ERITREA: SECTOR STUDY ON NATIONAL WATER RESOURCES AND IRRIGATION POTENTIAL

REPORT ON THE FIRST INPUT OF SURFACE GEOPHYSICS SPECIALIST (17 JUNE TO 13 AUGUST 1997) AND THE CORRELATION OF ACQUIRED GEOPHYSICAL DATA WITH SUBSEQUENT BOREHOLE CONTROL

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CONTENTS

FIGURES INCLUDED WITH THIS REPORT

ABBREVIATIONS USED IN THIS REPORT

DC	direct current
EM	electromagnetic
EM34	conductivity measuring equipment
GPS	global positioning system
mbgl	metres below ground level
rwl	rest water level
SP	spontaneous potential (geophysical log)
swl	standing water level
TDEM	time domain electromagnetics (a method of sounding)
VES	vertical electrical sounding (also known as DC sounding)
VLF	very low frequency electromagnetics
wth	weathered

1 INTRODUCTION

1.1 Objectives

The surface geophysical input is designed to assist in the characterisation of Eritrea' s various hydrogeological environments. In particular: to site boreholes in fractured zones in otherwise 'tight' lithologies (hopefully leading to enhanced yields), to delineate dolerite dykes that may control the flow of groundwater, to map the thickness and extent of basinal alluvial deposits and to define the presence and distribution of saline conditions. In addition, two Eritrean earth scientists will be trained in all aspects of groundwater geophysics and will be able to work independently following the completion of the specialist's four month input.

2 GENERAL APPROACH AND SURVEY PRODUCTION STATISTICS

Our work in this first phase has been largely dedicated to the investigation of fracture zones identified on 1:250 000 scale satellite imagery and/or described in published papers (eg by Drury et al, 1994). Figure 1 shows the approximate location of the geophysical, surveys conducted; precise details of the geophysical traverses made at each site (including GPS coordinates, bearings and distances) are included in figures presented for the individual locations (eg Fig. 3.1b_1 (Decamhare)).

The fracture zones to be investigated were located approximately in the field using GPS and one or more long (usually in excess of 1km) traverses were laid out normal to their strike direction.

All the available geophysical techniques were employed at the first two locations studied (Decamhare and Terra Emni). In this manner we confirmed that all the newly purchased equipment was working satisfactorily while our counterpart staff were given early exposure to the full range of available techniques. Our subsequent investigations of fracture zones have been confined largely to magnetometry, V(ery) L(ow) F(requency) EM and EM34 conductivity measurements. Appendices A and C show respectively the geophysical methods available to the Project and give a brief outline of the physical principles of these techniques.

To date twelve areas have been investigated and eleven promising borehole sites have been identified. The following total coverage has been achieved:

10.5 km conductivity traversing (EM34, 5 m station interval)
17 .2 km magnetometry (5 m station interval)
10.5 km VLF traversing (5 m station interval)
0.7 km resistivity traversing (dipole-dipole, N 1 to 6, 10 m interval)
DC electrical sounding (VES) 14
TDEM soundings 36

Summary sheets outlining the geophysical activities and coverage at each location are included with the figures enclosed with this report. Recommended borehole sites are included on these sheets (where appropriate) and are also tabulated in Section 4.

The raw field data has been processed and interpreted using a wide range of commercial and in house (British Geological Survey) software; details of the commercial software available to the Project are listed in Appendix B.

3 DETAIL OF SITES INVESTIGATED:

3.1 HIGHLAND ALLUVIALS:

3.1a Hazemo Plain (Mai-Aini)

Target and geophysical work completed:

The opportunity was taken to visit this site, remote from Asmara, with the project hydrogeologist who was undertaking a supervisory visit to the drilling crew during the first weekend of the geophysicist's input. The site was physically unconstrained and clearly free of electrical interference and hence it was decided to test the TDEM equipment here. A test/calibration TDEM sounding was made about 150 m from a project wildcat borehole, already in progress, in the centre of an extensive plain, sited to test the thickness and aquifer properties of both alluvials and the underlying Mesozoic Adigrat Sandstone (Fig. 3.1a_1). There was not sufficient time available to undertake more than one sounding on this occasion, neither was the intent to return to this site and investigate in detail the distribution of alluvium on the Hazemo Plain.

Existing data:

The project borehole proved 11 m of alluvials and bottomed at 102 m in Adigrat Sandstone. The Adigrat here is generally fine grained with shaley horizons. Borehole geophysical logs were run.

Results:

An interpretation of the TDEM sounding (Fig.3.1a_2) indicates potential aquifer conditions (resistivity in the range 20 to 130 ohm.m) to at least 72 m. It has not been possible to increase this modelled thickness significantly (to match the observed borehole results). Thus the Adigrat may become increasingly tight (and resistive) below about 80 m.

3.1b Decamhare (Gura airstrip) (E 504355 N1662469)

Target:

A regional-scale N-S trending satellite lineament, probably reflecting a major fault zone in this predominantly granitic terrain. This site was also chosen to investigate (in 2-D) possible variations in alluvium thickness across a broad plain.

Existing data:

The presence of recent boreholes within 3 km of our main traverse were reported but no data was made available. The current investigations include limited geophysical measurements made at a recent borehole in a nearby army camp (some 6 km south of our main traverse) and at a recently completed productive hand-dug well some 3 km south of main traverse.

Surface geophysical investigations conducted:

The full range of available geophysical techniques was applied at this 'show' geophysical site, proved with an initial conductivity traverse (ie: a profile enjoying an exceptionally well-defined anomaly, flat land, no fences or cultivated fields and easy access from Decamhare (Figs 3.1b_1 and 3.1b_2).

Subsequent investigations in this neighbourhood comprised measurements at the army camp borehole, the productive hand dug well and along a further traverse (some 2 km south of the initial profile) to test for continuity of the major fracture zone.

Results and recommendations:

A major, exceptionally well defined conductivity anomaly was detected with all coil separations and orientations on the initial traverse between stations 510 and 690 (Fig 3.1b_3). The conductivity profiles indicate an abrupt thickening of conductive material and thus probably reflect in-situ weathering products within a fracture zone rather than alluvial deposits.

TDEM and VES soundings were made at three characteristic locations selected from the conductivity profile (160 m, 446 m and 526 m) (Figs. 3.1b_4 to 3.1b_10); the interpreted sounding data is presented as two (uncontrolled) resistivity cross sections (Figs 3.1b_7 and 3.1b_11). These suggest contrasting conditions: TDEM data suggest the presence (at stations 446 and 526) of a shallow and thin conductive (4 ohm.m) horizon and shallow (c 20 m) hydrogeological basement, while the VES interpretation shows a more resistive (30 ohm.m) (and more likely aquiferous) horizon extending to some 40 m depth. This conflicting result could not be resolved within the limits of equivalence of the relevant soundings.

Additional (en echelon?) conductive fault/fracture/contact zones are suggested on both the VLF and magnetic profile (Figs 3.1b_12 and 3.1b_13) at stations 200 m, 300 m, 415 m and 460 m.

Geophysical measurements on the traverse some 2 km south (Fig 3.1b_14) did not yield such clear indications of a major fracture zone. The conductivity 'trough' between 480 m and 515 m (Fig 3.1b_15) results from instrumental fault. The step in the conductivity profile (Hc 40 m) at 545 m correlates with a step in the magnetic profile (Fig 3.1b_17) and may reflect a lithological contact but this does not display any associated conductivity and shows no VLF signature (Fig 3.1b_16). The apparent lack of consistent geophysical response along strike of the regional-scale fault zone is noteworthy.

Conditions near the army camp borehole were too electrically noisy for satisfactory TDEM measurement (Fig 3.1b_18). The VES made here (Fig 3.1b_19) indicate shallow resistive basement (at a depth of some 15 m) as proved by drilling.

The recently completed hand dug well in this area proved 12 m of regolith (with RWL at 9 m) overlying granite. The EM34 Hc 40 m values in the range 5 to 10 mS/m obtained at this site (Fig 3.1b_20) endorse the prospectivity of the main conductive zone at Decamhare where the respective range of values is 20 to 40 mS/m.

It is recommended that a borehole be drilled to 50m depth at station 580 m on Traverse 1.

3.2 TERTIARY FLOOD BASALTS:

3.2a Terra Emni (482700 E 1659900 N)

Targets:

a) zones of relatively thin basalt cover on basement (ie relatively shallow indurated (aquiferous?) contact zones)

b) thick, permeable intraflow horizons

c) fault/fracture zones (ie sub-vertical zones of enhanced permeability).

Existing data:

The large diameter (6 m) well near station 300 m (Traverse 1) reveals c 3m of black cotton soil overlying very weathered (and highly vesicular) basalt to its total depth of 8 m.

Surface geophysical investigations conducted:

Conductivity traversing, VES and TDEM soundings were made on Traverse 1 while magnetometer traversing was completed on a grid comprising 7 lines to confirm the strike extent of anomalous features (Figs 3.2a_1 and 3.2a_2). There was no suitable VLF signal at this orientation (290 deg).

Results and recommendations:

Conductivity traversing revealed two zones (centred at 80m and 310m) where 10m Vc values exceed 100mS/m (ie resistivity less than 10 ohm.m). It is clear, however, that these are only superficial features.

TDEM and VES soundings were again made at characteristic locations largely defined by the conductivity traversing (Figs 3.2a_4 to 3.2a_7 and 3.2a_9 to 3.2a_14) and (uncontrolled) resistivity sections were derived (Figs 3.2a_8 and 3.2a_15). These sections are far more consistent than those at Decamhare: both indicating an abrupt increase in thickness of a potentially aquiferous horizon (13 to 45 ohm.m) in the vicinity of station 150 m.

Magnetic profiling proved a major anomaly (c 600nT) at station 150 m on Traverse 1; this extends to traverse 50 N and possibly to 100 N (Fig 3.2a_16) while the contours derived from the grid survey data (Fig 3.2a_17) display a distinct pattern change between about 140 m and 150 m and indicate a strike length of a supposed fracture of at least 75m. The numerous 'bull's eye' anomalies are characteristic of basalt cover and reflect strong and impersistent susceptiblity contrasts within the individual lava flows.

The magnetic profile of traverse 1 has been partially modelled (Fig 3.2a_18). This reveals the anomaly near 150 m to be caused by a near vertical, narrow zone of much reduced susceptibility extending to at least 50m depth. The model indicates the presence of shallow (almost outcropping) basalt to the west of this feature which is thought to indicate a fault zone bounding vertically displaced blocks of basalt.

It is recommended that a borehole be drilled to at least 60m at station 150 m on Traverse 1.

3.2b Mailaham (E 470372 N1626975)

Target:

A regional-scale satellite lineament (trending 80 deg), reflecting normal faulting (downthrow to the south?) of Tertiary flood basalt as described by Drury et al (1994).

Existing data:

Nothing.

Surface geophysical investigations conducted:

Magnetometer and VLF traversing of two 1200 m lines, 100m separate, followed by conductivity traversing of apparent contact/conductive zone (Figs 3.2b_1 and 3.2b_2).

Results and recommendations:

Conductivity profiling revealed a major anomaly centred at 330 m where the 40m separation horizontal coil values (the deepest penetrating array) exceed the vertical coil values (Fig 3.2b_3). Similarly the VLF traverse (Fig 3.2b_4) indicates the presence of a well defined conductor here and this can be traced at least 100 m along strike to traverse 2 (Fig 3.2b_5).

The magnetic profile of traverse 1 reveals a large (700nT) field level change about station 330 m; this has been modelled as a faulted contact zone (Fig 3.2b_8). The minor bodies of negative susceptibility contrast required to match the observed profile to the south of this contact (ie bodies 2, 3, 4 and 6) may reflect additional fracture zones (especially where they coincide with conductivity anomalies, eg at 475 m) or the effects of remnant magnetisation. Again, the major features of this magnetic profile were proved on traverse 2, 100m to the west. It is concluded that the main anomalous zone (centred at 330 m) reflects the satellite lineament. In view of the amplitude of the geophysical anomalies, and the fact that the surrounding area is eminently suitable for agricultural development (ie it is generally undeveloped, flat-lying and covered with dark, fertile soil) it is strongly recommended that a borehole be drilled at station 330 on Traverse 1 to at least 60m depth.

3.3 BASEMENT FRACTURES:

3.3a Darotay (E416096 N1731268)

Target:

A regional-scale dilational (tensional) fracture zone, possibly including 'clastic dykes' as reported by Drury et al (1994), affecting predominantly granitic basement.

Existing data:

A hand dug well in the river bed c 40m off traverse line (near station 500m) indicated the water table at 8.5 mbgl. Abundant pegmatitic detritus and highly varied lithologies (granites, gneiss, pegmatites, slates(?)) were observed north of station 700 m (traverse 1).

Surface geophysical investigations conducted:

Partial conductivity- and dipole-dipole resistivity coverage of Line 1 was obtained; magnetometer and VLF surveying of the full length (1700 m) of Line 1 plus partial coverage of an adjacent parallel line (100 m separate) was undertaken to confirm the lateral persistence of major features. Two TDEM soundings were made at the southern end of Traverse 1 (Figs 3.3a_1 and 3.3a_2).

Results and recommendations:

Conductivity profiles (Fig 3.3a_3) indicate a significant (but shallow?) contact at about station 900 m. The two TDEM soundings at the southern end of traverse 1 (Figs 3.3a_4 and 3.3a_5) both indicate a regolith thickness of about 13 m; this is in accord with the results of the smoothly varying inversion of the dipole-dipole resistivity coverage (Figs 3.3a_6 and 3.3a_7). These inversions also indicate the presence of narrow, vertical conductive zones centred at stations 505 m and 560 m and it is recommended that the second (apparently stronger) of these be tested by drilling.

The VLF profile of traverse 1 (Fig 3.3a_9) indicates a strong and deep conductor at station 1140 m; this feature extends along strike to at least traverse 2 (Fig 3.3a_10) and is therefore a promising drilling target. The smoothly varying inversions of these VLF data (Figs 3.3a_12 and 3.3a_13) both confirm the existence of a major resistivity contrast in this vicinity but suggest a more northerly location (about station 1200 m) for the major contact on traverse 1.

Numerous well defined magnetic anomalies were located at Darotay, again showing along-strike persistence over at least 100 m (Figs 3.3a_14 to 3.3a_16). These have been modelled as narrow, moderately susceptible (0.0009 to 0.002 SI units) features dipping to the north at a high angle. The major of these features is coincident with the conductive zone located by VLF traversing (at c. station 1140 m on traverse 1) and probably reflects an intruded fracture zone. In view of the interpreted northerly dip of this feature it is suggested that the drilling site is located at 1160 m so that the fracture is intersected well below the water table.

Thus the following borehole sites are recommended:

a) at station 560 m on Traverse 1

b) at station 1160 m on Traverse 1

3.3b Shebak (E438812 N1723209)

Target:

The same regional-scale lineament as tested at Darotay, but some 23 km east of this location. Again the geology is predominantly granitic.

Existing data:

An unserviceable borehole was located some 600 m east of the main traverse; local inhabitants reported water struck at 28 m, total depth 68 m and yield 'good'.

Surface geophysical investigations conducted:

Limited conductivity measurements on the main traverse with magnetometer and VLF coverage totalling some 2500 m (each technique) on three parallel traverses, one some 600 m east of the main survey site (Figs 3.3b_1 and 3.3b_2).

Results and recommendations:

Conductivity values observed with the EM34 (both 40 m and 20 m coil separations) are generally low (in the range 1 to 20 mS/m), indicating shallow bedrock (Figs 3.3b_3 and 3.3b_4). The abrupt conductivity gradient centred on station 345 m possibly indicates a thickening of the regolith away from the river course (between 310 - 340 m). The strong VLF conductor revealed in this vicinity (Fig 3.3b_5) should be tested by drilling (in view of the recharge potential of a fracture zone at this site). The smooth inversion of this VLF data (Fig 3.3b_8) again endorses the presence of strong resistivity gradients at depth in this vicinity. Additional, moderately strong conductors are revealed by VLF traversing on traverse 3 at stations 315 m and 600 m. The smooth inversion of this data (Fig 3.3b_9) reveals a deep conductive zone between 400 m and 560 m and this also should be tested by drilling.

Well defined magnetic anomalies (at 395 m traverse 1 (Fig 3.3b_10) and 660 m (traverse 3 (Fig 3.3b_12) appear to be closely associated with the VLF conductors and again possibly represent the intrusion of magnetic material into fracture zones. The main anomaly of traverse 1 has been modelled (Fig 3.3b_10x); this suggests at least two thin bodies dipping steeply towards 20 deg M (of susceptibilities 0.004 (northernmost) and 0.0007 SI units) that separate lithologies of generally low susceptibility (0.0006 and 0.0008 (northernmost) SI units.The VLF/magnetic anomalies near 660 m on traverse 3 should, however, be treated with caution, for this is near the site of the existing borehole and modelling indicates that the large magnetic anomaly could be caused by a pipeline (Fig 3.3b_13).

It is recommended that boreholes are drilled (to at least 50 m) at 350 m on traverse 1 and at 400 m on traverse 3.

3.3c Mensura (E419237 N1710994)

Target:

A further regional-scale satellite lineament, parallel to that at Shebak but some 25 km south of this, and again reported by Drury and Behre as a dilational shear zone. Predominant lithologies here are granites and granodiorite, heavily intruded by pegmatitic material.

Existing data:

The Water Resources Department drilled a series of boreholes immediately adjacent to the drainage course occupying this feature (the major tributary of the Barka River?). The wells were drilled to some 60 m but in every case the results were disappointing with yields never more than 1l/s from the largely massive granodiorite proved virtually from the surface.

Surface geophysical investigations conducted:

The local topography is relatively rugged and precludes extensive geophysical survey. Limited EM34 coverage was achieved together with 1400 m of magnetometer observations (Figs 3.3c_1 and 3.3c_2).

Results and recommendations:

The short EM34 traverse again indicates the relatively thin cover of conductive material in the river bed (between 505 m and 610 m); the large excursions in the Hc readings to the north of the river may reflect conductive fractures but additional parallel traverses would be required to confirm their lateral extent (Fig 3.3c_3).

At least one of two magnetic features are worthy of testing, if accessible to a drilling rig: the minor step (5 nT) in the magnetic profile at c. 115 m (Fig 3.3c_4) which suggests an intruded contact zone and the major magnetic anomaly (3 500 nT) centred at 290 m (after a thorough examination for a possible cultural source). The step at c. 115m has been modelled (Fig 3.3c_4x). This suggests a steeply dipping (to 20 deg M) thin intrusion of susceptibility 0.008 SI units separating contrasting lithologies (susceptibilities of 0.00027 and 0.0001 (northernmost) SI units. A vertical borehole at 128 m should intersect this intruded contact zone at about 30 m depth (ie below the water table). The major anomaly centred at 290 m has also been modelled (Fig 3.3c_4xx). Again a northerly dipping intrusive is suggested but the modelled susceptibility of this feature (0.45 SI) is probably beyond the upper limit for basic intrusives and a man made source must be suspected.The contrast in magnetic signature to the north and south of c 475 m suggests a lithological contact.

3.3d Anseba Valley (E441766 N1754372)

Target:

A regional-scale NW striking satellite lineament reflecting a major shear zone affecting basement lithologies.

Existing data:

There is a 6 m deep well in the mango plantation near station 1300 m on traverse 1; water level is 2.5mbgl and the yield is reported as high, with water taken routinely by tanker to the nearby town of Keren.

Surface geophysical investigations conducted:

Conductivity, magnetometer and VLF observations were made on traverse 1; the measurements were strongly influenced by cultural noise (in the mango plantation) beyond about station 900, and hence a short parallel traverse (comprising conductivity and magnetic measurements) was made about 100m to the NW (Figs 3.3d_1 and 3.3d_2).

Results and recommendations:

The conductivity profiles (Fig 3.3d_3) again suggest the thinning of conductive overburden as a major river course is approached (at about 1430 m). The generally low values (in particular Hc) across the traverse are indicative of shallow bedrock. Similarly low conductivity values are observed across traverse 2 (Fig 3.3d_4); the enhanced vertical coil values NE of station 190 m reflect a belt of cultivated soil.

No significant conductive zones are revealed by the VLF data (Fig 3.3d_5); the feature centred at 1100 m is ascribed to a cultural source, there being several buildings, fences and pipelines to the NE of 900 m.

A well defined step (about 20 nT) on the magnetic profile of Traverse 1 probably indicates a faulted contact at about station 625 m (Fig 3.3d_6) but there is little corroborating evidence on either conductivity or VLF profiles. This feature has been roughly modelled (Fig 3.3d_6x). The sharp, strong, symmetrical positive anomaly required a reversely magnetised body (ie intruded at a time when the earth's field was polarised in the opposite direction to today's field) of magnetisation 3.8A/m and susceptibility 0.04 SI units. This body dips to the south west and separates contrasting lithologies (susceptibilities 0.00015 and 0.007 (northernmost) SI units. In view of the proximity of the major Anseba Shear zone (and the shortage of potable water currently suffered by the town of Keren) it is recommended that this site be drilled. A vertical bore at 600 m should intersect this feature at about 35m depth. The high amplitude anomalies NE of 900 m largely reflect cultural features.

3.4 LOWER BARKA ALLUVIALS:

3.4a Kailay (E366889 N1702551)

Target:

Following several attempts to undertake geophysical surveys on either the Barka floodplain or on an extensive interfluve zone identified on the satellite imagery to the north of this river (frustrated by high water levels) we were drawn to the Kailay site by the possibility of E-W fracturing traversing a river basin. This was suggested by the abrupt termination of an upstanding dyke swarm on the north side of the river. Access to this remote site was poor and there was no time available to make a return visit to complete a more comprehensive study.

Existing data:

Nothing.

Surface geophysical investigations conducted:

EM34 and magnetometer traverses supplemented by VES at characteristic conductivity locations (Figs 3.4a_1, 3.4a_2 and 3.4a_3).

