expression of the conductive zones in the seismic data apart from a distinct reduction in the near-surface velocity near 30NE. This again suggests that the effects are confined to the weathering profile with no wide zones of fracturing extending through the bedrock. The relatively small change in the proportion of clays in the overburden needed to account for the variations in conductivity would have much less effect on the seismic velocities.

3.4.2 *Resistivity*

Surface resistivity data were collected in the form of a detailed dipole-dipole pseudosection. This provided coverage from 90NE to 95SW along line 502SE (displaced slightly to avoid disturbance from the effects of drilling). The dipole length was 5 m and measurements were taken to a dipole separation of 40 m (n=1 to 8).

The pseudosection (Fig 3.13) conveys the sense of a central conductive zone flanked by resistive material, more so to the northeast than to the southwest. The form of the apparent resistivity contours cannot be related directly to a true section through the ground but it is possible to simulate numerically the 2D resistivity distribution that would reproduce the field data. Computer modelling confirms that most of the detailed variation seen in the pseudosection originates from small-scale changes within 2-3 m of the surface (Figs 3.13-14). The deeper part of the model is less well constrained but there is good evidence that the more massive bedrock dips down to the southwest from near-outcrop (at c. 50NE) to a depth of about 10 m beneath the main conductive zone.

A narrow zone of more resistive material coincides with the lineament itself (near 8NE) and a similar feature occurs 13-15 m further southwest beneath thin cover. These resistive bands probably represent less weathered material and may be associated with quartz veins, although these were not seen specifically at surface here. The main low resistivity zone, probably reflecting a clay-rich pocket, 5 m thick over a width of 10 m, is adjacent to the southwesterly 'vein', while a thinner clay-rich layer occurs to the northeast of the lineament where the bedrock is shallower. The bedrock appears to rise more slowly to the southwest. However, this may reflect a change in mineralogy or in the degree of microfracturing, such that the bulk resistivity of what is still in effect massive rock is lower than that on the northeast flank of the vlei.

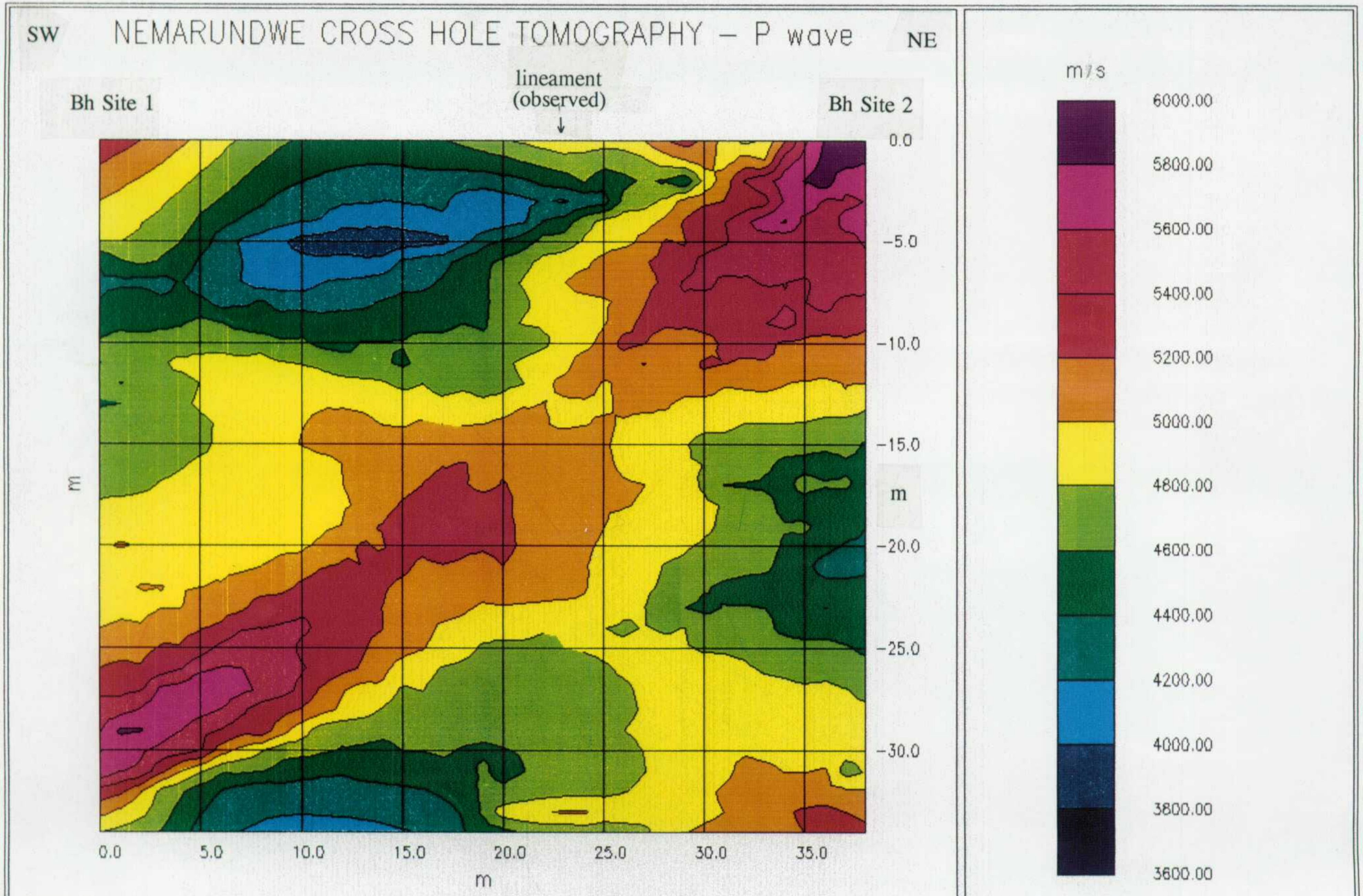


Figure 3.10 P-wave tomogram between Sites 1 and 2

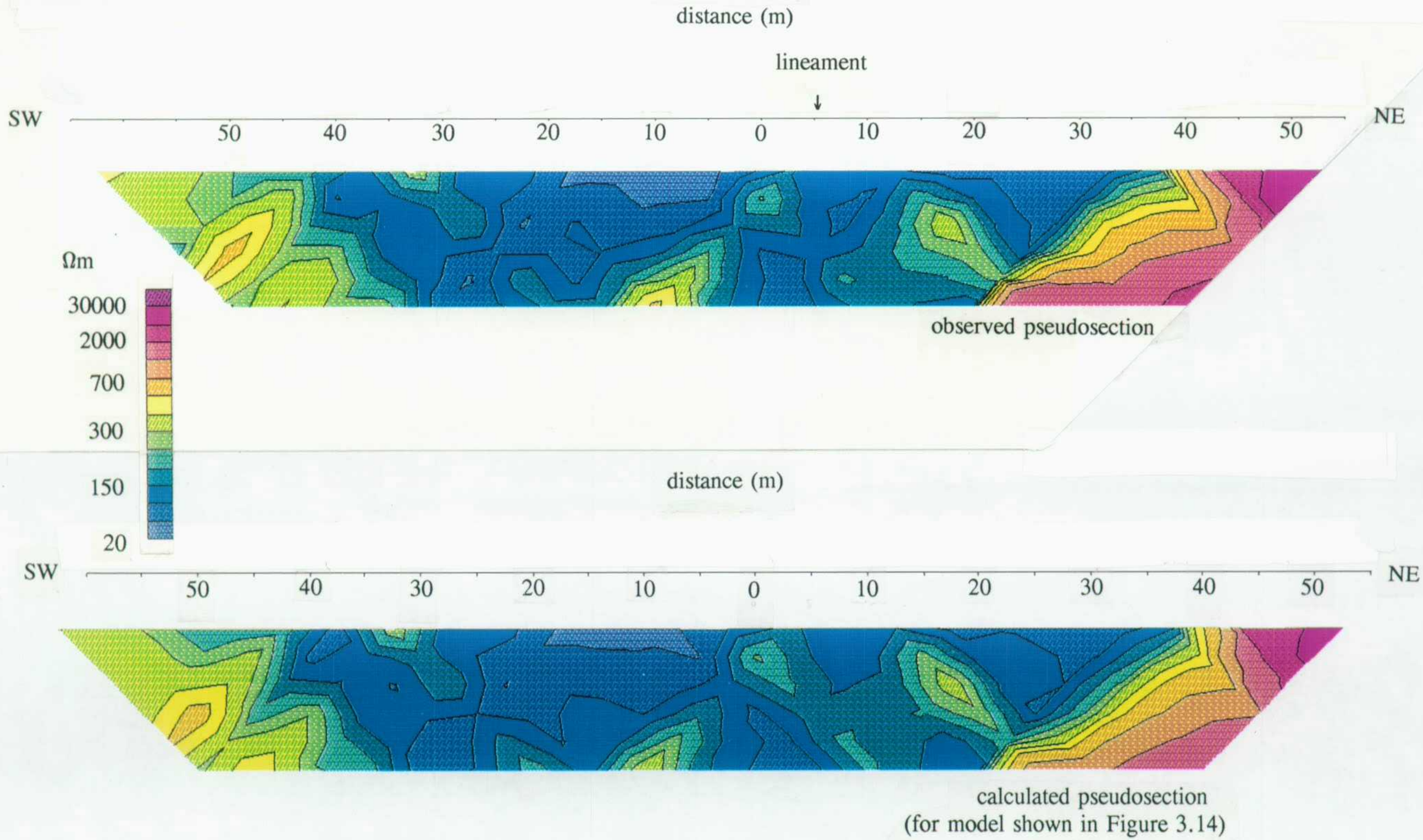


Figure 3.13 Observed and calculated resistivity pseudosections: Line 502SE

LOCATION: NEMARUNDWE - grid 1; line 502SE

Resistivity model as diagrammatic vertical section:

Dipole length = 5 m

Resisitivity code:	1	2	3	4	5	6	7
Resistivity value (ohm.m):	30	100	300	1500	4000	20000	60000

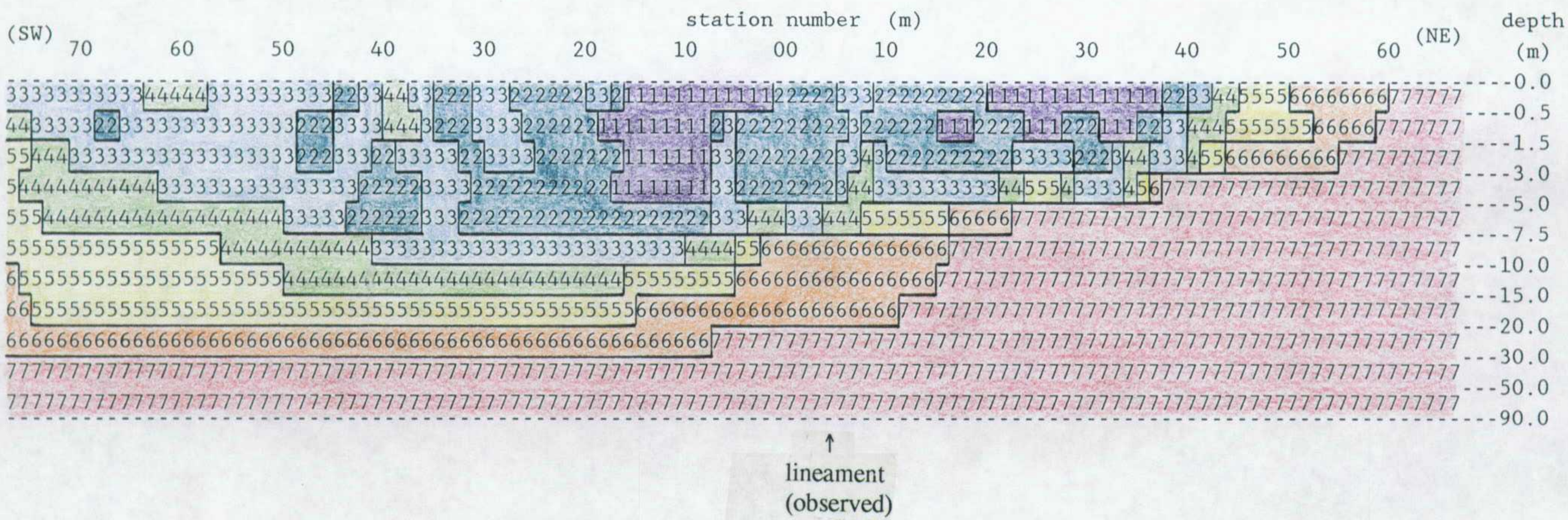


Figure 3.14 Resistivity model derived from dipole-dipole data for Line 502SE

3.4.3 *EM*

A detailed set of EM34 data was collected on three traverses, 300 m long and 30 m apart, centred on line 502SE (Fig 3.15). A station interval of 5 m was used at each of the three coil separations in order to provide good control on the anomaly pattern. The slight, but consistent, negative bias seen most clearly at the 20 m coil separation indicates that the instrument was not accurately calibrated for high resistivity measurements but this can be allowed for in any quantitative analysis of the results.

The profiles for the 10 m vertical coil configuration show the best definition of the near-surface variations. Maximum conductivities increase to the southeast, from 5 mmhos m on profile 472SE to 14 mmhos m (i.e. a reduction in resistivity from 200 ohm.m to 70 ohm.m) on line 532SE, but the broad conductive channel is clearly apparent on all three profiles. The anomaly amplitude decreases rapidly as the coil separation increases and it is barely detectable at the 40 m spacing. With the horizontal coil configuration, the profiles have a noisier appearance over the conductive zone. These variations almost certainly reflect lateral conductivity contrasts within the ground as the results are well controlled and do not represent isolated readings which might be considered suspect.

The two principal EM anomaly minima seen on line 502SE (Fig 3.16), at 10-15SW and 30NE, coincide with the clay-rich zones identified from the dipole-dipole modelling. Anomalies of this type are characteristic of the response given by narrow, steeply-dipping conductors but the weak response given at the 40 m coil separation suggests the effect is largely restricted to the near-surface here. The differences between the vertical and horizontal coil response are not compatible with a simple layered earth interpretation and some abrupt lateral discontinuities must be present. The smoothness of the profiles away from the conductive zone confirms the reliability of the data themselves.

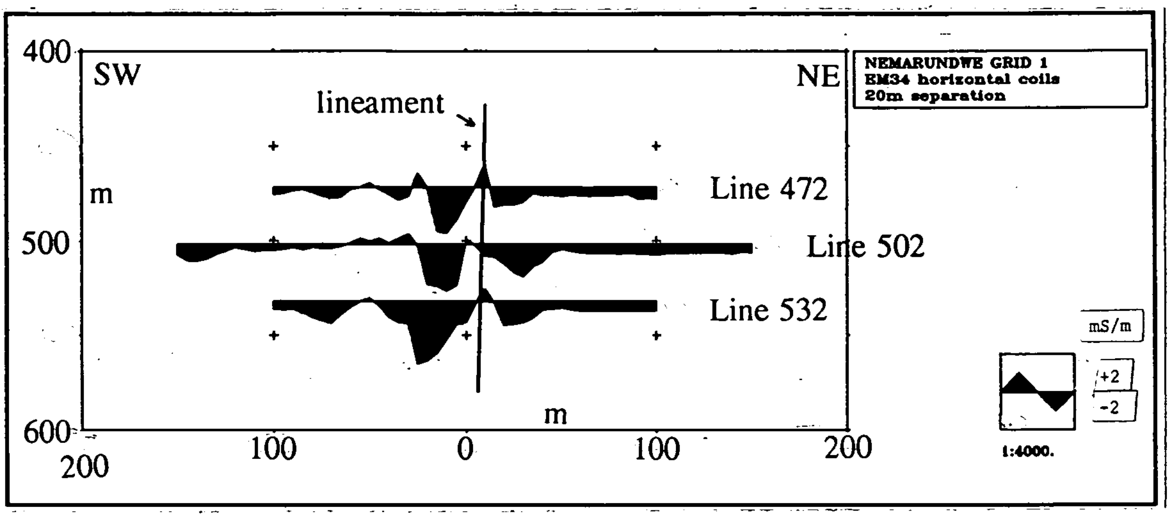
3.4.4 *Magnetic susceptibility*

Typical 'fresh' granites returned in situ Kappameter values (10^{-3} SI units) in the range 0.3-2.3, with some sugary, aplitic-looking rocks near 100NE on Line 1000SE as high as 5. The magnetic susceptibility of the finer grained (and typically darker) varieties of granite was generally higher. It is also noteworthy that in several instances the dark (weathered?) outer surface of a specimen returned higher readings (by a factor of up to 2) than its interior, but this may reflect partly the geometry of the tested surface. Pegmatitic material gave uniformly low readings, of the order 0.04.

Eight samples displaying a range of susceptibilities were taken from the vicinity of Line 900S at Nemarundwe and submitted to the Mineralogy and Petrology Group (BGS) for semi-quantitative determination of magnetic (opaque) minerals by Kontron analysis of thin sections. Kappameter readings (the average of eight per sample) ranged between 0.45 and 3.6 while the determined volume percentages of opaque minerals varied from 0.65 to 1.86. These two sets of values showed a direct correlation in general over their rather limited ranges, with the exception of the sample displaying the lowest susceptibility value which yielded the highest content of opaques. Serious limitations of this experiment are that not all opaques are magnetic and that the extension from a 2D observation on a single thin section to volume percent may not be valid.

Further susceptibility measurements were made on granite outcrops in the narrow course of the Munyambi River, at the road crossing approximately 1 km W of Nemarundwe. This drainage comprises lengthy straight NNW-trending sections and is apparently fault controlled. The measured susceptibilities suggest the presence of two distinct granites, with higher

EM34 20m horizontal coil



EM34 20m vertical coil

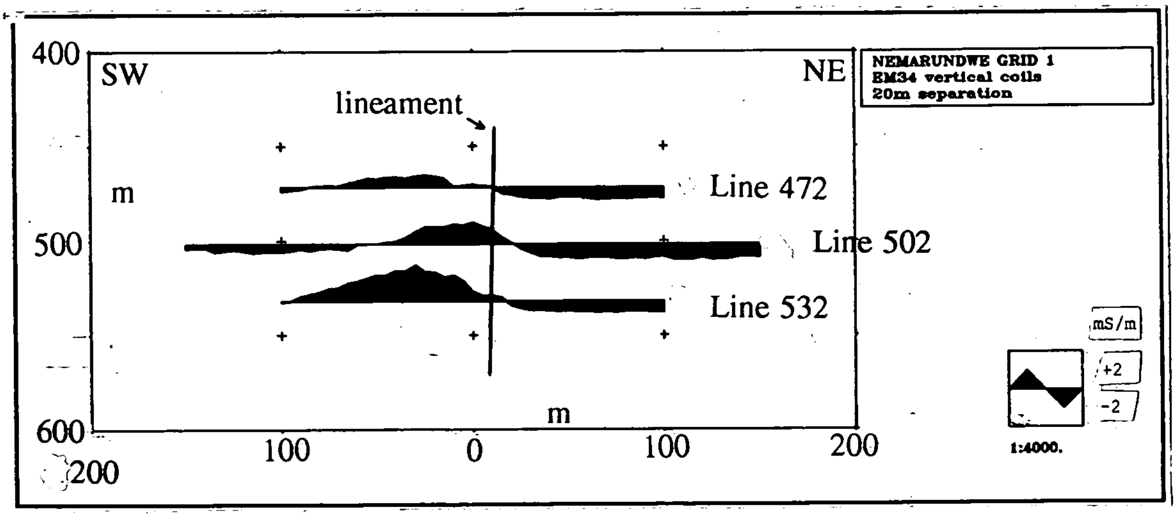


Figure 3.15 Stacked EM34 profile data at 20m coil separation

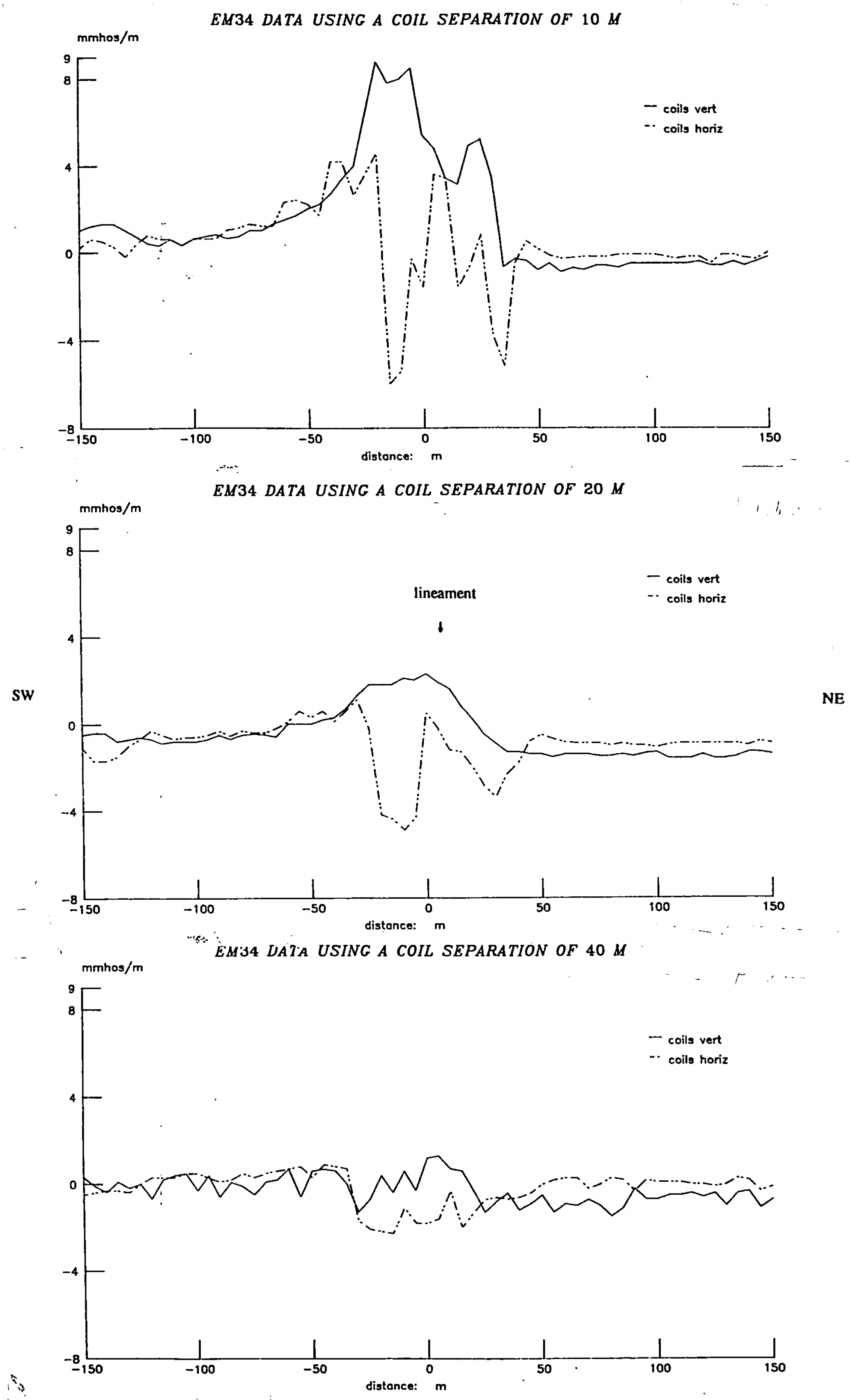


Figure 3.16 EM34 profile data from Line 502SE (various separations)

average values (of 3.6) to the east compared with 2.3 to the west. Thus, the magnetic data support the idea that two distinct granitic phases are juxtaposed here.

3.5 Synthesis and conclusions

The lineament at Nemarundwe was geomorphologically less well defined than at the other two sites, being in an area of more subdued topography. Previous geophysical investigations provided some evidence of an anomalous conductive zone within the vlei but a borehole drilled here and fitted with a handpump produced only a low yield and there was no evidence of significant fracturing.

Subsequent studies confirmed the existence of geophysical anomalies following the course of the vlei and its associated lineament. These could be explained largely in terms of superficial sources and it was not possible to identify a site along the lineament which would have been recommended for drilling for water-supply purposes. However, the borehole at Site 2 did appear to be a good water producer and it was recommended (to the MEWRD) that a handpump be fitted at the conclusion of the field programme.

Core drilling on the photolineament confirmed the unpromising geophysical interpretation in so far that no evidence of productive open fractures was found. A possible increase in the intensity of small-scale fissuring and quartz veining suggests that the lineament follows a narrow but extensive fracture system which has acted as a focal point for local weathering.

In the absence of any distinctive findings it is difficult to know how much weight to attach to specific observations. The shallow weathering profile did clearly show a southwesterly increase in thickness from near outcrop northeast of the lineament, and much of the geophysical response was dominated by this. Borehole logging data did show the presence of fracturing which was partially imaged using seismic tomography, mainly in terms of shallow-dipping zones with a near-vertical discontinuity in the latter linked to the lineament. While some doubt remains as to whether the cored borehole did intersect the main feature associated with the lineament, it is clear that no major zone of weakness is present here.

4. RESULTS FROM NANWI

4.1 Background

Nanwi lies about four kilometres south of Nemarundwe and shares a similar geology, the rocks being shown on the 1:1,000,000 geological map as forming part of the Younger Granites. Outcrops are of gneissic granite, quite strongly fractured and, as at Nemarundwe, veined by several generations of quartz and pegmatites.

The lineament is located to the west of the school, trends N162°E, and is traceable on the aerial photograph for about 1 km. It again occurs at the centre of a fairly shallow, broad vlei which is apparently only thinly covered by regolith as indicated by the scattered distribution of outcrop. It is marked by dark soil tones and a seasonal drainage line lies along its centre. The site is of particular interest since at one point outcrop constrains the fracture dimensions to a zone about 2 m wide. When first visited in the dry season this location was the site of a natural spring used by the local women as a source of drinking water and a washing pool. Its existence suggests that the fracture is open and acts as a passageway for groundwater at this point. The granitic outcrops on either side exhibit a series of parallel, closely-spaced, near-vertical, quartz-filled, narrow fractures, trending about N150°E. It seems probable that a concentration of these filled fractures, in part weathered to form an open conduit, make up the lineament at this point.

4.2 Previous work

An inclined hole, and a subsequent vertical borehole, drilled by BGS at this site during the final phase of the Basement Aquifer Study, both gave a good yield and the latter was equipped to provide the main supply for the nearby school. An inclined borehole, drilled westwards at an angle of 30° to the vertical from a location 2 m to the east of the lineament, and a radon high to the west, were interpreted to indicate a fracture zone dipping steeply westwards. An alternative interpretation of the water strikes in these two holes is that they penetrated near-horizontal fractures at true depths of 13 m and 18 m. Doubts as to the long-term viability of the equipped hole (given that the regolith is very thin and that the borehole encountered essentially fresh, if fractured rock) proved unfounded. It appears that either fractures tap into the storage of more weathered ground around the site, or the fracture system is sufficiently extensive and transmissive in itself.

Subsequent geophysical measurements were taken on two small grids, separated by about 700 m, in order to investigate the change in response as the lineament passed from its tightly constrained expression near the school into more open ground where a second productive borehole had been sited. A distinctive difference was in fact revealed in the conductivity sections, with the resistivity values being much reduced in the upper part of the sequence throughout most of the second grid, particularly in its western part. This contrast could be explained by the change in near-surface conditions - exposed rock being seen in grid 1 and some cultivated ground occurring within grid 2. The absence of any evidence of shallow bedrock near the lineament on grid 2 may reflect the influence of cross-cutting features seen on the aerial photographs.

Four azimuthal resistivity soundings near the centre of grid 2 differentiated a 3-4 layer sequence above a highly resistive substrate:

- a resistive surface layer, 300-500 ohm.m to 0.5 m;
- a transitional zone, 100-150 ohm.m to 1 m;
- a conductive zone, 30-45 ohm.m to 2.5-4 m;
- a zone of intermediate resistivity, 100-200 ohm.m to 7.5-10 m.