Results and recommendations:

VES data from stations 35 m, 120 m and 205 m and the derived (uncontrolled) resistivity cross section are presented as Figs 3.4a_4 to 3.4a_7. The cross section indicates a thickness of some 40 m of favourable resistivity range (ie 10 to 50 ohm.m) at station 35 m. Much shallower bedrock (resistivities in excess of 3 000 ohm.m at about 8 m depth) is indicated at the other two sites. It is recommended that station 35 m be tested by drilling.

3.5 MISCELLANEOUS SITES:

3.5a Sheketi (E484841 N1674969)

Target:

An investigation of the possible cause of reported artesian supplies.

Existing data:

Numerous wells in this area are reported never to run dry and in times of drought these wells supply tankers to augment Asmara's water supply.

Geophysical investigations conducted:

Magnetic observations on two parallel traverses totalling 700 m in length (Figs 3.5a_1 and 3.5a_2).

Results:

The observed (uncorrected) magnetic profiles are presented as Fig 3.5a_3. Data was not collected across the full length of the second traverse due to a malfunction. Profile 1 has been modelled (Fig 3.5a_4). This possible solution suggests a folded sill-like body underlying the zone of artesian wells of shallow depth (c 25 m) (projecting into the plane of the paper at about 200 m). This body outcrops in the vicinity of 300 m in accord with our observations in the field. In addition a dyke-like body is visible some 3 km to the NE, dipping at a high angle towards the SE. Thus a possible source of the artesian supply is the water, dammed on the upper surface of a relatively impermeable sill, that may be channeled from great distances along strike.

3.5b Adi Nebri (E505043 N1648326)

Target:

The intersection of regional-scale NS and EW satellite lineaments, promising a highly fractured and permeable zone.

Existing data:

Nothing.

Surface geophysical investigations conducted:

Three short conductivity traverses were completed at this physically constrained site (Figs 3.5b_1 and 3.5b_2).

Results and recommendations:

Conductivity features detected here do not persist from line to line and are seen to be directly related to superficial and topographical features (eg terracing retaining thicker soils and minor topographic defiles etc). The survey area is also traversed by a tarred road and no further geophysical work is recommended.

4. SUMMARY OF RECOMMENDED BOREHOLE SITES

The following borehole sites are recommended:

Location	Site	Depth (m)	Target
Decamhare	580 m Traverse 1	50	Fracture zone
Terra Emni	150 m Traverse 1	60+	Fracture zone
Mailaham	330 m Traverse 1	60+	Fracture zone
Darotay	560 m Traverse 1	60	Fracture zone
Darotay	1160 m Traverse 1	60	Fracture zone
Shebak	350 m Traverse 1	50+	Fracture zone
Shebak	400 m Traverse 3	50+	Fracture zone
Mensura	128 m Traverse 1	60	Fracture/contact
Mensura	320 m Traverse 1 [1]	60	Fracture/contact
Anseba	600 m Traverse 1	60	Fracture/contact
Kailay	35 m Traverse 1	50	Thick regolith

[1] Following careful check for man-made source

5 SUMMARY OF PROBLEMS ENCOUNTERED

a) To date our geophysical investigations have not been sufficiently focused. It is important that initial field reconnaissance visits are made by the hydrogeological team to ensure the general suitability of proposed locations (in terms of groundwater and irrigation potential, access for drilling rig etc). This initial visit would also be used to investigate security, local administrative procedures and requirements, general access (including the presence of crops etc).

b) Heavy rainfall has directly curtailed our activities on most days. Subsequent flooding has frequently impeded access while further time loss/degradation of EM data has been caused by the spherics accompanying even distant electrical storms.

c) Farming activities (ploughing and sowing) have further impeded access and fieldwork.

d) We have to train new assistants in basic field methods in each new area, occasionally employing as many as three new crews per week (due to site moves, drop-outs, sickness etc). It is recommended that a core of two assistants (based in Asmara) be employed for the remainder of the Project's geophysical investigations.

e) As a result of the slow drilling progress (to date only three of the recommended geophysical sites have been tested) we lack ground truth/geological control with which to refine our geophysical interpretations.

f) Minor bugs in interpretational software and a computer/printer conflict will be resolved during the mid-input UK break.

6. CORRELATION OF SURFACE GEOPHYSICAL DATA WITH SUBSEQUENT BOREHOLE CONTROL

6.1 INTRODUCTION

Of the eleven borehole sites recommended following surface geophysical surveys, only three were subsequently drilled (Decamhare (Bh 6), Terra Emni (Bh 7) and Kailay (Bh 12)). Limited surface geophysical observations were made at two other Project borehole sites: a single TDEM sounding near the Hazemo Plain (Mai Aini) borehole (Bh 4) (while this was in progress) for equipment testing and calibration purposes and limited EM34 traverses at the topographically constrained site at Adi Nebri (Bh 5). A further Project borehole was drilled 'somewhere' on our main geophysical traverse at Darotay (Bh 11) but not, unfortunately, at the recommended site.

In this section of the report we attempt to correlate the surface geophysical data with subsequent borehole control (occasionally supplemented by geophysical logging). This exercise should indicate (in spite of the very limited statistics) which geophysical technique (or combination of techniques) has been most successful in locating fracture zones. It should also allow refinement of the range of physical parameters (principally resistivity/conductivity) associated (locally) with productive aquifers. For each borehole site a brief reminder of the geology and nature of the target is given; then follows both the original (uncontrolled) and refined (controlled) geophysical interpretation.

6.2 CORRELATION OF DATA

<u>6.2.1 At Project boreholes sited following geophysical survey</u>

6.2.1.1 *Decamhare (borehole 6) (at 580 m on traverse 1)* (E 504355 N1662469)

Target: a regional-scale N-S trending satellite lineament, probably reflecting a major fault zone in this predominantly granitic terrain.

Geophysical indications: a major, exceptionally well defined conductivity anomaly was detected with all coil separations and orientations on the initial traverse between stations 510 and 690 (Fig 1). The conductivity profiles indicate an abrupt thickening of conductive material and thus probably reflect in-situ weathering products within a fracture zone rather than regular alluvial deposition. A VES made at 526 m (Fig. 2) indicated favourable resistivities (13 – and 30 ohm.m) to some 40 m depth. The reported typical thickness of regolith in this area is some 7 m only.

The borehole at 580 m (Fig 3) proved various grades and mixtures of sand to 42 m depth, bottoming in weathered granite at 49 m. The water table at this site is some 2.5 mbgl (as proved in the adjacent river bed) and yet the borehole is reported as being dry. Fig 4 shows the VES at 526 m re-interpreted to include the lithological contacts defined by drilling (ie 12-, 16- and 42 m). This has necessitated only minor modification to the specific resistivities of the relatively conductive layers (13-, 16- and 33 ohm.m).

Comments: An exceptional thickness of sands has been proved at the site of borehole 6 where the water table is known to be shallow. The range of specific resistivity of these sands (13 – to 33 ohm.m) would normally indicate promising aquiferous conditions and yet the borehole is dry. Is it possible that the drilling/development techniques caused a local reduction of porosity/permeability?

6.2.1.2 *Terra Emni (borehole 7) (at 150 m on traverse 1)* (482700 E 1659900 N)

Targets: a) fault/fracture zone in flood basalt terrain
- b) permeable intraflow sediments
- c) thin basalt cover/shallow indurated basement contact

Geophysical indications: magnetometer traversing revealed a step feature (of c 600 nT amplitude) between stations 150 m and 410 m on traverse 1; adjacent traverses showed this feature to have significant strike extent (Fig 5). Partial modelling of the traverse 1 profile (Fig 6) suggests a fracture zone centred at station 150 m, about which the basalt cover has suffered vertical displacement. Mutually consistent resistivity sections of traverse 1 derived from VES and TDEM soundings (Figs 7 and 8) suggest an abrupt deepening of hydrogeological basement (ie values in excess of c 150 ohm.m) in the vicinity of station 150. The VES at 150 m (Fig 9) suggests a considerable thickness (in excess of 50 m) of favourable resistivity (45 ohm.m); it should be noted, however, that a sounding made directly above a fracture zone will suffer some distortion. This sounding has been re-interpreted to include the lithological boundaries proved by drilling (Figs 10 and 11); the resulting specific resistivities for the various units are as follows:

silty clay (7- and 52 ohm.m)
laterite (13 ohm.m)
upper weathered basalt (31 ohm.m)
weathered tuff (26 ohm.m)
lower weathered basalt (plus weathered basement?) (52 ohm.m)

The interpreted resistivities are low for all units below the surficial clay. This implies either (or both) a high degree of weathering (reflecting close proximity to a fracture zone) or the presence of highly conductive groundwaters. The relatively resistive units in this sequence (ie the upper and lower weathered basalts) are also clearly defined by the point resistance log of borehole 7 (Fig 12). Minor negative-going excursions of this log possibly indicate additional fractures (eg at about 24 m depth, where a water strike was reported).

Comments: borehole 7, drilled to only 29 m, proved highly successful. Transmissivity at this site was calculated as 205 m^2/d, a value approaching two orders of magnitude greater than the previous best Project borehole drilled in similar basalt terrain but without the benefit of geophysical siting. Similarly, its measured yield/drawdown (2.1 l/s/m) is approaching some two orders of magnitude greater than the previous best basalt borehole. The estimated safe yield is some 8 l/s while the various variable discharge pump tests conducted showed little evidence of de-watering of the fissures encountered in the borehole.

6.2.1.3 *Kailay (borehole 12)* (at 35 m on traverse 1) (E366889 N1702551)

Target: We were drawn to investigate this site by the possibility of E-W fracturing traversing a river basin, as suggested by the abrupt termination of an upstanding dyke swarm immediately north of the river.

Geophysical indications: VES were made at three characteristic locations identified by conductivity traversing. The VES at 35 m indicated an anomalous thickness of favourable resistivities (ie 50- and 20 ohm.m to about 40 m depth) (Figs 13 and 14).

Comments: borehole 12 proved sand and gravel/cobbles to 24 m depth, underlain by granite (Fig 15). The VES at this site has been re-interpreted (Fig 16) incorporating this borehole control. The indicated specific resistivities are:

silty clay (22- , 206- and 3.5 ohm.m)
sand (137 ohm.m)
gravels/cobbles (10 ohm.m)
granite (weathered) (860 ohm.m)

The borehole was dry, in spite of the anomalous thickness of gravel/cobbles and the proximity to a river course. If the drilling/development techniques were not at fault, it must be assumed that the low resistivity value for the gravel/cobbles (10 ohm.m) indicates a high clay content resulting in diminished porosity/permeability.

6.2.2 At Project boreholes sited **without** the benefit of geophysical survey

6.2.2.1 *Hazemo (Mai Aini) (Project borehole 4)*

Target: a calibration/test TDEM sounding was made about 150 m north of the Project borehole being drilled in the centre of an extensive plain to test the thickness and aquifer properties of both alluvials and the underlying Mesozoic Adigrat Sandstone.

Geophysical indications: Fig 17 shows an uncontrolled interpretation of the TDEM sounding, indicating potential aquifer conditions (resistivity in the range 25- to 130 ohm.m) between depths of about 23 m to 72 m.

Comments: Borehole 4 (Fig 18) proved 11 m of dry alluvials overlying Adigrat Sandstone to total depth (102 m). Water was struck at 52 m and 82 m with rest level at 33.5 mbgl. The point resistance log of this borehole (Fig 19) confirms the deep water table and suggests the presence of two discrete conductive zones below this, with a boundary at about 70 m, the lower zone extending to at least 94 m. Since it has not proved possible to increase the TDEM sounding modelled depth to basement significantly below about 72 m it is assumed that basement shallows towards the north. The high value of specific resistivity indicated for the Adigrat Sandstone (c 130 ohm.m) suggests that it is of low porosity. Indeed, the main groundwater contributors to the borehole were discrete strikes at 52 m and 82 m (some evidence of which are seen on the point resistance- and SP logs (Figs. 19 and 20) suggesting that the Adigrat Sandstone here is predominantly a secondary aquifer.

6.2.2.2 *Adi Nebri (Project borehole 5)* (E505043 N1648326)

Target: the intersection of regional-scale NS and EW satellite lineaments, promising a highly fractured and permeable zone.

Geophysical indications: the three short conductivity traverses made near this borehole site did not reveal any consistent features reflecting structure at depth.

Comments: the borehole was drilled to 64 m at which stage it was abandoned due to severe collapse problems (suggesting intense fracturing?) (Fig 21). The point resistance and SP borehole logs (Figs 22 and 23) suggest a water level at about 28 mbgl at the time of logging; both logs are of poor quality (showing erratic excursions and unrealistically high values), possibly reflecting inadequate earthing of the reference electrode or a dirty tool. Some of the coincident excursions may reflect conductive fractures (eg at 33 mbgl). The natural gamma log (Fig 24) is also sub-standard; it appears that the time constant was too short and the logging speed too fast.

6.2.3 Miscellaneous borehole

6.2.3.1 Darotay (borehole 11) ('somewhere on traverse 1')(E416096 N1731268)

Target: a regional-scale dilational (tensional) fracture zone, possibly including 'clastic dykes' as reported by Drury et al (1994), affecting predominantly granitic basement.

Geophysical indications: numerous discrete conductive fracture zones were located on traverse 1, with some displaying strike extent of at least 100 m. Magnetic modelling suggests that many of these fractures dip at a high angle towards the north. A regolith thickness of about 13 m to 20 m is suggested by both Dipole-Dipole resistivity inversion and TDEM sounding. Closer correlation between surface observations and borehole control (see below) will be attempted when the exact traverse position of this borehole has been established.

Comments: borehole 11 was drilled to 45 m, encountering variably fractured and weathered granodiorite and granite between 4 m and 43 m (Fig 25). Water strikes were made at 29 m and 35 m and the calculated safe yield of this borehole is 3.66 l/s. The point resistance and SP logs (Figs 26 and 27) confirm the swl at about 10 m. The point resistance log indicates three discrete units below this; the centralmost (resistive) feature (between 21 m and 31 m) being coincident with the upper part of the logged granite. Numerous minor excursions on both logs may indicate additional conductive fractures.

7 PLANNED ACTIVITIES FOR SUBSEQUENT INPUT OF GEOPHYSICS SPECIALIST

Forthcoming geophysical activities will be focused in specific locations (selected following desk studies and reconnaissance visits by the hydrogeological team) in the following environments:

a) alluvial basins of the Western Lowlands (Barka, Gash-Settit areas) (to locate the greatest thickness of coarse deposits, outline their 3-D extent and investigate potential quality problems.

b) basins and wadis of the Red Sea Lowlands (to investigate the presence of freshwater lenses (their thickness and lateral extent) and the extent of high permeability wadi deposits).

c) minor alluvial basins in the Central Highlands (eg east of Nacfa and north of the Barka River (west of Akordat)).

Software packages not yet fully explored (eg TEMIXXL) will be investigated further with the counterparts. A contribution to the final mission report will be prepared.

8. CONCLUSIONS

The geophysical equipment purchased by the Project is working to specifications. The counterpart geophysicists have received instruction in the operation of all this equipment and in the processing and interpretation of most of the resulting data.

Our work during this first half input has been dedicated to locating fracture zones which should act as reservoirs and conduits for groundwater. Magnetometry, VLF and conductivity traversing appear to have been especially useful in this application. Since these fracture zones generally have little or no surface expression (when viewed in the field) it is essential to employ geophysics for their efficient detection. They are also generally narrow features and it is important that boreholes are drilled within a couple of metres of the recommended sites.

Of the eleven promising borehole sites located by geophysical survey only three have been tested by drilling. Two of these (Decamhare (Bh 6) and Terra Emni (Bh 7)) were drilled to test fracture zones. The Decamhare borehole proved an exceptional thickness (42 m) of regolith but yielded no water. The controlled interpretation of a VES near this borehole site indicated favourable specific resistivities for the regolith (in the range 13- to 33 ohm.m); thus it is considered possible that the drilling/development techniques employed at this site have locally diminished the formation porosity/permeability.

The Terra Emni borehole proved fractured and weathered basalts and tuffs to its total depth of only 29 m. This borehole is highly successful. Both the calculated transmissivity (m^2/d) and yield/drawdown (l/s/m) at this site approach two orders of magnitude greater than at the best Project borehole drilled in similar basalt terrain, sited *without* the benefit of geophysical survey. Variable discharge pump tests showed no significant dewatering of the fractures/fissures and a safe yield of at least 8 l/s is estimated.

The third promising site tested was at Kailay where an anomalous thickness of regolith identified by conductivity traversing and subsequent electrical sounding was tested by borehole 12. The uncontrolled VES interpretation here indicated a thickness of some 40 m of regolith while the borehole proved only some 24 m of alluvials overlying granite. Such over-estimation results from the problem of equivalence (whereby numerous different arrangements of layer resistivities and thicknesses yield an identical sounding curve). The problem is best overcome by the inclusion of borehole control. However, even in the absence of such control, a series of VES can still be interpreted to indicate the *thickest* development of a particular layer (provided its resistivity remains constant) even if its absolute thickness/depth cannot be forecast. The Kailay borehole is also dry. The controlled interpretation of the VES at this site indicates a specific resistivity of about 10 ohm.m for the alluvials. Provided the drilling/development techniques were appropriate at this site, then it must be assumed that these alluvials contain a high clay content resulting in low porosity/permeability.

Limited surface measurements were made at two further Project boreholes that had been sited without the benefit of geophysical survey. The Adigrat Sandstone tested at Mai Aini (Hazemo) (borehole 4) displays a relatively high specific resistivity (about 130 ohm.m); this suggests that the intrinsic porosity/permeability of this sandstone is rather low. The main water contributions at this borehole appear to be from deep fissures. Conductivity traverses at the Adi Nebri site (borehole 5) did not reveal any consistent trends reflecting deep structure.

Project borehole 11 was drilled at an unknown location on geophysical traverse 1 at Darotay where we investigated a regional-scale tensional shear identified on satellite imagery. This borehole proved variously weathered granodiorite and granite to 43 m and encountered several fractures/fissures, yielding some 3.66 l/s. Had the borehole been drilled at one of the two recommended locations (where large conductive fractures had been identified) we could anticipate a considerably greater yield.

Magnetometry and conductivity traversing (supplemented by VES) have been especially useful in locating fracture zones to date. Since these fracture zones generally have little or no surface expression (when viewed in the field) it is essential to employ geophysics for their efficient detection. They are also generally narrow features and it is important that boreholes are drilled within a couple of metres of the recommended sites.

It should be emphasised that geophysical techniques do not *directly* indicate the presence of available groundwater, but rather indicate where conditions are favourable for its occurrence. For instance, we can detect a thick sequence of alluvials displaying favourable resistivity (in the range, say, 20 to 100 ohm.m) but cannot guarantee a successful borehole. However, as more local information becomes available the range of 'likely successful' resistivity values can be refined.

9. REFERENCE

Drury, S A, Kelley, S P, Berhe, S M, Collier, R E and Abraha, M. 1994. Structures related to Red Sea evolution in northern Eritrea. TECTONICS, Vol 13, No 6 pp 1371-1380

APPENDIX A

Surface hydrogeophysical techniques available to the Project

The Project is fortunate in possessing a wide range of "state of the art" equipment. This comprises:

Geonics time domain electromagnetics (em) (TDEM47)
Geonics EM34-3 conductivity meter
ABEM WADI V(ery) L(ow) F(requency) EM
ABEM Terrameter DC resistivity meter (SAS 300C plus booster)
GEM proton magnetometer

We also have a GARMIN 45 global positioning system to assist with navigation, locating satellite lineaments in the field, determining traverse locations etc.

APPENDIX B

Data processing/interpretation packages available

The Project also has a wide range of sophisticated processing/modelling software, comprising:

TEMIX-XL (TDEM47)
PROTEM/RECTAN
EMIX34P (EM34-3)
EMIX-VLF
Sector (WADI)
RESIXP
RESIX-IP2D
RES2DECO
MAGIXP
SURFER (gridding, contouring, 3-D projection)

The above software is mounted on an COMPAQ ARMADA lap-top computer served by a Cannon A3 colour bubble jet printer.

APPENDIX C

Physical principles of the surface geophysical techniques applied

Electrical methods

Electrical methods are particularly suitable for groundwater studies because the resistivity/conductivity of a rock largely reflects its porosity and permeability, its degree of saturation and the fluid conductivity of its pore water. Hence electrical surveys can indicate groundwater quality and content and, in certain uniform conditions, can also yield an indication of transmissivity etc. In most rocks electricity is conducted electrolytically through the interstitial fluids and hence it is the conductivity of these fluids that controls the rock resistivity, rather than the resistivity of the rock matrix. The situation is complicated by the presence of clay minerals, however, because such minerals conduct electricity electronically; thus current flow through clayey lithologies is both electronic and electrolytic.

The fundamental division of the electrical methods is between direct current (dc) and electromagnetic techniques (em). Traditionally the dc or galvanic systems were preferred because the equipment is relatively simple and cheap and the method is easy to understand. However with the introduction of light-weight and sophisticated electronics, the em methods are rapidly eclipsing the dc techniques. EM enjoys superior resolution and more rapid data collection since electrode contact with the ground is not required. Use of the two basic techniques is not mutually exclusive however and there are several potential applications where the contrasting methods yield complementary data. This results primarily from the fact that the dc and em techniques respond best to resistive and conductive targets respectively.

Direct current (dc) methods

The electrical resistivity of earth materials is measured by introducing an electric current (usually switched direct current) into the ground via two electrodes and observing the resultant potential field developed across two additional electrodes. The apparent resistivity (in ohm.metres) of the volume of ground influencing the current flow is calculated by multiplying the quotient (V/1) by a geometrical factor dependant on the separations and arrangement of the electrodes used. In the rare case of homogenous ground this value of apparent resistivity is equal to the actual or specific resistivity of the ground; more often, however. it represents a weighted average value of all the influencing lithologies.