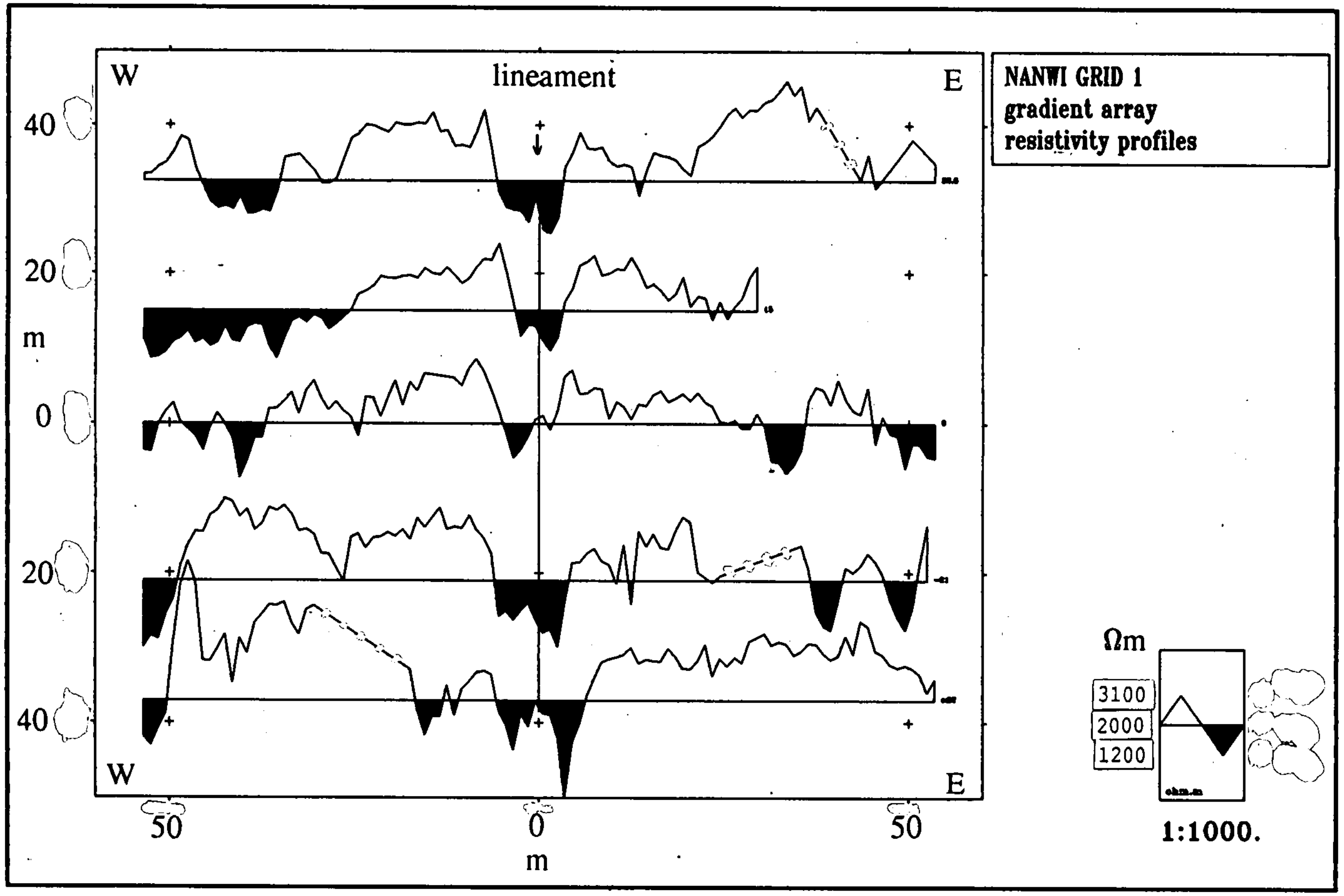


Figure 4.1 Nanwi: gradient array resistivity data covering borehole sites

The upper transitional zone was the least clearly defined. A thicker development of the conductive layer would be predicted on the western side of grid 2 while on parts of grid 1 this layer is much attenuated and even absent or not resolvable from the resistive zone above it.

Gradient array data from grid 1 were not continuous because of the outcropping rock, but the coverage was good enough to pick out a distinctive zone of reduced resistivity coinciding with the lineament/vlei (Fig 4.1). While other lows of similar amplitude were recorded elsewhere on this grid, the same degree of continuity across the grid was not apparent.

A single EM34 profile at a 10 m coil separation on grid 1 provided no evidence of a steeply dipping conductor beneath the vlei; previous results at the wider coil separations were similarly subdued with only one point suggesting a weak negative anomaly with the coils horizontal. Vertical coil conductivities did increase from <1 mmho/m to 2-3 mmho/m upslope towards the school without indicating any significant thickening of the saprolite.

4.3 Borehole results

The drilling plan for Nanwi is shown in Fig 4.2. The site is located on map sheet Makaholi 1930 D4 at approximately 28200/779680. All holes lie on, or close to, line 00. The main reference point is the borehole fitted with a hand pump near to the former washing pool. The baseline runs through this point on a bearing 172°M. Line 00 is 86.4 m southwards of this borehole along the baseline. A 30° inclined hole (on bearing 82°M), drilled to obtain core through the fracture zone, is located 5 m westwards from the baseline along line 00 and 2 m northwards of it (Site C). Two 50 m vertical holes were drilled: Site 1 is 10 m west of the baseline on line 00 and Site 2 is 23.8 m east and just to the north of line 00. (It was later recommended to the MEWRD that this hole be fitted with a handpump). Four shallow (10 m deep) vertical holes were drilled between Sites 1 and 2.

4.3.1 *Geological logs*

BH/3 (Site C) - inclined

Location

Hole collared 5 m to west of the lineament and inclined 30° to vertical on a bearing of 82°. The hole was drilled to an inclined depth of 30 m (approx 26 m vertical). The main rock type is a medium grained granite injected by occasional pegmatite especially near the bottom of the hole.

Description

0.00 to 2.40 m:	unconsolidated granite sands (regolith) encountered.
2.40 m to 5.80 m:	recovery of strongly weathered, yellowish granite. Losses moderate over this interval (80% recovery) and strong fracturing not evident.
5.80 m to 8.15 m:	rocks less obviously weathered but the presence of epidote is more conspicuous. The degree of fracturing/fissuring/ veining starts to increase at about 5.50 m.

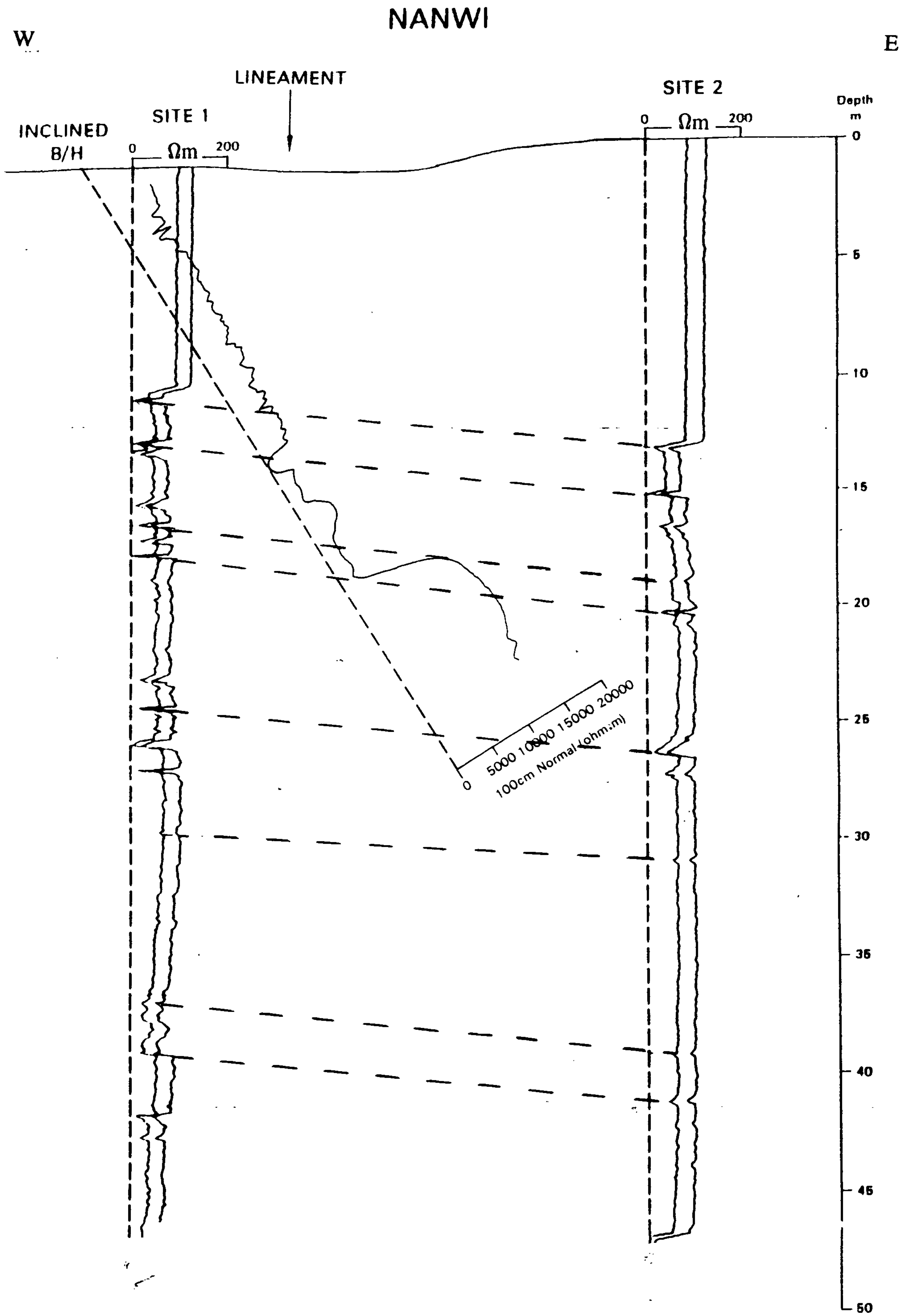


Figure 4.4 Comparison of resistivity logs between Sites 1, C and 2

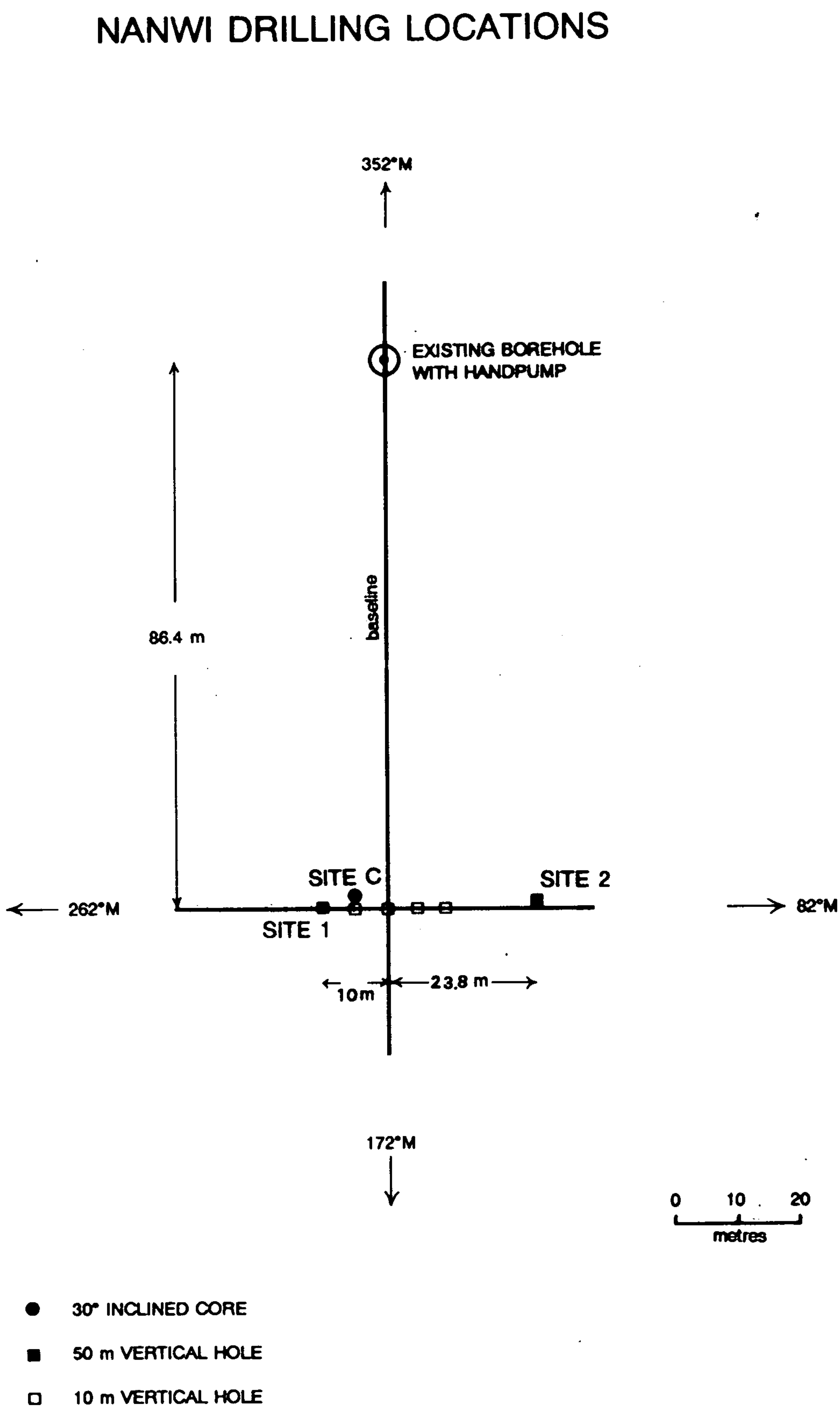


Figure 4.2 Nanwi: drilling site plan

BH/3 NANWI INCLINED (SITE C)
SUMMARY GEOLOGICAL LOG

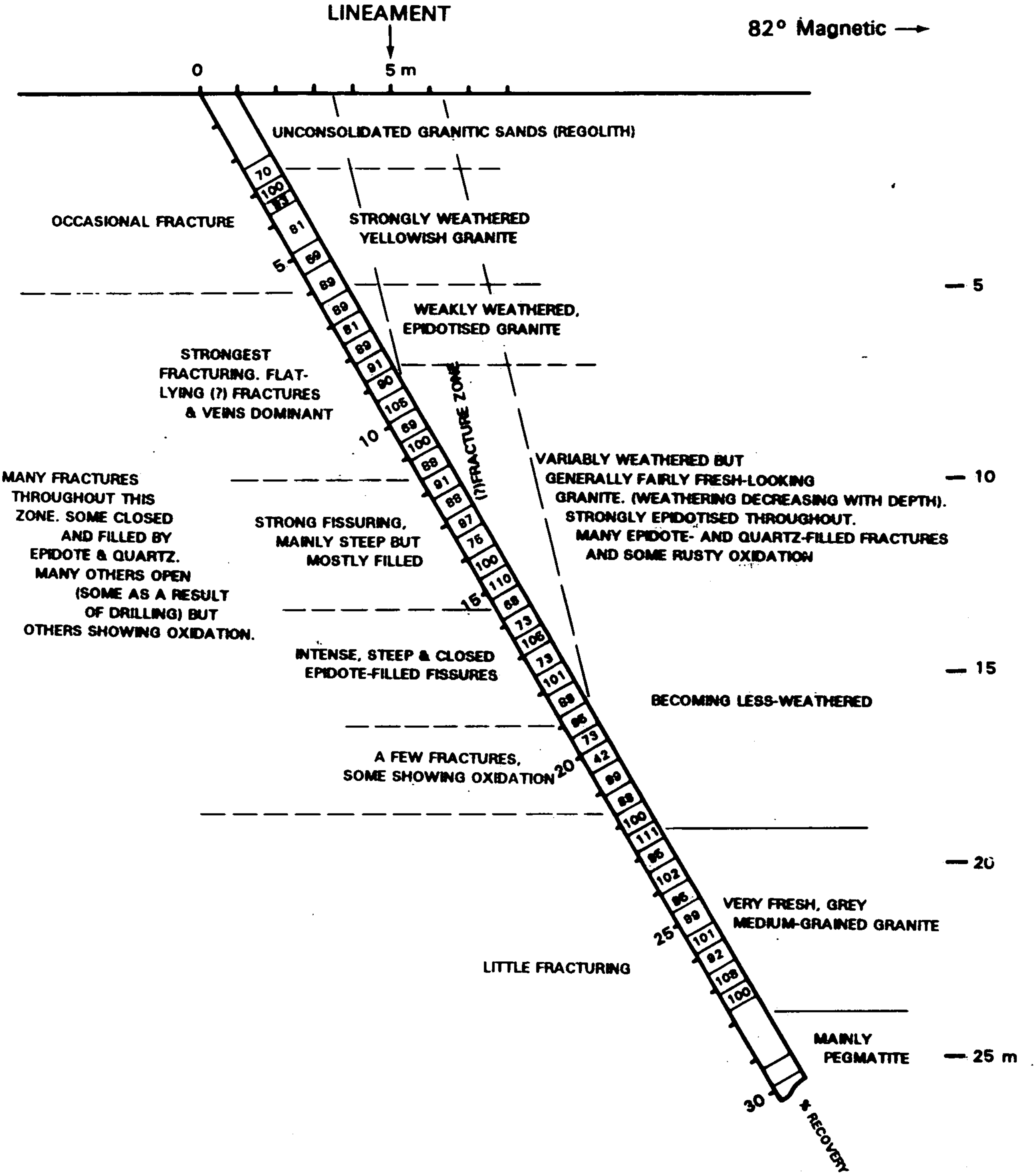


Figure 4.3 Summary geological log from Site C

8.15 m to about 22 m:	the rocks are variably weathered but are generally fresh-looking granites, becoming less weathered in the lower part of this interval. They are strongly epidotised throughout, often in the form of fissure infillings. Much of this is in the form of filled (sealed) narrow fractures (veins) some of which are partially open and show associated oxidation (rusty staining) suggesting groundwater circulation. Many of the filled fractures were split open as a consequence of coring but some of these may have been open in situ. The sealed fractures are filled with greenish, fine-grained quartz, probably rich in epidote and possibly chlorite or other minerals; this material is similar in appearance to that seen filling steep veins parallelling the lineament in adjacent outcrop. (These are probably an expression of the same fracture zone at depth). Fissuring extends throughout this zone and is fairly abundant. Within this interval the strongest fracturing occurs from about 7.50 m to 11.50 m. From about 16.50 m to 22 m there are still many filled fractures but fewer of them are open.
Below about 22 m:	the rocks are fresh-looking granites with minor epidote and little fracturing/fissuring/veining.

Interpretation

A difficulty with any interpretation is the lack of unambiguous evidence for the dip of the fractures; because the core was not orientated, the inclination of each observed fracture can be interpreted in a range varying between plus-or-minus 30° of its angle with the direction of coring. A possible scenario is that fractures that make an acute intersection with the core axis are most likely to be steep while those fractures which make a larger intersection are more probably more flat-lying. Using this approach, most of the fractures would fall into the latter category.

The total fracturing observed between inclined depths of about 5.50 m and 22.00 m could be explained in terms of a vertical zone of filled and open parallel fissures some 8 m wide (see Fig 4.3). Within this interval various sub-zones could be interpreted representing fracturing of different intensity and openness. A region of more intense fracturing some 2 m wide linking with the surface lineament could be postulated, but this is not located centrally within the overall zone of fracturing

If only the steeper fractures are considered there is seen to be a majority that have an apparent hade of around 30° (rather than being truly vertical). Taking just these, the above conclusions regarding intensity of fracturing as related to a steep fracture zone do not hold. Nor is there a great deal of correlation between these steep fractures and the resistivity logs.

If the geological log of recorded fractures is plotted, separating as far as possible probably-steep from probably-sub-horizontal veins and fissures, a different picture emerges. Flat-lying structures are dominant from about 6 m to 11 m (but are well represented down to 16 m) whereas steep structures occur from about 12 m to 19 m. This could be interpreted as a mainly surface-parallel set in the upper part of the hole and a steep set at greater depth. The steep set (if correlated with the surface lineament) would indicate a zone less than 3 m wide hading 11° eastwards. This would be the preferred interpretation based on the geological evidence.

In either case, it is clear that just below 20 m inclined depth the hole passes from a zone of weathering and veining into fairly fresh, unveined/unfractured granite. Although it is impossible to completely separate vertical from lateral variations in the inclined hole, this change to fresh, massive granite supports the idea that the hole passed through a (steep) fracture zone of some sort. Furthermore, we can say something about the nature of this zone: that it consists of fairly strongly veined, fissured and broken rocks in which some of the structures show evidence of water circulation (i.e. oxidation). The horizontal fracturing may be an element of the zone but seems more likely to be largely a function of depth (unloading). No single, large, steep fracture is present but instead the lineament corresponds to a zone several metres wide comprising numerous filled fissures. This would account for the terrain expression of the lineament without necessarily implying a major groundwater conduit. If, however, as the surface evidence and the successful drilling of two boreholes suggest, the structure does act as a water-bearing conduit, it seems reasonable to conclude that channels are only weathered open along restricted, interconnected pathways within the zone as a whole.

4.3.2 *Geophysical logs*

Geophysical logging was undertaken at Site 1, Site 2, inclined borehole site C and the four shallow hydrophone boreholes. Each vertical borehole was logged with micro-resisitivity and the two deep boreholes additionally with caliper and normal resistivity. The small drilled diameter of the inclined borehole meant that only normal resistivity logs could be run. Standing water levels across the site were generally within 3 m of the surface.

Micro-resistivity logging within the hydrophone boreholes did not indicate any marked change across the lineament, although the formations appeared to be strongly fractured. Both the inclined and deep boreholes also showed zones comprising a series of discrete fractures (Fig 4.4). The micro-resistivity logs from Sites 1 and 2 show good correlation, more particularly within 30 m of the surface, and it is postulated that sub-horizontal fracturing extends across the lineament. It is interesting to note that the well-developed responses between 10 m and 20 m are at similar depths to the main water strikes in the boreholes drilled previously to the north (Section 4.2). These fractures were almost certainly not drilling-induced as comparison of the resistivity logs suggests that they extend some distance into the formation (Fig 4.5). Uncorrelated resistivity lows may represent either steeply-dipping or discontinuous, flat-lying fractures (bearing in mind that the log response does not of itself differentiate between shallow and steep dips).

The normal resistivity log of the inclined borehole (Fig 4.6a) was generally consistent both with the material seen in the core and with the logs from the vertical boreholes; resistivity values in the massive bedrock were about 15000 ohm.m. The similarity of the resistivity logs across the lineament suggests that there is no marked change in formation mineralogy, and that the photolineament is directly related to the fracturing.

Analysis of rock samples from the inclined borehole showed little variation in grain density, while magnetic susceptibility values were generally low (Fig 4.6b) with values less than 0.5×10^{-3} SI. The sample from 24 m showed an anomalously high value of magnetic susceptibility (4.5×10^{-3} SI).

4.3.3 *Seismic tomography*

Seismic crosshole tomographic studies were undertaken with the sparker source located in Site 1 and the active hydrophone array located within the Site 2 borehole; additional control was provided by hydrophones in the intervening shallow boreholes.

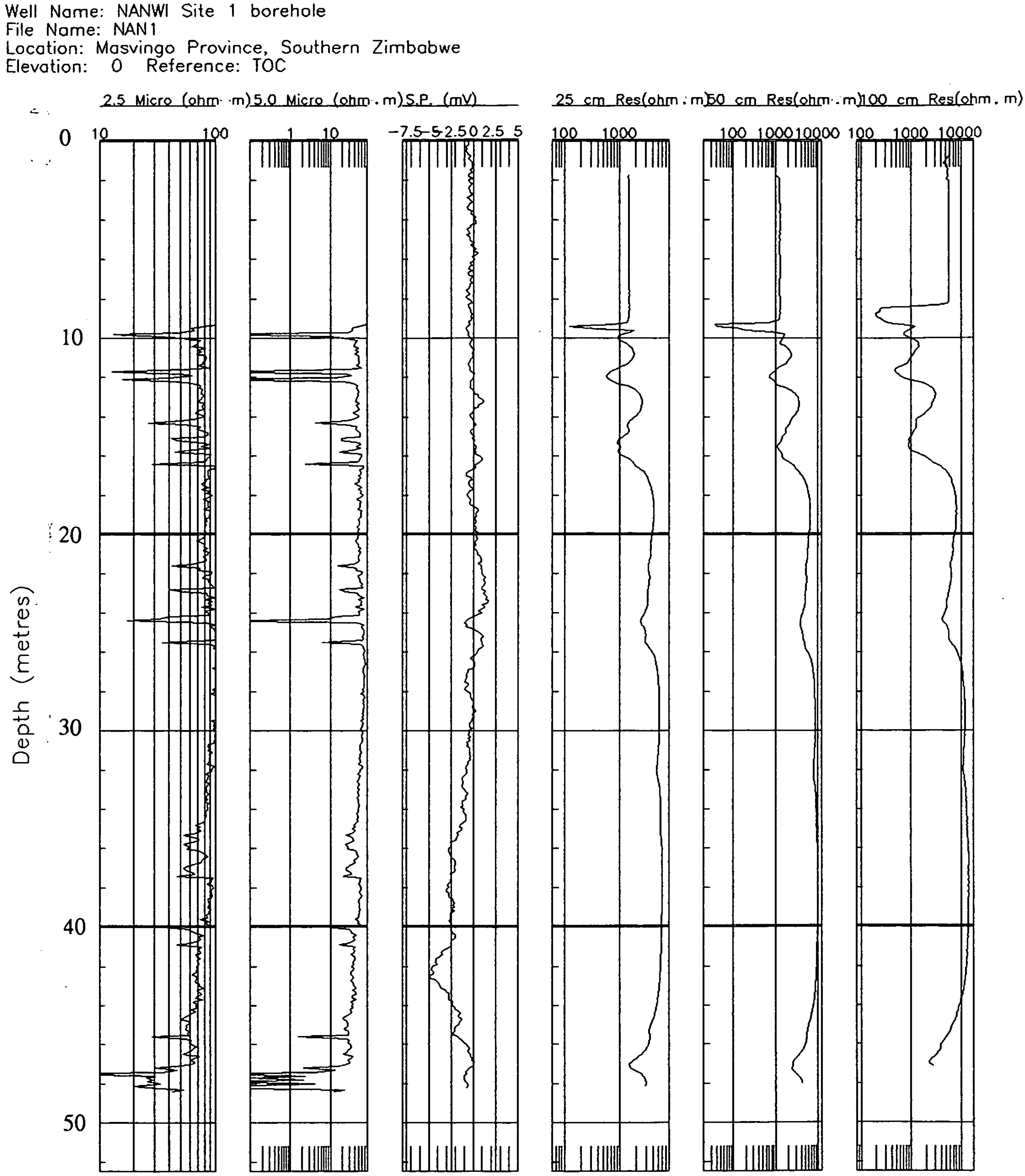


Figure 4.5 Comparison of geophysical borehole logs from Site 1

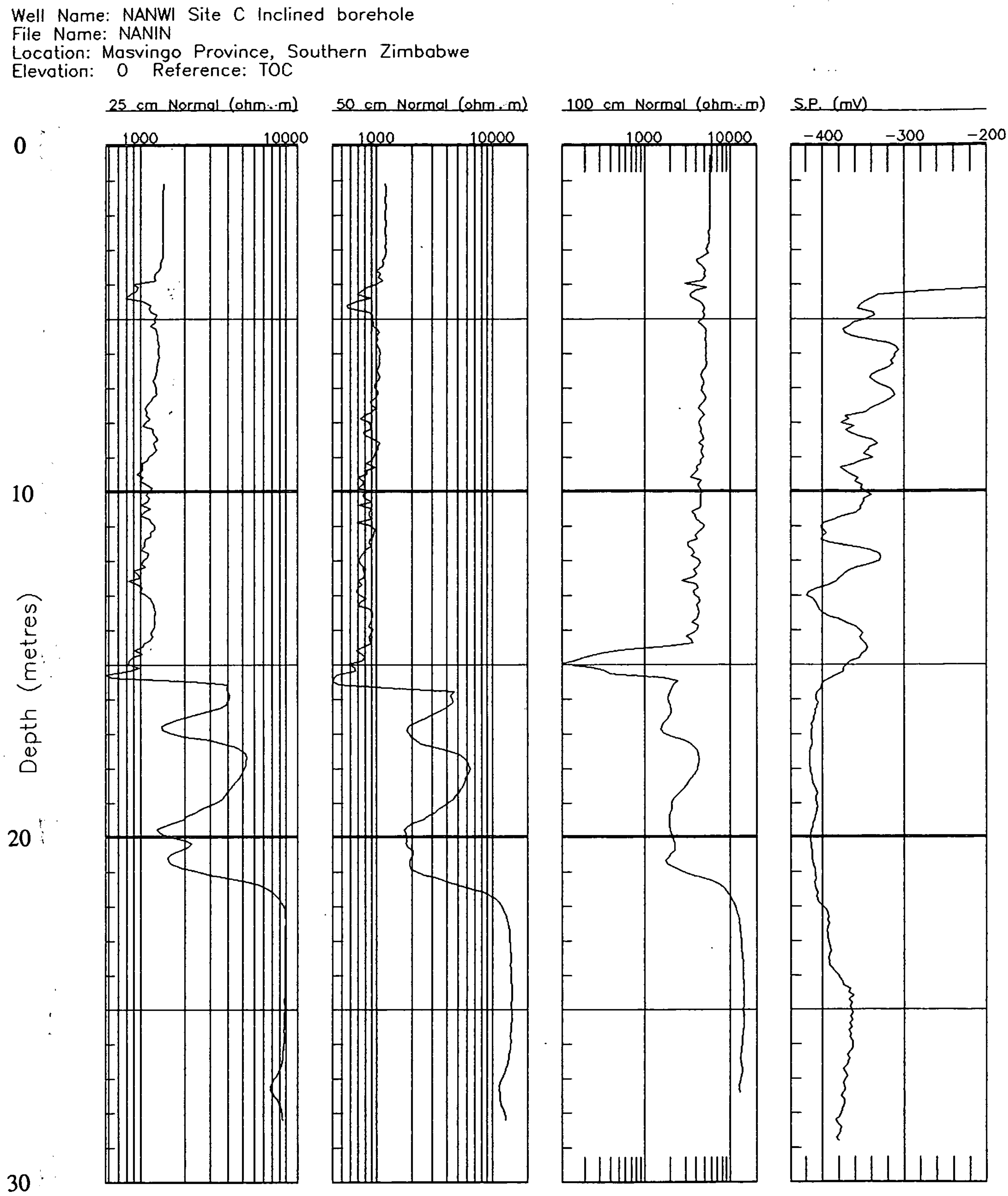
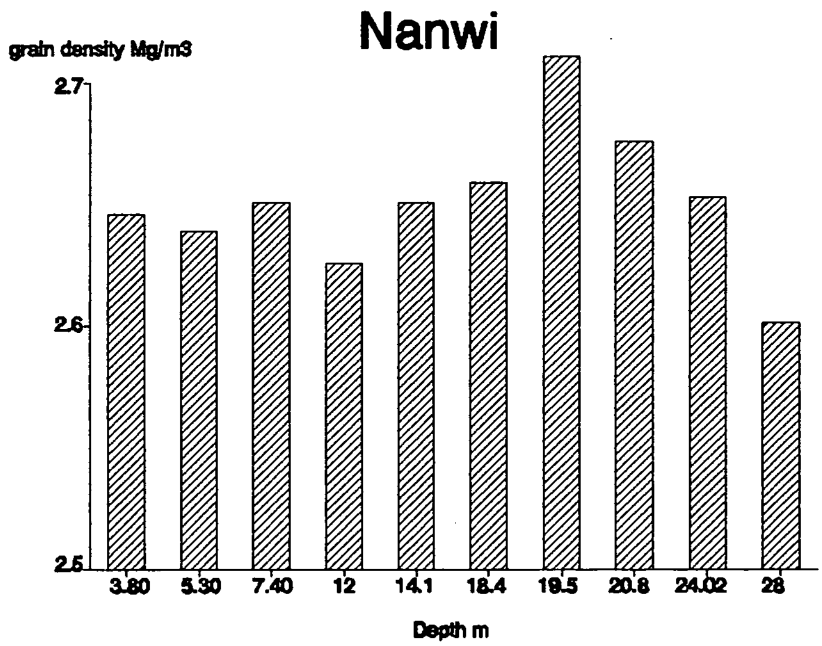