Profiling: Observations of lateral variations in apparent resistivity are made in the profiling mode where the entire electrode array is moved along traverse lines, maintaining a constant separation between the electrodes and hence investigating to a fairly uniform depth. Normally at least two separations are employed to allow some depth discrimination, the larger separations yielding information from greater depth. The results are plotted as profiles and are usually interpreted only qualitatively to indicate contacts between units of different resistivity, fault zones (usually manifested as relatively conductive features) and variations in overburden thickness. In the present work we used the dipole-dipole array in which measurements are made with potential electrode pairs at successively greater distances (usually integer multiples of the electrode separation) from the current electrode pair. In this manner a pseudo-section is derived which shows in a very general way both the lateral and vertical variations in resistivity.

Sounding: The vertical distribution of resistivity is mapped in the sounding mode (*V*ertical *E*lectrical *S*ounding) which involves increasing the current penetration by progressively increasing (usually in logarithmic intervals) the current electrode separation about a fixed central point. In the present work we used the Schlumberger array in which the potential electrode separation is kept constant until the potential difference becomes too small to measure accurately, at which stage the separation is increased. A major advantage of this array in semi-arid areas is the reduced number of electrode moves required to complete a sounding.

The electrodes must be expanded parallel to geological strike and topographic features where possible, while fences, ditches and powerlines should be crossed at right angles. The calculated apparent resistivity values are plotted against the respective electrode separation to produce a sounding curve. This is usually interpreted in terms of layer thicknesses and resistivities bv comparing the observed curve with one derived by computer for a specific model, adjusting the model until a close fit is achieved.

Two problems confronting the interpreter of VES curves are equivalence and suppression. Equivalence is the condition where a large number of quite different geoelectrical arrangements yield practically identical sounding curves. Suppression occurs where a lithological unit has either insufficient thickness (in relation to its depth) or resistivity contrast to be resolved on the sounding curve. To help resolve these problems it is important to incorporate all available data (borehole logs, observed geology etc) in the interpretation. In addition, the use of other techniques (eg induced polarisation or electromagnetic sounding) may help resolve ambiguities through constrained joint interpretations.

The dc resistivity techniques are relatively labour intensive and slow. A further disadvantage is that large electrode separations are required relative to the depth of investigation (typically 10 times this depth). Because of this, large volumes of ground are sampled and this leads to loss of resolution while rendering the technique susceptible to lateral resistivity variations.

Electromagnetic (EM) methods

The traditional EM techniques (frequency domain EM (FEM)) employ a continuous fixed frequency signal, typically in the range 100-8 000 Hz. Occasionally measurements are made at several different frequencies. The receiver coil detects the directly transmitted field combined with any secondary fields generated by conductors within the ground. The effective depth of penetration is controlled by factors such as the distance between the transmitter and receiver coils, transmitter frequency, coil orientation and ground conductivities. Interpretation is typically qualitative, outlining shallow conductivity distributions that may reflect the presence of fault zones, clayey horizons and contaminant plumes etc.

An alternative approach, based on a pulsed source (TDEM), has become increasingly popular with the advent of more sophisticated instrumentation. In TDEM the receiver measures the decay of a transient field in the absence of the primary signal. The magnitude and rate of decay of the transients provide information on the variation of conductivity with depth and the use of time in this context can be considered as analogous to the electrode spacing in VES.

The FEM and TDEM techniques are largely complementary; FEM investigations are restricted to the top 50m or so while targets below this depth are best detected using TDEM.

Frequency domain EM (FEM)

Terrain Conductivity measurements (TCM)

The Geonics EM34 comprises a transmitter and receiver coil in the form of moulded portable loops that are moved together, a fixed distance apart, along the traverse. The received field is measured relative to the primary field as transferred directly through a reference cable. The instrument displays the out of phase response converted to a scale of apparent conductivity and uses the in-phase response to indicate when the spacing between the transmitter and receiving coils is near the 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 constant and low enough for the linear conversion of the out of phase value to ground conductivity. Readings are made with the coils co-planar, either horizontal or vertical, giving respective penetration of approximately 1.5- or 0.7 times the coil separation. (ie ranging from c 7m to 60m). It is usual to repeat a traverse using several different coil separations and/or orientations to derive information on the conductivity distribution with depth. Such data may be crudely interpreted quantitatively to yield a series of 1-D geoelectrical sections.

The Very Low Frequency (VLF) technique

The VLF method exploits signals in the frequency range 15 kHz to 25 kHz that are broadcast by powerful military transmitters and can be detected in most parts of the world. The magnetic field components (in phase and out of phase) of the remote transmissions are measured. Conductive zones (eg saturated fault zones) are indicated by the distortion of the horizontal and linearly polarised primarv magnetic field. Buried conductors cause this field to become elliptically polarised and the major axis to tilt with respect to the horizontal. The exploration depth for typical overburden resistivity (50ohm.m) is about 20m.VLF equipment is relatively cheap and the technique is rapid; a single operator can cover several kilometres per day.

Time domain (pulse) EM (TDEM)

By abruptly turning off a steady (square wave) current flowing in a large loop on the earth's surface, a transient electromagnetic field is created. This in turn induces secondary electric currents (with associated magnetic fields) to flow in horizontal circles under the transmitter loop. The decay, with time, of the vertical magnetic field component of the induced currents is measured by an adjacent smaller multi-turn loop. The rate of decay of the vertical magnetic field is a function of the electrical conductivity of the earth under the loops. With longer times after current switch off the induced fields have penetrated further into the earth and later measurements are therefore representative of greater depths, this relationship being governed by the distribution of conductivities present.

The results are plotted in similar fashion to a standard VES. with apparent resistivity (derived from the voltages induced in the receiver coil by the secondary magnetic fields) as ordinate and time (equivalent to depth) as abscissa (cf electrode separation). Forward modelling is used to calculate the response expected over a given 1-D geo-electrical section; inversion modelling is limited to matching the observed curve to the case of a few horizontal layers of variable thickness/conductivity.

Typical transmitter loop sizes are in the range 40m by 40m to 200m by 200m, with current in the range 2 A to 10 A. The depth of investigation is limited by the time after switch-off that the decaying signal can be measured above noise; this can be extended by increasing the current, by increasing the loop dimension (since signal strength is proportional to the product of loop area and current flowing) and by stacking many transients. Penetration down to about 500 m can be routinely achieved with large loops. There is also a minimum depth of investigation with TEM, presently about 5m, due to the problems of measuring the transient field immediately following current switch off. The field operation typically requires two or three workers who can measure between 15 and 30 soundings per day.

The TDEM technique is operationally superior to VES since there is no requirement for galvanic contact with the ground, nor for very large electrode spreads. Hence TDEM soundings may be made in relatively confined spaces. Because TDEM samples a relatively small volume of ground for any given depth of investigation the results are less likely to be degraded by insignificant lateral conductivity variations and hence TDEM offers enhanced resolution of layers compared with VES.

Magnetic method

In this technique the strength of the earth's magnetic field is measured at regular intervals using a magnetometer; local variations in this field strength reflect contrasting magnetic susceptibilities. The susceptibility of a rock is a measure of how strongly magnetised it becomes in the earth's inducing field and is determined almost entirely by the 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 and hence magnetometry, probably the most cost effective geophysical technique, can be a very sensitive tool for geological mapping (locating lithological contacts, dolerite dykes etc). In addition fault zones are sometimes revealed as either positive or negative linear features. Positive anomalies reflect the intrusion of material more susceptible than the host rock while negative features result from the alteration of magnetite to haematite in the fractured rock.

Measurements of the total magnetic field are made very rapidly using proton precession magnetometers, instruments that exploit the fact that the precession frequency of hydrogen protons is directly proportional to the ambient magnetic field strength. The absolute value of the magnetic field is measured, typically with a sensitivity of 1 nanotesla (nT) which is about 1/50 000 part of the earth's field strength. The operation is very rapid with a complete reading taking about 5 seconds.

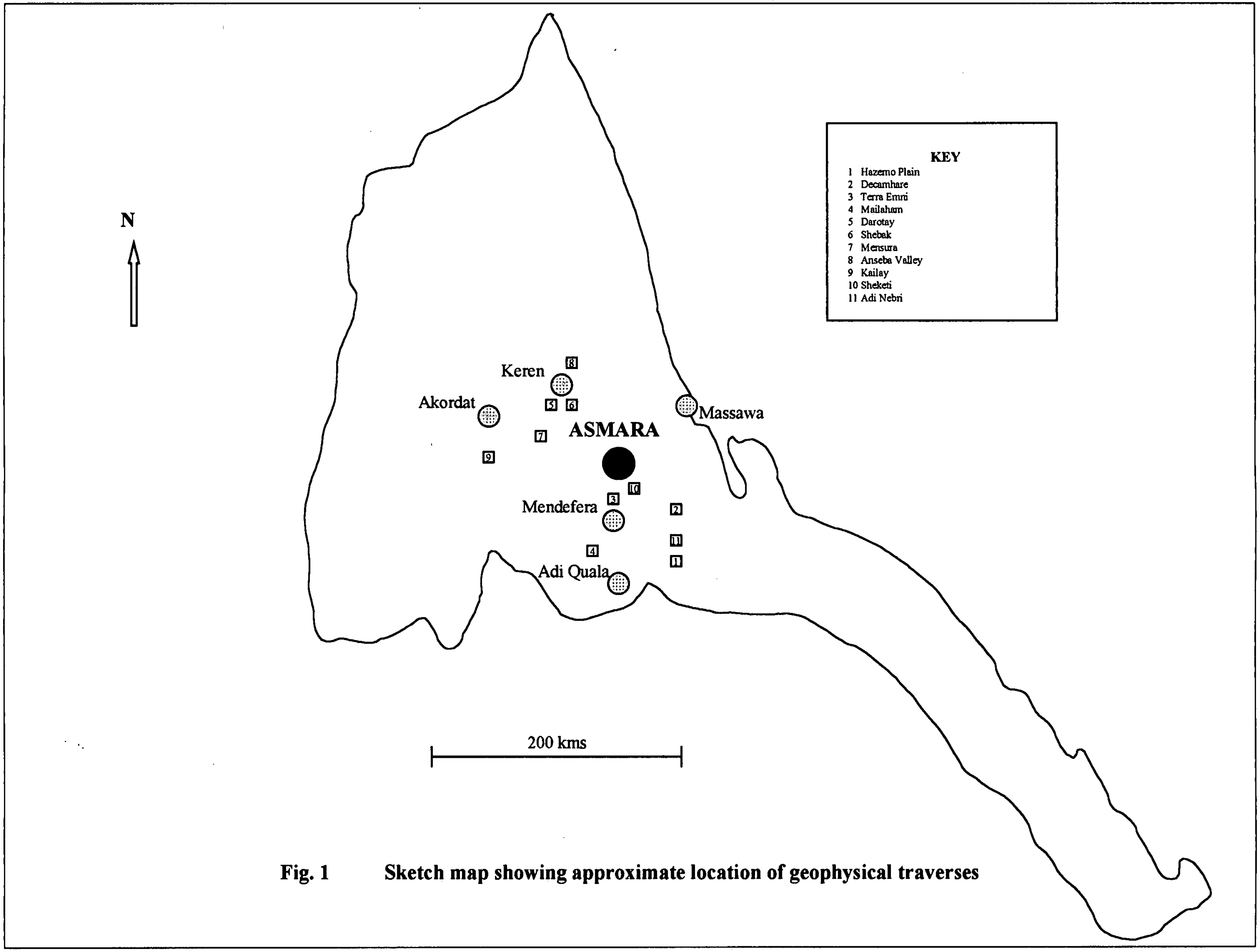


Fig. 1 Sketch map showing approximate location of geophysical traverses

ERITREA: SECTOR STUDY ON NATIONAL WATER RESOURCES AND IRRIGATION POTENTIAL

GROUNDWATER EXPLORATION

GEOPHYSICAL INVESTIGATIONS COMPLETED

SHEET No: **LOCATION:** HAZEMO (S of MAE AENE) **UTM Co-ords: E** **N**

Geology: Adigrat sst. + colluvium **Target:** Test TDEM (conductive lithology) at Project Bh site.

GEOPHYSICAL TECHNIQUES	Used?	Line/Grid	cover m/No.	Comments
Conductivity EM34 40m				
Conductivity EM34 20m				
Conductivity EM34 10m				
TDEM 47 sounding (5m*5m)	✓		1 No	c. 150 m from Project Bh
TDEM 47 sounding (40m*40m)	✓		1 No	c. 150 m from Project Bh
TDEM47 sounding (100m*100m)				
TDEM 47 traversing (5m*5m)				
TDEM 47 traversing (40m*40m)				
TDEM 47 traversing (100m*100m)				
Resistivity (ABEM 300C) sounding				
Resistivity (ABEM 300C) traversing				
VLF (WADI) traversing				
Magnetometry (GEM) traversing				
Gravimetry				
Seismic refraction				

Previous work:

Borehole sited ?: NO (not by geoph) **Location:** **Project Bh No:** BH4

Borehole drilled (date): 21/06/ – 07/07/97

Result: 0-11 m alluvium

11 - 102 m fine gr. sst.
TD with many horizons

Fig. 3.1a_1 Hazemo: table summarising geophysical investigations

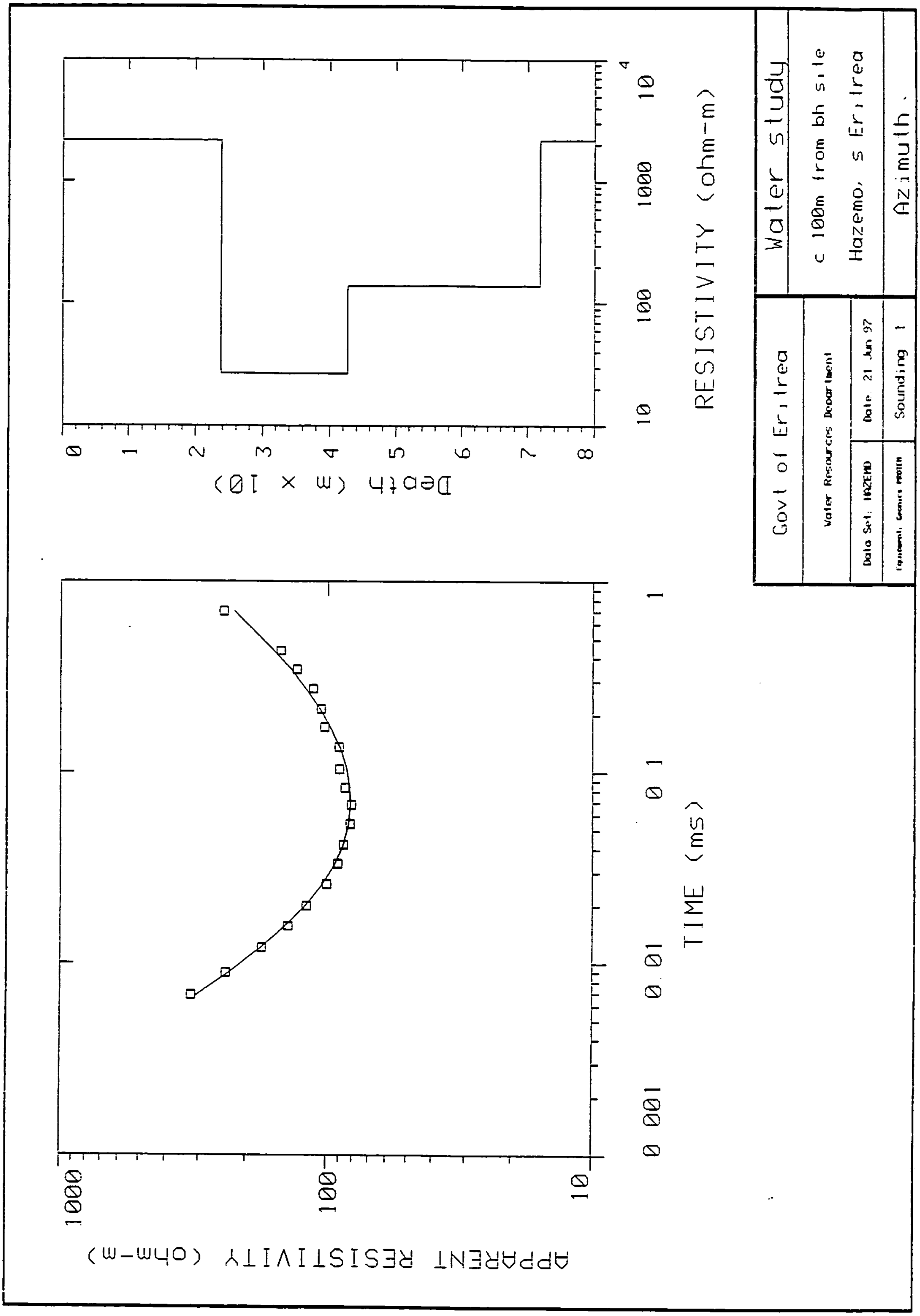


Fig. 3.1a_2 Hazemo: TDEM sounding c.~~100~~ 150 m N of borehole site

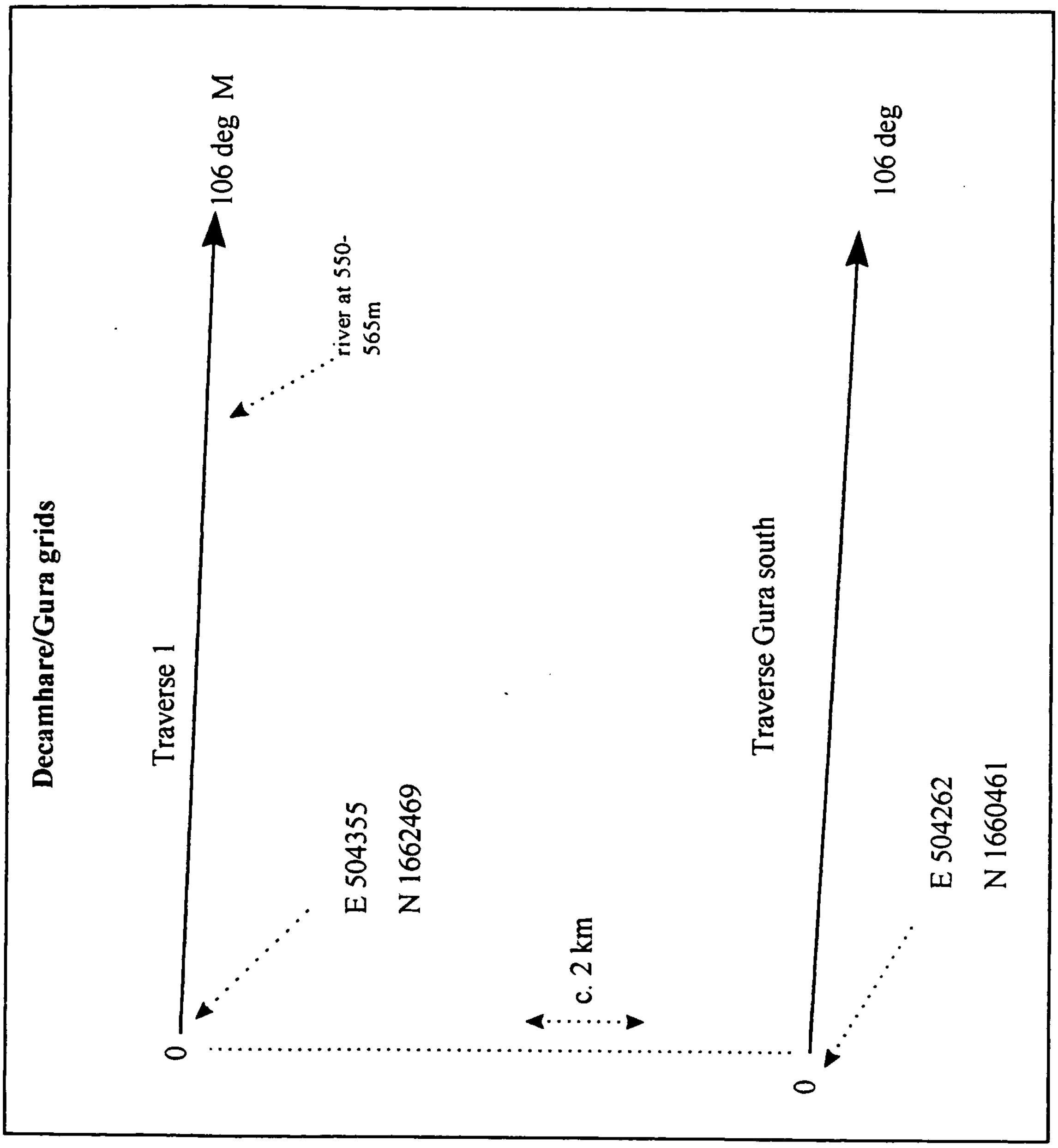


Fig. 3.1b_1 **Decamhare: geophysical grids at Decamhare and Gura south**

ERITREA: SECTOR STUDY ON NATIONAL WATER RESOURCES AND IRRIGATION POTENTIAL

GROUNDWATER EXPLORATION

GEOPHYSICAL INVESTIGATIONS COMPLETED

(Stn. 0 Traverse 1)

SHEET No: **LOCATION:** Gura airstrip (S of Decamhare) **UTM Co-ords: E** 504355 **N** 1662469

Geology: Granite/alluvium **Target:** Satellite lineament (shear zone?)

GEOPHYSICAL TECHNIQUES	Used?	Line/Grid	cover m/No.	Comments
Conductivity EM34 40m	✓	L	760 m	
Conductivity EM34 20m	✓	L	800 m	
Conductivity EM34 10m	✓	L	400 m	
TDEM 47 sounding (5m*5m)				
TDEM 47 sounding (40m*40m)	✓	L	4 No.	Incl. 1 at army bh 3km south
TDEM47 sounding (100m*100m)				
TDEM 47 traversing (5m*5m)	✓	L	24 No.	
TDEM 47 traversing (40m*40m)				
TDEM 47 traversing (100m*100m)				
Resistivity (ABEM 300C) sounding	✓	L	4 No	Incl. 1 at army bh 3km south
Resistivity (ABEM 300C) traversing				
VLF (WADI) traversing	✓	L	550 m	
Magnetometry (GEM) traversing	✓	L	550 m	
Gravimetry				
Seismic refraction				

Previous work:

Borehole sited ?: YES **Location:** 580 m Traverse 1 **Project Bh No:**

Borehole drilled (date):

Result:

Fig. 3.1b_2 Decamhare: table summarising geophysical investigations

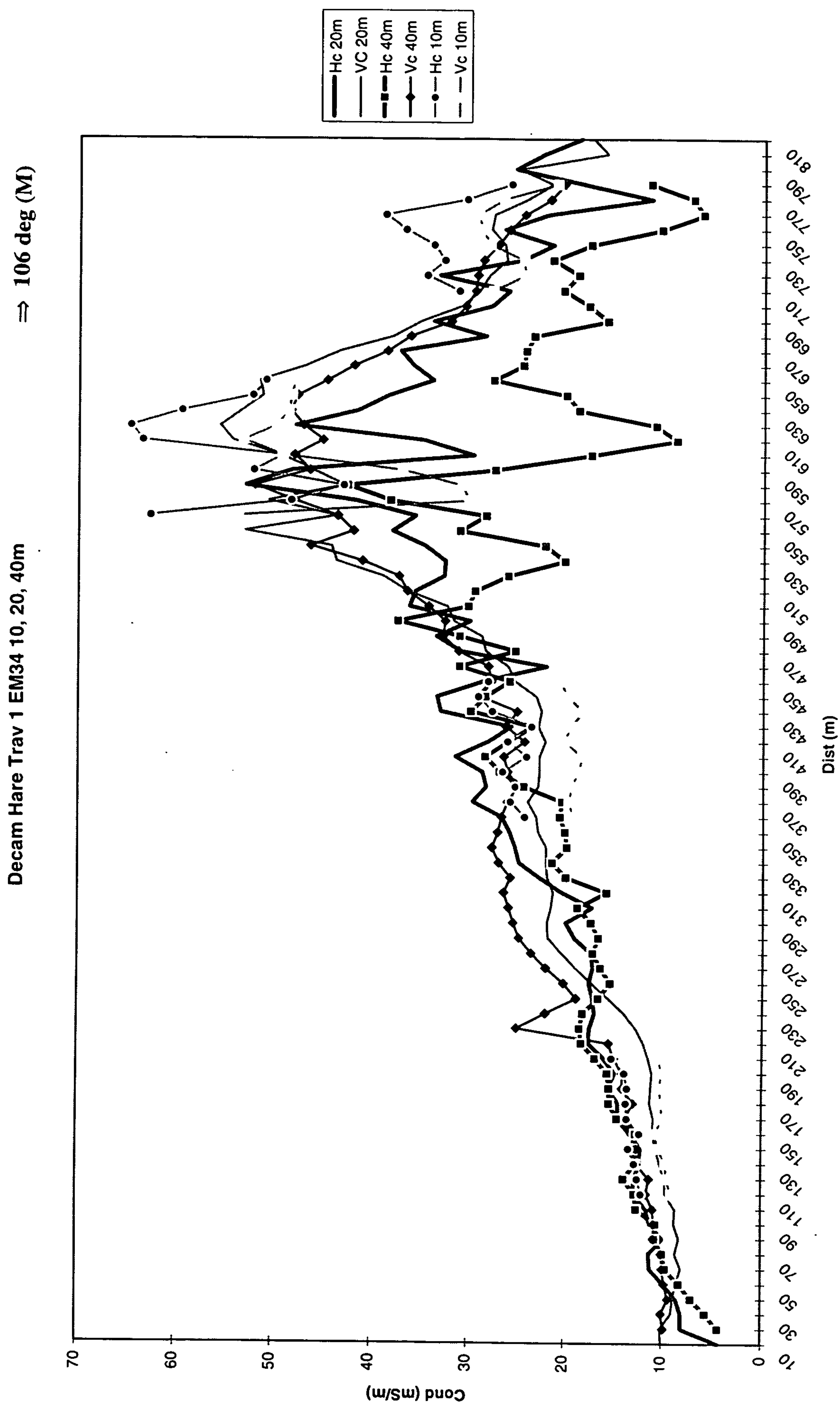


Fig. 3.1b_3 Decamhare: EM34 data on Traverse 1

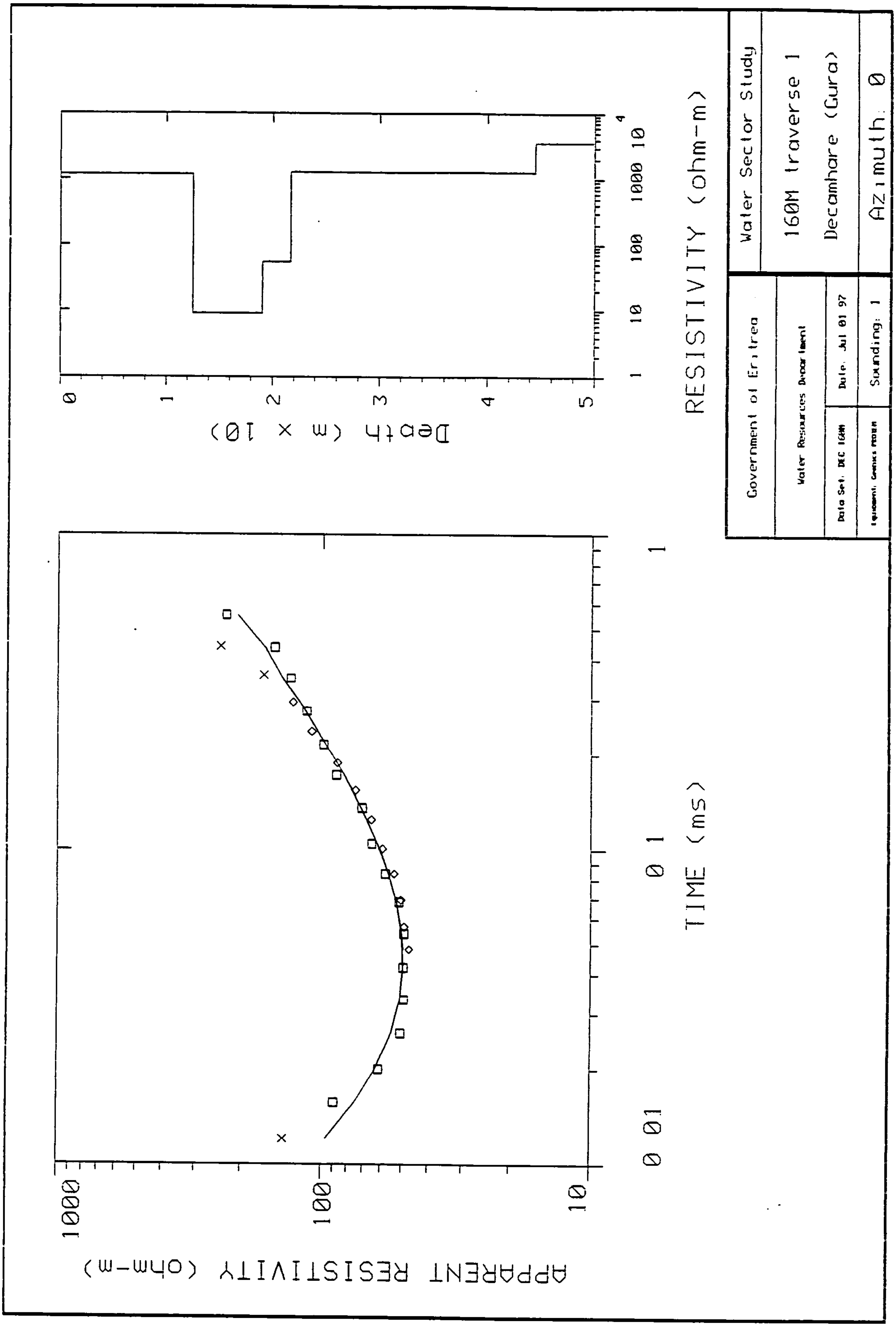


Fig. 3.1b_4 Decamhare: TDEM sounding at 160 m Traverse 1

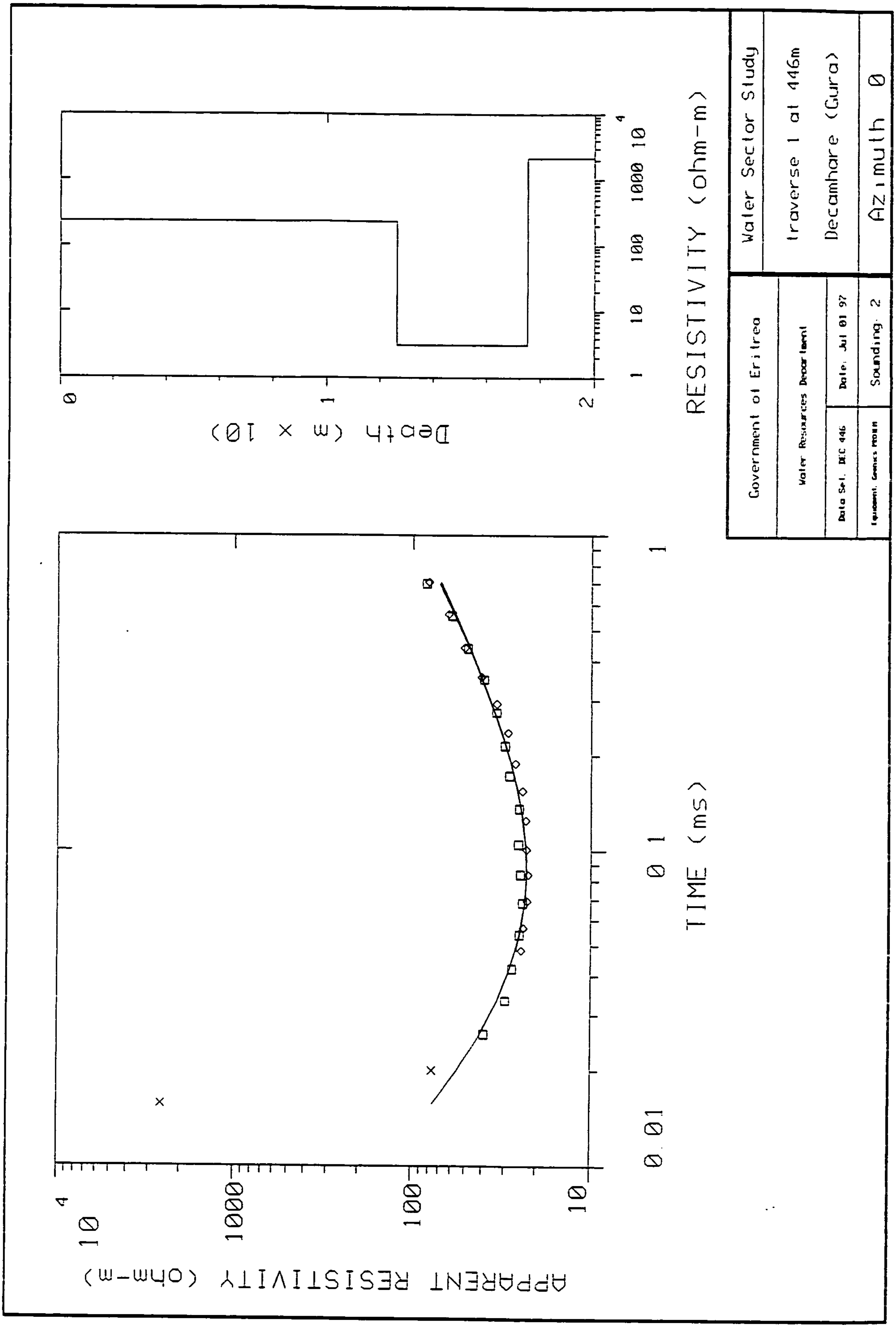


Fig. 3.1b_5 Decamhare: TDEM sounding at 446 m Traverse 1