Figure 4.6 (a) Geophysical results from Site C: resistivity logs



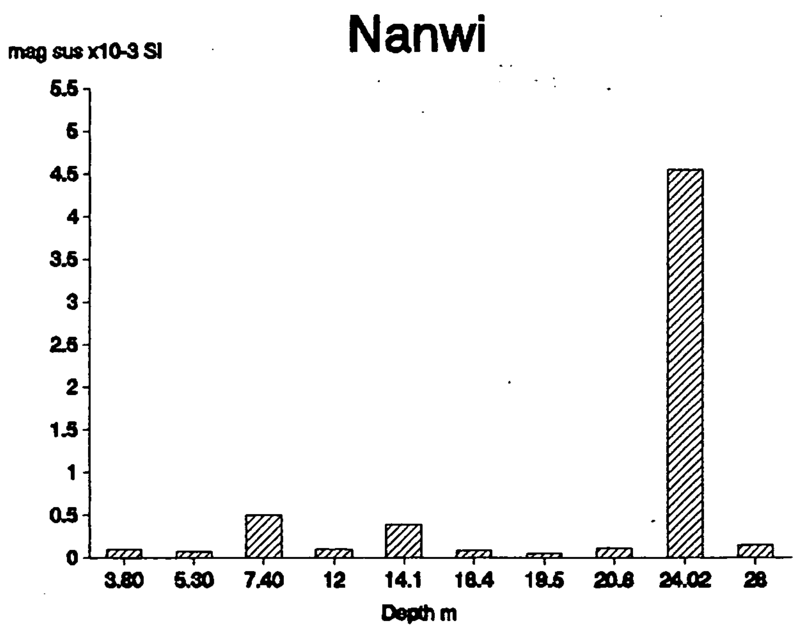


Figure 4.6 (b) Geophysical results from Site C: physical property data

Typical tomogram velocities of 4.3-4.7 m/ms (Fig 4.7) are representative of jointed bedrock and the values exceeding 5.0 m/ms expected from fresh, massive rock were attained only locally. Sub-horizontal features dominate the tomogram although no low velocity zones were resolved intersecting Site 2. There are, also, more subtle indications of a lack of continuity along these events which are thought to be significant; thus, the break approximately 17 m to the east of Site 1 is interpreted as a steep to vertical feature although it is somewhat removed from the inferred position of the lineament itself (mapped as 10-12 m from Site 1).

The difference between the responses close to the deep boreholes reflects the change in resolution resulting from the ray path geometry (Fig 2.3) rather than any lateral variation within the rock mass. Ideally, both source and receiver intervals would have been reduced to 0.5 m to provide additional detail but at the time of the survey it was expected that the main target would be on a larger scale. Comparison of the tomogram with the micro-resistivity logs (Fig 4.7) confirms the predominance of flat-lying trends but also reveals that fracture responses in the latter correspond to both high and low velocity zones. The reason for this is not clear. It does not appear to be explained entirely by the difference in resolution as the 100 cm normal log (Fig 4.5) shows a similar discrepancy. One possibility is that some tight fractures have a lining of conductive clays; alternatively, more steeply-dipping fractures, which are less easily detected by tomography, may be present. Further studies are required to determine whether the combination of low resistivity and low velocity does represent the more open fractures.

4.3.4 *Discussion and general implications*

Normal resistivity logs from the inclined borehole show a good measure of correlation with the *general* changes noted above. From 3 m to about 14 m the response is even but shows many troughs assumed to represent fractures; however, it is difficult to correlate individual resistivity responses to observed fractures in the core and this increases the suspicion that the most important fractures result in core losses and are poorly sampled geologically. The resistivity response is essentially similar between 14 m and 21 m but with fewer lows, correlating possibly with the observation of fewer open fractures here. Below 21 m the resistivity rises sharply correlating with fresh, unweathered and unfractured granite.

The normal resistivity logs correlate well in general with the geological logs. The change from fissured/fractured rock to fresh, unfractured rock below about 22 m is particularly well marked. This observed correlation is with the intensity of fracturing/fissuring as a whole; it is more difficult to relate the *steep* fractures alone to the resistivity logs.

More striking is the inter-hole correlation between the two vertical air-hammer holes at sites 1 and 2 and the inclined hole (Site C). This correlation (Fig 4.4) is remarkable and can only be interpreted in terms of flat-lying fractures over a lateral distance of approximately 34 m. Moreover, it means that the main fractures represented on the resistivity logs, and consequently the largest fractures present in the inclined hole, are not steep but shallow-dipping.

This is a significant result that supports the idea that flat-lying fractures are an important component even in holes sited along lineaments in supposed vertical fracture zones. The fact that a good water supply was encountered in a vertical air-hammer hole drilled by BGS 23.8 m east of the baseline (lineament) may be taken as further evidence that horizontal fractures play an important role in groundwater circulation.

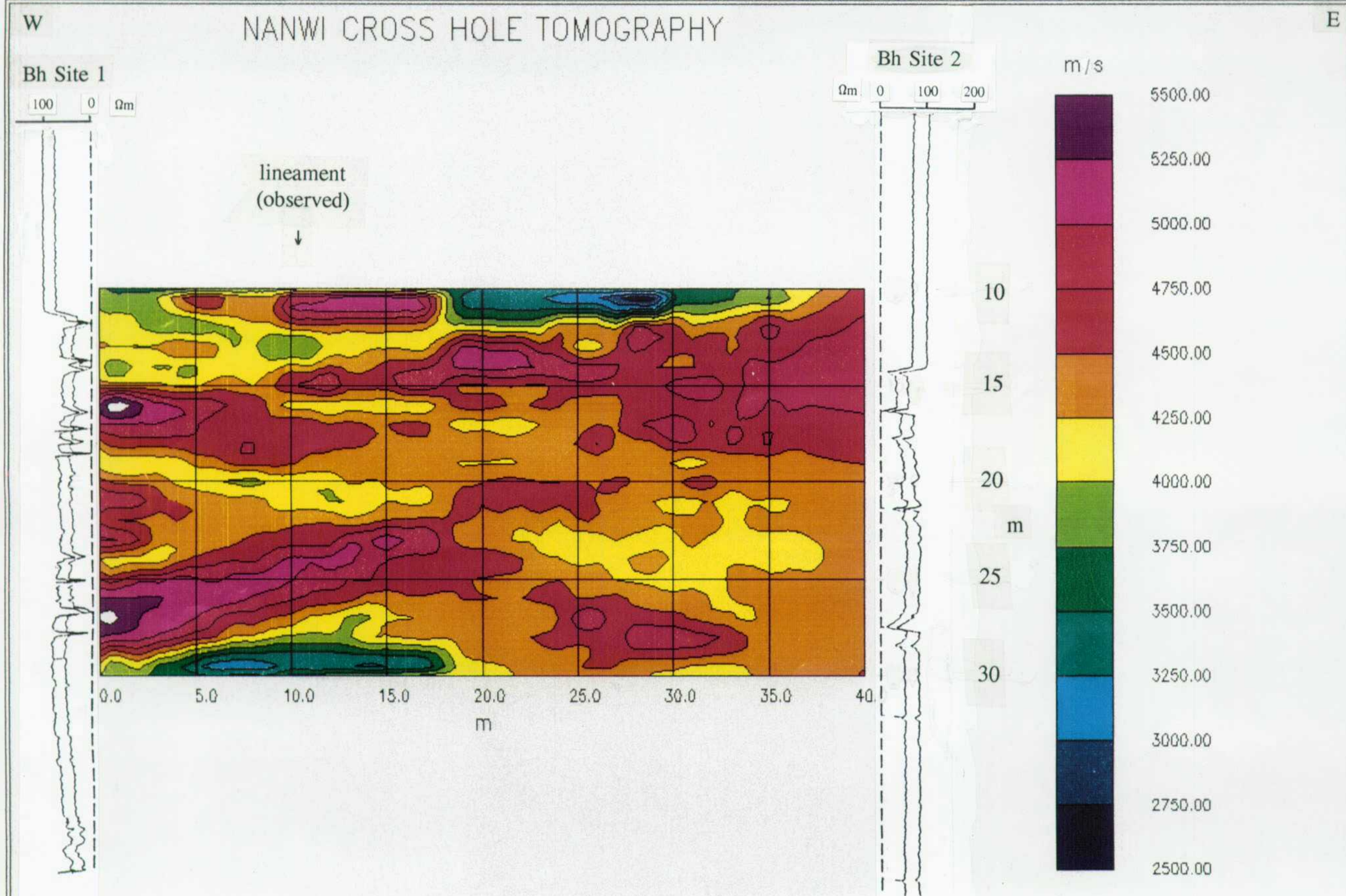


Figure 4.7 **Seismic tomogram between Sites 1 and 2 with micro-resistivity logs**

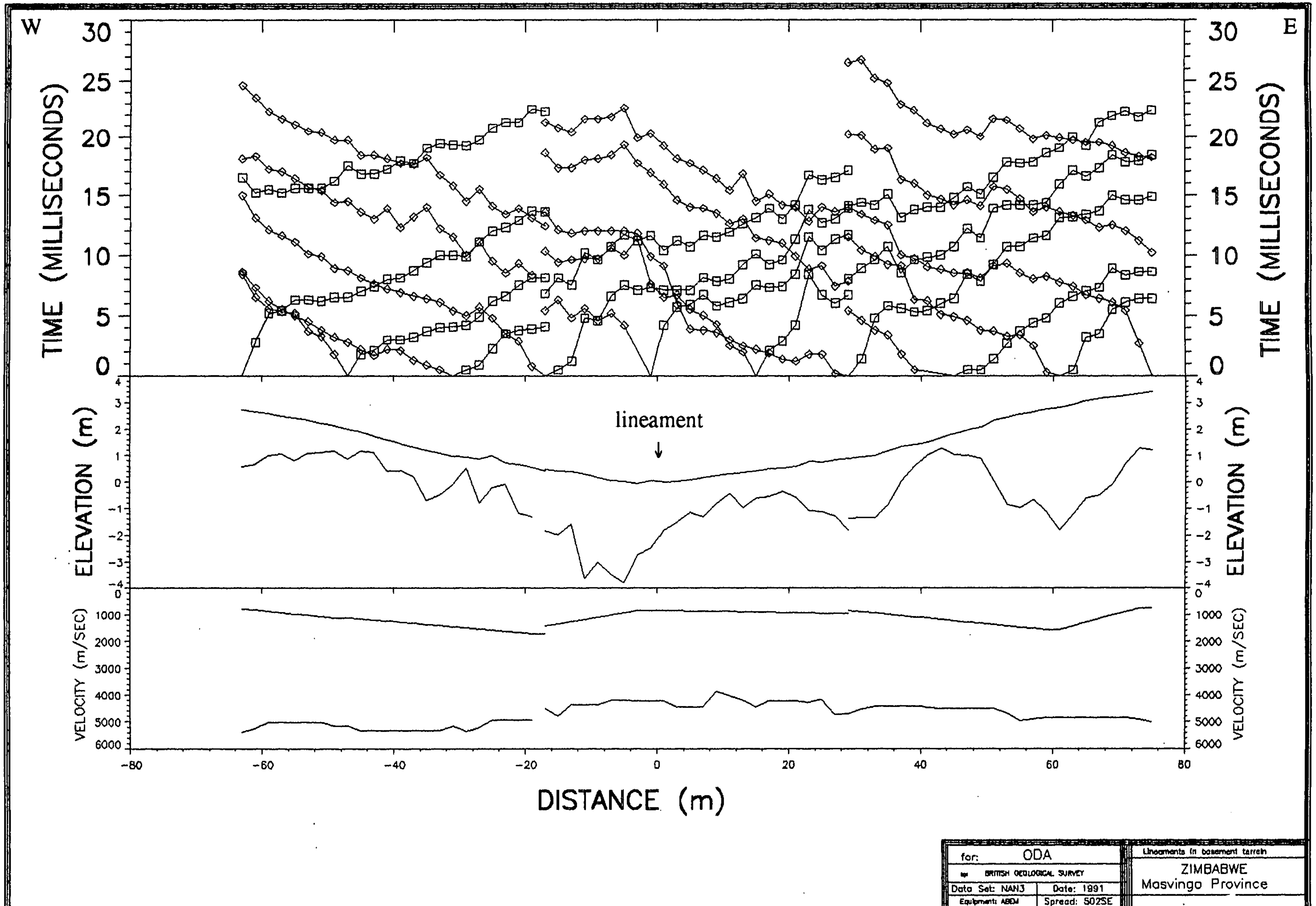


Figure 4.8 Seismic refraction results and interpretation from Line 00

4.4 Additional geophysical surveys

4.4.1 *Seismic refraction*

Three spreads were used to cover line 00 of grid 1 from 63W to 75E with a 2 m geophone separation. A conventional 8-shot pattern (4 offset, 2 end and 2 internal shots) was adopted for the outer spreads, with additional internal shots on the centre spread providing records from each geophone position.

The signal-to-noise ratios were not very favourable because of wind vibration and cultural disturbance but the data quality was generally adequate. The main uncertainties concerned the apparent phase reversals on the first arrivals seen on some of the near geophones, and the possibility of delayed triggering at the shot point geophone. While the phase reversals appear genuine, they are not easily explained as such and the true first arrivals may have been suppressed. The presence locally of very shallow bedrock may have contributed to the short transit times to the near geophones at some locations but the inferred velocities remain too high to be genuine.

Only one refractor could be identified and there was no evidence of any pockets where an intermediate layer might exist. The maximum depth interpreted to the refractor was 5 m below ground level, with the undulating surface effectively outcropping at 38-44E (Fig 4.8). No specific feature of refractor geometry was associated with the position of the lineament (at 0E), where the interface lay at an intermediate depth. There did appear to be some reduction in the velocity of the direct arrivals over the lineament, to less than 1 m/ms as compared to 1.5 m/ms nearby, suggesting less consolidated material within the vlei itself.

Overburden velocities decreased steadily from 1.5 m/ms to 0.8 m/ms over the length of the spread to the west, while to the east they largely remained less than 1 m/ms. Refractor velocities were highest to the west, reaching 5.5 m/ms, and decreased to less than 4 m/ms locally within the central spread before stabilizing near 5 m/ms to the east. These changes are consistent with the tomography data and may be attributed either directly to the degree of fracturing within the bedrock or to locally enhanced weathering.

4.4.2 *Resistivity*

The dipole-dipole resistivity pseudosection data acquired in 1990 were remodelled in an attempt to improve the fit (Fig 4.9). This proved more difficult to achieve than at the other sites and it seems likely that the presence of lateral variations orthogonal to the traverse, in particular the occurrence of outcrop adjacent to the line, produce effects which cannot be accommodated fully using a 2D approximation. Despite these reservations, the derived model (Fig 4.10) identifies a number of interesting features.

Two relatively conductive zones are defined, centred near 6W and 30E, each with a width of about 8 m and extending to a depth of 8 m. Even at these localities the resistivities, of 150-350 ohm.m, are noticeably higher than at both Nemarundwe and Mhatiwa, although the rate of increase with depth is small. The zones correspond to the deeper parts of the seismically defined bedrock profile, albeit that their depths appear greater. Shallow bedrock near 42E is not marked by particularly high resistivities, possibly because off-line outcrop has more effect on the seismic arrival times. The situation within the vlei itself appears to be complex in detail but it is clear that the more conductive ground, with a deeper bedrock is centred west of the lineament.

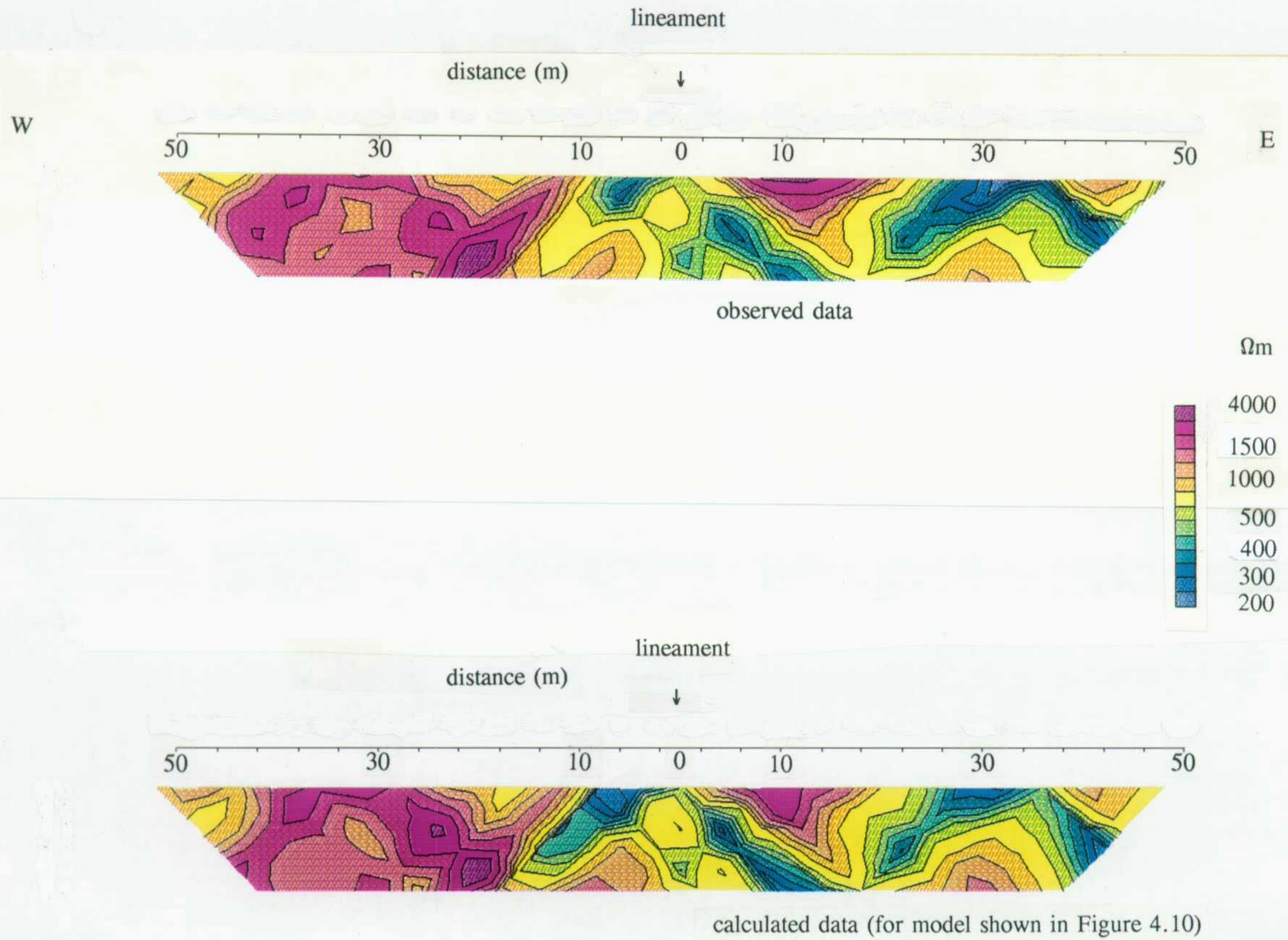


Figure 4.9 Observed and calculated resistivity pseudosections from Line 00

LOCATION: NANWI - grid 1; line 00

Resistivity model as diagrammatic vertical section:

Dipole length = 4 m

Resisitivity code:	1	2	3	4	5
Resistivity value (ohm.m):	150	350	1600	5000	700

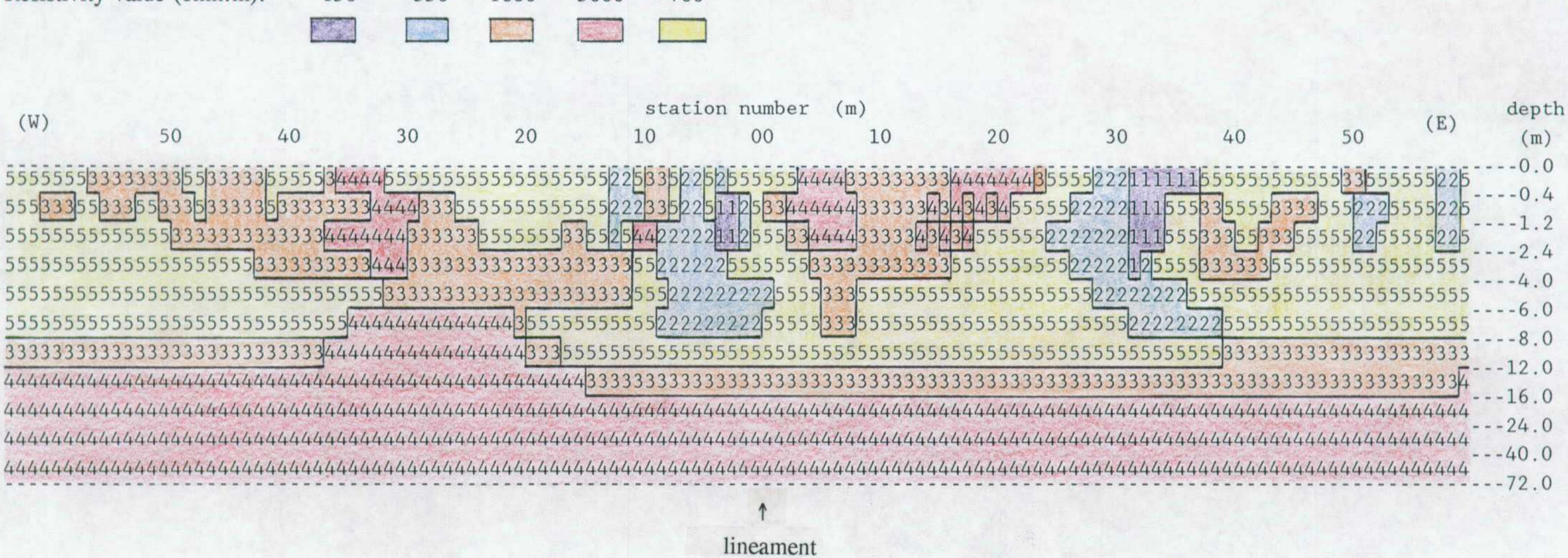


Figure 4.10 Resistivity model derived from dipole-dipole data for Line 00

4.4.3 *EM*

No further EM surveys were undertaken over this site because of the relatively high background resistivity levels. Such levels reduce the ability to resolve variations in resistivity while the instrument itself has to be operated on its most sensitive range, making it difficult to obtain good quality data. The lack of any clear EM anomalies in the previous work was consistent with the regolith being thin here and with the absence of any significant conductive infill (i.e. in the form of clays or poor-quality water) to the fractured rock.

4.5 Synthesis and conclusions

This locality was known to be relatively productive from previous drilling but the site investigation studies did not bring out any particularly favourable characteristics. While some more well-fractured rock could be seen at surface, the absence of regolith would normally be regarded as an adverse factor. There was in fact evidence that the weathering profile was more fully developed further along the vlei and given continuity along the lineament this could account for the sustained yield.

Coring through the lineament confirmed the more open nature of the rock mass here. Despite this, there was no conclusive evidence regarding the geometry of the fracture system. However, consideration of all the borehole data around this site supports the view that enhanced fracturing is not restricted to a narrow, steeply-dipping zone identifiable as a photolineament; it almost certainly extends laterally, with sub-horizontal connections particularly in the upper part of the sequence. This is seen as an important conclusion since it provides for the first time strong evidence that shallow-dipping fractures play an important role in the development of a fractured aquifer. The significance for borehole siting is twofold: first, the interconnections of shallow-dipping and steep fractures suggest the possibility of reasonable storage within the fracture system itself; and second, the target for drilling can be considered as extending away from the actual lineament to include multiple targets corresponding to shallow-dipping open fractures at different depths.