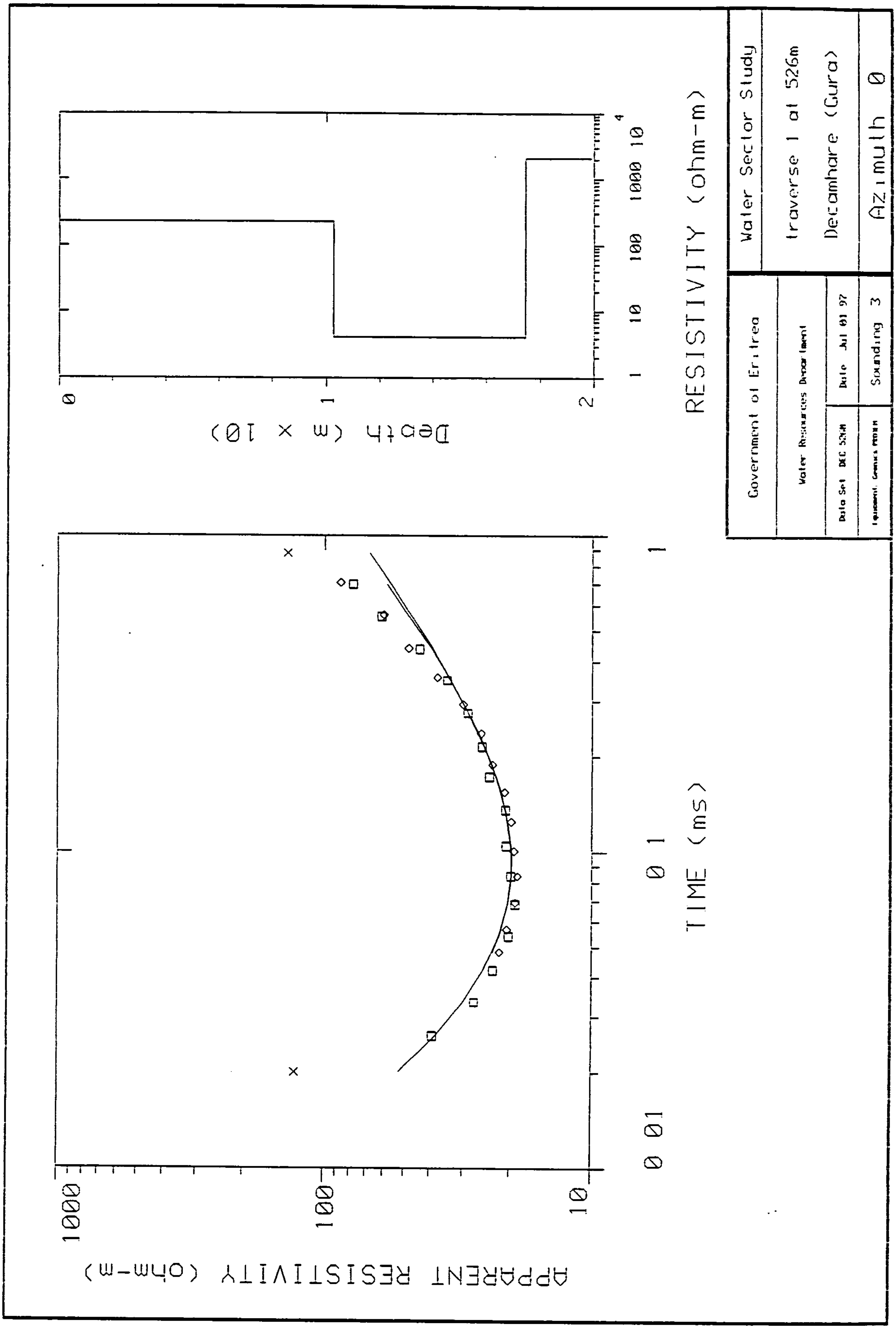


Fig. 3.1b_6 Decamhare: TDEM sounding at 526 m Traverse 1

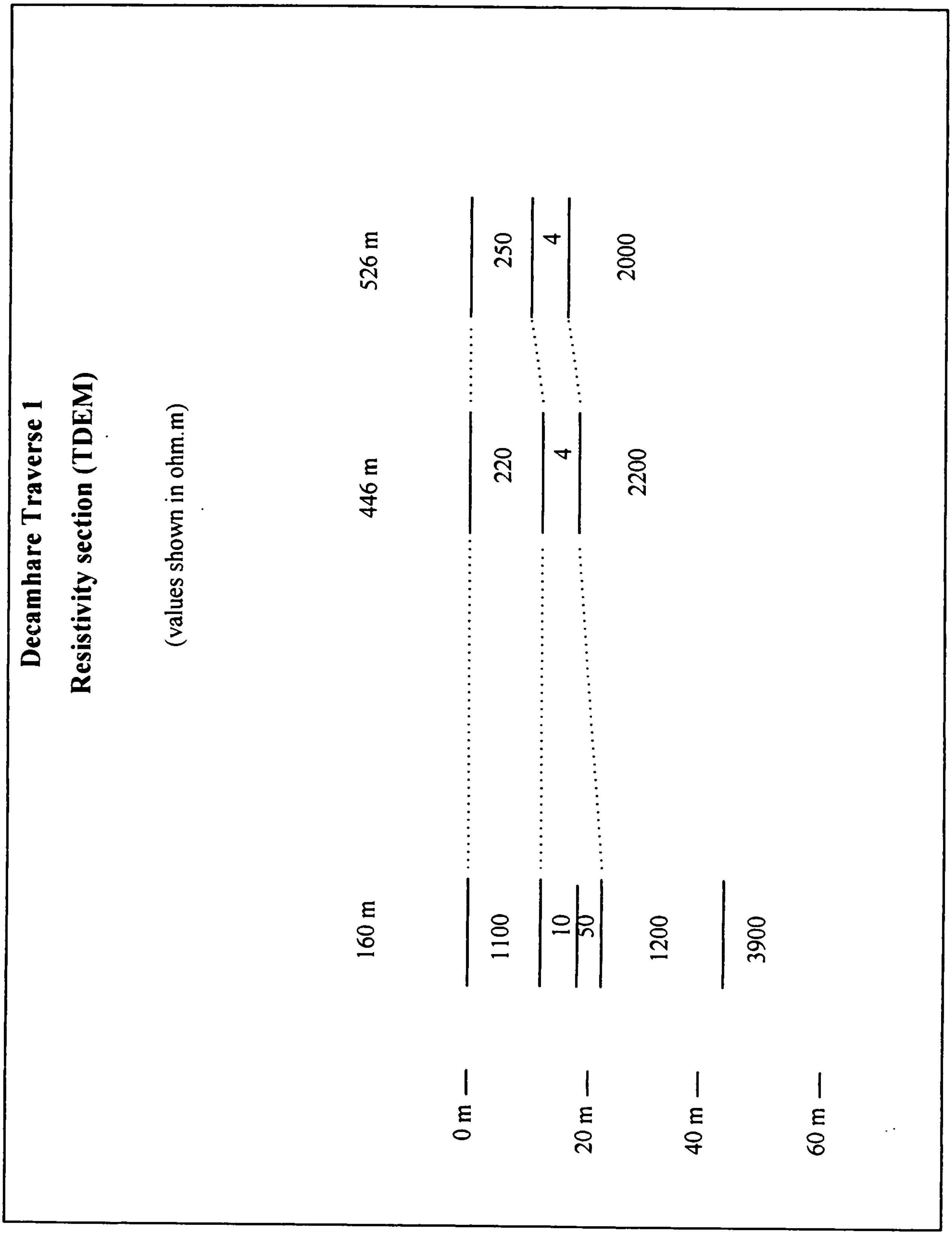


Fig. 3.1b_7 Decamhare: Resistivity section (Traverse 1) :TDEM sounding

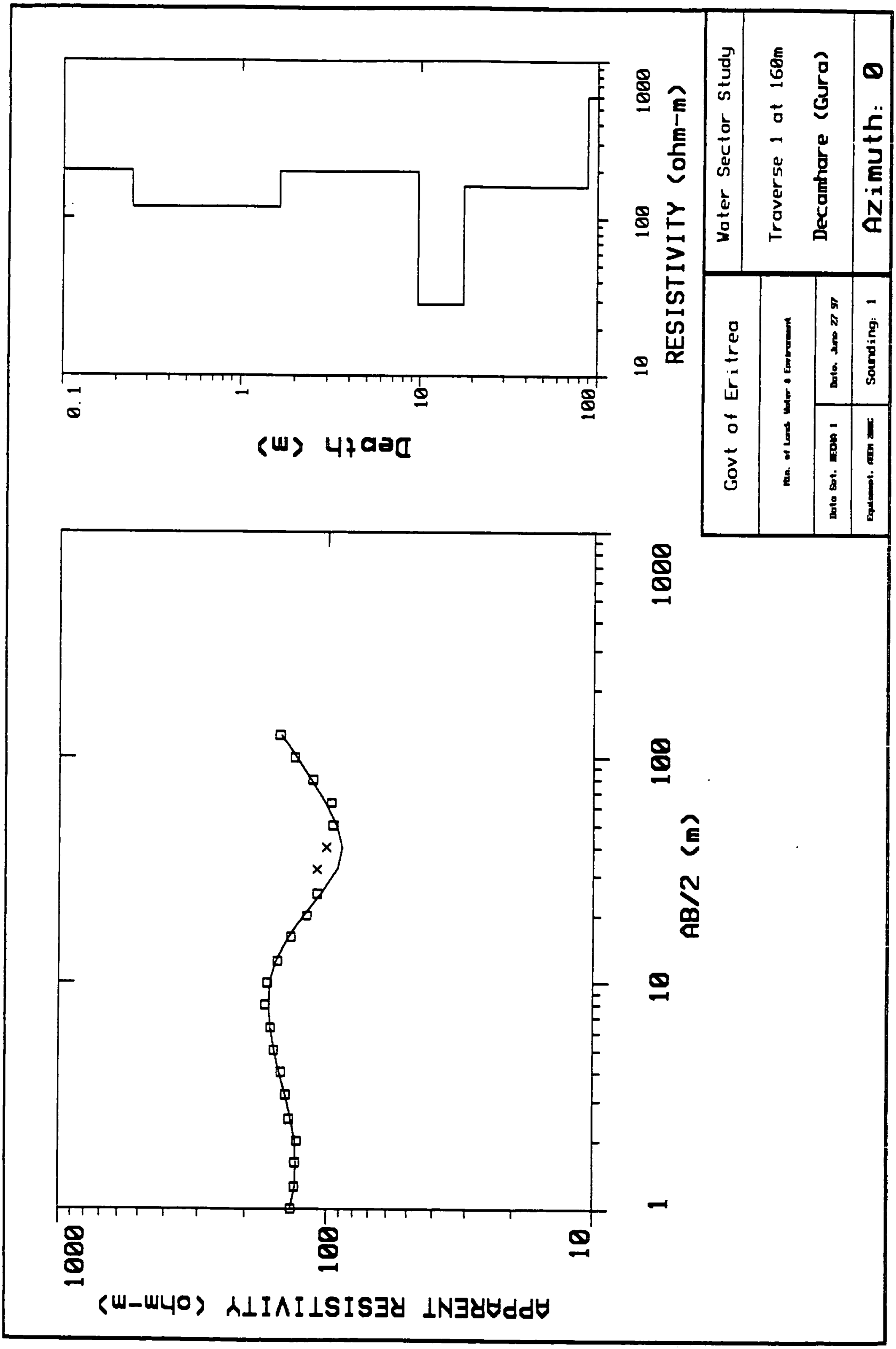


Fig. 3.1b_8 Decamhare: DC sounding at 160 m Traverse 1

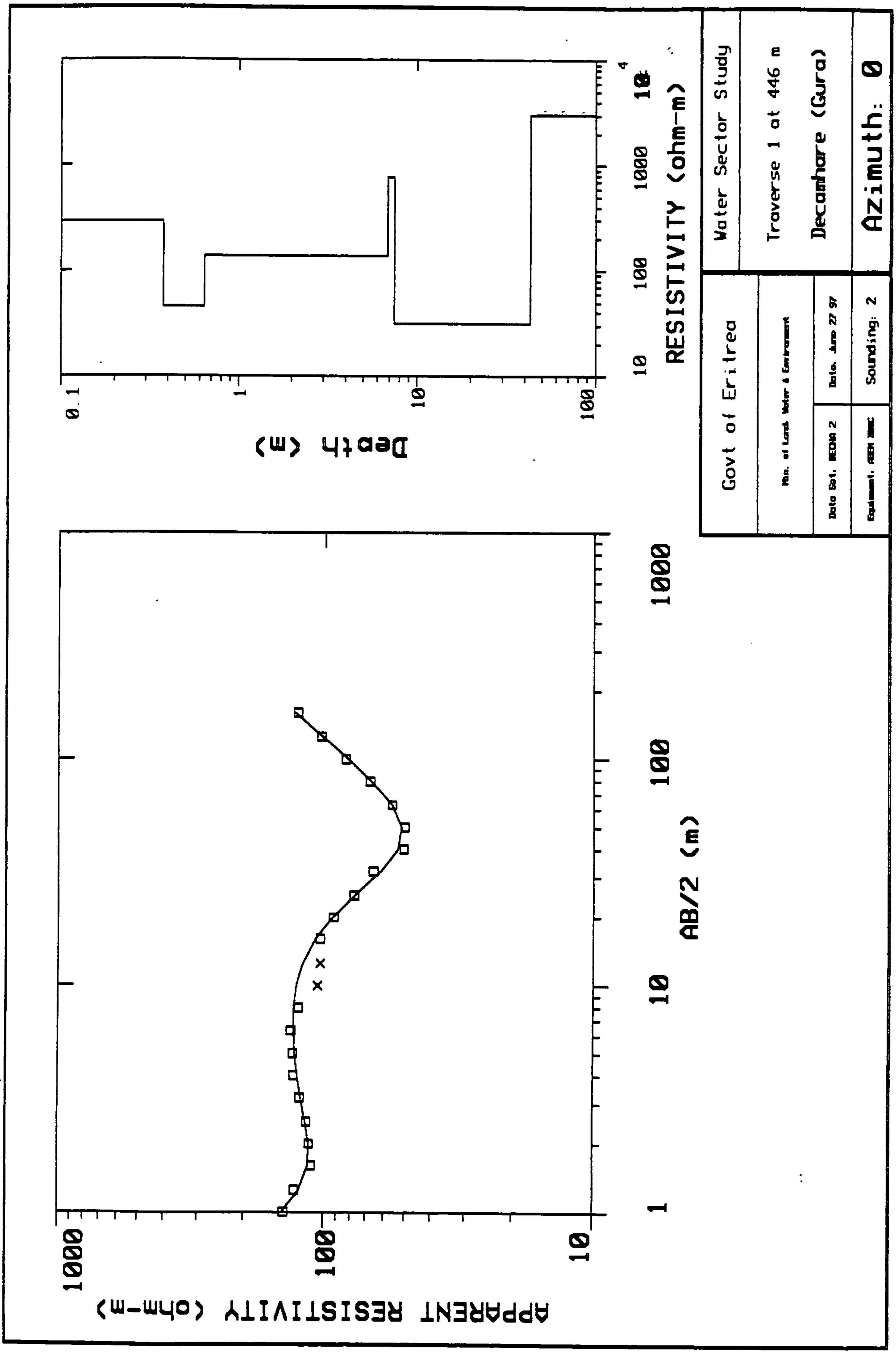


Fig. 3.1b_9 Decamhare: DC sounding at 446 m Traverse 1

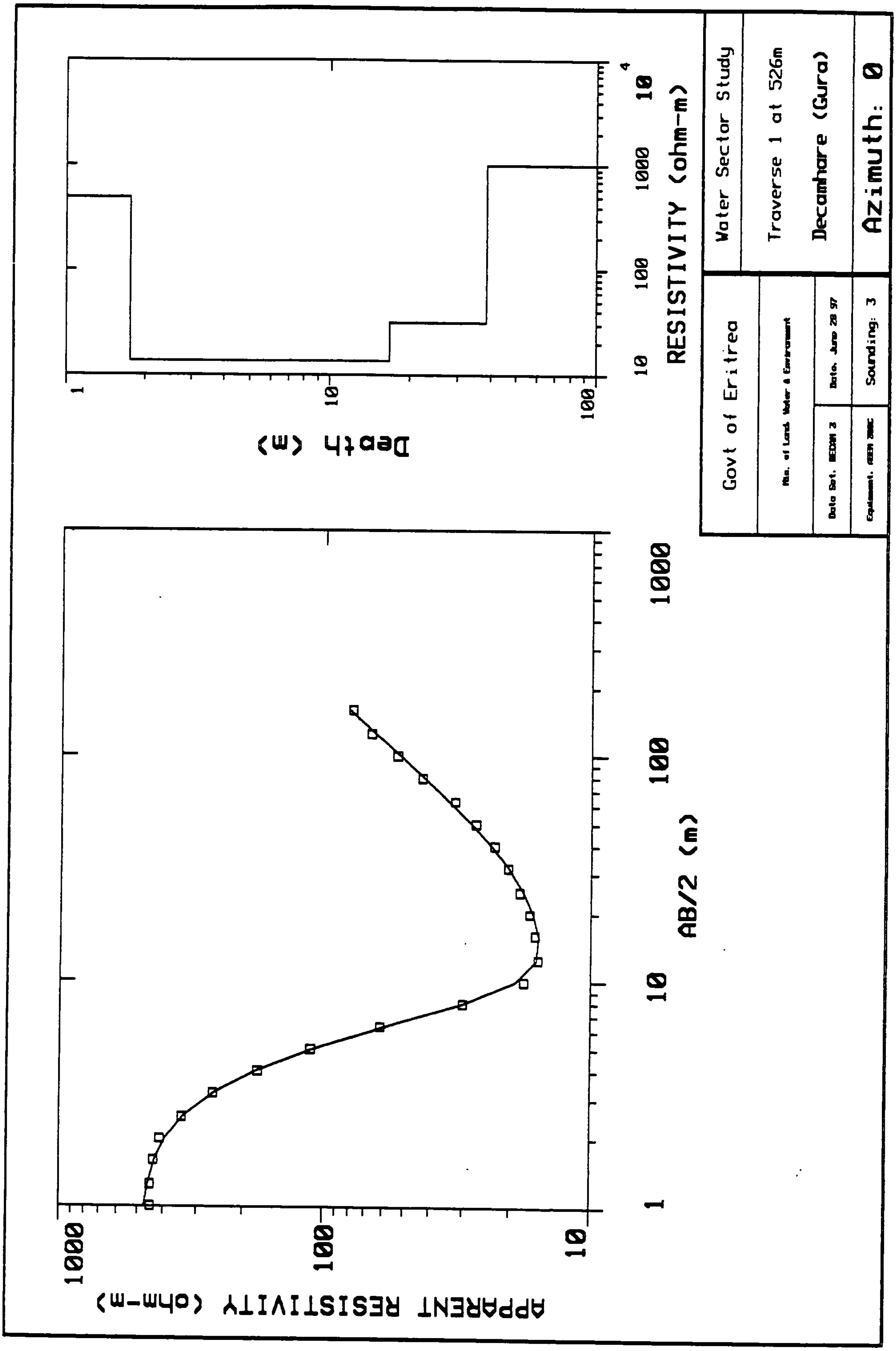


Fig. 3.1b_10 Decamhare: DC sounding at 526 m Traverse 1

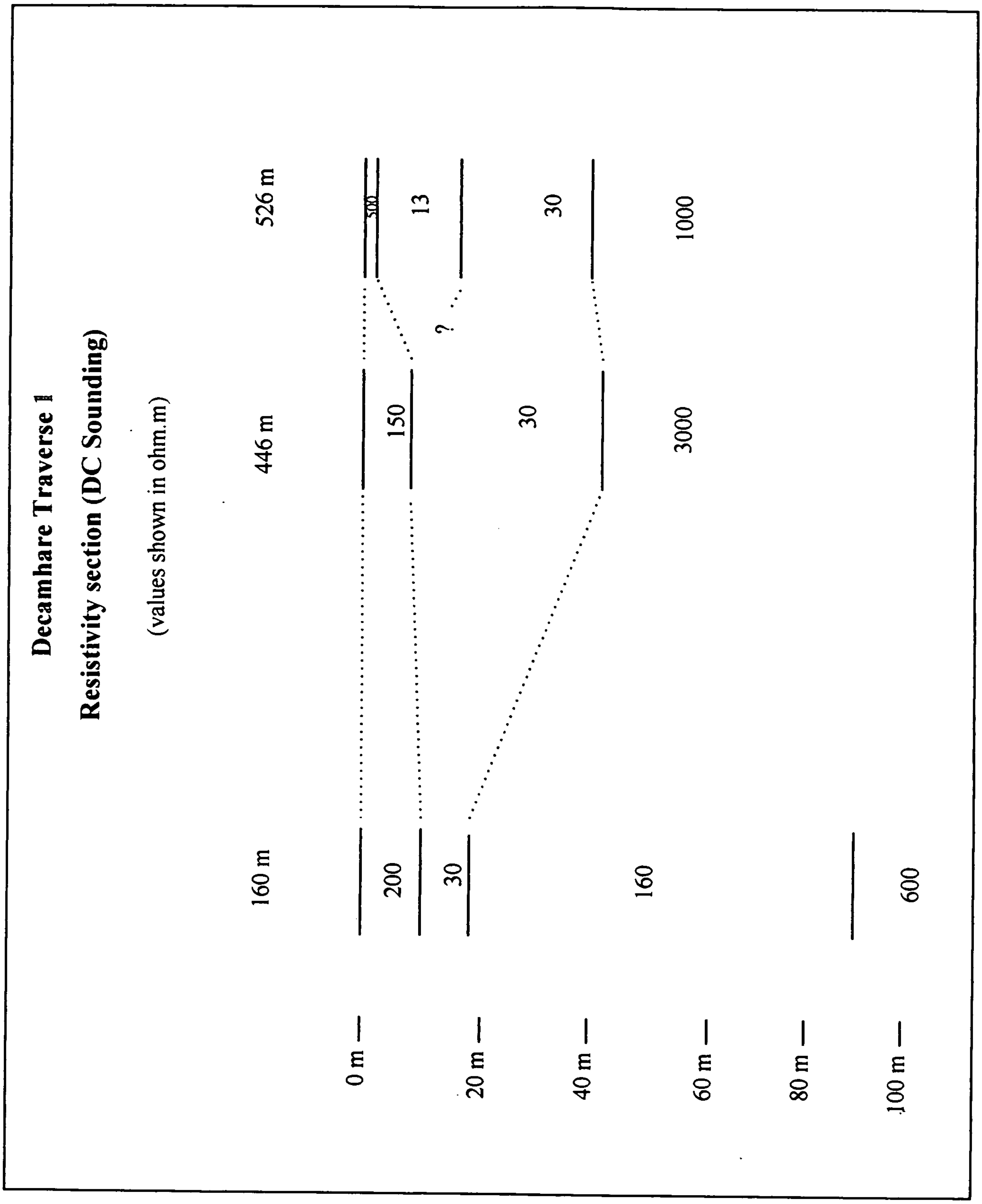


Fig. 3.1b_11 Decamhare: Resistivity section (Traverse 1): DC sounding

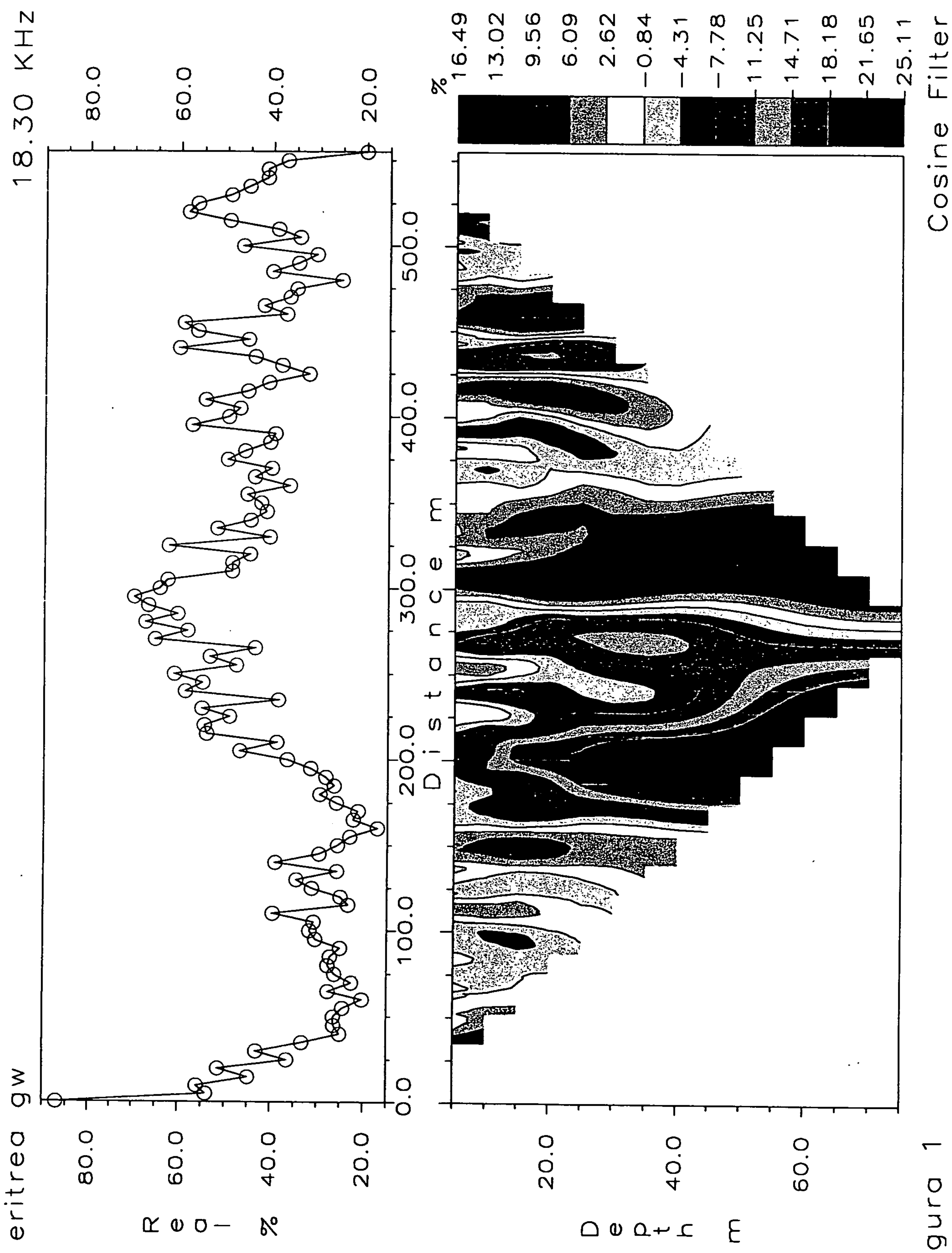


Fig. 3.1b_12 Decamhare: VLF in phase data and Karous-Hjelt filter result of Traverse 1

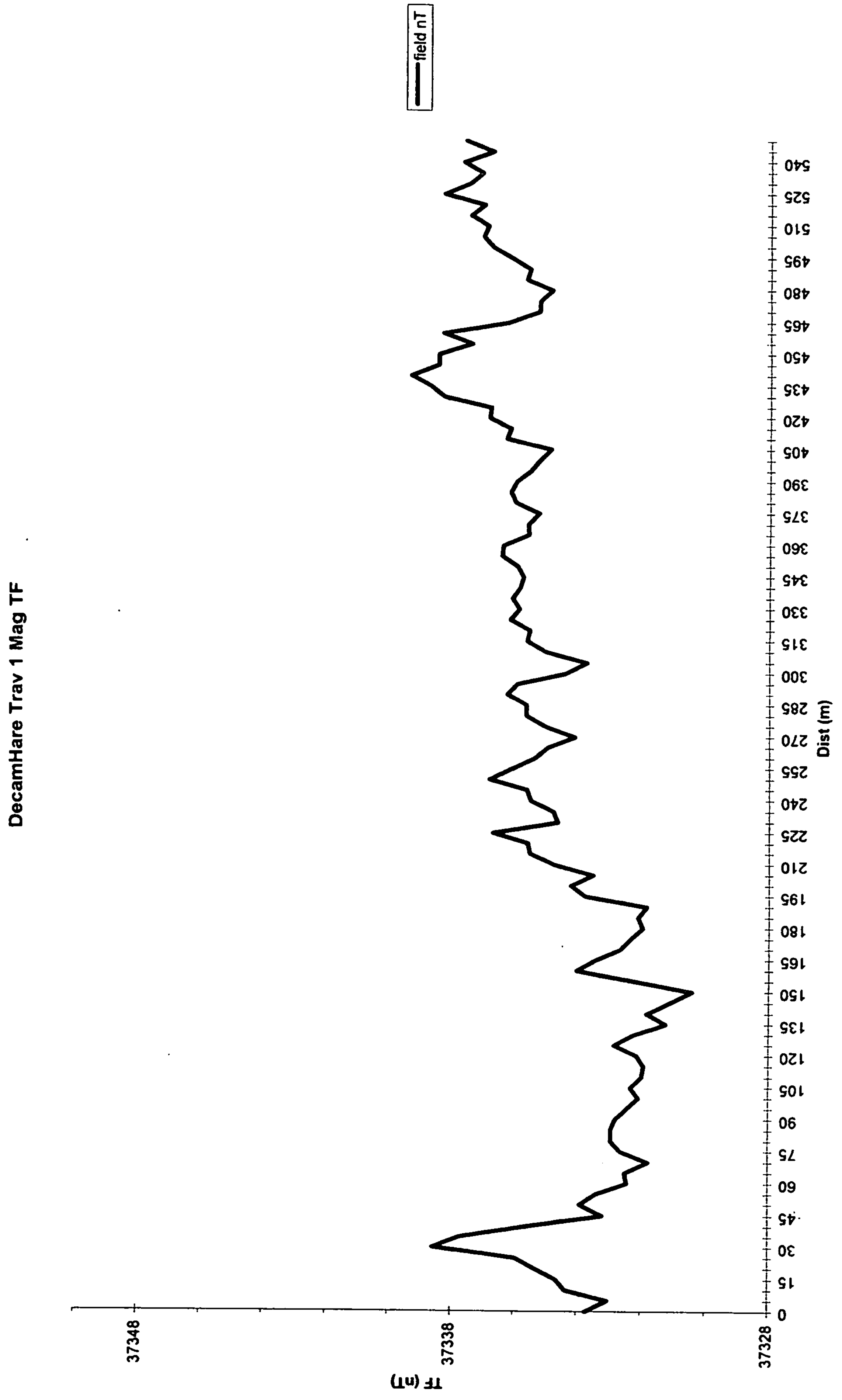


Fig. 3.1b_13 Decamhare: Total field magnetic data of Traverse 1

ERITREA: SECTOR STUDY ON NATIONAL WATER RESOURCES AND IRRIGATION POTENTIAL

GROUNDWATER EXPLORATION

GEOPHYSICAL INVESTIGATIONS COMPLETED

from initial traverse 2km south (along airstrip)

SHEET No: **LOCATION:** Gura airstrip (South) **UTM Co-ords:** E 534262 N 1660461