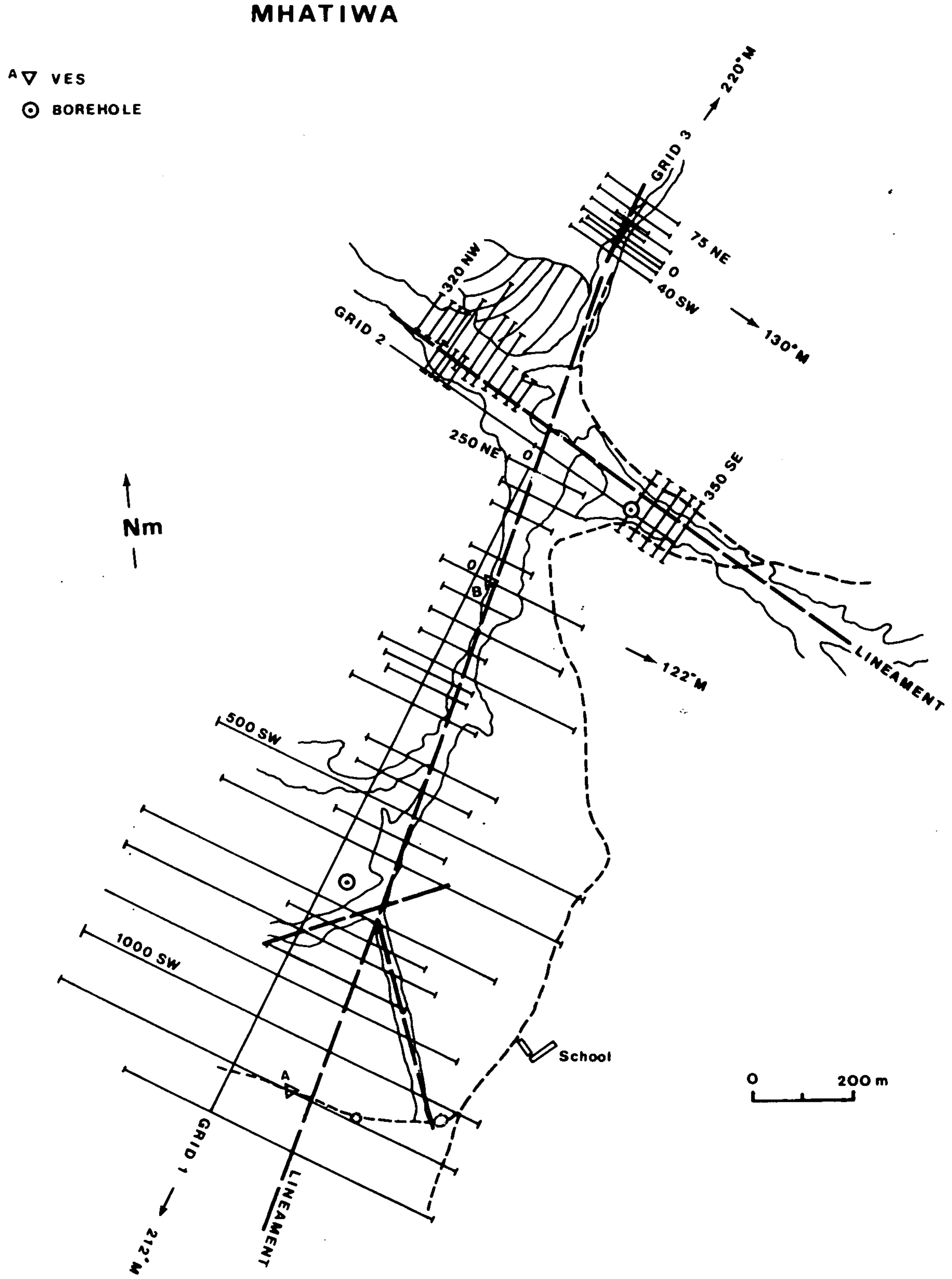


Figure 5.1 Mhatiwa: site location map

5. RESULTS FROM MHATIWA

5.1 Background

The area around Mhatiwa School and northwards lies within the outcrop of the Chibi Granite, a batholithic intrusion of Younger Granite forming spectacular bornhardt terrain. The rocks are medium-grained, grey to pink granitic gneisses with a moderate to well-developed foliation. Compositionally they are adamellites and potash granites. The granites are pervasively injected by pegmatite veins ranging in width from less than 1 cm to more than a metre, belonging to several generations formed during the late emplacement (ductile) and post-emplacement (brittle) stages. Although their directions vary widely, the veins frequently occur in sub-parallel sets, usually trending between NNW and NE, and are often steeply dipping. Pegmatite veins fill former fractures in many instances, and are commonly re-fractured along their centres. All pegmatite exposures display preferential weathering and may thus have some hydrogeological significance.

The Chibi Granite is strongly fractured along major NNE and NW-to-NNW directions which appear as long lineaments on aerial photographs and satellite images. These divide the Chibi Granite into a series of impressive bornhardts of overall diamond shape in plan. A previous lineament analysis of the area (Greenbaum, 1987) found that the principal fracture direction in the Chibi area was N325E with important directions at around N10E and N65E; many lesser lineaments occurred along directions between NNW and WNW.

The dominant NNE lineaments are shown as fractures on the geological map and some are indicated as filled by massive quartz veins. In outcrop, the NNE fractures occur as closed, planar, vertical joints sometimes filled with narrow quartz veins. Occasionally, they show small sinistral strike-slip displacements (and rarely, dextral movement), and displacements of the batholith margin also suggest sinistral movement. The NNE fracture set, widely-spaced on a regional scale, is parallel to the Great Dyke and Popoteke Fault, and is probably related to the same tectonic event. The northwesterly fractures are probably a composite set with NNW fractures dominant in the west and NW fractures in the east (such as at Mhatiwa). Earlier studies concluded that the NW/NNW and NNE fracture sets were probably not contemporary and therefore not conjugate.

In the Mhatiwa area, the two main lineaments trend N15E and N302E. The NNE lineament is the longer and can be traced on aerial photographs and satellite imagery for at least 9 km; the NW lineament extends at least 6 km. However, neither lineament is continuous over its entire length. They are most conspicuous along sections where drainages and associated dark soil tones occur, and in steep valley sections between outcrops, but are elsewhere difficult to detect especially where they cross interfluves. Drainages are not wholly controlled by these structures and commonly deviate from them. However, in the case of both lineaments, the individual lineament segments align sufficiently well to indicate that they are expressions of the same structure. This does not necessarily imply that the fractures are equally developed along their length, and indeed the evidence is against this.

The general distribution of outcrop over the main grid (Grid 1) at Mhatiwa suggests that the principal NNE lineament marks a change from thin regolith to the ESE of the N15E fracture to thicker regolith to the WNW. The stream course deviates considerably from the line of the lineament from north of about G1/100SW and it often flows over outcrop approaching the intersection of the two main lineaments. It is interesting to note that in the vicinity of this intersection the more northerly-flowing drainage veers to the east and the easterly-flowing drainage veers to the north (Fig 5.1), indicating that a barrier exists at this point. This is an area of shallow bedrock where groundwater is present virtually at the surface, possibly as a perched aquifer, and it appears that the intersection represents a compressional zone at the present time.

The northern extension of the NNE lineament, investigated with Grid 3, is more constrained by bornhardts on either side, and its exact location can be better inferred.

5.2 Previous work

By far the most striking and consistent correlation between lineament and geophysical response at Mhatiwa is displayed by the total field magnetic data of the main grid (Grid 1) and its probable continuation to Grid 3, some 600 m to the NE. This is expressed as a magnetic anomaly low (Fig 5.2), with an amplitude 100-150 nT below background, extending for at least 900 m; it is for the most part parallel to the main NNE trending lineament (L1), although offset from this by up to 70 m to the northwest. Further evidence of the correlation is seen in the vicinity of lineament L3 where the most negative closures within the magnetic 'low' are aligned sub-parallel to this subordinate feature. It should be noted that these anomalies are not particularly distinctive when seen on standard profiles and that they have been emphasised by the selective use of colour and contour interval. At Grid 3 the amplitude is reduced to about 80 nT and the anomaly here is more nearly coincident with the lineament. The cause of this extensive magnetic anomaly was considered to be either a fracture zone in which magnetic minerals had been oxidised, or a large scale quartz-rich (low susceptibility) foliation.

Gradient array profiles clearly delineated a zone of shallow bedrock (associated with very high resistivity values in excess of 30 kohm.m) in the northeast part of Grid 1. These profiles indicate a very abrupt shallowing of basement towards the southeast and this transition is traced by both a drainage channel and the main lineament in this zone. It was noted that, paradoxically, the drainage course was marked by high resistivity values; this was assumed to indicate that the drainage channel cuts through the regolith to expose relatively fresh resistive rocks. Much lower resistivity values (less than 300 ohm.m) dominate the remainder of Grid 1, to the northwest of the lineament, reflecting the presence of thicker regolith. An exception is a sharply defined resistive peak running sub-parallel to the baseline and largely coincident with the negative magnetic anomaly referred to above.

At Grid 3 the gradient array defined a low resistivity zone extending across the grid, its northwest edge closely following the projection of the main lineament (L1) from Grid 1 (Fig 5.3). Again, abrupt shallowing of basement is indicated to the southeast. Modelling of dipole- and pole-dipole resistivity measurements from line 25S. Figure 5.4 shows the resistivity distribution achieved by modelling. Most of the anomalies are attributable to variations within 10 m of the surface. The most conductive material lies in two zones separated near 10NW by a narrow band with a more resistive cap. This model shows clearly the abrupt transition to shallow bedrock in the vicinity of 25SE.

Azimuthal Schlumberger soundings at Grid 1 gave some indication of fracturing consistent with the main lineament trend. Similarly tenuous indications of fracture trend were displayed by mise-a-la-masse experiments at Grid 3 and between Grids 1 and 3.

The EM techniques generally confirmed the indications of shallow resistive bedrock and the remaining areas of thicker regolith as defined by the DC resistivity work. The abrupt transition from shallow basement in the NE of Grid 1 to the zone of thicker conductive regolith NW of the lineament was well marked by both EM34 and VLF techniques. The narrow resistive feature within this conductive zone (partly coincident with the magnetic anomaly) was clearly indicated by all EM methods. In addition to being a more efficient technique than gradient array resistivity, the EM34 has the added advantage of depth discrimination by virtue of the different coil separations available.

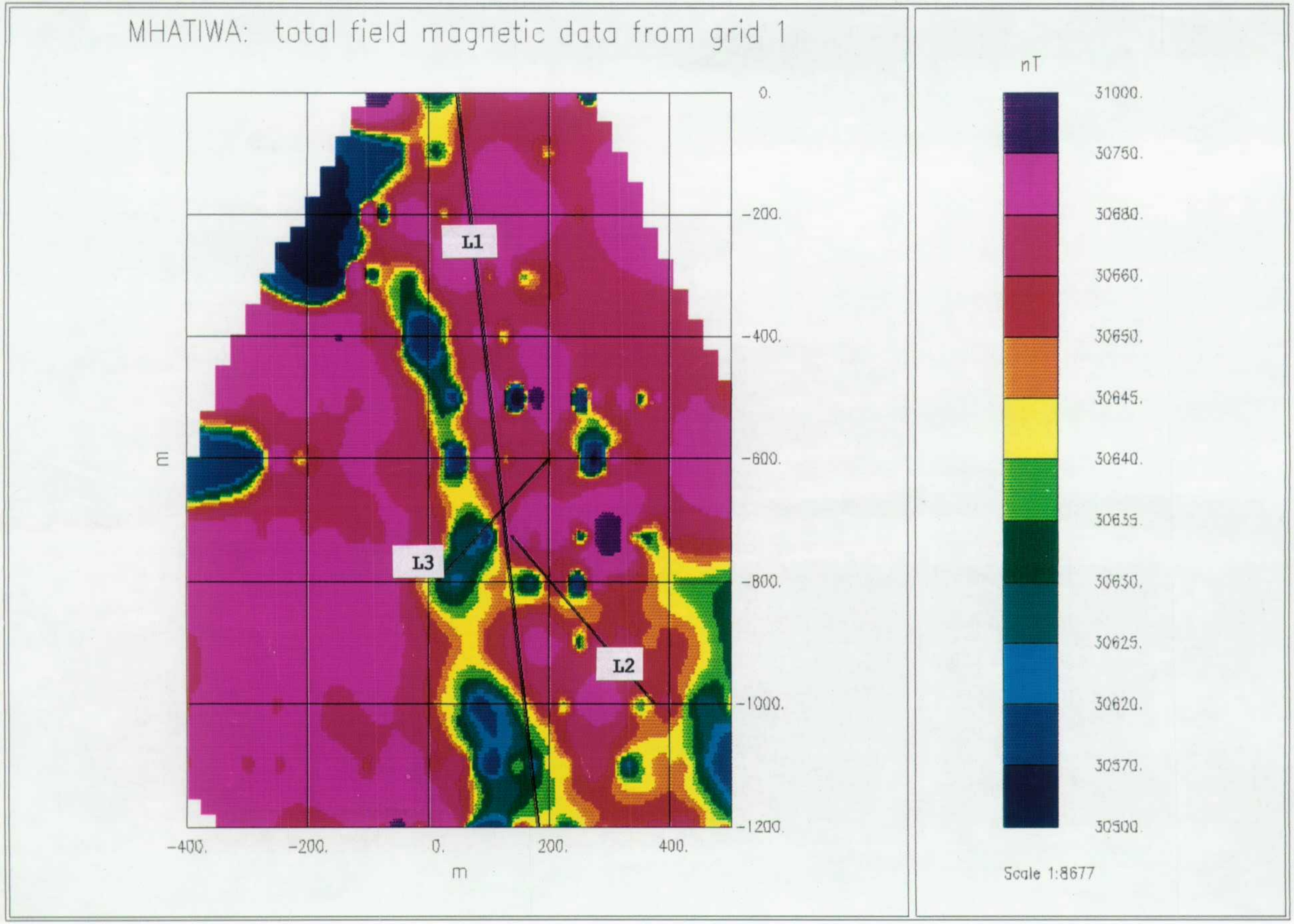


Figure 5.2 Filled contour map of magnetic results from Grid1, Mhatiwa

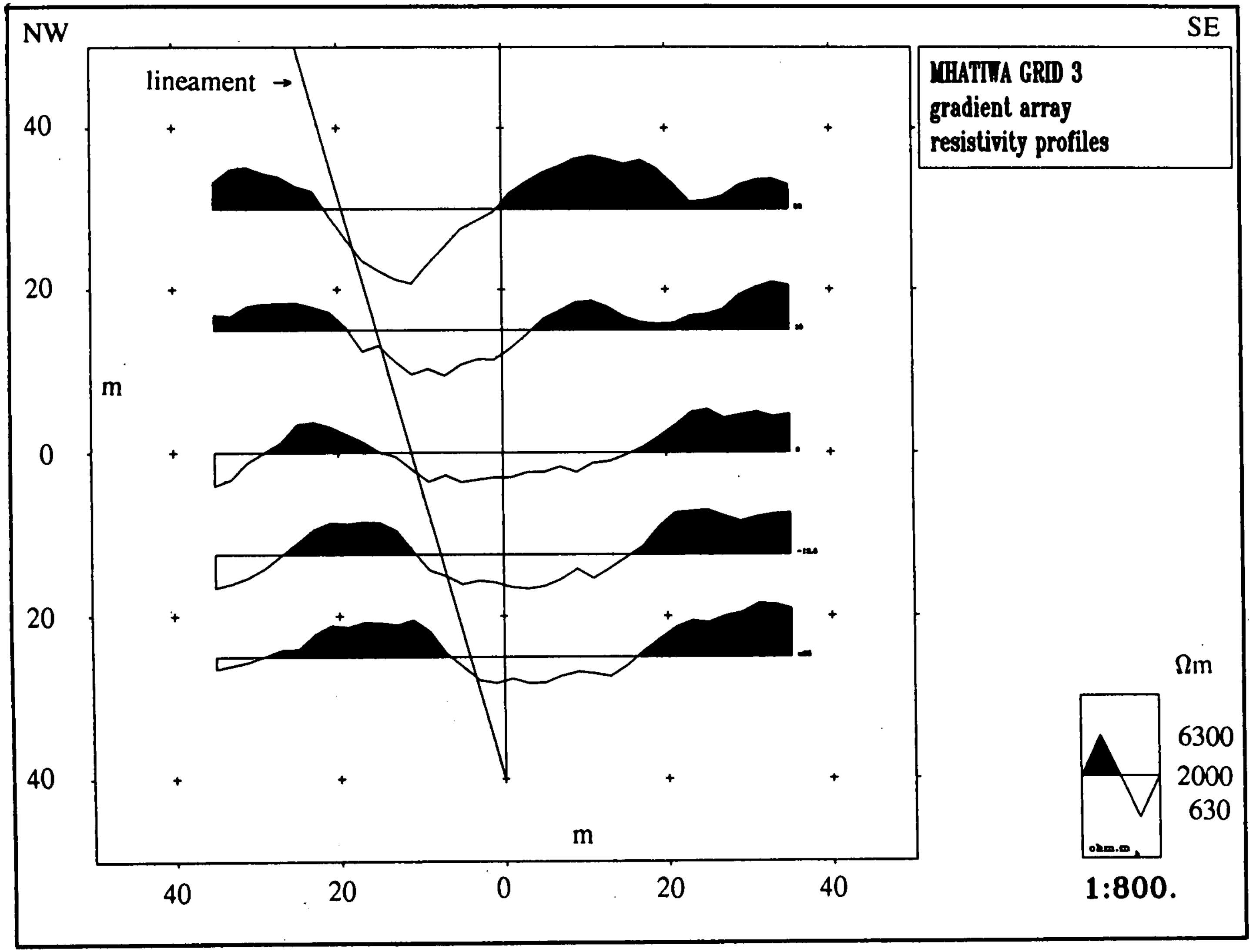


Figure 5.3 Gradient array resistivity profiles from Grid 3, Mhatiwa

LOCATION: MHATIWA - grid 3; line 25SW

Resistivity model as diagrammatic vertical section:

Dipole length = 5 m

Resisitivity code:	1	2	3	4	5	6
Resistivity value (ohm.m):	100	150	300	700	3000	6000

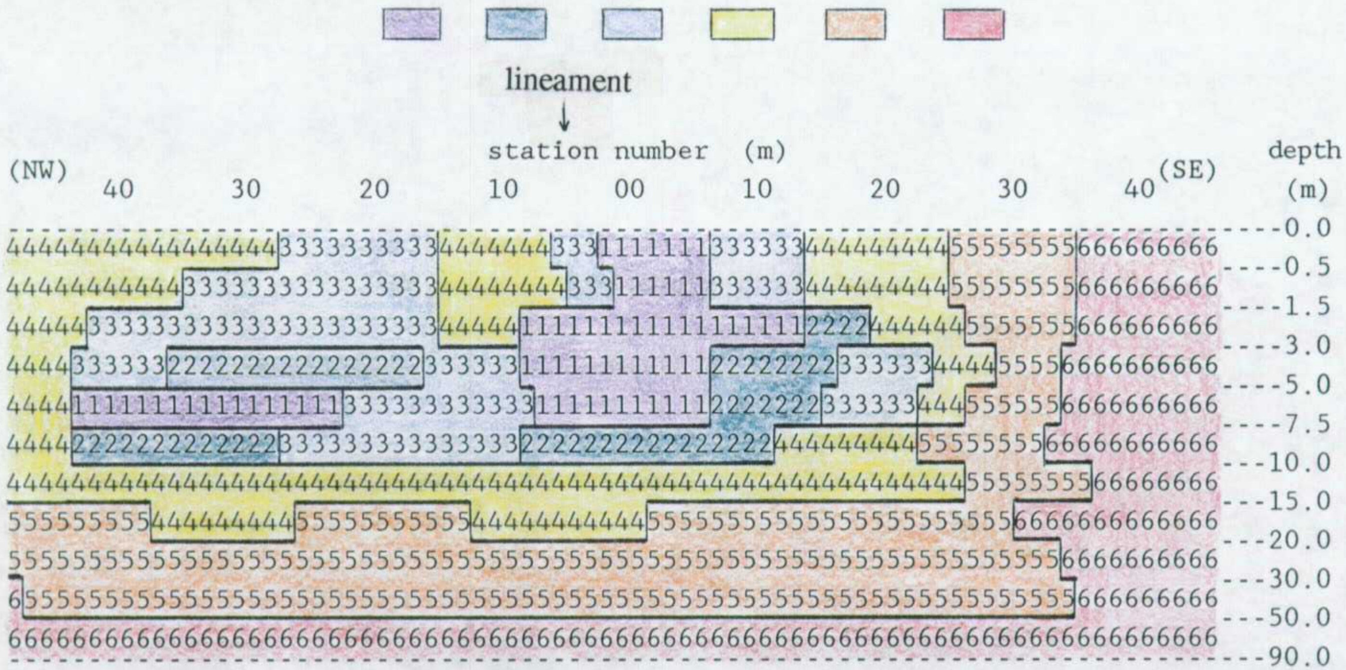


Figure 5.4 Interpreted resistivity distribution at Line 25SW, Grid 3

In conclusion, it was noted that while the extensive range of geophysical techniques applied at Mhatiwa yielded some anomaly trends paralleling the main lineament, the results failed to provide direct evidence of fracturing. Careful field examination had failed to find such evidence and, as previous boreholes had not produced good results, it seemed likely that any open fracturing would be of limited extent here.

5.3 Borehole results

The drilling plans for Mhatiwa Grid 1 and Grid 3 are shown in Figures 5.5a and 5.5b. The sites are located on map sheet Chibi 2030 B3 at approximately 24900/774750 (Grid 1) and 24930/774900 (Grid 3).

At Grid 1, an inclined borehole (Site E) was drilled at a location 115 m SE along line 500SW (Fig 5.5a). The hole was inclined at an angle of 30° to the vertical on bearing 302°M. The distance to the gully, which possibly marks the position of lineament on line 500SW, is 14.5 m.

At Grid 3, an inclined, cored hole (Site D) was drilled from a location 2 m northeastwards of line 25SW along the baseline (Fig 5.5b). This was inclined 30° to the vertical on bearing 310°M; collar position is approximately 6 m from the lineament. Two deep (50 m) vertical holes were drilled on 25SW: Site 1, 30 m to NW and Site 2, 5 m to SE of baseline. Six shallow (10 m) vertical holes were drilled at 5 m spacings between them.

5.3.1 *Geological logs*

BH/5 Mhatiwa Grid 1 (Site E) - inclined

Location

Hole collared 14.50 m SE of supposed photolineament (marked at surface by a gully) and drilled at 30° to vertical towards 302°. The hole was successfully drilled to its planned inclined depth of 40.83 m (recorded by drillers as 40.27 m) corresponding to a true depth of approximately 35 m.

Description

A summary geological log is shown in Figure 5.6a.

0.00 to 1.14 m:	unconsolidated sands, clay-rich above becoming less so downwards (regolith and dambo clays).
1.14 to c. 4.00 m:	grey, medium- to fine-grained massive granite, weathered yellowish (iron oxidation). Few sealed, epidotised hairline fractures.
c.4.13 m:	weathered and unconsolidated sandy material with associated core loss in overlying section (3.43 - 4.13 m). Could possibly represent ?flat-lying weathered-out fracture.

MHATIWA GRID 1 DRILLING LOCATIONS

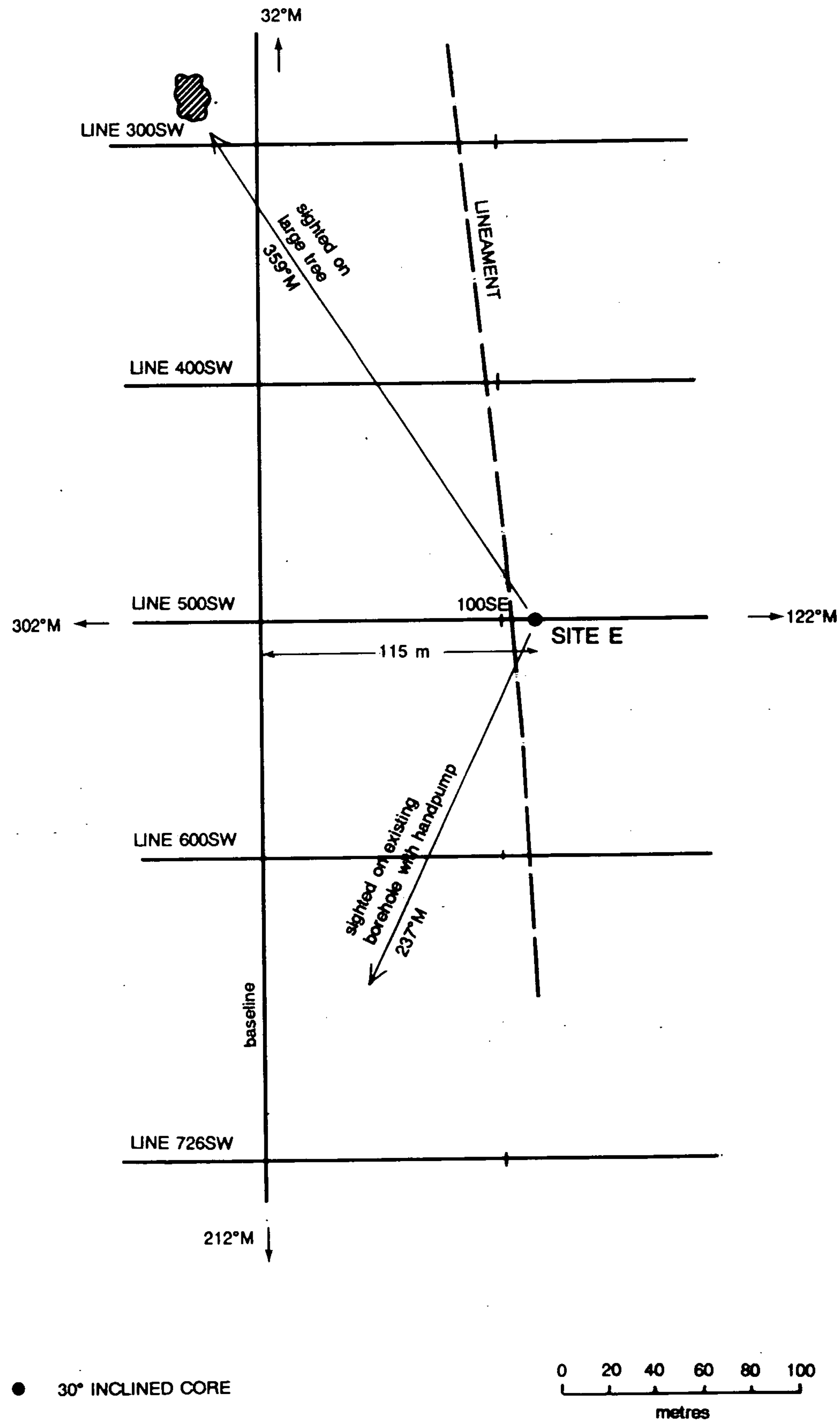


Figure 5.5(a) Mhatiwa: drilling site plans Site E, Grid 1

MHATIWA GRID 3 DRILLING LOCATIONS

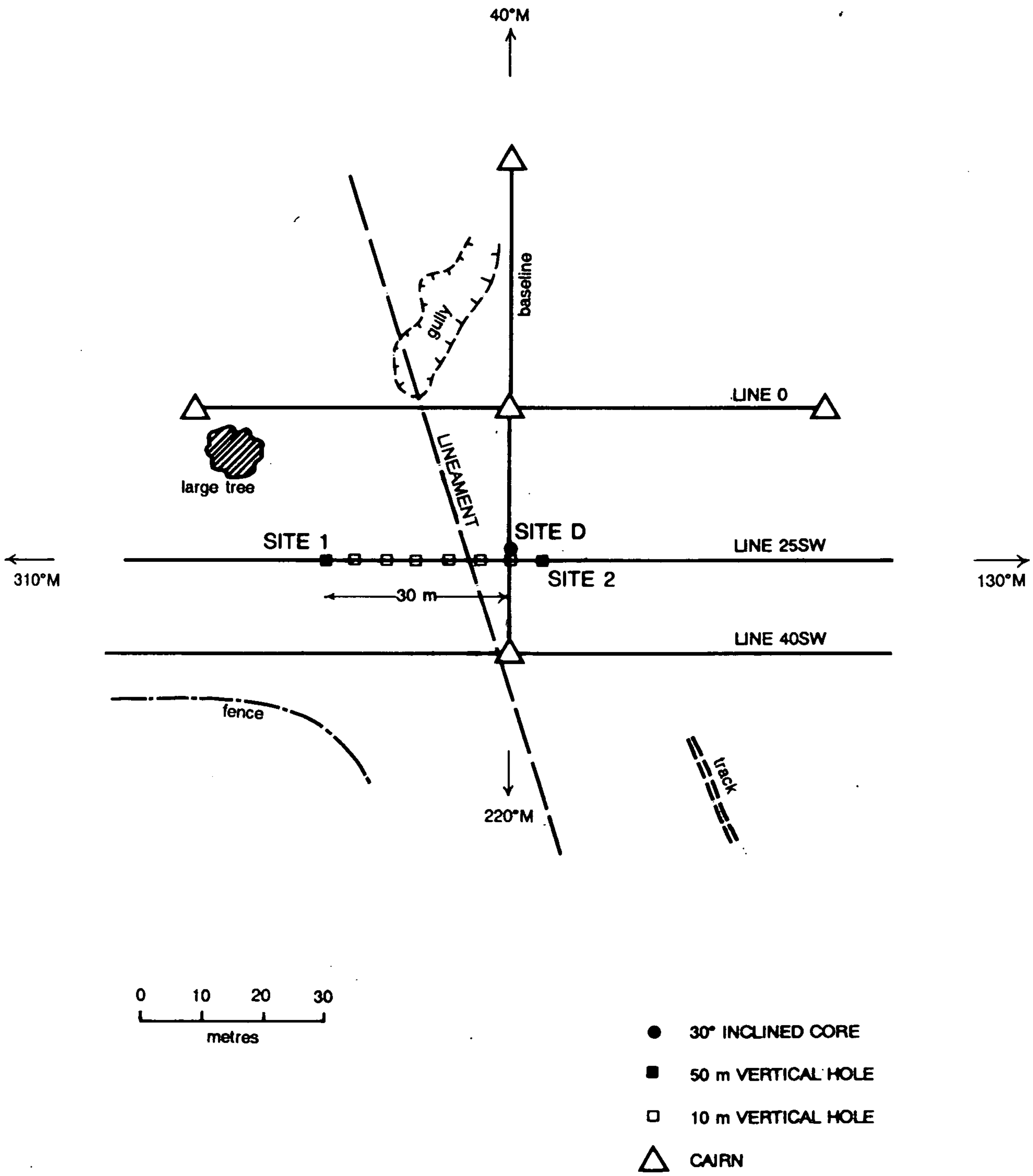


Figure 5.5 (b) Mhatiwa: drilling site plans **Site D, Grid 3**

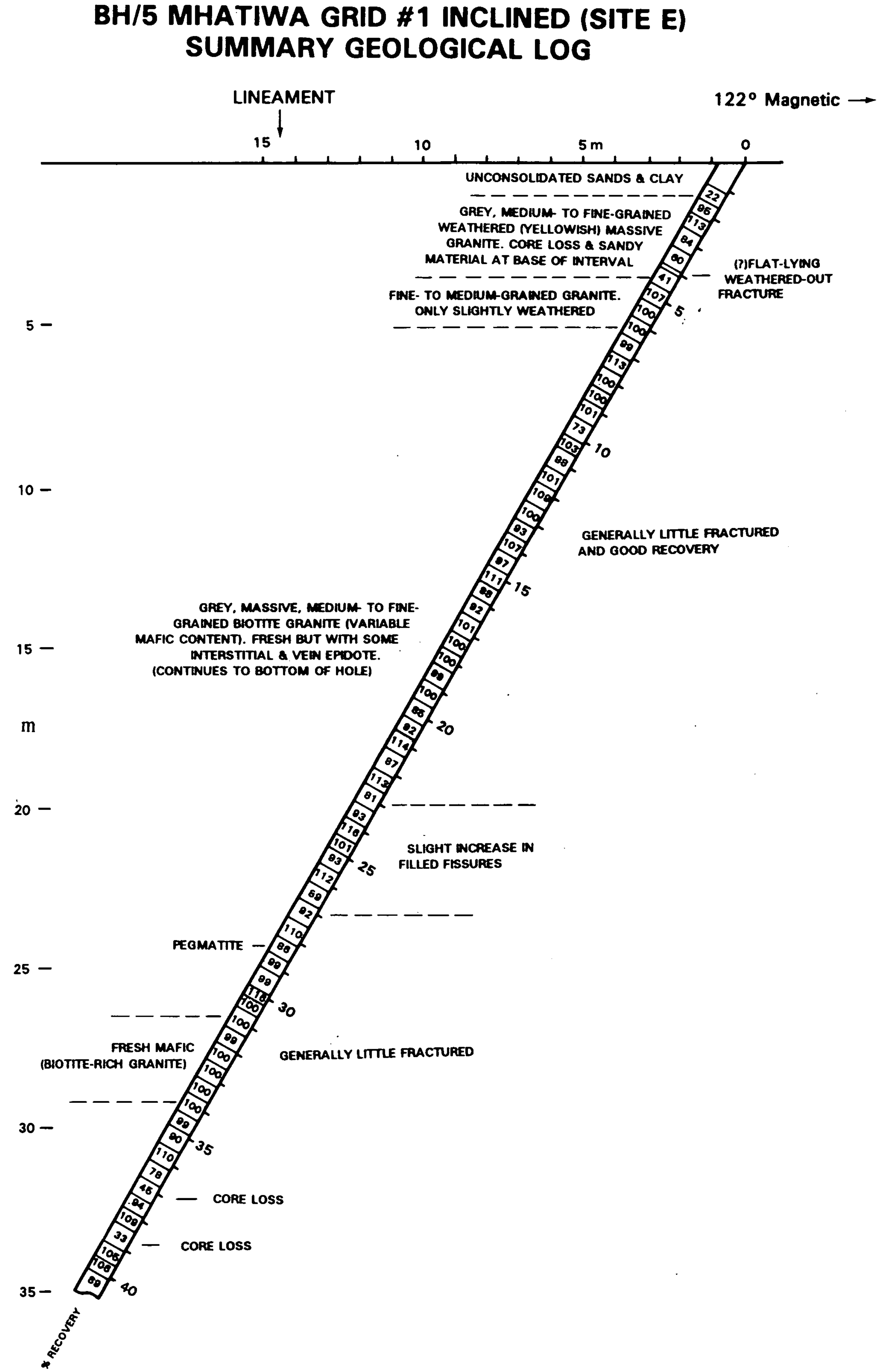


Figure 5.6 (a). Summary geological log for Site E, Grid 1

4.13 to 5.88 m:	similar fine/medium granite only slightly weathered with degree of weathering decreasing downwards so that by end of this interval the rock is nearly fresh. A few closed, epidote-filled hairline fractures but otherwise massive with good recovery.
5.88 to 40.83 m	grey, massive medium- to fine-grained biotite granite, of varying mafic minerals content (mainly biotite but also some pyroxene and/or amphibole). Essentially fresh but with occasional epidote in interstices and very occasional closed, hairline fissures. Pegmatite at several points, the thickest (36 cm) just below 28 m. Fresh mafic granite (biotite rich) from about 31 to 34 m. The entire core is generally little fractured: the highest concentration of filled fissures occurs between about 23 m and 27 m (especially around 25 m). Core losses occur between 36.79 and 37.30 m and between 38.46 and 39.06 m but there is no supporting evidence of fracturing or increased weathering.

Interpretation

The uppermost weathered material is related to surface processes. The second zone of unconsolidated material at about 4 m could represent either a flat or steep fracture, but does not correspond to the photolineament. Below this, recovery is nearly complete and there is no evidence of significant fracturing. It is concluded that this hole did not intersect the supposed fracture zone associated with the photolineament. Therefore, if the gully does represent the surface location of the fracture, it must have a hade of more than 15°NW (i.e. away from the drill site) for the hole to have missed it.

Re-examination of the aerial photographs has yielded little new information. It is difficult to be certain of the exact locus of the lineament at this point, but if the dark soil tones are taken to mark its course then it should lie roughly along the gully as originally proposed. Despite this, other (geophysical) evidence suggests that the photolineament does not in fact indicate the position of the main fracture zone. This is concluded from (i) the original resistivity survey on which the school's borehole was sited (ii) the results of the radon survey (Wright, 1988) and (iii) new magnetic data which suggests that the 'geophysical lineament' runs parallel to the photolineament but displaced some 70 m to the northwest.

BH/4 Mhatiwa Grid 3 (Site D) - inclined

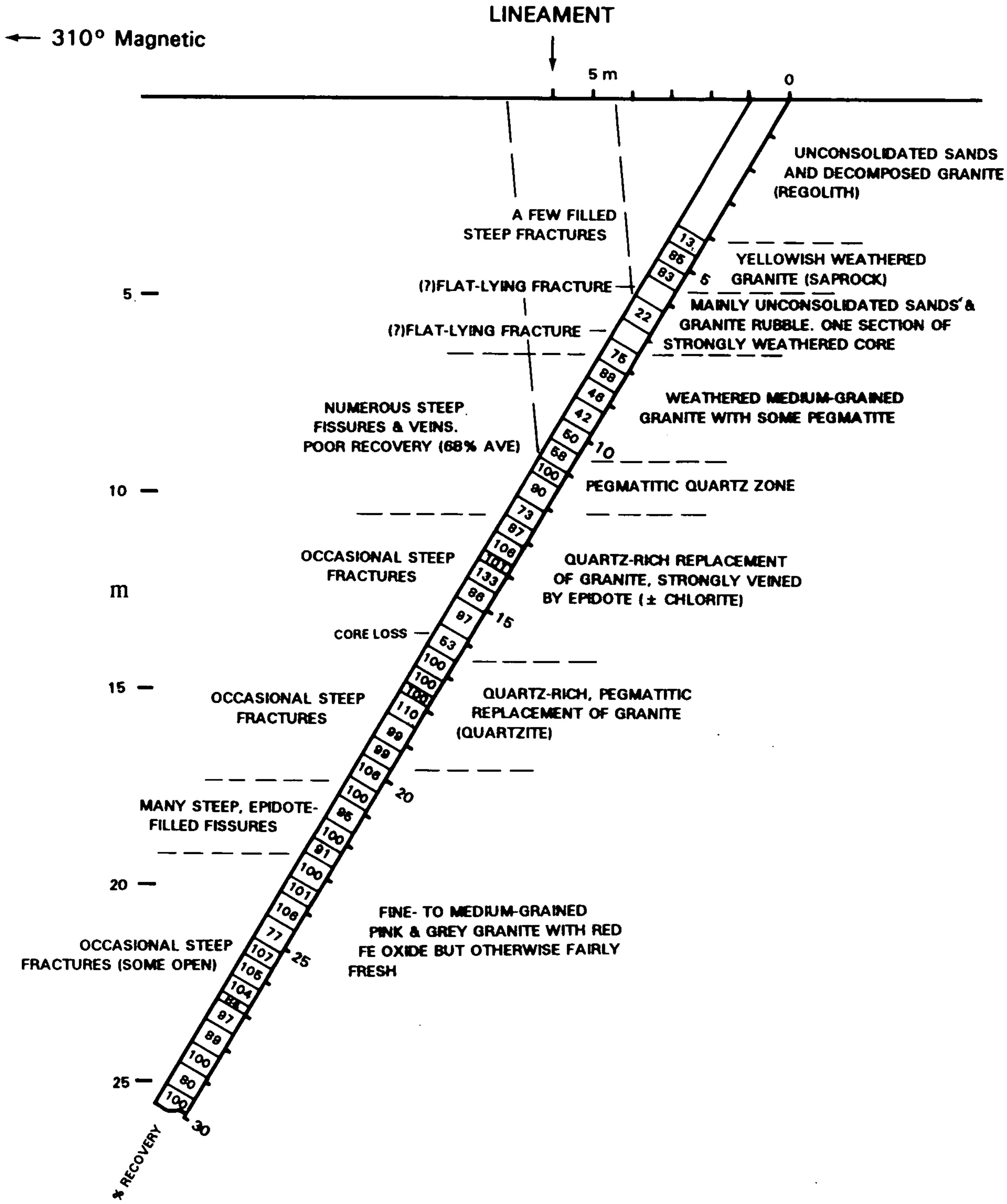
Location

The hole was sited 6 m to the SE of the lineament trace (marked by gully) and drilled at an angle of 30° to the vertical towards 310° (Fig 5.5b). It was completed at 30.02 m down-hole depth (about 26 m true depth).

Description

A summary geological log is shown in Figure 5.6b.

Surface to 4.08 m:	unconsolidated sands and decomposed granite were recovered (regolith).



BH/4 MHATIWA GRID #3 INCLINED (SITE D) SUMMARY GEOLOGICAL LOG

Figure 5.6.(b) Summary geological log for Site D, Grid 3

4.08 m to 5.65 m:	broken, yellowish weathered granite showing some steep epidote-filled hairline fissures.
5.65 m to 7.42 m:	mainly unconsolidated sands and granite rubble but with one small section of strongly-weathered granite containing steeply-dipping, epidote-filled fissures. This zone could represent (i) the regolith in which case the above section would correspond to a weathered core stone; (ii) a completely-weathered surface-parallel fracture; or (iii) a vertical fracture zone. Either (i) or (ii) is preferred since there is no surface evidence for a vertical fracture at this point.
7.42 to approx 10.70 m:	weathered medium-grained granite with some pegmatite material. Below this passes gradually into more silicified zone of strong quartz veining and pegmatite. Steep, epidote-filled veins and more open fissures, some oxidised, are common. Core recovery is poor. In general this corresponds to a steep zone of fissuring/veining (which continues downwards below 10.70 m).
10.70 to 12.09 m:	Pegmatitic quartz zone. The rock is a pinkish granite strongly veined and replaced by coarse-grained quartz and by veinlets and disseminations of epidote. Fracturing diminishes but still steep, filled fissures in this section.

[Note: the section 7.40-12.10 m (approx.) appears to be a major zone of fracturing and veining in which core recovery is poor].

12.09 to 16.48 m:	Quartz-rich pegmatitic replacement of granite, strongly veined by epidote. Less fracturing generally and good recovery, but losses and evidence of another set of fractures near base of this interval.
16.48 to 19.76 m:	This is again a siliceous pegmatite replacement of granite. The rock is a leucocratic, silicified unit, almost a sugary quartzite, interlaced by irregular veins of epidote and possibly some chlorite. It is generally unfractured and recovery is almost total, but one or two steep fractures do occur.
19.76 to 30.02 m:	Fine to medium-grained pink/grey granite. The rocks contain various amounts of interstitial hematite, which is partly responsible for the pink coloration. Recovery is good throughout and, apart from the presence of reddish iron oxides, the core does not appear strongly weathered. Over some intervals (especially c. 20 to 22 m) there is an intense set of steep, closed epidote-filled fissures. Elsewhere throughout this section of the hole are opened-up steep fractures (probably as a result of coring).

Interpretation

The upper zone of unconsolidated materials and regolith (5.65-7.42 m) probably corresponds to a sub-horizontal weathered-out fracture of significant width.

The main zone of fracturing and core loss occurs between approximately 7.40 and 12.10 m and is believed to represent a steeply-dipping zone; average recovery is 68%. Below this interval, core recovery is good almost throughout. If projected to the position of the surface lineament it would correspond to a zone about 2.75 m wide hading approx 9° towards 130°. This interval occurs mainly in weathered granite but the lower part (equivalent to the NW side) passes into siliceous pegmatite replacement. This silicic rock continues for some way to the northwest and, if interpreted as a steeply dipping body parallel to the fracturing, would have a width of about 4.50 m. It is generally massive and unfractured except near to 16 m where core losses occur that might relate to another fracture zone. A possible explanation for this pegmatite is that it invades a former fracture, completely infilling it. Along its southeast margin this fracturing and vein infilling continues into the adjacent granite country rocks: it is this zone that is structurally weak and corresponds to the photolineament and topographic depression.

Below this level (i.e. further to the northwest) the rock is again a normal granite, epidote-veined in part and showing some steep fractures.

5.3.2 *Geophysical logs*

Two deep boreholes, to 50 m, and a series of shallow (10 m) hydrophone boreholes were logged on Grid 3 but the inclined borehole was incomplete at the time of this investigation. The deep boreholes were geophysically logged with micro- and normal resistivity and caliper, and micro-resistivity was used in the hydrophone boreholes. The main borehole at Site 1 and the three shallow boreholes northwest of the lineament had collapsed due to running sand. Despite cleaning operations, the Site 1 borehole collapsed repeatedly at a depth of 16 m and large quantities of a medium- to fine-grained sand were removed from this borehole during rehabilitation operations.

Micro-resistivity logs of the hydrophone boreholes showed very little evidence of any significant formation changes with 2.5 cm micro resistivity values being measured in the range 115-125 ohm.m (Fig 5.7a). At 5 m bgl there was an indication of a weathered horizon extending across the site, with the formations below this level being of a lower resistivity.

The deep borehole logs were consistent with those obtained from the hydrophone boreholes and indicated a fractured/weathered zone extending down to c.9 m (Fig 5.7b). Taking height differences into account, this weathered section may relate to the 'running sand' problem in the Site 1.

Grain density and magnetic susceptibility values were measured on selected core samples from inclined holes at sites D and E. As had been previously observed grain density showed very little variation apart from a single low value at 8.6 m from Site D and 15.4 m from Site E (Fig 5.8). The magnetic susceptibility values were consistently low (generally less than 0.5×10^{-3} SI) at Site D (Fig 5.9) and did not indicate any variation either side of the lineament; a single high value at 15.9 m is anomalous. Susceptibilities from Site E were significantly higher, even near the surface, and most lay in the range $1\text{-}4 \times 10^{-3}$SI. Thus, there is a clear difference in mineralogy between the two sites (as expressed by magnetite content).

5.3.3 *Seismic tomography*

The amount of tomographic work that could be undertaken at Site D was restricted both by the length of open hole available and by time constraints. Some data were collected using a 2 m source interval but they proved too limited to allow identification of any fracture-related features.

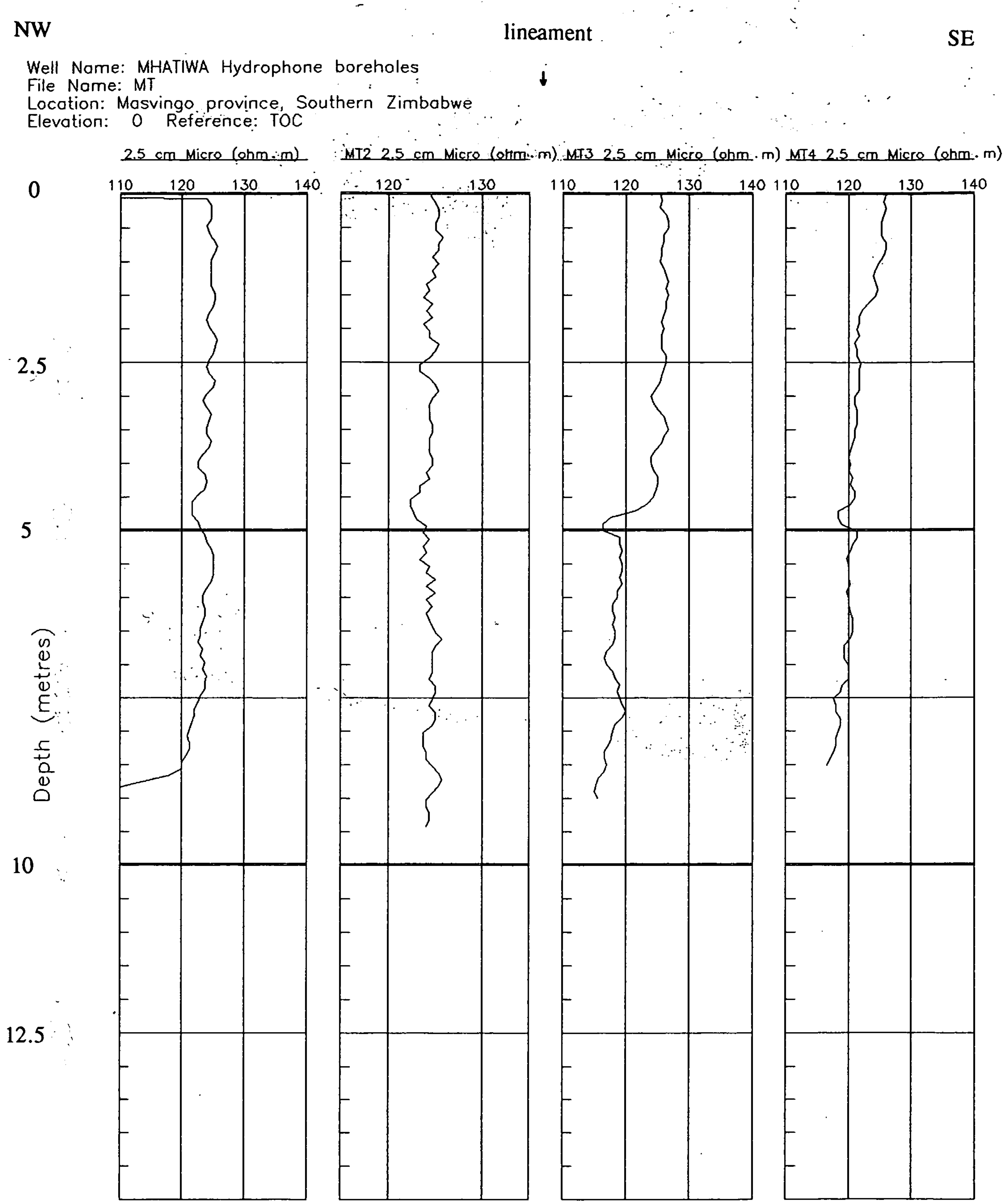


Figure 5.7 (a) Geophysical logs from Grid 3, hydrophone boreholes

Well Name: MHATIWA Borehole 2
File Name: MHA2
Location: Masvingo Province, Southern Zimbabwe
Elevation: 0 Reference: TOC

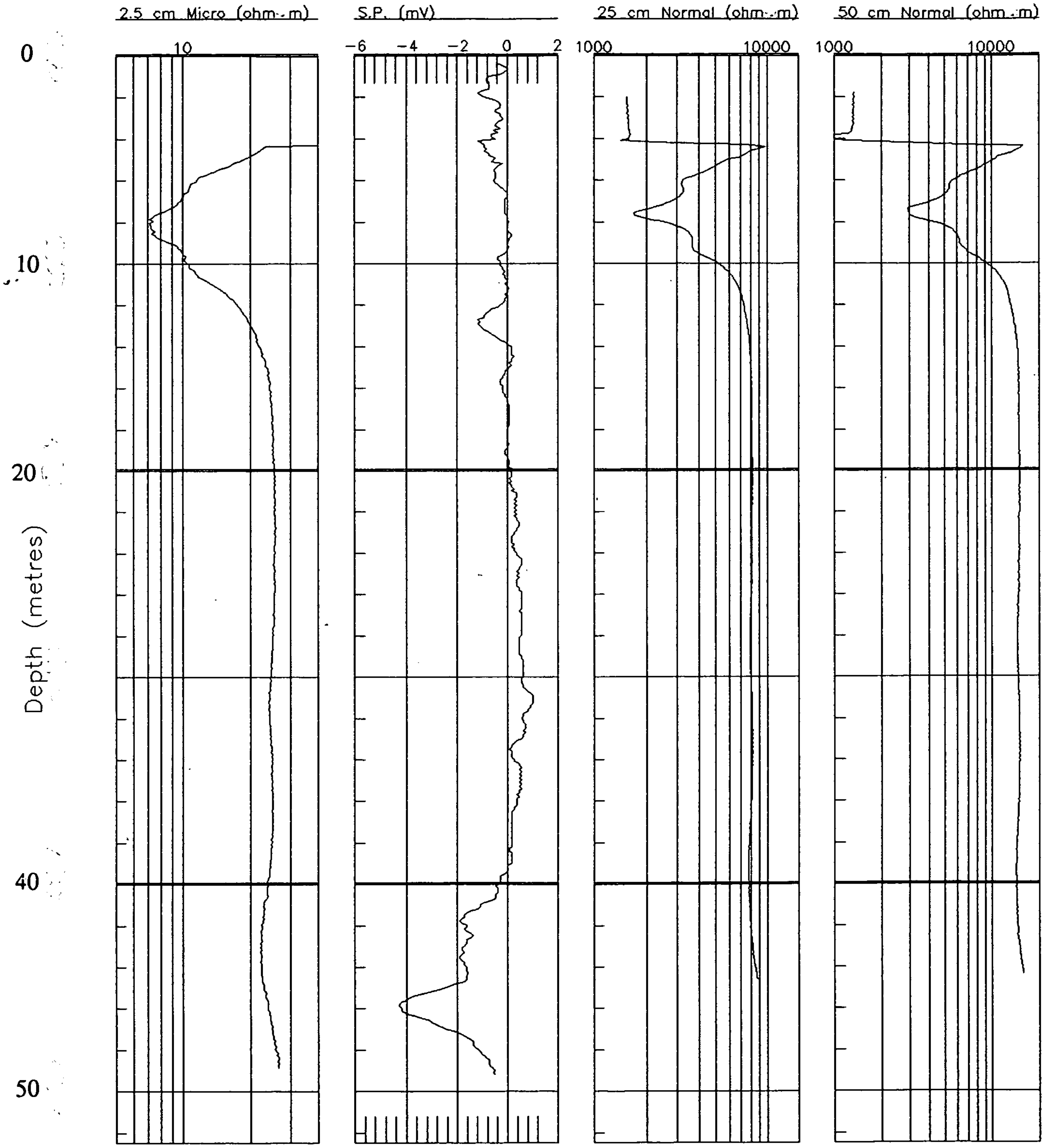


Figure 5.7 (b) Geophysical logs from Grid 3, Site 2

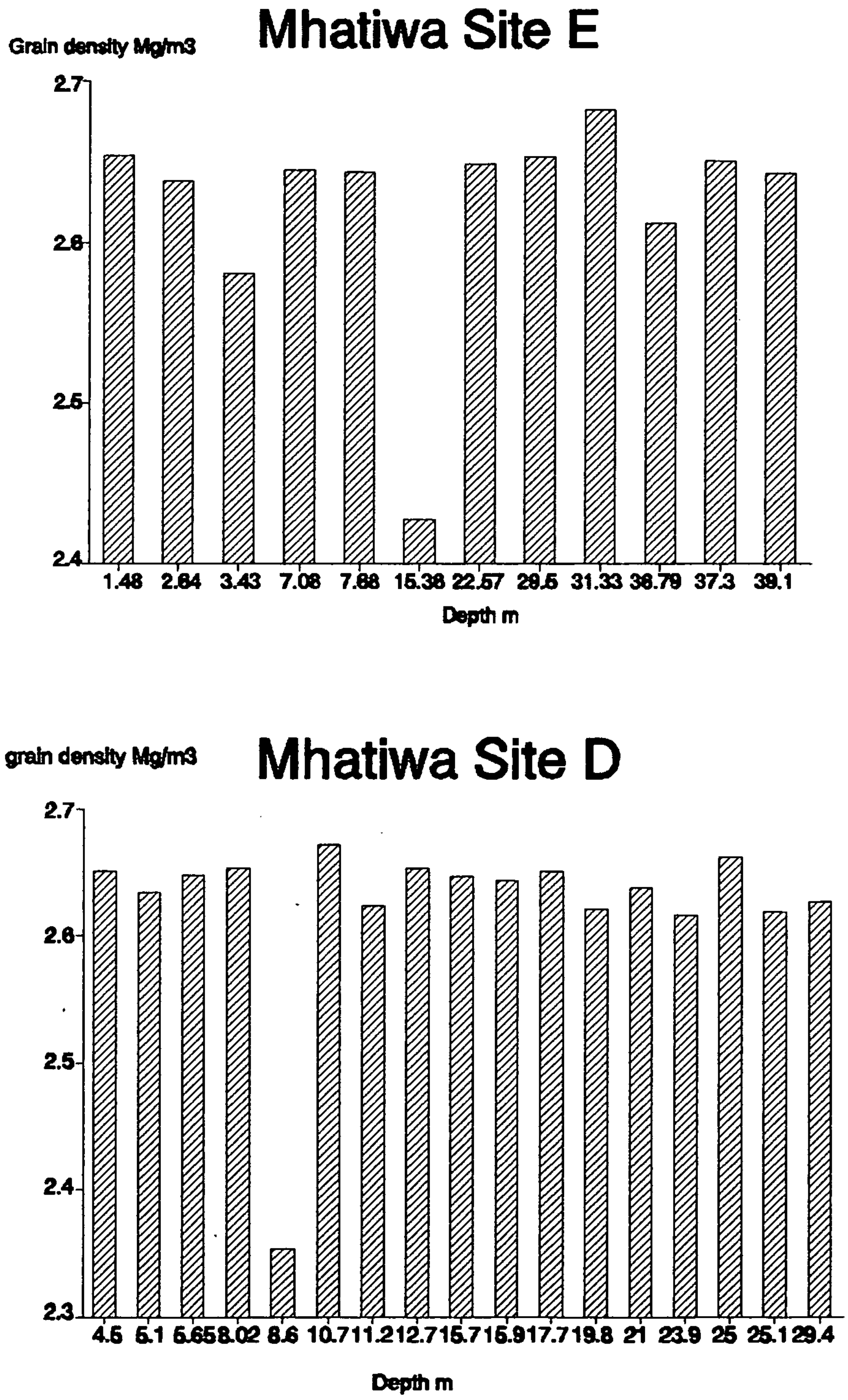


Figure 5.8 Densities of core samples from Sites D and E

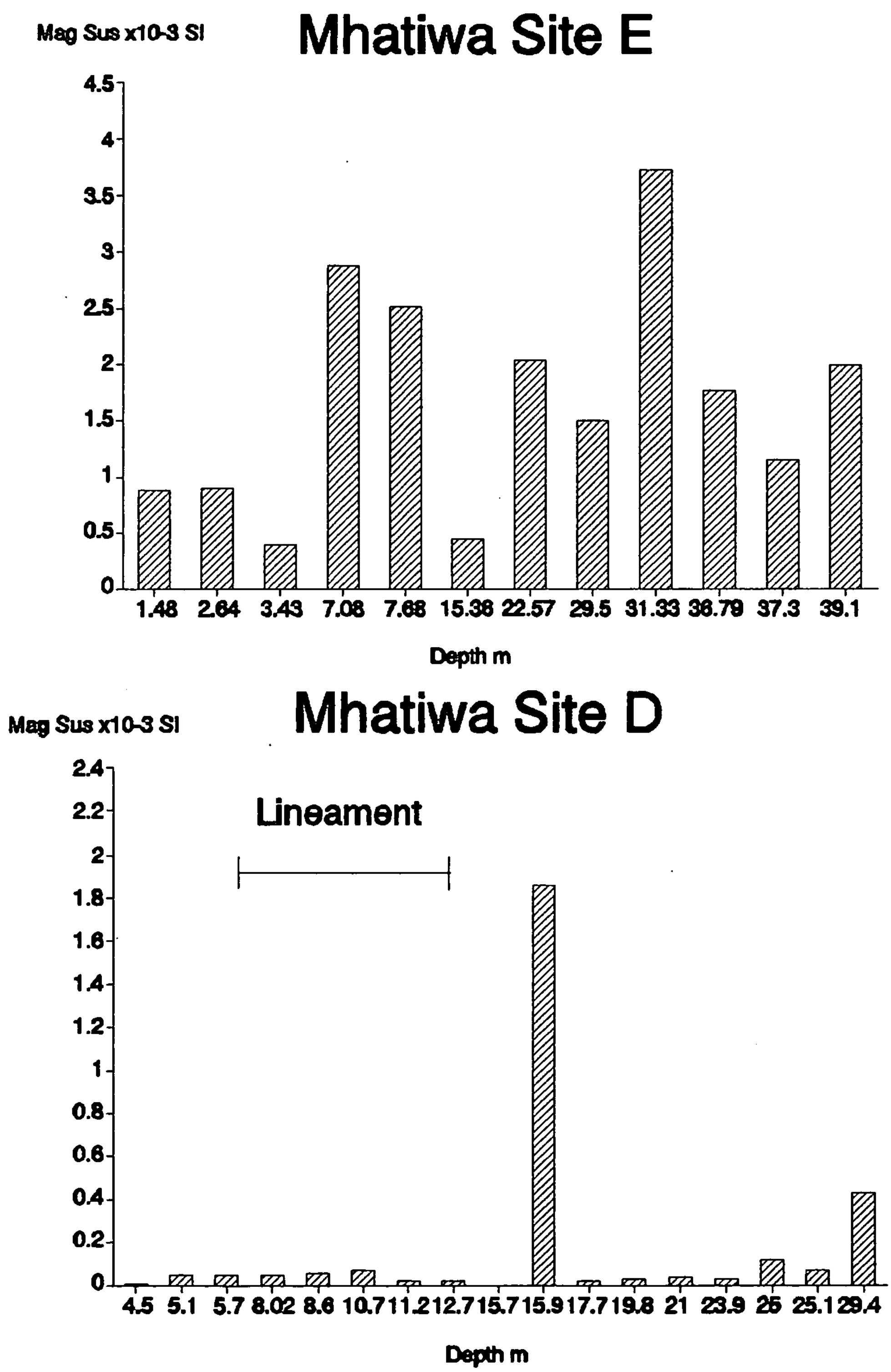


Figure 5.9 Magnetic susceptibilities of core samples from Sites D and E

5.3.4 *Discussion and general implications*

Borehole resistivity logs around Site D show a similar signature: of regolith down to 9 m, leading into a competent, massive formation, with no evidence of significant fracturing. However, the core did reveal the presence of a major pegmatite and a high silica content; fracturing and the lineament were developed on the margin of this zone. The abundance of quartzitic material is evident in the repeated collapse of three shallow and one deep borehole as a result of running sand. These findings clearly contrast with data from Site E where a more typical, massive granite was penetrated beneath thin cover.