Geology: Granite / alluvials **Target:** Satellite lineament

GEOPHYSICAL TECHNIQUES	Used?	Line/Grid	cover m/No.	Comments
Conductivity EM34 40m	✓	L	390 m	includes short traverse
Conductivity EM34 20m	✓	L	20 m	with all seps/orientations
Conductivity EM34 10m	✓	L	20 m	at well site (>12m alluvium)
TDEM 47 sounding (5m*5m)				
TDEM 47 sounding (40m*40m)				
TDEM47 sounding (100m*100m)				
TDEM 47 traversing (5m*5m)				
TDEM 47 traversing (40m*40m)				
TDEM 47 traversing (100m*100m)				
Resistivity (ABEM 300C) sounding				
Resistivity (ABEM 300C) traversing				
VLF (WADI) traversing	✓	L	900 m	
Magnetometry (GEM) traversing	✓	L	900 m	
Gravimetry				
Seismic refraction				

Previous work:

Borehole sited ?: NO **Location:** **Project Bh No:**

Borehole drilled (date):

Result:

Fig. 3.1b_14 Gura south: table summarising geophysical investigations

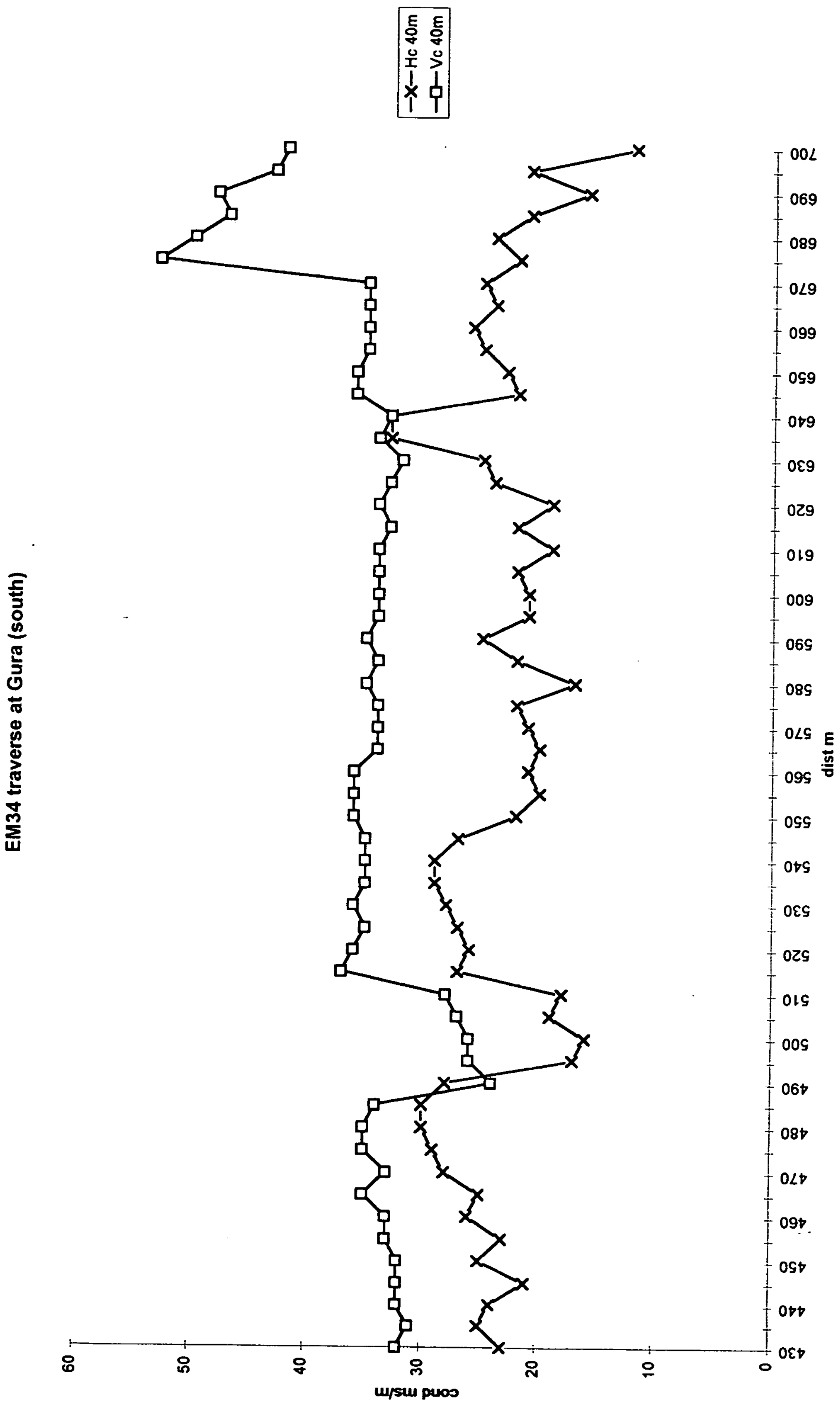


Fig. 3.1b_15 Gura south: EM34 data on Traverse 1

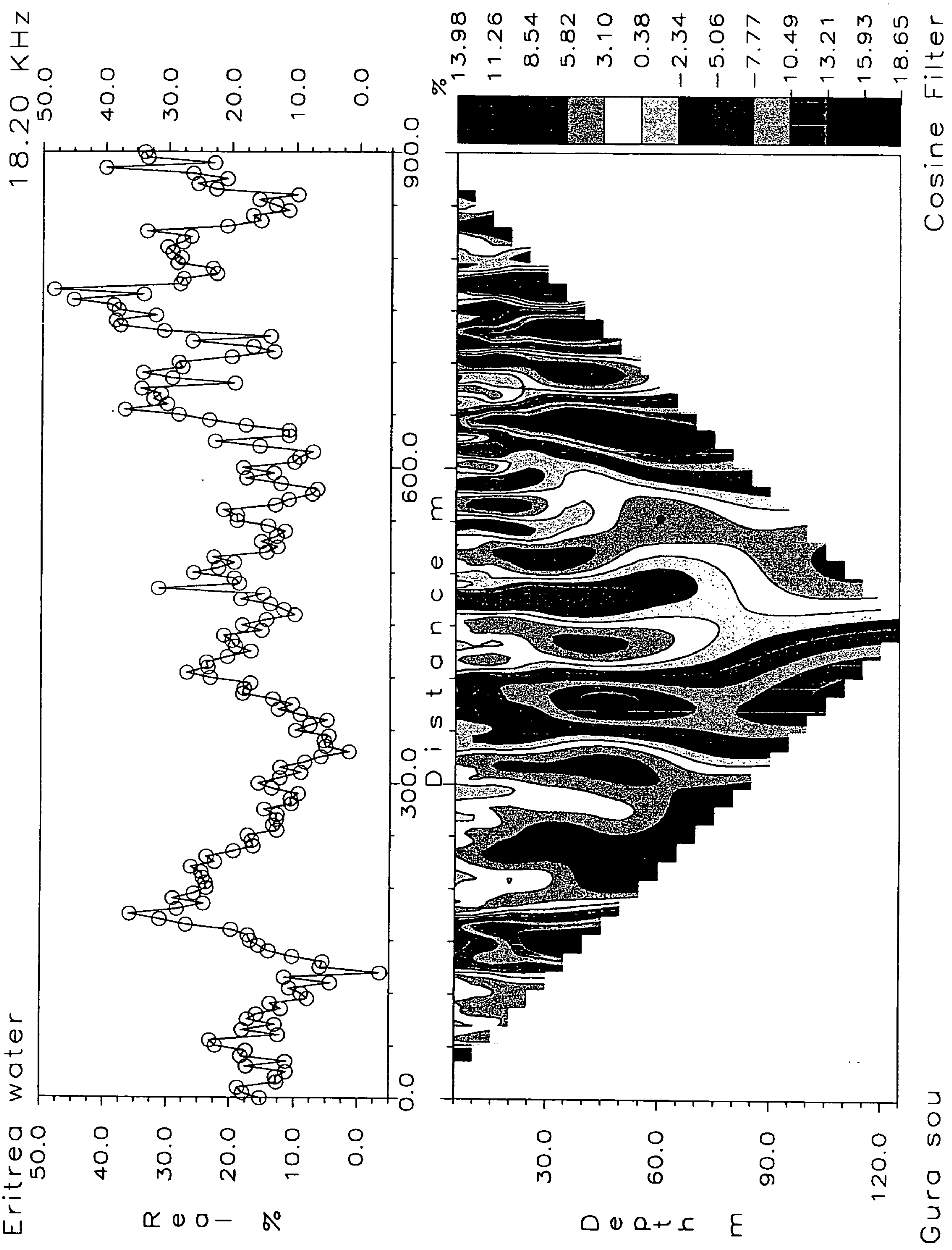


Fig. 3.1b_16 Gura south: VLF in phase data and Karous-Hjelt filter result of Traverse 1

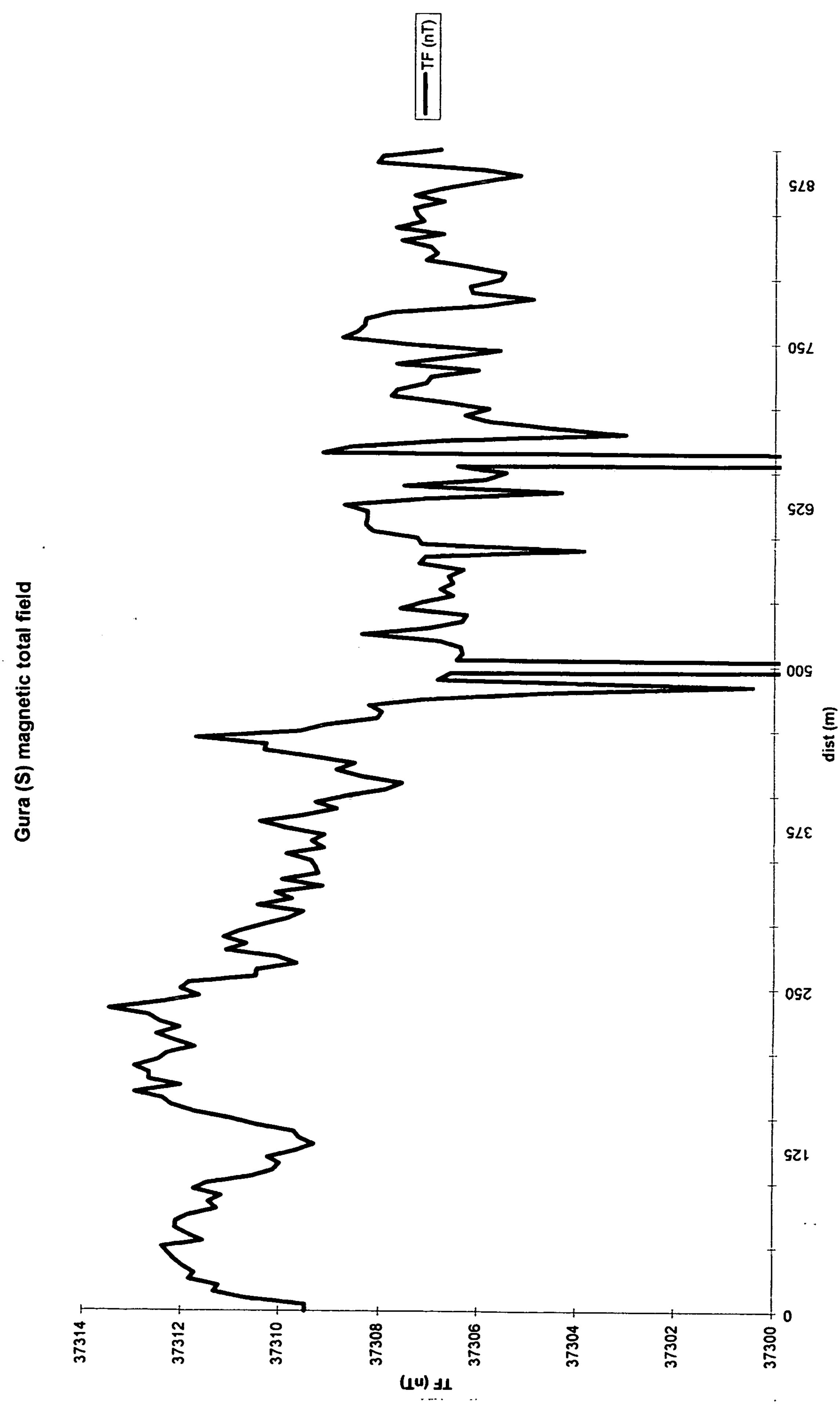


Fig. 3.1b_17 Gura south: Total field magnetic data of Traverse 1

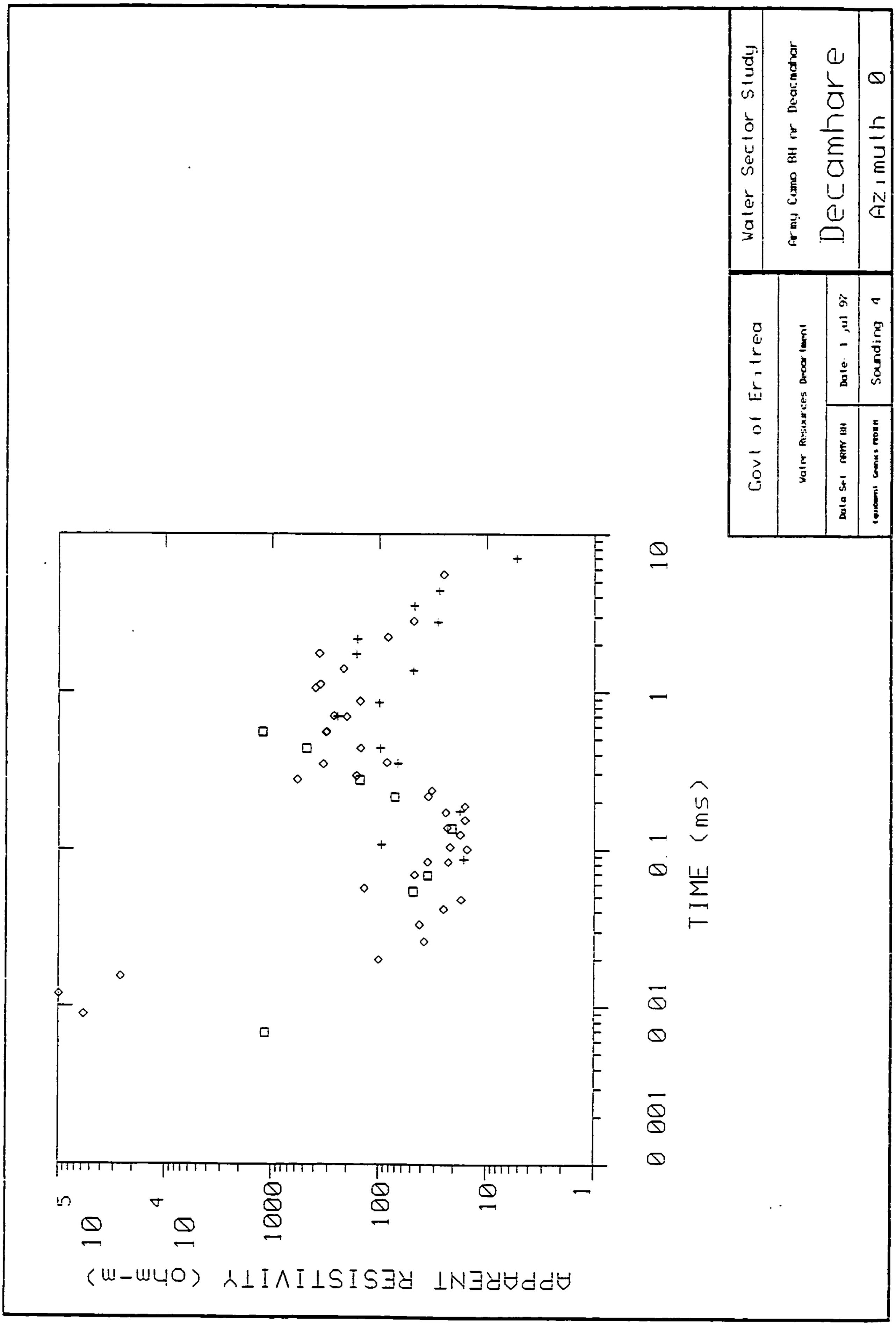


Fig. 3.1b_18 Army camp borehole: TDEM sounding

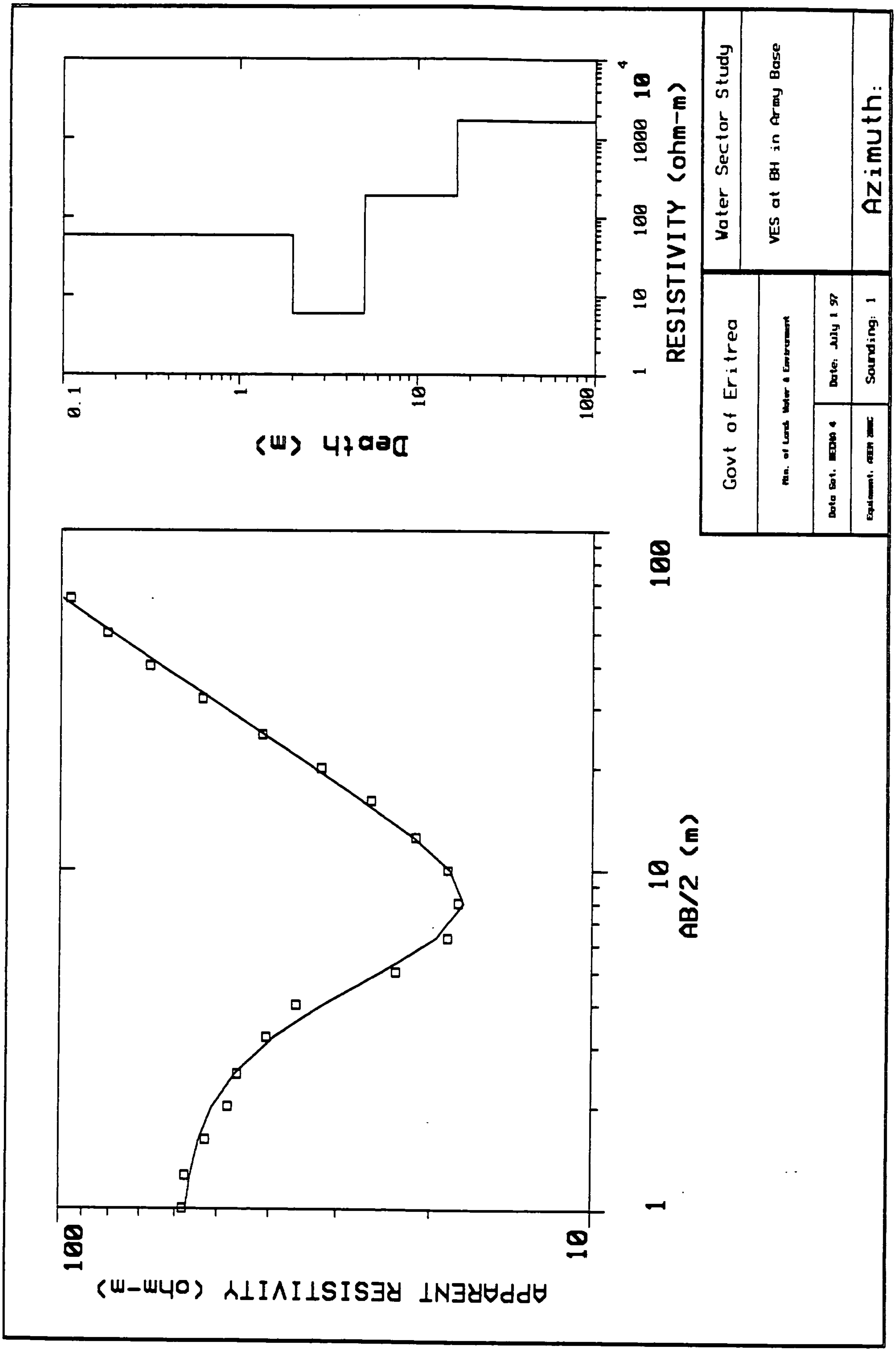


Fig. 3.1b_19 Army camp borehole: DC sounding

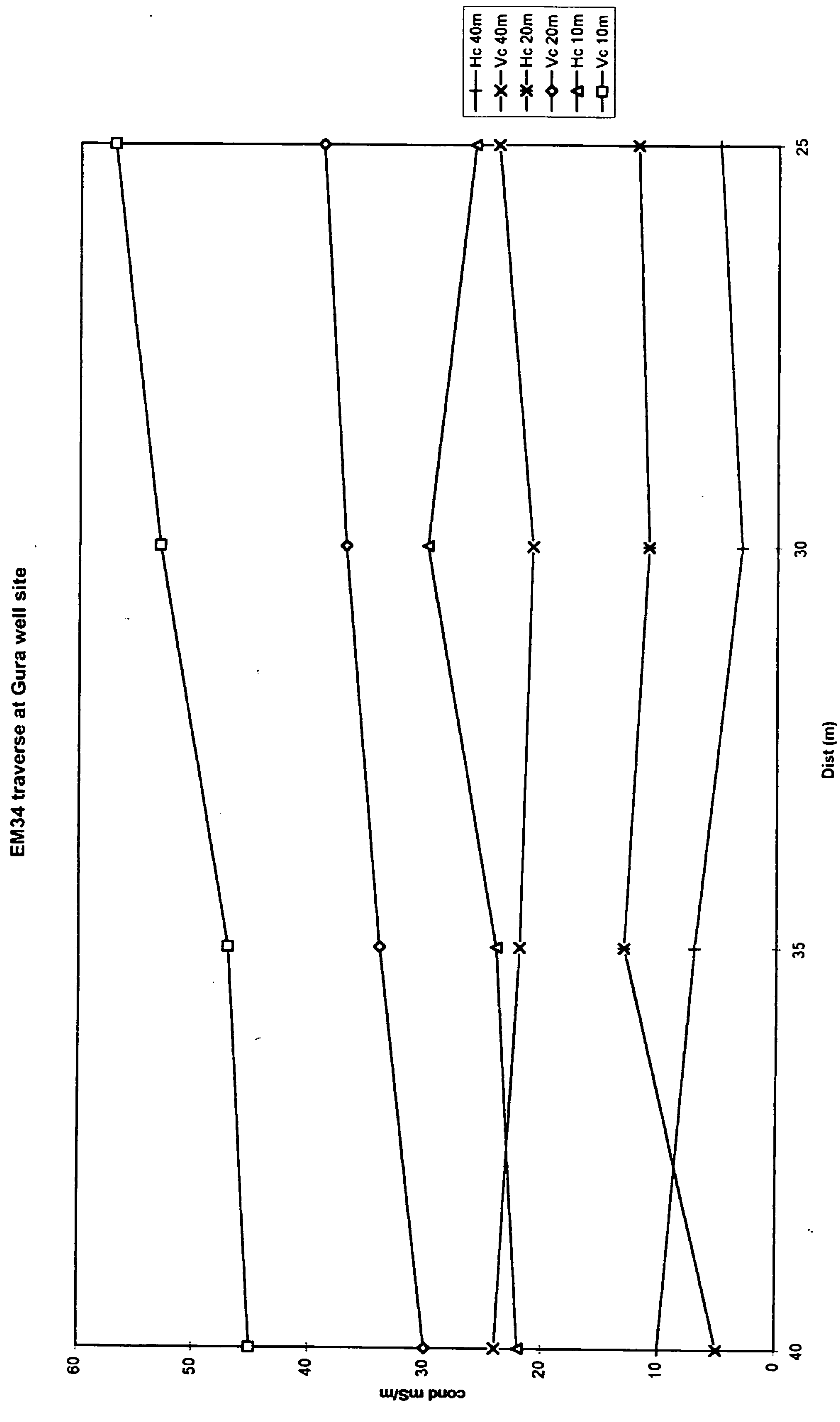


Fig. 3.1b_20 Gura well site: EM34 traverses

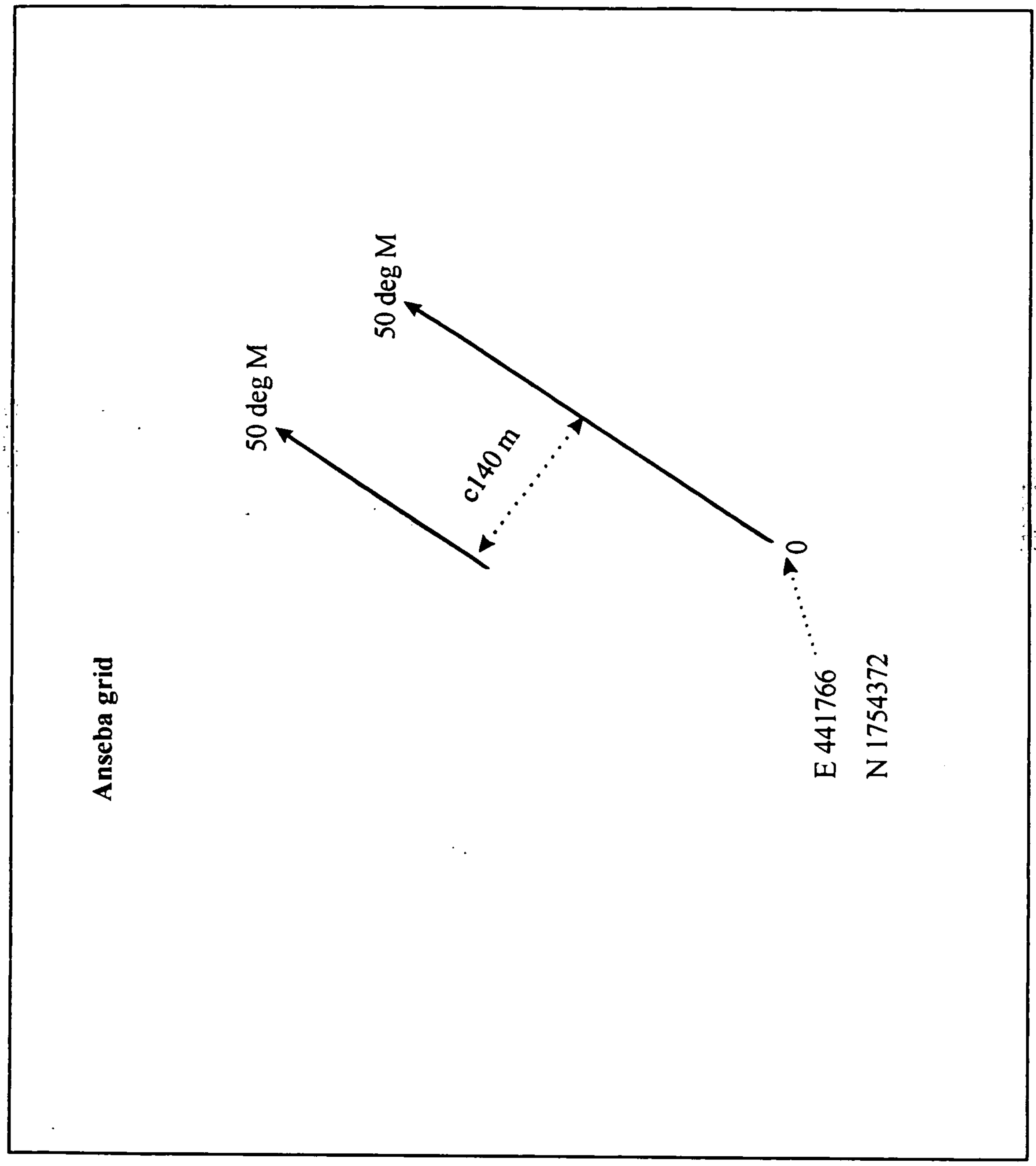


Fig. 3.3d_1 Anseba: geophysical grid at Anseba

ERITREA: SECTOR STUDY ON NATIONAL WATER RESOURCES AND IRRIGATION POTENTIAL

GROUNDWATER EXPLORATION

GEOPHYSICAL INVESTIGATIONS COMPLETED

SHEET No: **LOCATION:** ANSEBA R. (c.15 km NE Keren) **UTM Co-ords: E** 441766 **N** 1754372

Geology: **Target:** ANSEBA shear zone

GEOPHYSICAL TECHNIQUES	Used?	Line/Grid	cover m/No.	Comments
Conductivity EM34 40m	✓	L (2)		1740 m
Conductivity EM34 20m	✓	L (1)	205 m	
Conductivity EM34 10m				
TDEM 47 sounding (5m*5m)				
TDEM 47 sounding (40m*40m)				
TDEM47 sounding (100m*100m)				
TDEM 47 traversing (5m*5m)				
TDEM 47 traversing (40m*40m)				
TDEM 47 traversing (100m*100m)				
Resistivity (ABEM 300C) sounding				
Resistivity (ABEM 300C) traversing				
VLF (WADI) traversing	✓	L	1450 m	
Magnetometry (GEM) traversing	✓	L (2)	1700 m	
Gravimetry				
Seismic refraction				

Previous work: Well in mango plantation (at c. 1300 m Traverse 1) 6 m deep WL c. 2.5 m bgl – yield reported excellent. (supplies tankers for Keren(?))

Borehole sited ?: YES **Location:** ~~1300m Line 2~~ 600 m Line 1 **Project Bh No:**

Borehole drilled (date):

Result:

Fig. 3.3d_2 Anseba: table summarising geophysical investigations

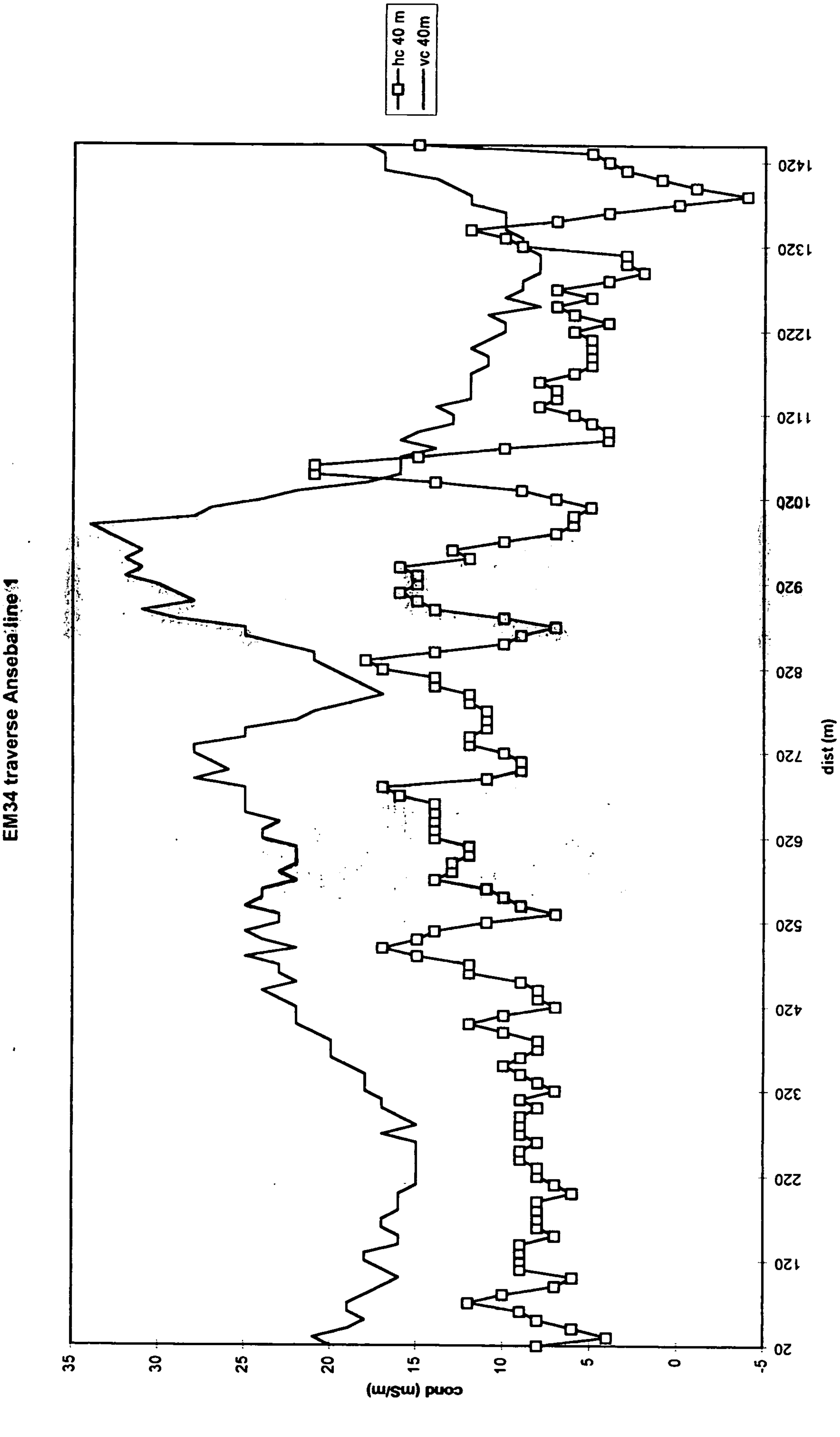


Fig. 3.3d_3 Anseba: EM34 data of Traverse 1 (20 m to 1420 m)

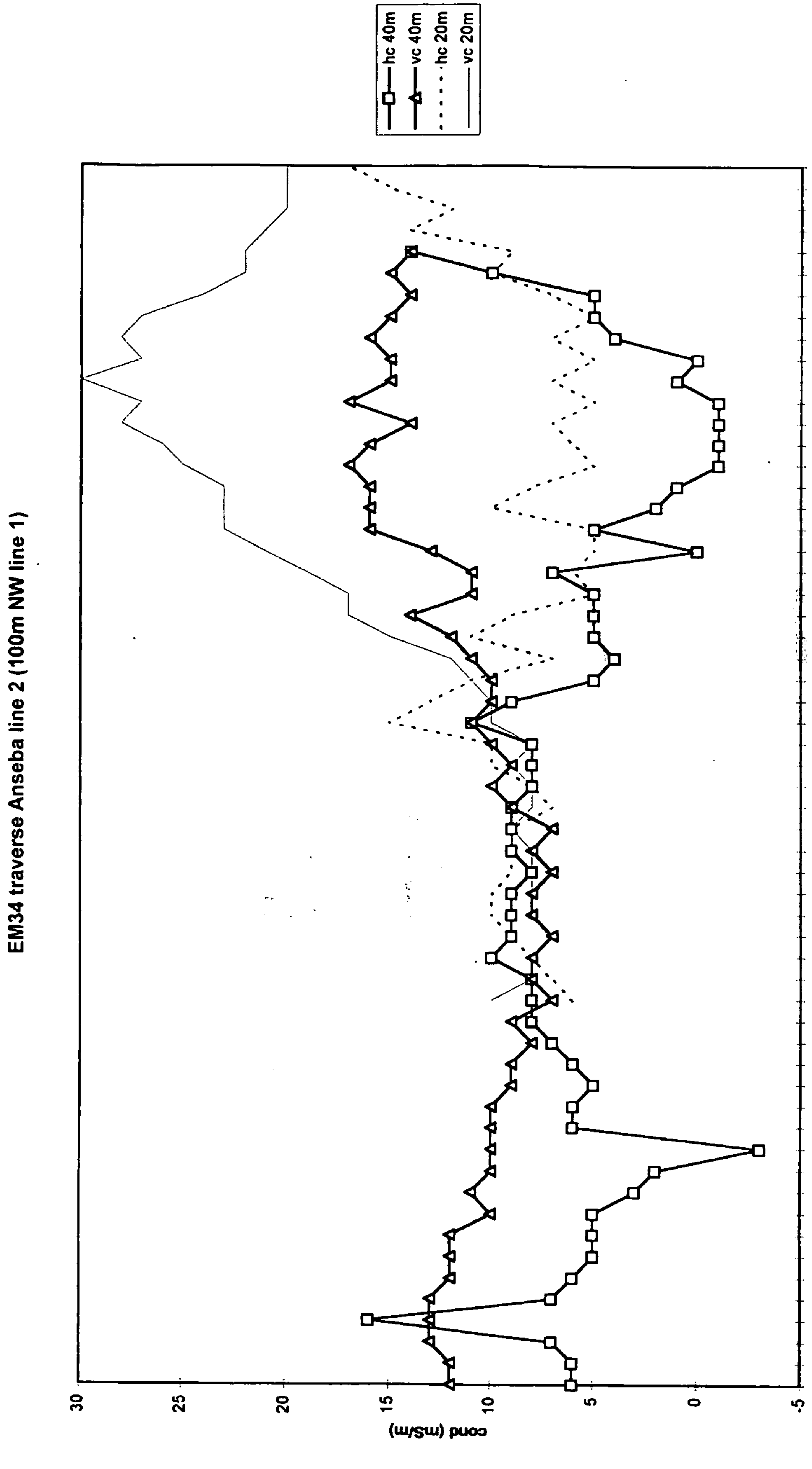


Fig. 3.3d_4 Anseba: EM34 data of Traverse 2 (20 m to 280 m)

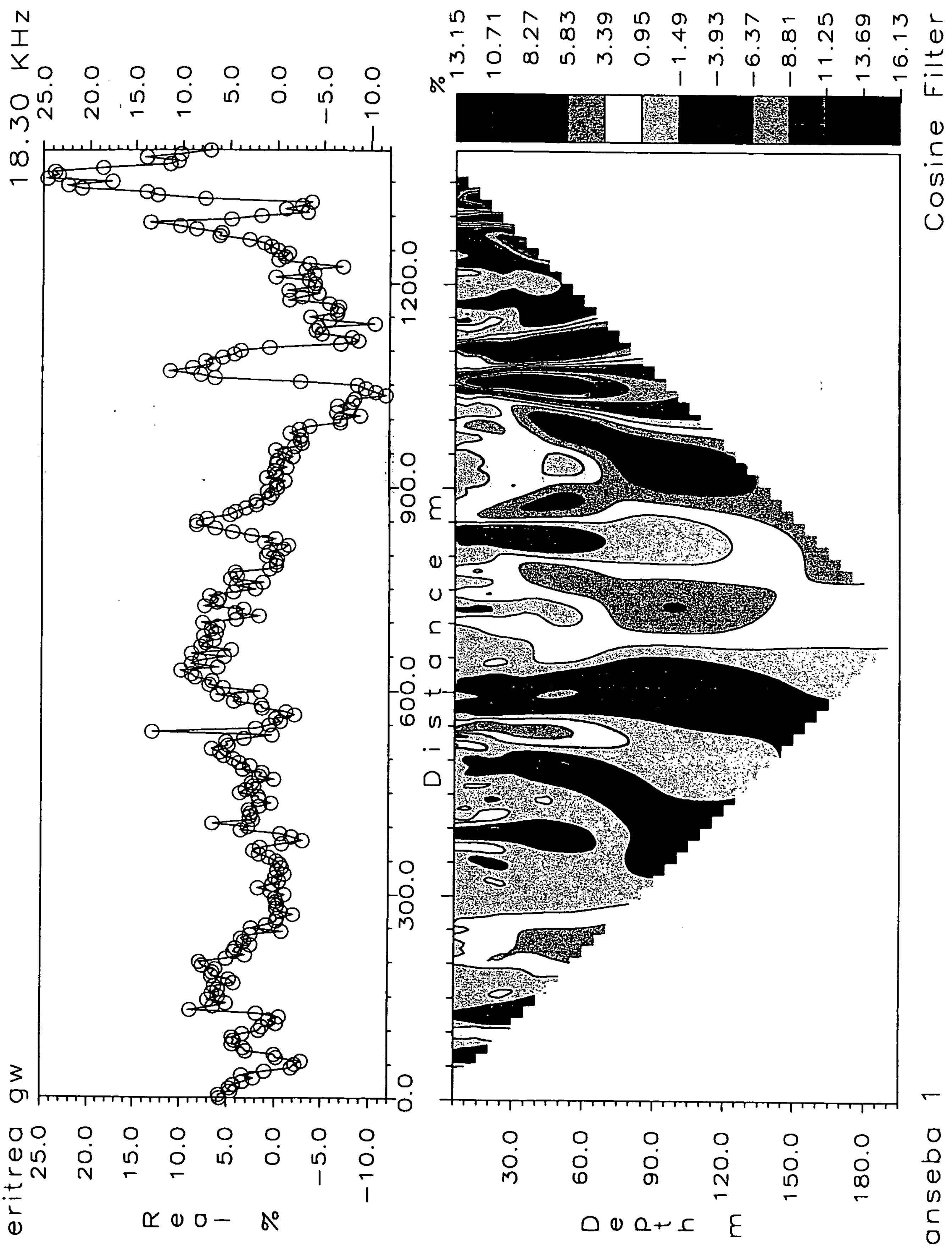


Fig. 3.3d_5 Anseba: VLF in phase data and Karous-Hjelt filter result:Traverse 1

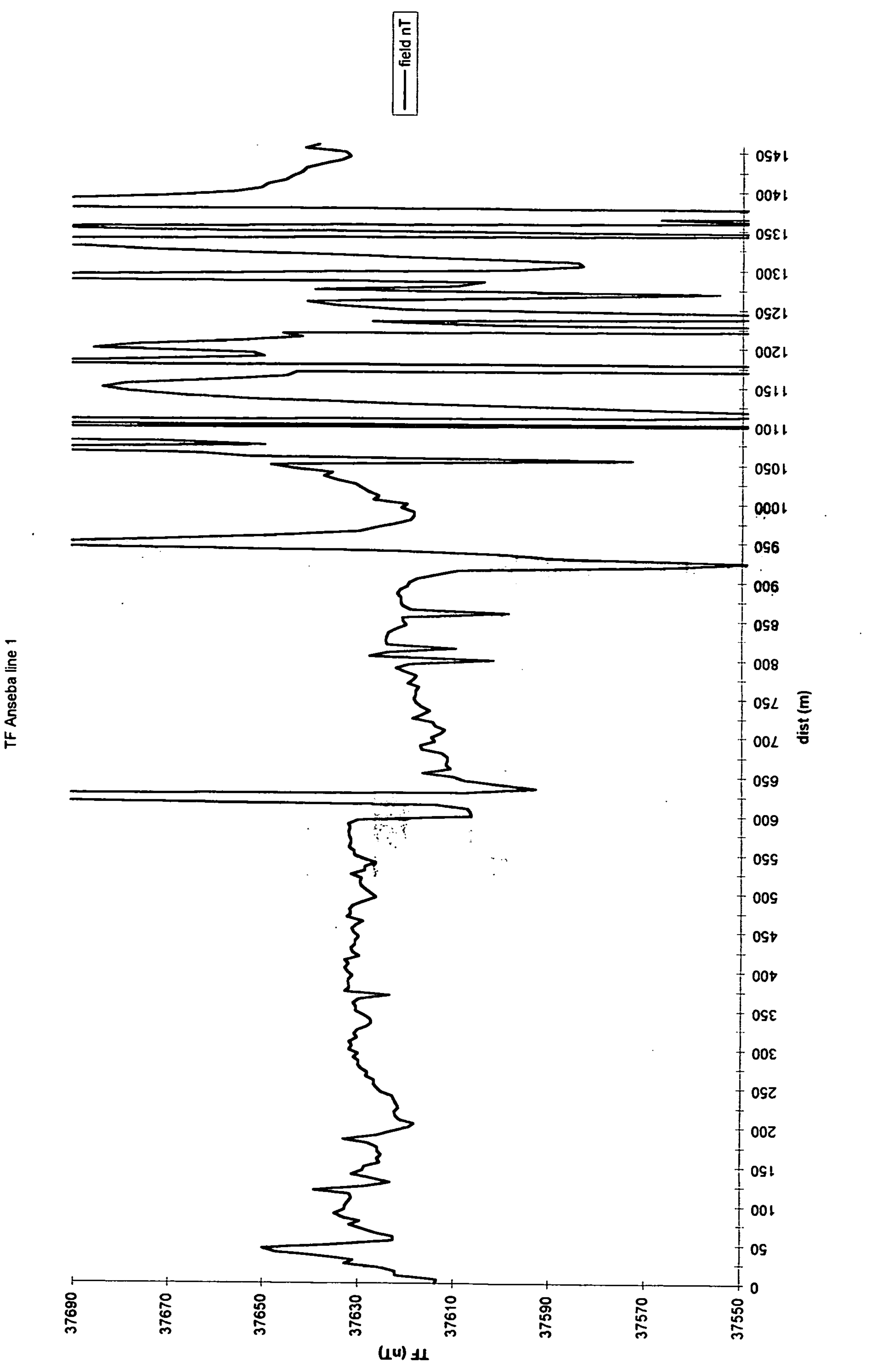


Fig. 3.3d_6 Anseba: Total field magnetic profile of Traverse 1 (0 m to 1450 m)