The data from Site E were unique in providing no real evidence of increased (even closed) fracturing. It thus appears that the main structure was missed by the drilling and that the photolineament and associated drainage are offset from the main structure here. In the absence of drilling on the 'geophysical' lineament further to the northwest, the existence of any structure here remains speculative although Site D provides confirmation of its presence to the north. The data do not provide an explanation for this divergence. One possibility is that the fracture zone in this region lies *en echelon* to the main alignment. Another is that the discrepancy resulted from movements, younger than and independent of the two main lineament trends, which induced sufficient block tilting to cause an eastwards migration of the drainage line. To the north of Site E the lineament is interpreted as lying westward of the drainage over a several hundred metres stretch. Also, the right-angled diversion of flow from a NNE to a SE direction could be explained in this way. There is no direct evidence to substantiate any single hypothesis. It is, however, important to note that the role of ground geophysics in borehole siting here was not to refine the location of a photolineament but to redefine its position.

5.4 Additional geophysical work

5.4.1 *Seismic refraction*

Seismic refraction coverage was obtained from five spreads between 200SE and 50NW on line 500SW and from three spreads between 80SE and 80NW on line 25SW, Grids 1 and 3 respectively, employing a constant geophone spacing of 2 m. Detailed coverage (replacement mode) was acquired on both lines in the vicinity of the lineament. The resulting time-distance plots and interpreted depth and velocity sections are presented in Figures 5.10 and 5.11. The occasional inconsistency between segments derived from adjacent spreads (e.g. the velocity section of Fig 5.10) indicate lack of refinement; however, further adjustment was considered unnecessary in that the gross indications should be valid.

Both sections define only one refractor, with velocity in the range 4-5 m/ms (ignoring the maladjusted section showing velocity at nearly 7 m/ms in Fig 5.10). In both sections there is evidence of increasing velocity towards the southeast, suggesting the presence of more massive bedrock in this direction, which is in agreement with the resistivity results. Minor perturbations of this refractor velocity are indicated; these may reflect local changes (e.g. near 00 on line 500SW) but it is not clear to what extent they reflect basement topography. Overburden velocities vary in the range 0.4-1.4 m/ms, with the highest values occurring at the southeast end of line 500SW. This probably reflects the presence of shallow saprock here compared with looser superficial deposits elsewhere.

Along line 500SW, depth to bedrock varies between near 0 m, at the gully and coincident lineament, to about 6 m at 40SE. The bedrock high at about 10SE is responsible for the well-defined high resistivity feature recorded here. The relatively thick wedge of overburden between this point and the lineament is reflected by the results of all the electrical

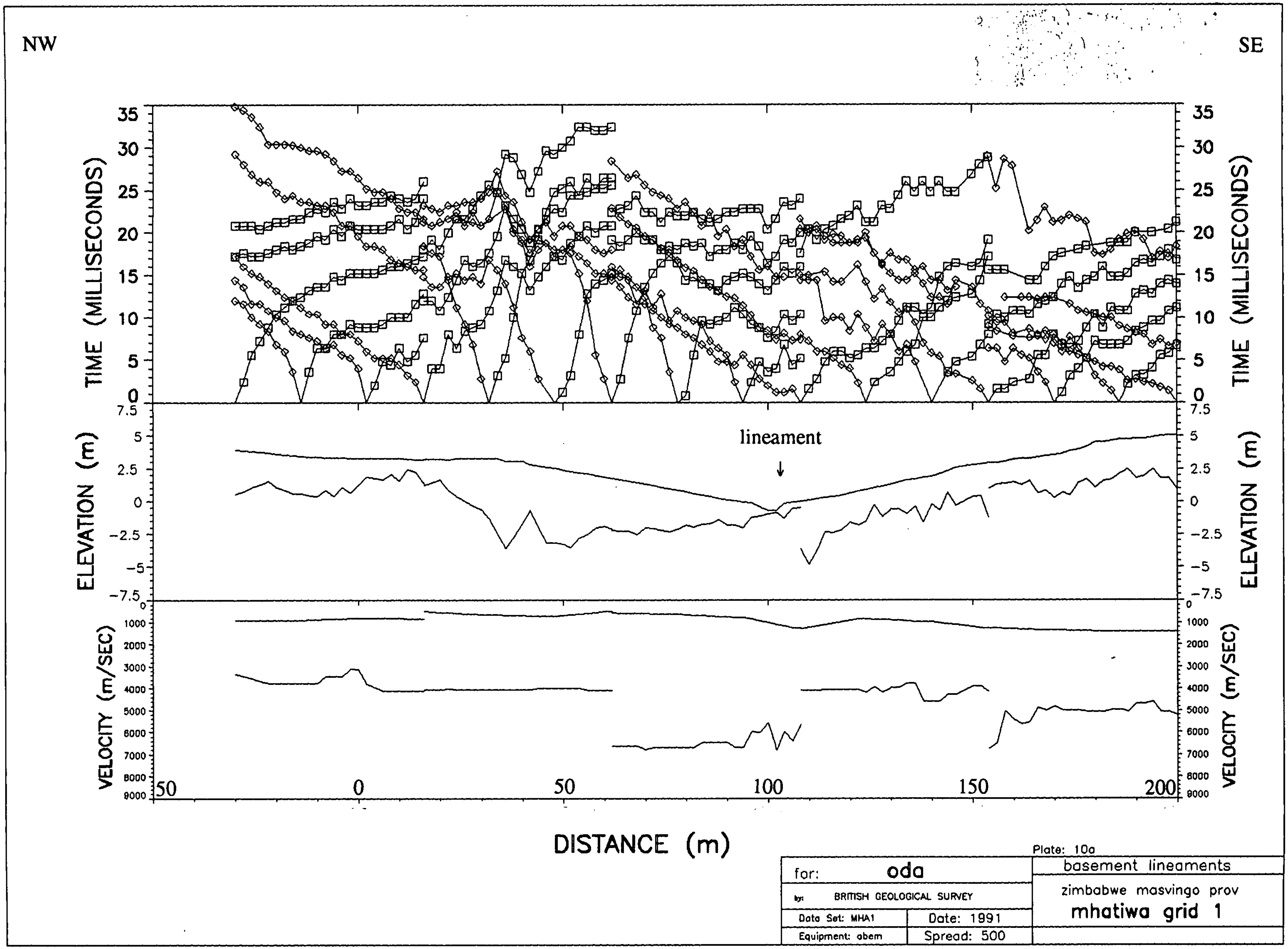


Figure 5.10 Seismic refraction results from Grid 1, Line 500SW

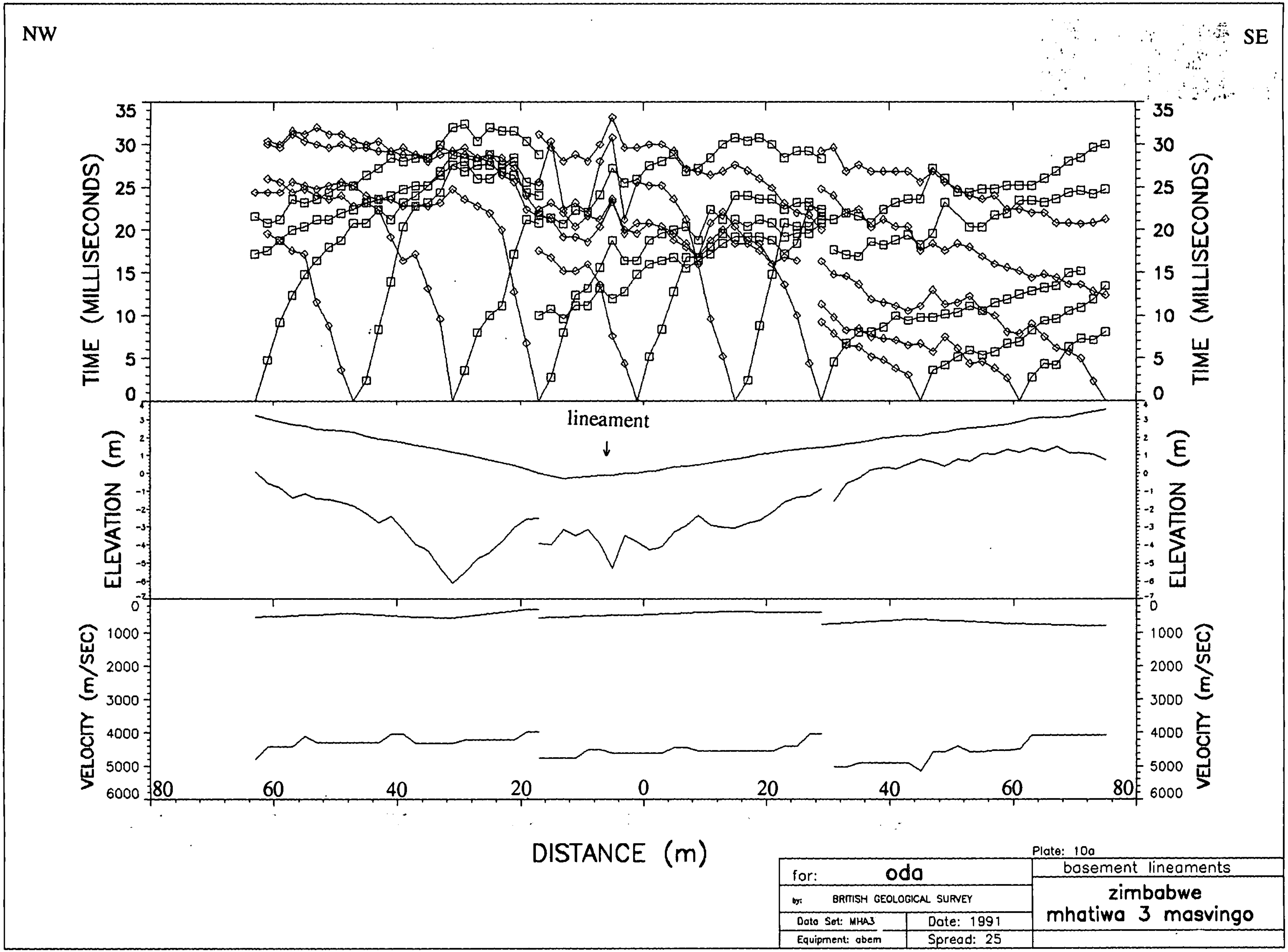


Figure 5.11 Seismic refraction results from Grid 3, Line 25SW

techniques. Southeast from the lineament, the thickness of overburden is shown as some 2 m; this overburden, however, has a relatively high velocity.

At Grid 3 the thinnest overburden (1.5 m) lies on the southeast side of the valley while bedrock reaches a depth of 7 m near 30NW. The position of the lineament is marked by a local deepening of bedrock which may indicate fracturing, with the intervening bedrock high being associated with the resistivity high recorded by the gradient array traversing (Fig 5.3). The latter feature is modelled in the pseudo-section as being underlain by a zone of lower resistivity, but this may be influenced by the water table and suggests saprock rather than the more weathered saprolite.

5.4.2 *Resistivity modelling*

The gradient array profiles of lines 500SE (Grid 1) and 25SW (Grid 3) were modelled using RES3D. Results from Line 25SW (Fig 5.12) indicate the presence of two conductive zones of resistivity about 30 ohm.m set in a host of 3000 ohm.m, overlain by a shallow resistive (1000 ohm.m) overburden. These zones, extending between 18SE and 8NW and from c.23NW to beyond the end of the profile, are in broad agreement with the conductive features interpreted in the earlier pole- and dipole-dipole modelling (Fig 5.4).

The central conductive zone, coincident with the lineament, extends to a similar depth (c.7 m) to that interpreted in this earlier modelling, but it should be noted that the gradient array appears from modelling to be rather insensitive to depth extent. The main difference in the models lies in the emphasis given to shallow bedrock separating the two conductive features (see also comments in Section 5.4.1) in order to account for the observed resistive peak. Similarly broad agreement is shown with both the magnetic model (Fig 5.14) and the seismic interpretation (Fig 5.11), confirming a relationship between low resistivity, low magnetic susceptibility and low seismic velocity.

Figure 5.12 further supports pseudosection modelling in suggesting that bedrock to the southeast of c.20SE is of much higher resistivity than to the northwest, although this part of the observed curve could not be matched satisfactorily because of constraints with RES3D. This observation is weakly supported by the interpreted seismic section which shows marginally higher velocities to the southeast. Similarly, to achieve a reasonable match with the observed profile, the gradient array model for Line 500SE (not shown) required a bedrock of far higher resistivity to the southeast of the lineament. Thus, as at Nemarundwe, it seems possible that the lineament marks the divide between two types (phases?) of granite of contrasting physical properties.

5.4.3 *EM*

Additional EM data were collected on lines 470SW and 500SW of the main Grid 1. The occurrence of more uniform, shallow bedrock to the southeast of the gully (near 100SE) is clearly indicated by the coincidence of near-zero readings from both coil orientations and all three separations. Values exceed 10 mS/m to the northwest but the rapid reduction in level as the coil separation increases is good evidence that the regolith, although conductive, remains thin.

Despite some marked variations over the northwestern section of the profiles, there is no example of the classic, steeply-dipping conductor response which could be linked to a major fracture zone. A broad high is seen in the vertical coil data, centred about 40 m northwest of the gully and this ties in with the wedge of regolith interpreted from the seismic results. The horizontal coil data here are characteristic of a thin, flat-lying conductor with its edges

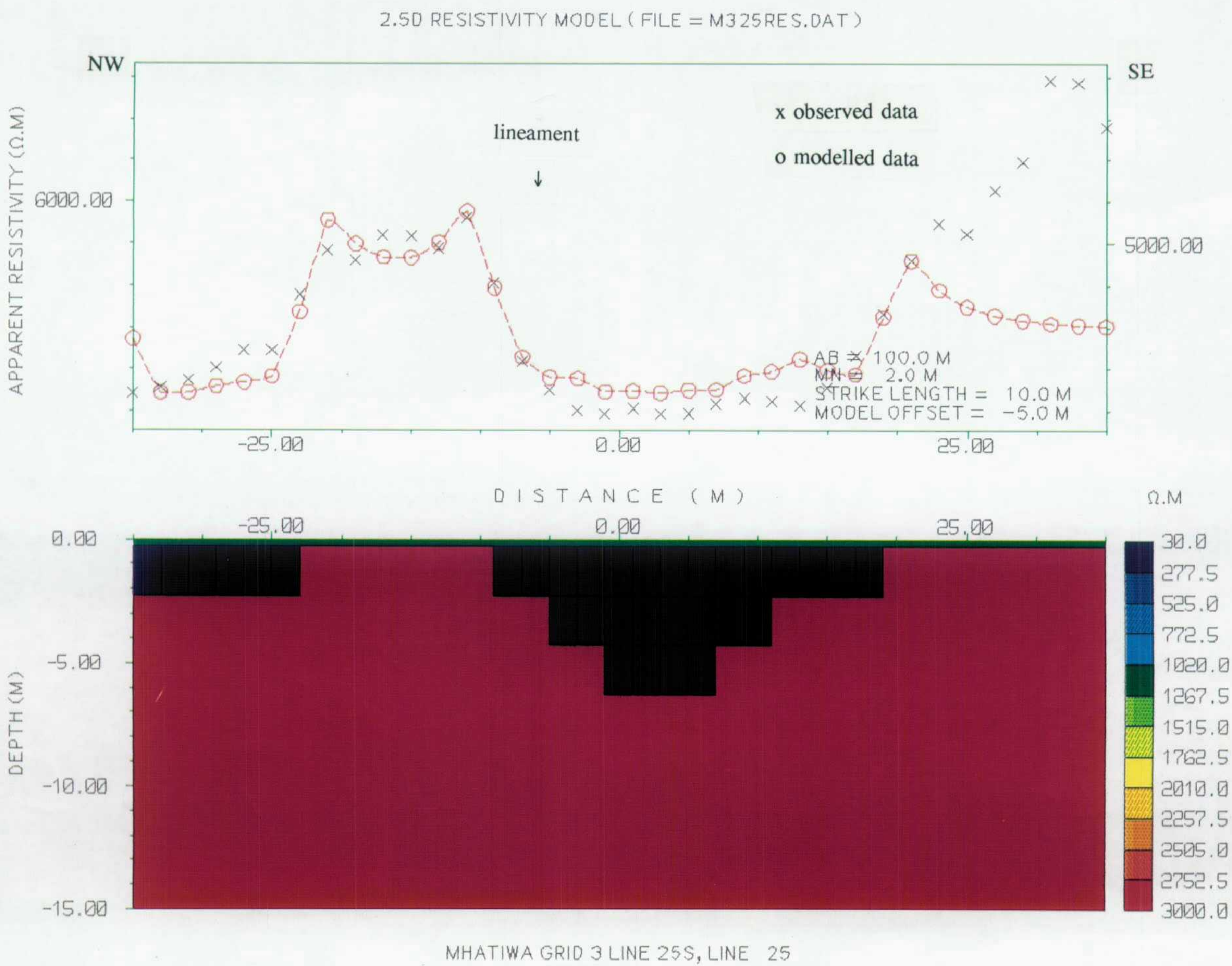


Figure 5.12 Gradient array resistivity model from Grid 3, Line 25SW

being associated with the minima best seen at the 20 m coil separation (Fig 5.13). The distinctive anomaly high in the horizontal coil response near 15SE on line 500SW coincides with a marked thinning of the regolith. The equivalent anomaly on line 470SW is less distinctive at the closer separations, suggesting that the cover is somewhat thicker here.

5.4.4 *Magnetic modelling*

Kappameter readings were made in-situ at sites on Grid 1 where the earlier magnetic total field survey had indicated anomalous values. The observed susceptibility values ranged between 0.24 and 5.67 with only occasional correlation between these values and total field anomalies. The inclusion of these observed magnetic susceptibility data (including core sample values) has permitted more realistic modelling, although it should be noted that Kappameter readings taken in-situ on unprepared, rough surfaces are likely to be underestimated by a factor of at least two.

The negative magnetic anomaly (rather unimpressive on this particular line) associated with the main lineament of Grid 1 can be modelled by a 60 m wide body of negative susceptibility contrast (-5×10^{-3} SI units) lying between c.30SE and 90SE, and dipping to the northwest. This is thought to represent a pegmatite-rich zone. The fact that pegmatites and quartz veins are seen to be preferentially weathered in outcrop may partly explain the seismic refraction indication of deeper bedrock here.

The total field profile of line 40SW at Grid 3 (Fig 5.14) is considerably quieter and the negative anomaly associated with the lineament relatively more impressive than at Grid 1. Three low and one high susceptibility bodies (respectively pegmatite rich zones and magnetite/ilmenite rich foliations) account well for the observed field. This result is broadly consistent with both the seismic refraction and resistivity observations of deeper weathering, and core drilling which encountered extensive pegmatites. Similarly, the more subdued nature of the magnetic profile here is reflected in the difference in magnetic susceptibilities measured on the core samples from sites D and E.

5.5 Synthesis and conclusions

Despite the clear and extensive nature of the photolineaments passing through Mhatiwa little evidence was found of any major underlying structure. The steep fracturing and core loss at Site D to an inclined depth of 12 m, which then gives way to pegmatite and silicified granite, could be interpreted as injection along an earlier fracture system. A more general, regional association of pegmatites (and other infilling) with the fractures is suggested both by the geophysical evidence and the number of low-yielding or dry boreholes.

The experience of Site E emphasises the need to exercise caution in over-reliance on the expression of photolineaments as an indication of underlying structure, even in this type of area where the regolith is thin. The surface geophysical data indicate strike-extensive features (particularly magnetic anomalies) offset from the photolineament by up to 70 m. Time constraints prevented the drilling of these indications.

Although on the face of it the results from Mhatiwa are somewhat negative, they are nonetheless informative and highly significant, and go some way towards explaining the difficulties so often encountered in siting boreholes in this terrain. There can be little doubt that lineaments of this size, which are so conspicuous on aerial photographs and satellite imagery and which are important geomorphological features, represent real elements of the geology. What the Mhatiwa dataset demonstrates is that, despite their extent, such structures do not necessarily represent open fracture systems.

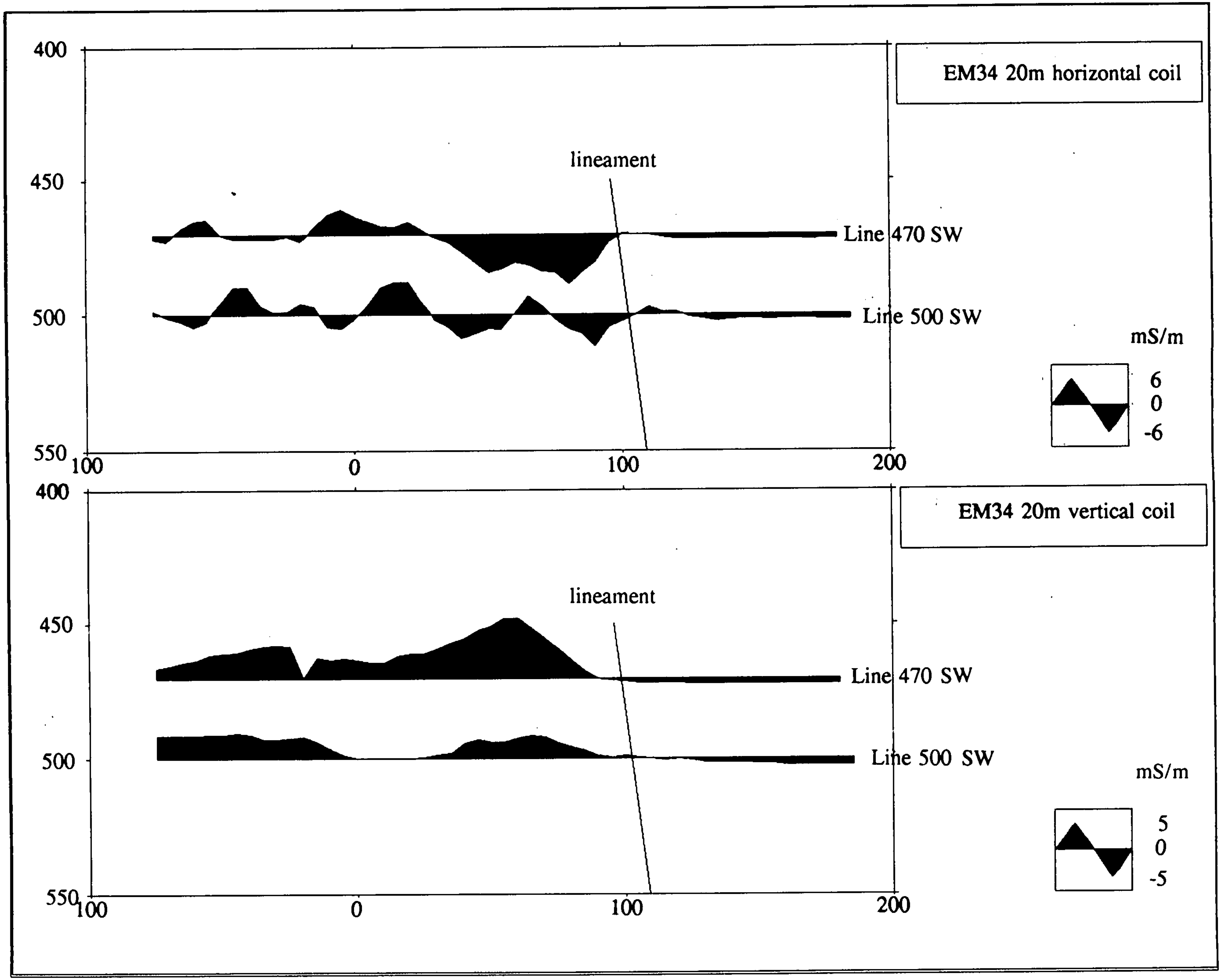


Figure 5.13 EM34 profile data (20m separation) from Grid 1, Line 500SW

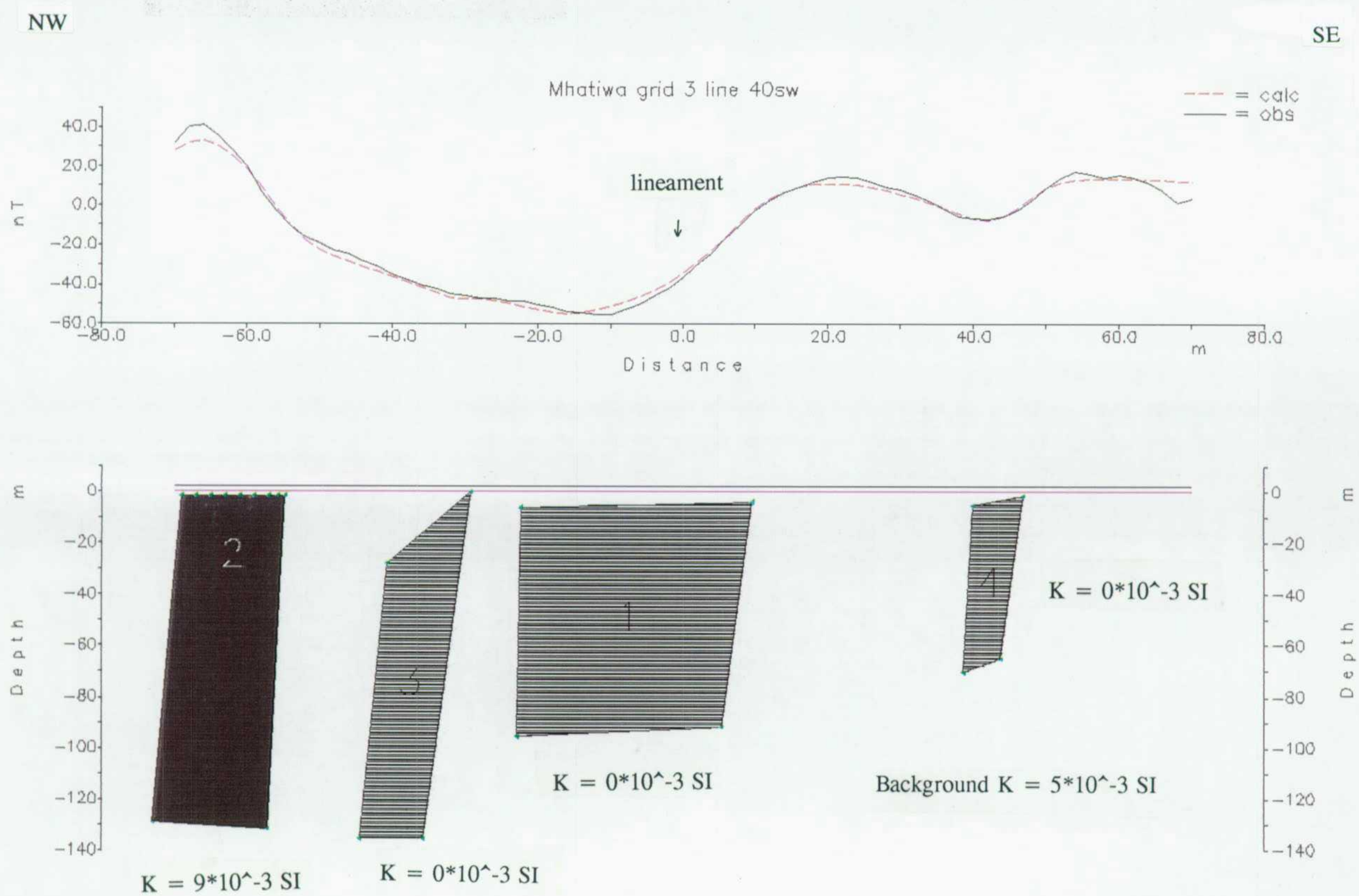


Figure 5.14 Magnetic model for Grid 3, Line 40SW

SARAHURU

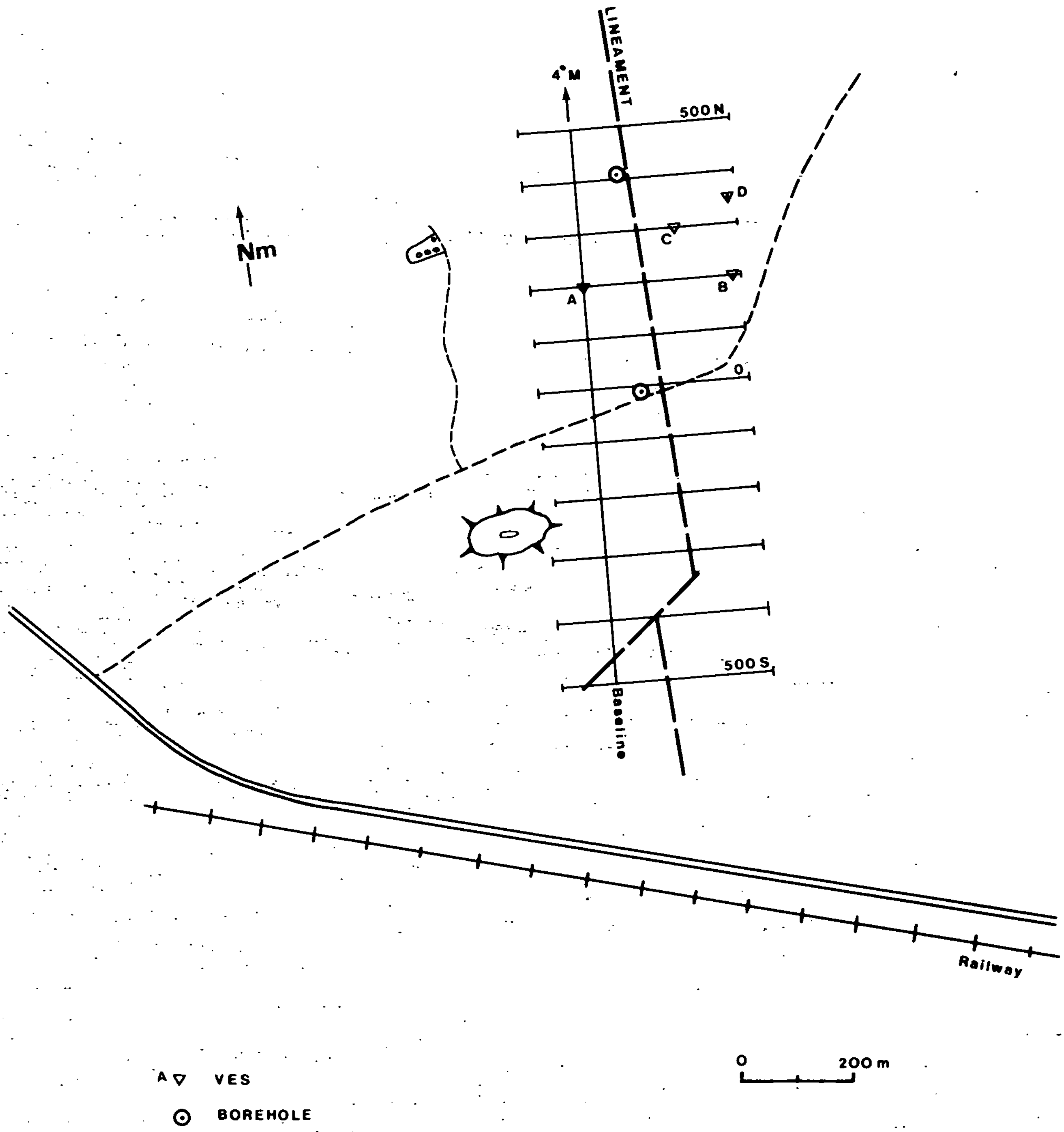


Figure 6.1 Sarahuru: survey grid plan

6. RESULTS FROM SARAHURU

6.1 Background

For logistical reasons, this site was studied only during the first phase of the geophysical fieldwork, despite the interesting nature of the results obtained. No additional drilling was undertaken here as the site was less typical of the granitic terrain of primary concern: it lies within the Northern Marginal Zone of the Limpopo Mobile Belt, in an area mapped as granitic gneisses and deformed mafic sheets metamorphosed to the granulite facies grade. The structure of the Limpopo Mobile Belt is extremely complex; the rocks have suffered intense polyphase metamorphism and deformation, and are sheared and mylonitised along many broad zones enclosing other regions of lesser deformation. The region is thought to represent the reworked equivalents of the rocks of the Zimbabwe Craton immediately to the north (Cox *et al.*, 1965; Barton, 1983). The Northern Marginal Zone within Zimbabwe appears to represent a wide ductile shear zone thrust at a low angle NNW onto the granites and greenstones of the Craton (James, 1975).

On Landsat TM imagery the Limpopo Belt appears as an area of strongly aligned fold axes trending ENE. Complex structures are visible, and it is evident that the region is more complicated than much of the existing geological mapping suggests. The darker tones of mafic granulite units are clearly visible and emphasise the highly deformed nature of the region.

Several NNE and NNW lineaments occur in the area, as well as numerous ENE lineaments corresponding to foliation and fracturing parallel to the main structural trend of the Limpopo Belt. At Sarahuru, the satellite imagery and aerial photographs show the existence of a marked lineament traceable for some 30 km, trending approximately N162E regionally. The regional extent of this lineament and its more-or-less straight form suggest it to be a vertical or near-vertical structure. This feature is unlike many of those seen elsewhere in that it is much broader (up to about 80 m) and strongly associated with prolific vegetation and dark soil tones. It bears some similarities to a dyke, but possibly one more deeply weathered than others to the north and covered by a thicker zone of regolith. This is perhaps confirmed by the drilling previously undertaken by BGS which found weathered rock to about 37 m in a well where the yield exceeded 5 l/s. The drillers also recorded the presence of hornblende chips below this level, lending support to the idea that this is a fracture filled by a now-metamorphosed dyke.

6.2 Description of fieldwork

This was the only site at which an extensive amount of line cutting had to be undertaken in order to establish straight lines through the patchy thorn scrub which tended to lie in a zone following the course of the lineation; away from this zone the bush had been cleared for cultivation. The origin of the grid was established at a large tree near the productive new borehole and west-east lines, 400 m in length, were cut at 100 m intervals for 500 m to either side of it (Fig 6.1). The baseline ran parallel to the general trend of the lineation and about 100 m to the west of it.

Elevations were determined over the full grid by optical levelling and all of the available techniques except for VLF were applied. Schlumberger resistivity soundings were located at four sites: 200N/00 (an orthogonal pair); 200N/292E; 300N/190E and 300N/300E while dipole-dipole pseudosections were obtained for parts of lines 200N (using both 5 m and 10 m dipoles) and 200S (with 10 m dipoles). Complete coverage was obtained with the gradient array employing a current electrode separation of 500 m. Slingram measurements were obtained with coil separations of 60 m and 100 m and a nearly complete set of EM34 data was also recorded. The grid was fully covered with total field magnetics and gradiometer results were collected over most of it.

The more conductive environment prevailing at Sarahuru meant that conditions were more favourable for testing the TEM technique and usable data were provided from lines 200S and 200N; progress was however slow due to the problems of laying out a 5 m square transmitter loop through the scrub beside the cut sections of line.

A limited number of radiometric measurements were taken over the central part of the grid.

6.3 Summary and conclusions

The occurrence of black-cotton soils and a correlation between northerly trending magnetic and conductivity anomalies strongly suggest that a basic dyke is associated with the lineation. Despite some drilling evidence that the weathering extends much deeper at this site compared to the others nearer Masvingo, the difference in geophysical response arises predominantly from a veneer of highly conductive material associated with these black-cotton soils. The influence of any intermediate layers tends to be suppressed due to the large resistivity contrast between the surficial layer and bedrock. It is suggested that the increased depth of weathering proved in the borehole near line 00 results from its location in a fracture zone that has not been delineated by the geophysical survey owing to its E-W trend (i.e. paralleling the geophysical traverse direction).

The gradient array results were less informative in this environment, probably due to masking by the overburden. Conversely, the EM methods were more satisfactory and, with conductivities measured by the EM34 reaching 70 mS/m, the EM47 provided usable data.

Magnetic profiling was particularly effective and quickly established the main features of the trends associated with the lineation. A more detailed assessment of the course of the dyke/sill and the nature of the large anomalies near the margins of the grid would have been possible given additional infill traversing; in particular, the change in anomaly character near Line 00 and the indication of cross-cutting features following the Limpopo Mobile Belt trend warrant further investigation for a better understanding of this site. A more reliable interpretation of the dip and depth to the source of the anomalies depends on getting some idea of its magnetic properties, either from measurements on related outcrop or from borehole control at two or more points.

The EM34 data complemented the magnetic results (Fig 6.2) as they respond mainly to the less-magnetic weathering products derived from the intrusion and indicate the presence of other zones which may represent associated fracturing; they also give clear evidence of the superficial nature of the main conductor.

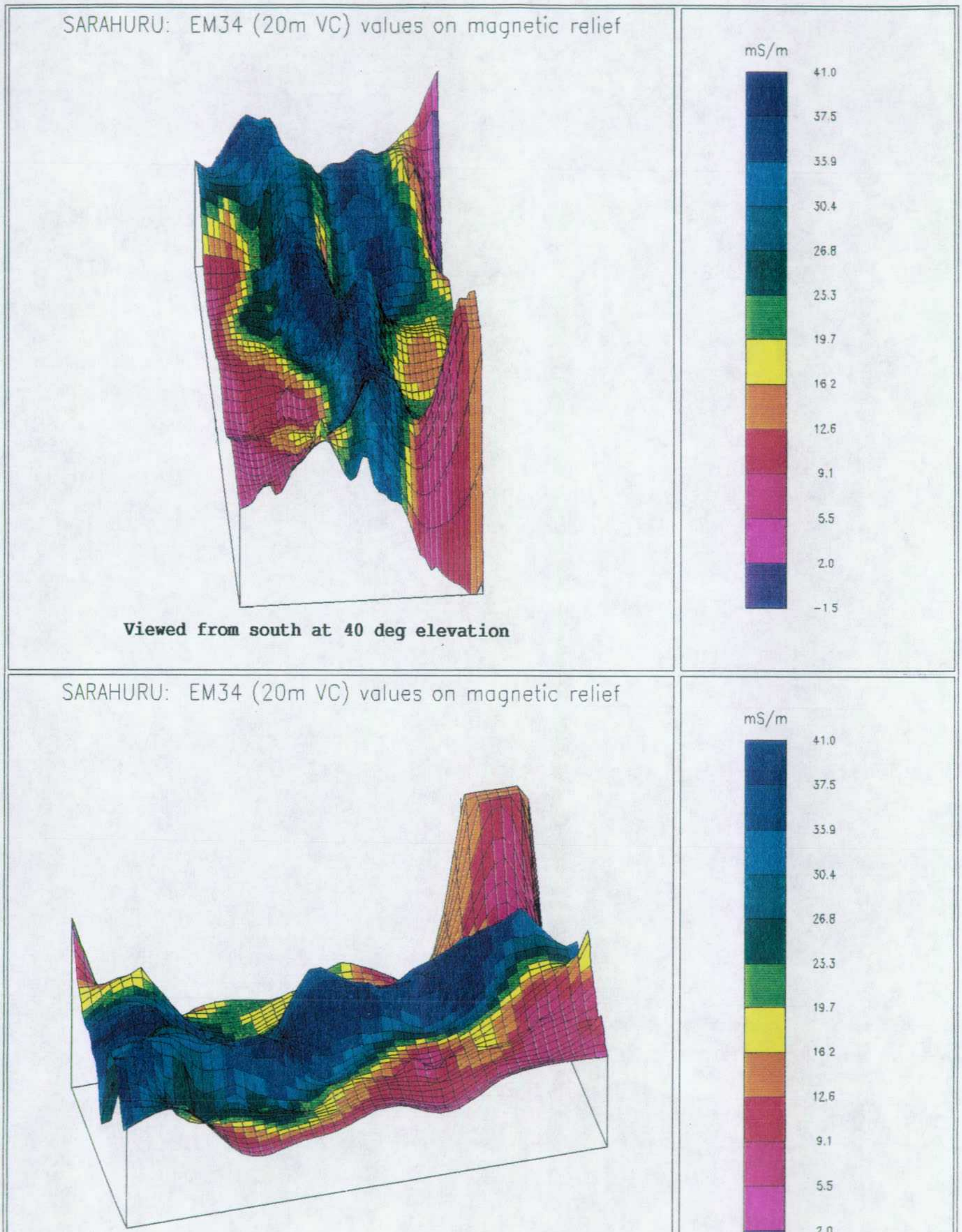


Figure 6.2 Combined plot of EM34 and magnetic data from Sarahuru

7. MODELLING STUDIES

7.1 3D resistivity fracture zone response

Preliminary 3D modelling has been completed for the type of resistivity structure expected across a fracture zone associated with a vlei (Fig 7.1). This assumes that a preferentially weathered zone overlies a lineament, extending for perhaps 15 m laterally, and with conductive grey clays (resistivities typically 20-50 ohm-m) to a depth of about 3 m within the vlei. Enhanced weathering, locally increasing the depth to bedrock, is also likely beneath these clays but any fracturing within the bedrock attributable directly to the lineament is expected to provide a much smaller resistivity anomaly, with its reduced width and resistivity contrast offsetting the large depth extent.

The objectives of the modelling were as follows:

1. to determine the lateral resolution of the gradient array in terms of mapping the near surface weathered zone;

2. to assess whether a narrower, partially weathered fault zone, of great depth extent could be distinguished when situated beneath the near surface zone described above.

3. to assess the effect of dip of the fracture zone.

Four 3-D models have been constructed as shown in Figure 7.1: model (a) represents the near surface zone alone; model (b) includes a vertical fault-zone; model (c) is the vertical fault alone; model (d) simulates an inclined fault zone. The adopted resistivity values were based on the results obtained in the field. The resistivity model sections are also shown in Figure 7.2 using the same colour coding as for the calculated apparent resistivities. Also included in plan in Figure 7.2 are the colour-filled contours produced from the computer modelling.

The results indicate the extremely good resolution of the method to lateral resistivity changes in the near-surface layers. In model (b), the response due to the near-surface zone tends to dominate the deeper and narrower zone representing the fault but a secondary low which coincides with the position of the model fault can be seen at the centre of the main anomaly. Models (c) and (d) show similar responses, with a slight relative reduction in resistivity seen in Figure 7.2(iid) overlying the inclined portion of the fault. A slight asymmetry in the model has tended to obscure this effect in the raw apparent resistivity data.

The effect of the simulated fault has been emphasised by displaying the calculated resistivities for models (a) and (b) over the restricted resistivity range 100-300 ohm.m. These results (Fig 7.3) show the effect of the simulated fault as a more distinct anomaly although edge effects of the modelling tend to obscure the difference between the two cases. Taking the fractional difference between models (a) and (b) further enhances the fault response, which now corresponds in lateral extent with the model fault (Fig 7.4(i)). The observed change in anomaly of 25% should be detectable in favourable field conditions where the background geological 'noise' levels are low.

The effect of the dipping fault was enhanced in a similar way by plotting the fractional difference between the vertical and inclined cases (Fig 7.4(ii)). The results show good agreement with the position of the incline, with a maximum difference of 20%. This magnitude of anomaly variation is clearly resolvable in the field although, again, only assuming a uniform background response.

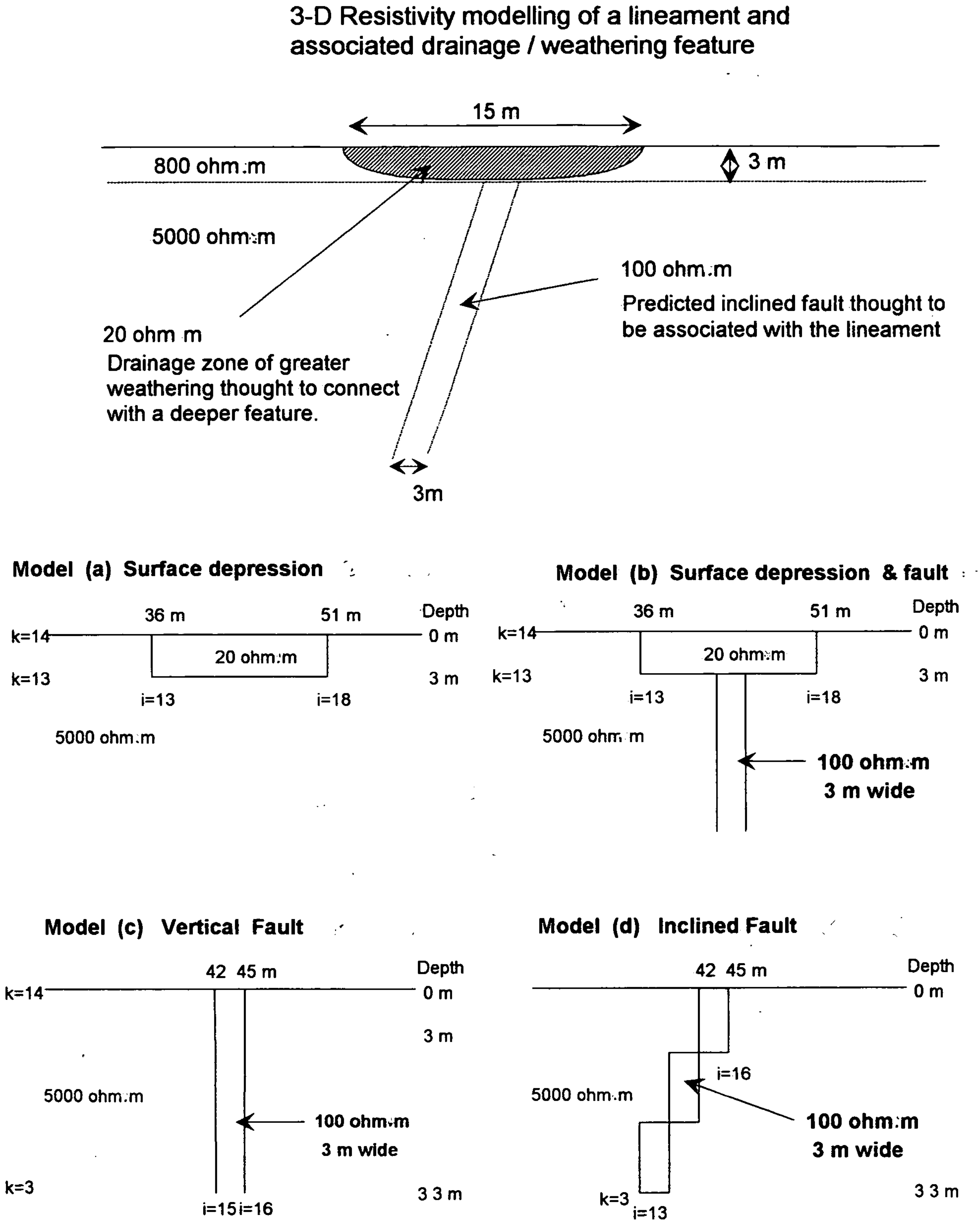
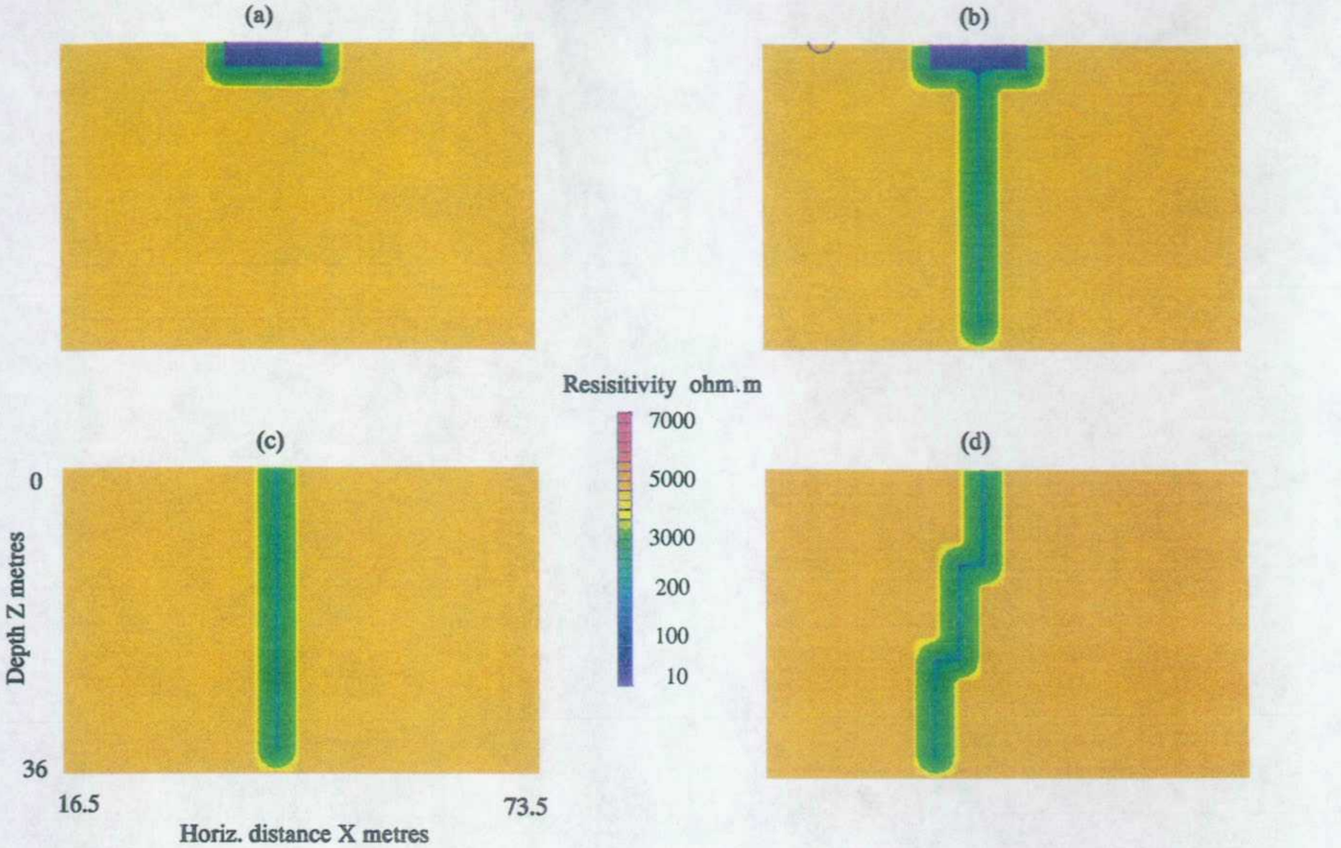


Figure 7.1 Schematic sections of geological setting and resistivity models



(i) model cross-sections

(ii) calculated surface resistivity response

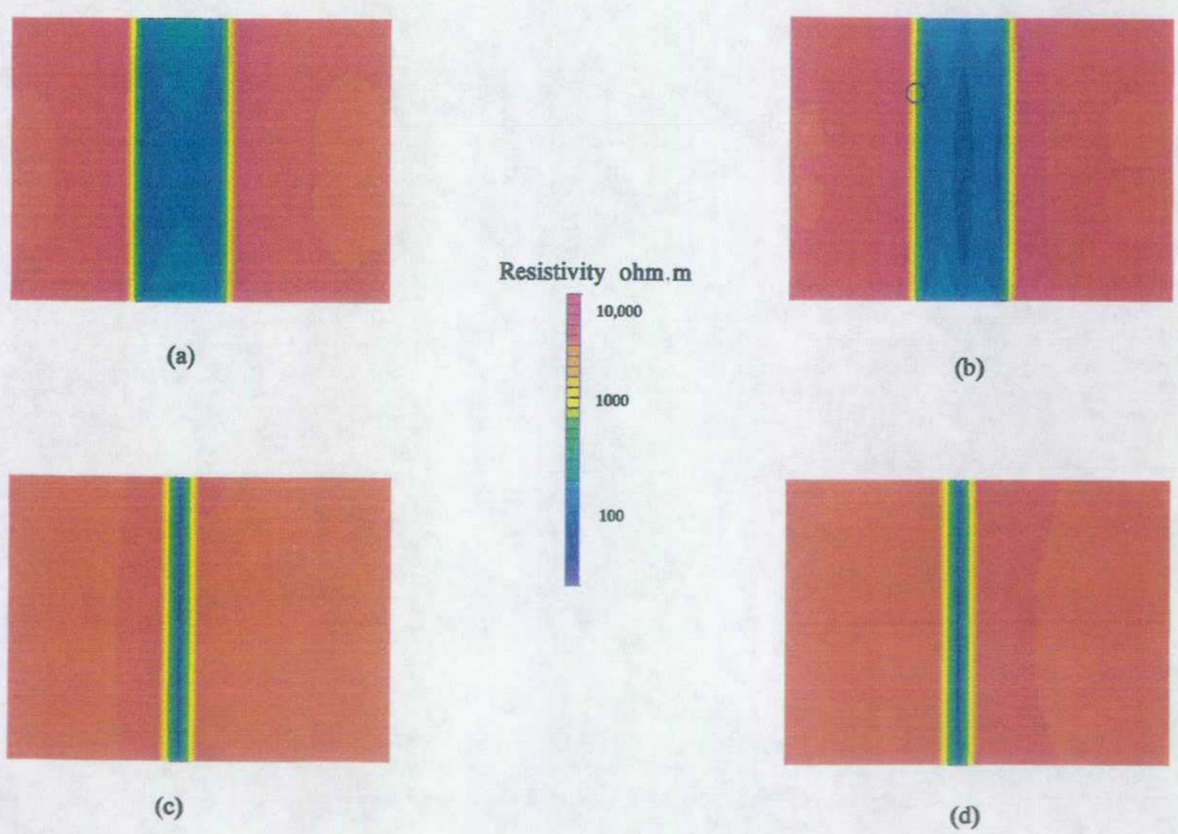


Figure 7.2 Comparison of models and calculated responses

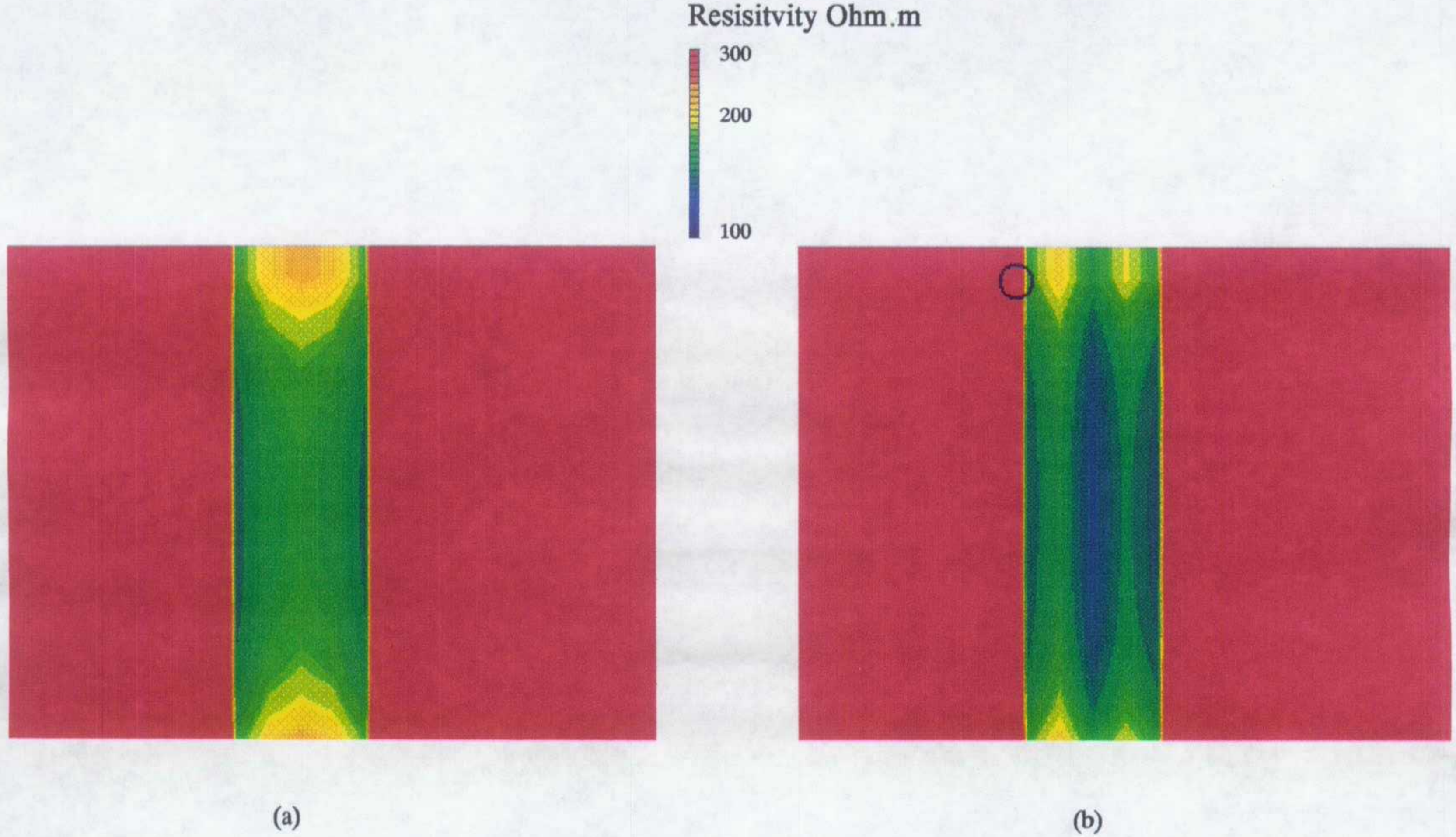
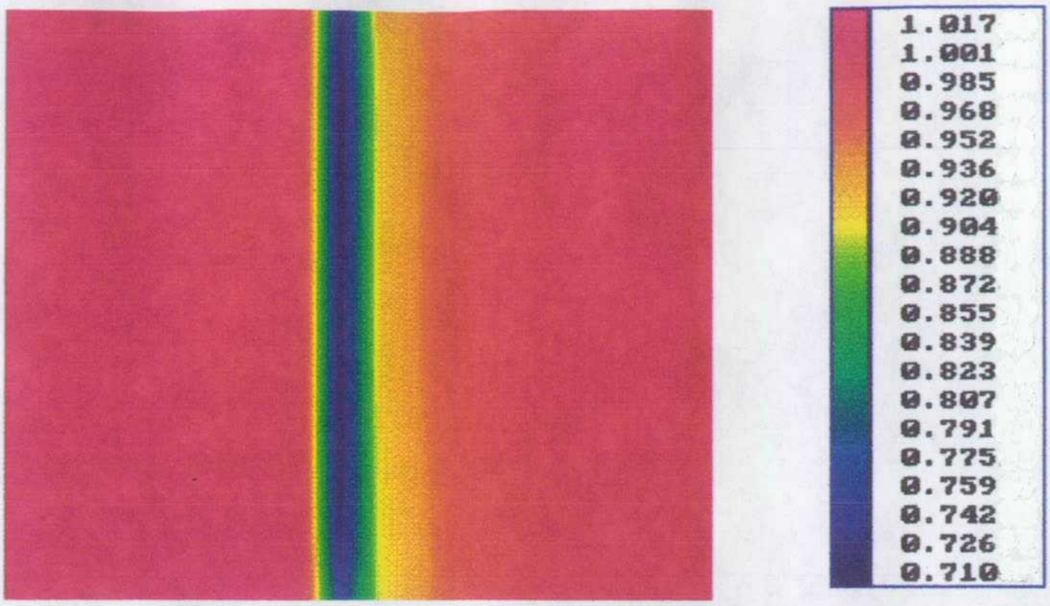
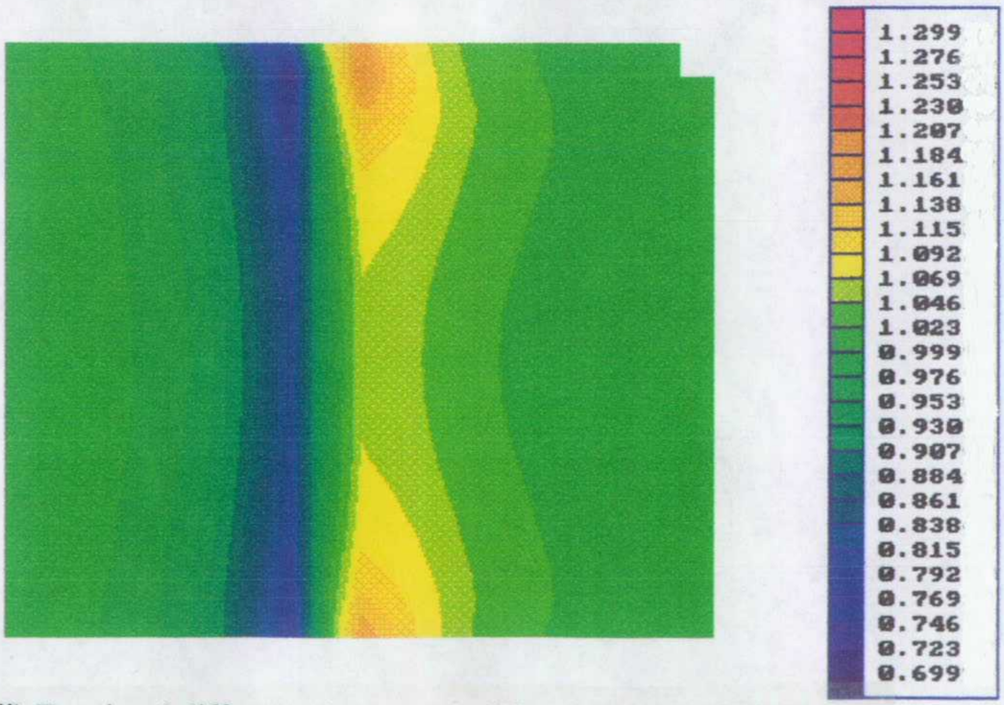


Figure 7.3 Expanded plot of calculated response from models (a) and (b)



(i) Fractional difference between models (a) and (b) of Figure 7.1



(ii) Fractional difference between models (c) and (d) of Figure 7.1

Figure 7.4 Fractional difference plots for pairs of models

Further modelling, using examples of field data, may provide greater insight into the practicality of identifying such changes. However, the evidence from the sites investigated here suggests that the shallow basement terrain is too variable both laterally and with depth to distinguish the expected type of signature. It also has to be remembered that the differencing technique needed to enhance the results relies on the ability to define a reference against which to compare the response.

7.2 3D resistivity bedrock depression response

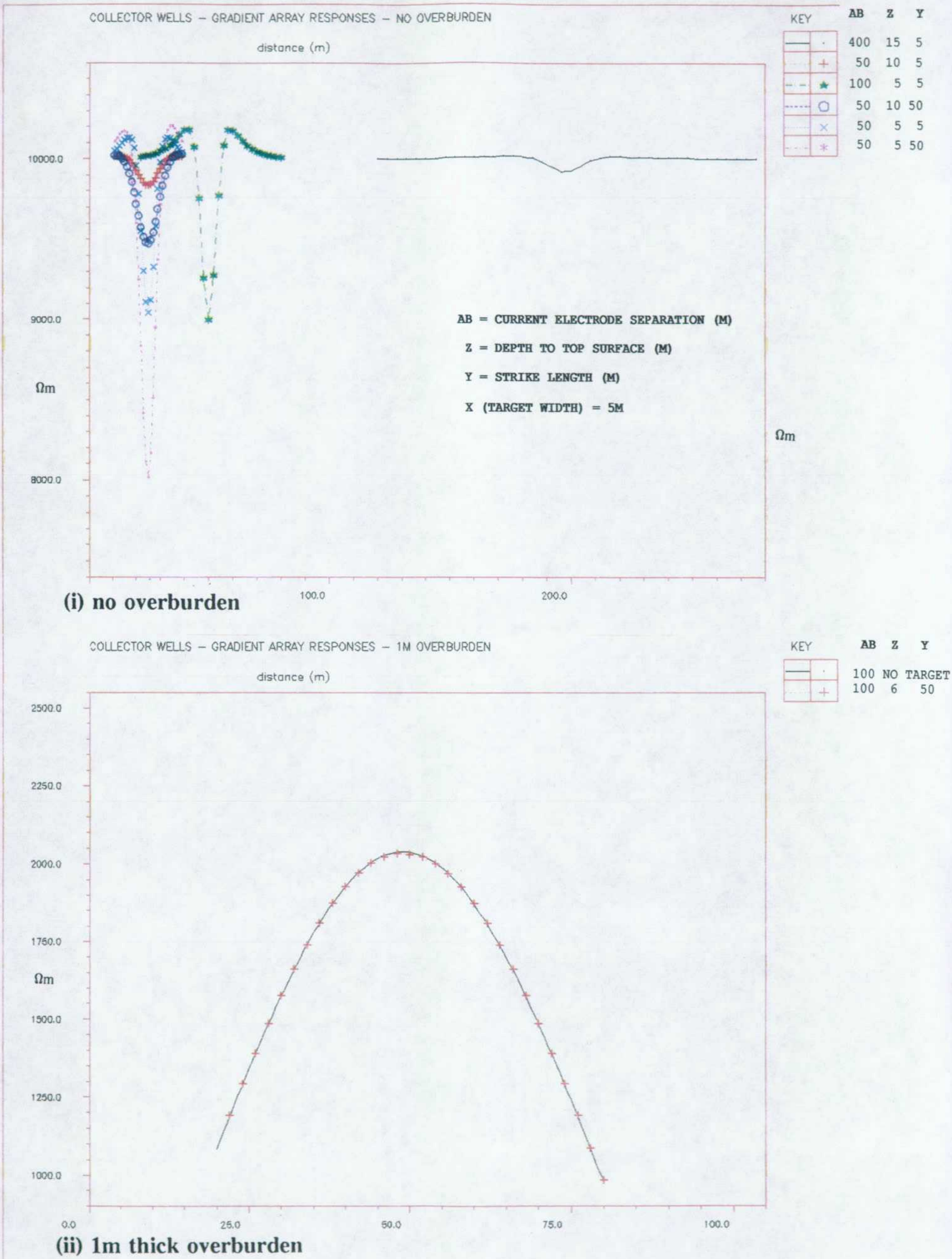
Ideally, collector wells should be sunk into the locally deepest parts of the weathered profile which will act as groundwater sumps. Thus, the aim of this modelling, undertaken using the RES3D program, was to determine the resolving power of the gradient array in detecting depressions on a buried bedrock surface. A limitation of RES3D required that these depressions (of relatively low resistivity) be treated as isolated anomalous volumes lying at varying depths within resistive basement, whereas in reality they occur as downwards extensions of the weathered layer. As the overlying weathered layer is relatively conductive it will have a suppressing effect on the gradient array response, and so the results of this predictive modelling should be considered as a best-case scenario.

Experience suggests that these depressions may display relief of up to 5 m and extend over a diameter of between 5 m and 10 m at depths of 5 m to 20 m. Accordingly the responses were calculated initially for a conductive cube of side 5 m and specific resistivity 150 ohm.m set in a resistive host (10000 ohm.m) at depths between 5 m and 16 m. Subsequently the effects of varying thicknesses of conductive overburden (between 1 m and 3 m of 50 ohm.m), varying strike length of the conductive target (between 5 m and 200 m) and varying current electrode separations (AB from 50 m to 400 m) were also examined. A selection of the observed responses is displayed in Figure 7.5(i) and (ii); for each example the target is set at the centre of the electrode spread and the anomaly is symmetrical about it.

With the top of the target (cube of side 5 m) set at 15 m depth, the response is barely perceptible (0.6% for AB 50 m and 1.2% for AB 400 m), even in the absence of overburden. Such minute anomalies would certainly not be discernable under field conditions. Still in the absence of overburden and with the target raised to 10 m depth, the response has increased to between 2% (AB 50 m) and 2.4% (AB 400 m) but it is doubtful that such features would be detectable in the presence of geological noise. With the target set at a depth of only 5 m a clearly defined anomaly results, with positive shoulders and total amplitude of some 10% to 12% (maximum at AB 100 m).

Increasing the strike length has a dramatic effect on the anomaly amplitude, as the target geometry approaches the fracture zone (2D) situation. The response with the target at 10 m depth (again with no overburden) increases from 2.3% to 6.5% as its strike length is increased from 5 m to 50 m, although there is no further increase in amplitude for strike lengths greater than about 50 m. With the target at 5 m depth even greater increases in amplitude with increasing strike length were recorded (from 12% to 25%). The current electrode separation (AB) had surprisingly little influence on the size of the response at all three depths.

The inclusion in the model of just 1 m of conductive overburden (at 50 ohm.m) had an alarming effect on all the responses, with that of even the shallowest target (6 m) with 50 m strike extent becoming indiscernible in relation to the accuracy of measurements in the field (Fig 7.5). The dominant parabolic shape of the response curve is a characteristic geometric effect seen with the gradient array over a layered earth: as the potential dipole approaches a current electrode the apparent resistivity becomes closer to that of the uppermost layers.



(i) no overburden

(ii) 1m thick overburden

Figure 7.5 Calculated gradient array responses over bedrock depression

This distortion influences the observed values even over the central section of the array to which measurements should normally be restricted and adds to the difficulty of recognising the target response in practice, even under more favourable circumstances. With a homogeneous earth, as in the previous examples, the background response is constant.

Recalling that these responses are likely to be the most favourable cases, due to the constraints of RES3D and the absence of geological noise, then it appears that the gradient array will have very limited application in the search for collector well sites in the type of environment outlined above.

7.3 EM34 model response

Analogue scale modelling of EM data can reproduce the effects of metallic conductors but it is difficult to find or to make materials that are representative of the intermediate conductivities relevant to the present problem. The alternative approach, of using numerical modelling techniques, is inherently more difficult than the resistivity equivalent because of the additional complexity of the mathematical expressions which have to be solved. Numerical solutions of the 1D layered earth and dipping plate models have been available for several years but more flexible 3D programs are still under development. Access to one of the latter was obtained for this project and modifications were made to adapt it for calculating EM34 results directly (in collaboration with the Australian institute with overall responsibility for the program).

The program uses a model with three components: a horizontally layered overburden and an underlying host medium within which a target is situated. The target comprises a block of rectangular cells to which resistivities can be assigned individually. As computing time increases rapidly with the number of cells it is preferable to keep the models as simple as possible and a nominal limit is set of 7x7x7 cells.

While significant progress was made in the design and implementation of a graphics input interface program, problems remained with the basic calculation algorithm for the specific requirements of the project i.e. reproducing EM34 response data in both horizontal and vertical coil configurations. As the resolution of these difficulties relied on the designers of the source code, it proved impossible to provide a fully operational version of the program within the time-scale of this project. Nevertheless, the results of this work will be valuable in the future evaluation of aquifer systems in basement terrains.

8. IMPLICATIONS FOR COLLECTOR WELL SITING

8.1 General points

As noted above (Section 7.2), a primary objective in siting collector wells in crystalline basement terrain is to locate local depressions in the bedrock surface, typically within an operating depth range of 10-20 m. Ideally, the nature of the weathered material would also be assessed for the availability of water and to identify the more permeable zones within it. This is a standard geophysical problem for which the electrical (resistivity and EM) and seismic refraction techniques are usually most appropriate, the latter often being more definitive but significantly slower in operation.

Bedrock mapping is straightforward in principle, the main limitation being on the number of parameters which are allowed to vary before the range of possible solutions becomes unacceptable. In the simplest 2-layer case, there are three potential variables i.e. the depth to the interface and the value of the property being measured (resistivity or seismic velocity) in the two media. A 1D model approximation is adequate if the lateral changes are on a broad enough scale; this permits simplification of field procedures and a reliable interpretation would be expected. For example, the conductance (ratio of thickness to resistivity) of the overburden is measured by a single Schlumberger traverse providing the current electrode separation is at least three times the maximum depth to a resistive bedrock; resistivities within the overburden can be monitored using a short electrode spacing (less than the minimum thickness) if necessary.

The gradient array modelling (described above) illustrates how quickly the resolution of resistivity techniques decreases with factors such as a reduction in the diameter of the depression, an increase in its depth and, more especially, the presence of a conductive superficial cover. In all cases, detection limits will be further reduced by the superposition of anomalies from geological 'noise' i.e. other variations within the regolith. While it is theoretically possible to model complex 2D and 3D resistivity distributions, the starting models are rarely constrained sufficiently for the effects of specific interest to be isolated *a priori* for routine exploration purposes. However, forward 2D modelling can be undertaken as a guide to the type of anomalies to be expected (e.g. Radstake *et al.*, 1991) and portable computers permit calculation in the field if required. Borehole control would obviously limit the range of allowed solutions but location of a site by further drilling may prove more cost effective than a combination with such geophysical studies.

EM techniques suffer from similar limitations to resistivity, with an additional inherent loss of sensitivity in the more resistive environments. Their main advantages are the increased speed in collecting data, giving a direct indication of changes in overall ground conductivity both laterally and with depth, and avoiding the need to make electrical contract through grounded electrodes.

Seismic refraction undoubtedly offers the best prospects for mapping the bedrock surface in detail although not without its own difficulties. Experience from this and previous studies indicates the importance of a sufficiently powerful energy source, even when a sensitive, signal averaging recording system is available. The hammer/plate system is generally inadequate for the offset shots needed for efficient bedrock coverage but a heavier weight-drop system constructed locally for earlier BGS investigations (Smith and Raines, 1988) proved too cumbersome and gave insufficient improvement to justify its routine use. Small explosive charges would be ideal if both the logistical problems of storage, security etc. could be solved and augering shallow shot-holes (0.5-1 m deep) was practical. Other commercial energy sources which are produced would not usually be available in developing countries.

Seismic interpretation in terms of uniform dipping layers is inappropriate and a delay-time type of approach with full reversed coverage must be employed in general. It is also necessary to design the fieldwork so that there is adequate control on velocities within the upper part of the sequence. This will usually require a geophone separation of 2-4 m and a shot point interval of 20-30 m; in-line offset shots are used to provide complete coverage from the bedrock refractor.

There is no evidence that geophysical data can pick up the more permeable, granular zones near the bedrock surface. However, it is possible that trends identified from the data may be associated with the development of such zones or point to preferred directions for drilling the radials from a well site.

8.2 Recommended survey approach

Although relatively simple in concept, shallow basement terrain comprises a set of components of variable properties, whose boundaries are often very irregular and indistinct. In these circumstances, the resolution available from geophysical survey techniques is limited, leading to discrepancies between interpretations and individual borehole sites. Nevertheless, the geophysical data can highlight specific features to guide the siting programme and, if required, to interpolate between exploratory boreholes.

EM traversing is a rapid means of mapping conductive zones within the regolith and can differentiate superficial clays from a thicker saprolite. Narrow dipping conductors give a characteristic response which may indicate enhanced weathering above fractured bedrock. Reconnaissance profiles at a 20 m coil separation (horizontal and vertical orientations) can be supplemented with 10 m and 40 m data in anomalous areas. Data should ideally be collected on a grid basis; at least, line directions should be varied as this may influence anomaly response. Areas showing persistently low conductivities using EM equipment are unlikely to be prospective for collector well purposes but resistivity profiling may be appropriate to confirm the calibration of the EM equipment and that values are above an acceptable limit (typically 200 ohm.m).

Resistivity soundings (VES) should be used to estimate 'average' depths to bedrock, particularly in areas where the EM results indicate it to be relatively deep. VES need to be sited over the more uniform ground and results are required from orthogonal spreads as a check against lateral variations.

Seismic refraction is best used selectively across the more promising sites interpreted from the electrical surveys. The bedrock geometry should be confirmed at promising sites by means of parallel and orthogonally oriented spreads. All the available data should be considered in the final interpretation as the results are often complementary and help in reducing the ambiguity related to any one method.

It is important to ensure that geophysical studies are fully integrated into any exploration programme so that the results can be assessed on a continuing basis in terms of the naturre of the regolith and local groundwater regime as determined by drilling. As a minimum contribution, routine geophysical surveys (EM and resistivity) are valuable in excluding areas of shallow, massive bedrock from further consideration; in favourable situations, the form of the bedrock surface can also be mapped with sufficient reliability to guide exploratory drilling. Further developments in the design of EM equipment can be expected within the next few years, and any improvements in the resolution of near-surface variations will have a direct application to this type of environment. The difficulties in modelling the 3D EM response will also be solved in the near future, allowing the range of suitable operating conditions to be set more rigorously.

9. GENERAL CONCLUSIONS

The evidence from the drilling programme suggests that, at least at the sites drilled, the photolineaments do not correspond to ***major*** open fracture systems of the type expected. In the case of BH/3 (Nanwi) and BH/4 (Mhatiwa - Grid 3) it is apparent from the geological logs and generally from the geophysical logs that the holes passed through zones of increased fracturing/fissuring/veining which, compared to the deeper levels in the hole (showing only massive rock with high core recovery) *could* represent permeable materials. The existence of these steep zones provides a physical explanation for the photolineament though this does not fully conform with the conceptual idea of a major, permeable fracture zone. At Mhatiwa Grid 3, for example, it would seem that the lineament is associated with the silicic replacement and pegmatite infilling of an ancient fracture. In BH/1 and BH/2 (Nemarundwe) it is not clear whether the holes penetrated a weak fracture zone, while BH/5 (Mhatiwa Grid 1) evidently did not intersect the expected structure.

What emerges from the drilling, resistivity logging and tomography is that at some sites (particularly Nanwi) sub-horizontal fracturing is more apparent than steep, open fractures. This may correspond to surface-parallel 'sheeting' which is common in granitic terrains and is thought to be a product of tensional unloading and pressure release associated with erosion (Ollier, 1984). Though poorly expressed on photographs and imagery, sheeting is commonly seen in road-cuts, quarries and 'castle kopjes', suggesting it to be a widespread sub-surface phenomenon. Such fractures appear to be most abundant in the immediate surface zone and decrease in frequency with depth (increased lithostatic loading). Tensional fractures of this type have a tendency to form open structures but because individually they are not very extensive and may not have a surface connection, they have not been generally regarded as significant in the occurrence of groundwater.

Given the predominantly closed nature of steep fractures as observed in core, it is not surprising that many of the boreholes in the Masvingo area fail to provide an adequate handpump yield. Yet, at the same time it is necessary to explain why some boreholes along lineaments *do* give good supplies. A possible answer is that, although steep shear planes do not regularly form open structures *over their full extent*, open conduits formed by fluid movement exist within some of them, perhaps developed preferentially at the intersections of cross-cutting fracture planes. If this is so, then the chance of a narrow borehole intersecting the open, water-bearing part of the fracture system will be slight. This would also account for the difficulty of identifying successful sites from geophysical evidence which reflects the bulk properties of the rock mass.

Based on these ideas, it is possible to propose a conceptual model that takes account of both the sub-vertical and sub-horizontal fractures to explain the existence of successful sites. Thus it is conjectured that, even where a steep fracture zone (corresponding to a photolineament) is only permeable in part (as described above), its intersection with associated sub-horizontal open fissuring may provide sufficient interconnections for the rock mass as a whole to make up a fractured aquifer. Not only does this imply increased storage but since the horizontal fractures are now part of an interconnecting fracture system, the target zone for siting a borehole is greatly increased away from the lineament itself. This hypothesis, though consistent with observations, cannot be *proved* by the available data. It provides a conceptual model for lineaments and, if correct, justifies their continued targeting in the face of the otherwise limited confirmation that the vertical zones in themselves form aquifers.

An added possibility is that in the vicinity of steep fracture zones the intensity of flat-lying fractures is higher (due to a general weakness of the rock mass) which could increase the chances of a water strike still further. A role for shallow-dipping fractures would also explain the phenomenon of multiple water strikes within a vertical borehole; this is more difficult to explain where the target is a single steep fracture zone.

Conventional surface geophysical techniques provide useful information on variations in the nature of both the regolith and the underlying bedrock. The best results are obtained where there is a direct link between the near-surface weathering profile and underlying structures, or where the structures are more significant in themselves. Thus, major open fracture systems should be detected, together with areas where the regolith is thick enough in itself to sustain hand-pump yields. In more marginal situations, the geophysical data will tend to improve success rates overall and provide indications of water quality, without guaranteeing success at any one location; the techniques are not, in general, capable of resolving the smaller-scale features which may by critical to the success of a borehole at any particular site. Further advances in the technology of ground-probing radar and EM survey techniques can be expected to provide additional exploration tools in the near future but an understanding of the local environment is still likely to be a key factor in their successful application.

10. RECOMMENDATIONS: A POSSIBLE STRATEGY FOR RURAL WATER SUPPLY

Based on several years research on basement aquifers in SE Zimbabwe we are of the opinion that what is needed is not just a better understanding of the geological controls (which are complex and variable), but also a new look at the overall strategy and logistics for rural water supply in districts such as Masvingo Province. The following paragraphs offer some thoughts on how our results could be applied in the context of an overall strategy for rural water supply.

The scattered nature of population distribution in rural Zimbabwe presents a problem for any borehole siting programme. Because large numbers of individual boreholes are needed, each serving only a small number of people, and because each must be sited within carrying distance, severe constraints apply to site selection. During routine siting programmes little time can be devoted to photogeological/geophysical methods (typically half a day) and some of the geologically better localities are necessarily excluded due to distance. These constraints perhaps partly explain the high failure rate. Maintaining the pumps on large numbers of boreholes also presents a major logistical difficulty. Breakdowns as a result of overpumping, which are common with low-yielding boreholes, only serve to increase the problem. The net result is that at any one time large numbers of pumps are likely to be unserviceable.

The severity of the recent drought in southern Africa has emphasised the need for a re-think of the long-term strategy for rural water supply. Given the above geological conditions and existing social constraints it seems unlikely that major improvements can be achieved wholly through new 'rapid siting' methods (although it is believed that systematic remote sensing combined with ground geophysical surveying can provide a higher success rate under certain conditions). Rather, we now believe that significant improvements in drilling success rate can only be achieved if (1) only the most promising sites are targeted, and (2) more time is allowed to investigate (and drill) each borehole. With this in mind an outline strategy is here proposed that we believe could provide longer term improvement and drought relief.

The concept involves the establishment of a network of higher-yielding boreholes each capable of providing a reliable supply during periods of severe shortage. Such a network would be superimposed upon the existing borehole system at a spacing that would permit supplies to be accessible to the majority of communities during times of drought. The new network, once established, would complement existing boreholes under 'normal' rainfall conditions, though high-yielding sites would form a priority for maintenance. These sources would provide a fallback during times of severe shortage. Many of the higher producers could be fitted with a motorised pump and possibly have storage and limited distribution facilities built.

The starting point would be a regional borehole/well network based upon some nominal spacing to be decided, but actual sites would depend on the distribution of local communities, communications networks (roads, tracks) and *the existence of favourable geological settings.* The new network would also take account of existing good producers which have a record of sustained yields throughout periods of drought; it is anticipated that the first stage would be to upgrade such boreholes. Having established a basic network and decided on the general target areas requiring new high-yielders, studies would be carried out to locate the most favourable drilling sites. This would be based initially on the identification of 'significant' lineaments (those having larger catchments and showing preserved dry-season vegetation), and would require the systematic use of satellite imagery and aerial photographs (see Greenbaum, 1992), and ground reconnaissance. This would be followed by detailed ground geophysical surveys at identified sites, and finally drilling.

Though there can be no simple long-term solution to water supply in areas of low, erratic rainfall and poor storage, it is considered that such an approach could provide a significant improvement over the present situation. What is proposed is not an 'immediate' solution but is one that is achievable in the medium term (5-10 years) and which may provide longer term security of supplies on a systematic basis. It is also felt that such a scheme could provide a natural and practical extension of the existing system.

Clearly, the scheme as outlined is no more than a simplified concept which would require considerable further thought and detailed planning. Such a programme could form the basis of a Technical Cooperation development project. An aid project of this type would not only provide a means of establishing a more stable rural water supply network without disrupting the essential ongoing work, but it would allow for the continued development of practical siting procedures arising out of this and other past studies carried out by BGS. It is recommended that further consideration be given to the implementation of such a programme.

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Final Report

Geological and geophysical characterisation of lineaments in southeast Zimbabwe and implications for groundwater exploration

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