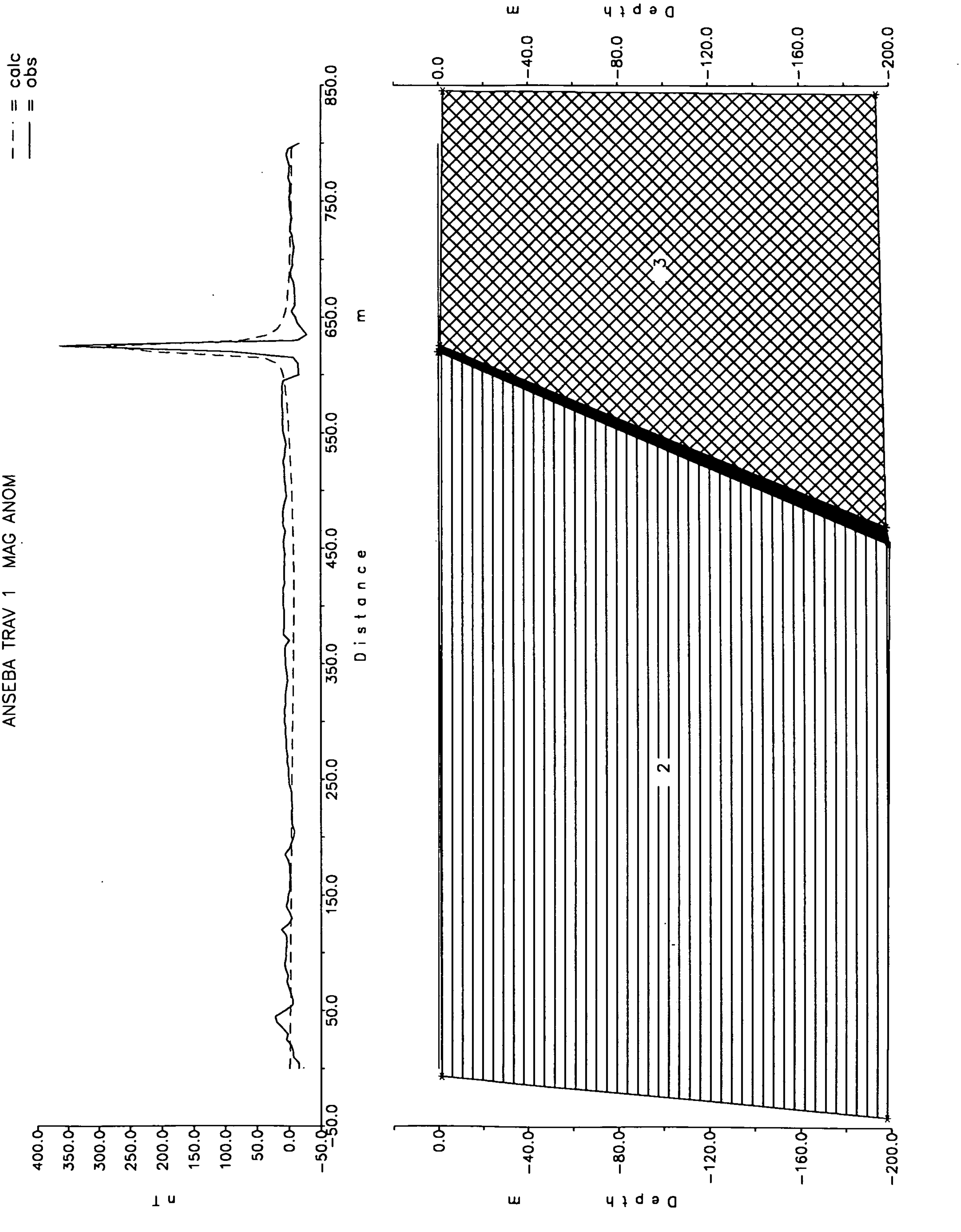


Fig. 3.3d_6x Anseba: modelled magnetic anomaly (c. 625 m traverse 1)

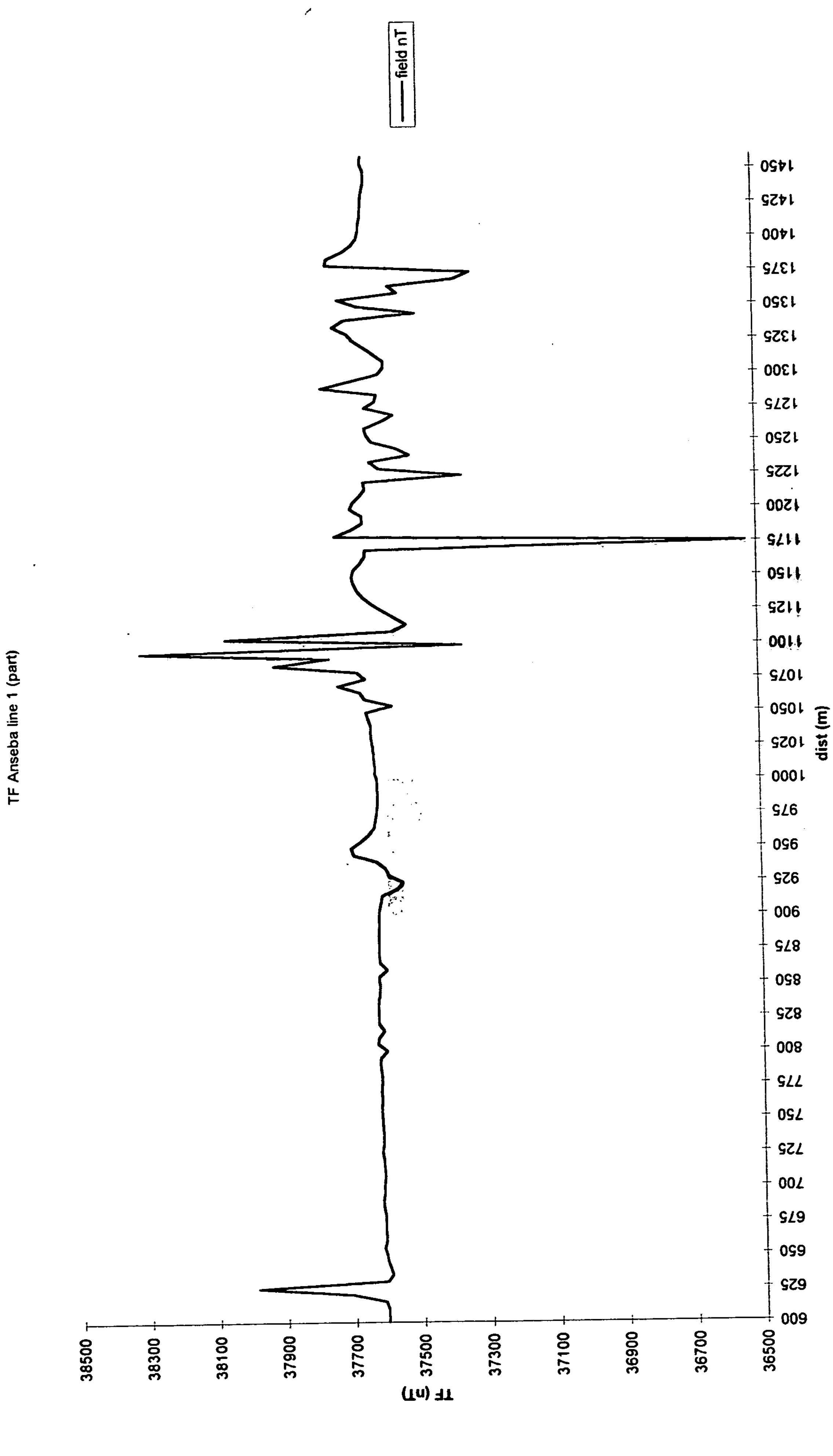


Fig. 3.3d_7 Anseba: Total field magnetic profile of Traverse 1 (600 m to 1450 m)

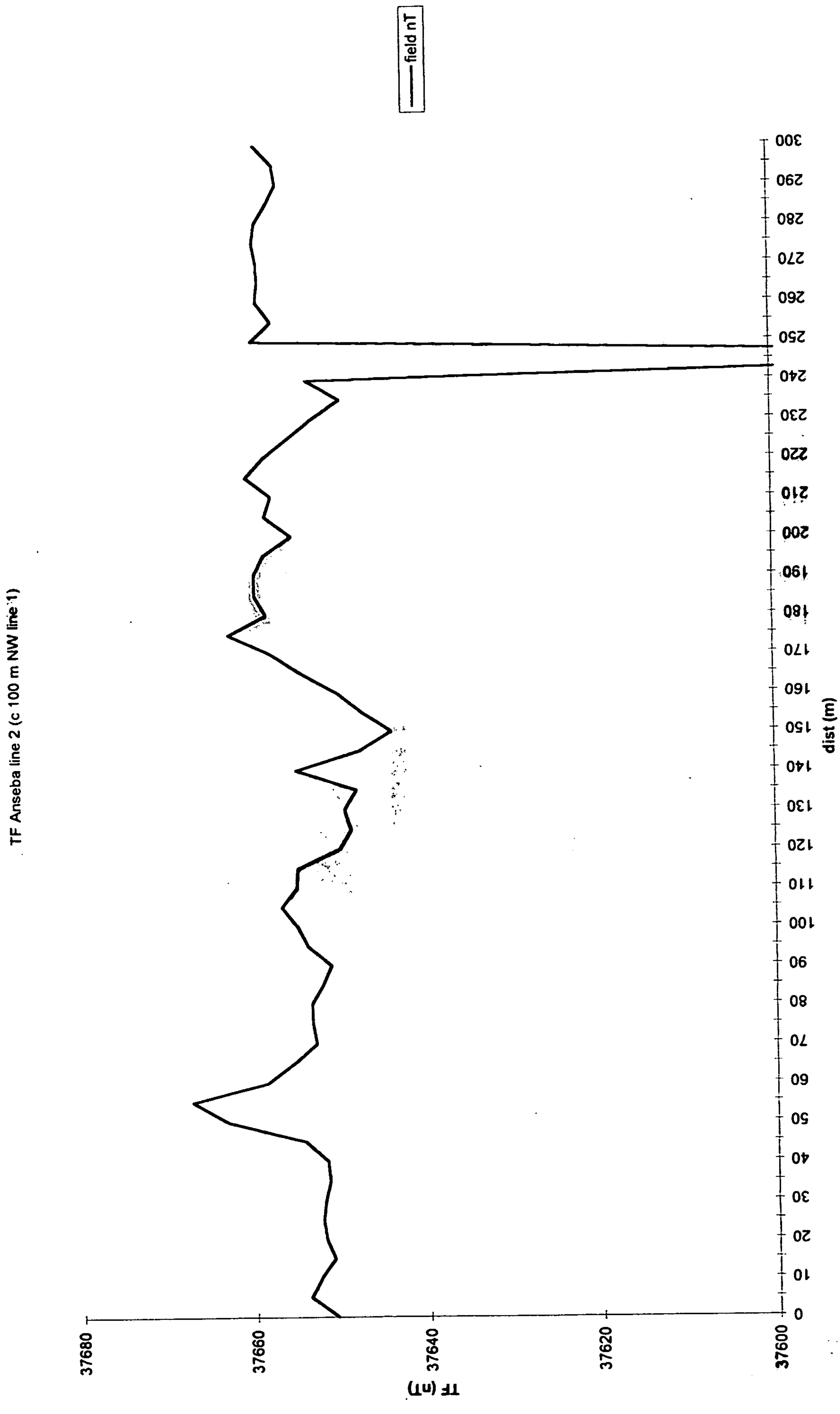


Fig. 3.3d_8 Anseba: Total field magnetic profile of Traverse 2

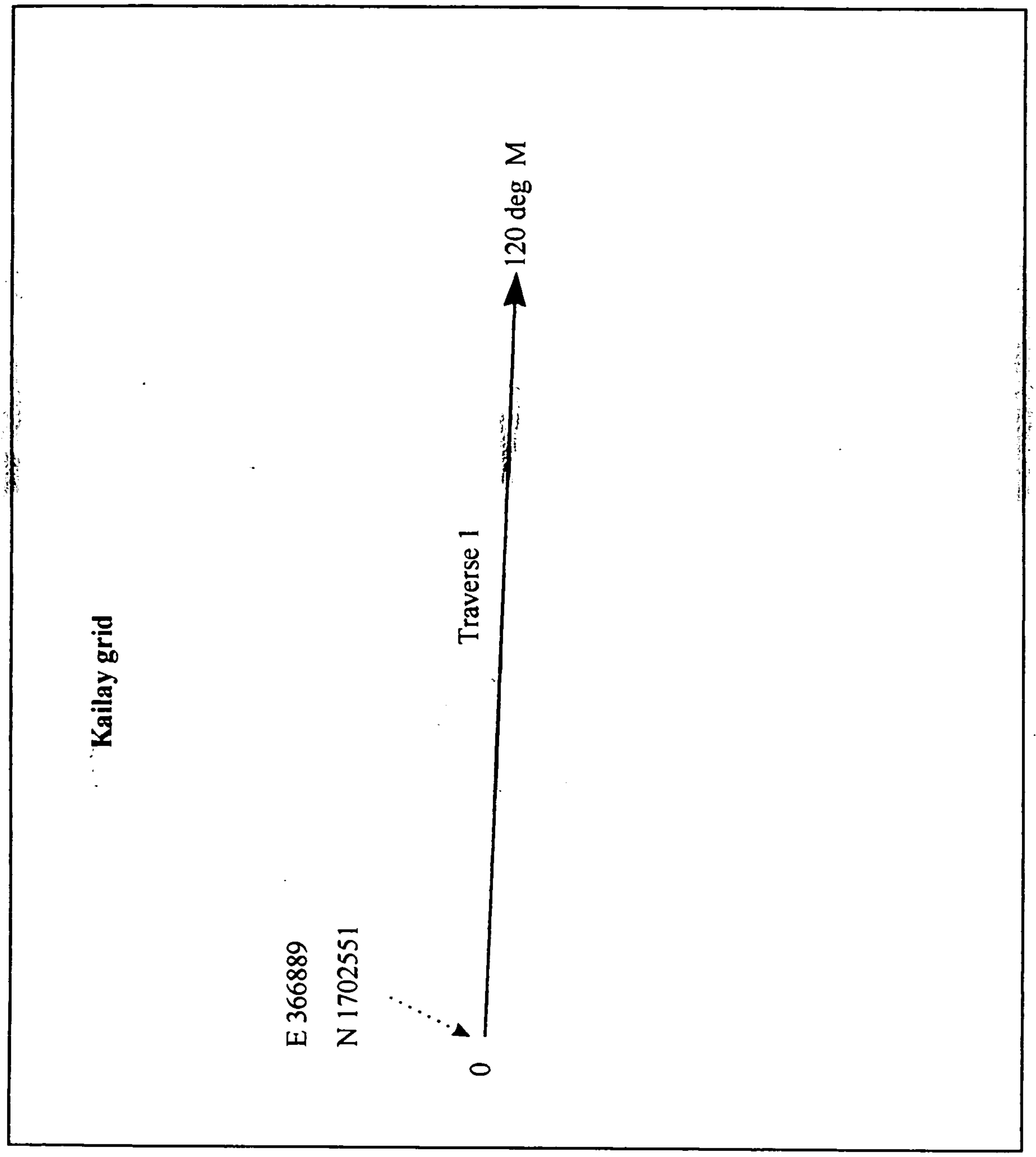


Fig. 3.4a_1 Kailay: geophysical grid at Kailay

ERITREA: SECTOR STUDY ON NATIONAL WATER RESOURCES AND IRRIGATION POTENTIAL

GROUNDWATER EXPLORATION

GEOPHYSICAL INVESTIGATIONS COMPLETED

SHEET No: **LOCATION:** KAILAY (off Barentu - Akordat road) **UTM Co-ords: E** 366889 **N** 1702551

Geology: Basement / dolerite dykes (GN) + colluvium (riverside). **Target:** Fracture (abrupt termination dykes) plus thick regolith

GEOPHYSICAL TECHNIQUES				
	Used?	Line/Grid	cover m/No.	Comments
Conductivity EM34 40m	✓	L	400m	
Conductivity EM34 20m				
Conductivity EM34 10m				
TDEM 47 sounding (5m*5m)				
TDEM 47 sounding (40m*40m)				
TDEM47 sounding (100m*100m)				
TDEM 47 traversing (5m*5m)				
TDEM 47 traversing (40m*40m)				
TDEM 47 traversing (100m*100m)				
Resistivity (ABEM 300C) sounding	✓	L	3 No.	
Resistivity (ABEM 300C) traversing				
VLF (WADI) traversing				
Magnetometry (GEM) traversing	✓	L	400 m	
Gravimetry				
Seismic refraction				

Previous work:

Borehole sited ?: YES **Location:** Stn. 35m Line 1 (366719, 1702640) **Project Bh No:**

Borehole drilled (date):

Result:

Fig. 3.4a_2 Kailay: table summarising geophysical investigations

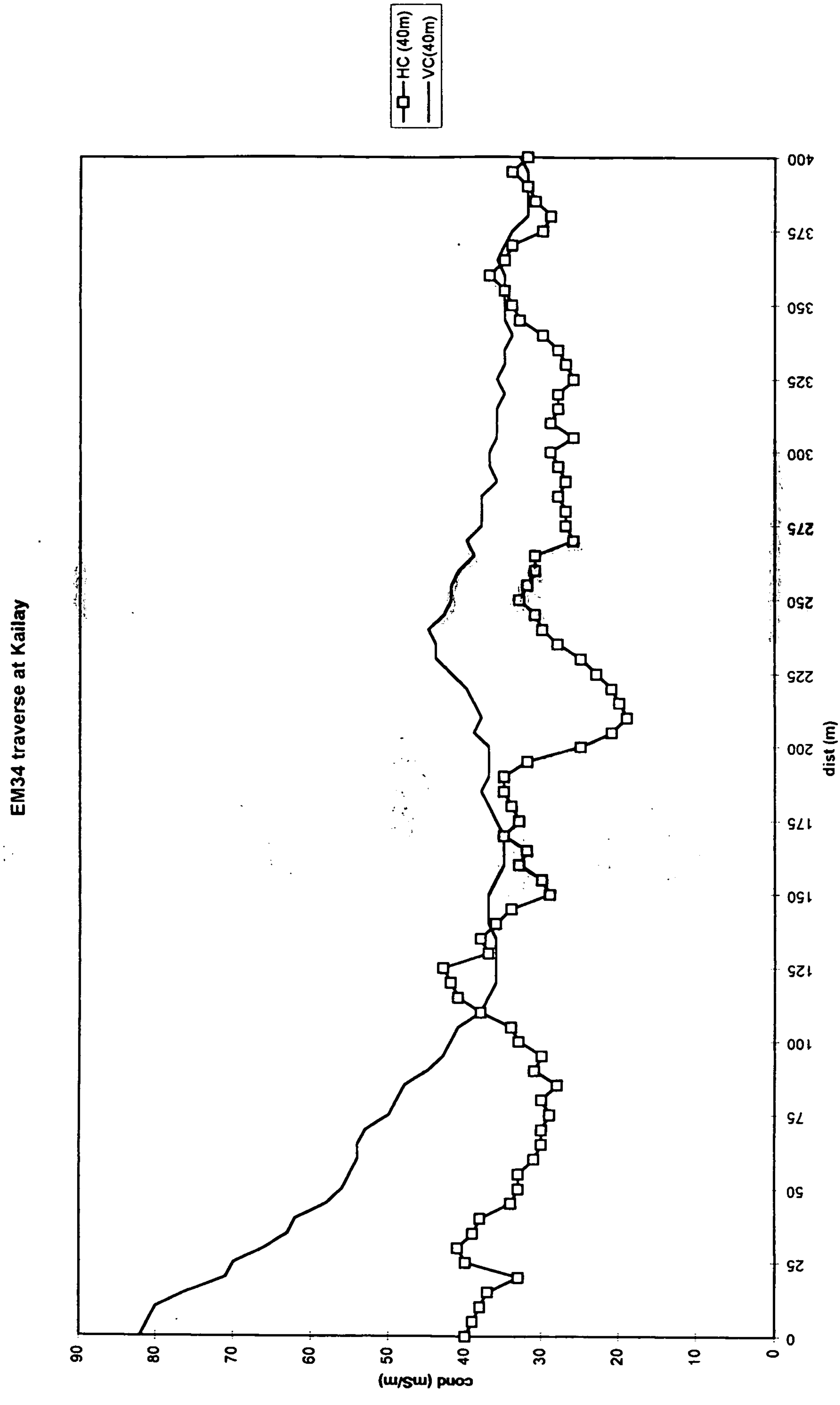


Fig. 3.4a_3 Kailay: EM34 data of Traverse 1 (0 m to 400 m)

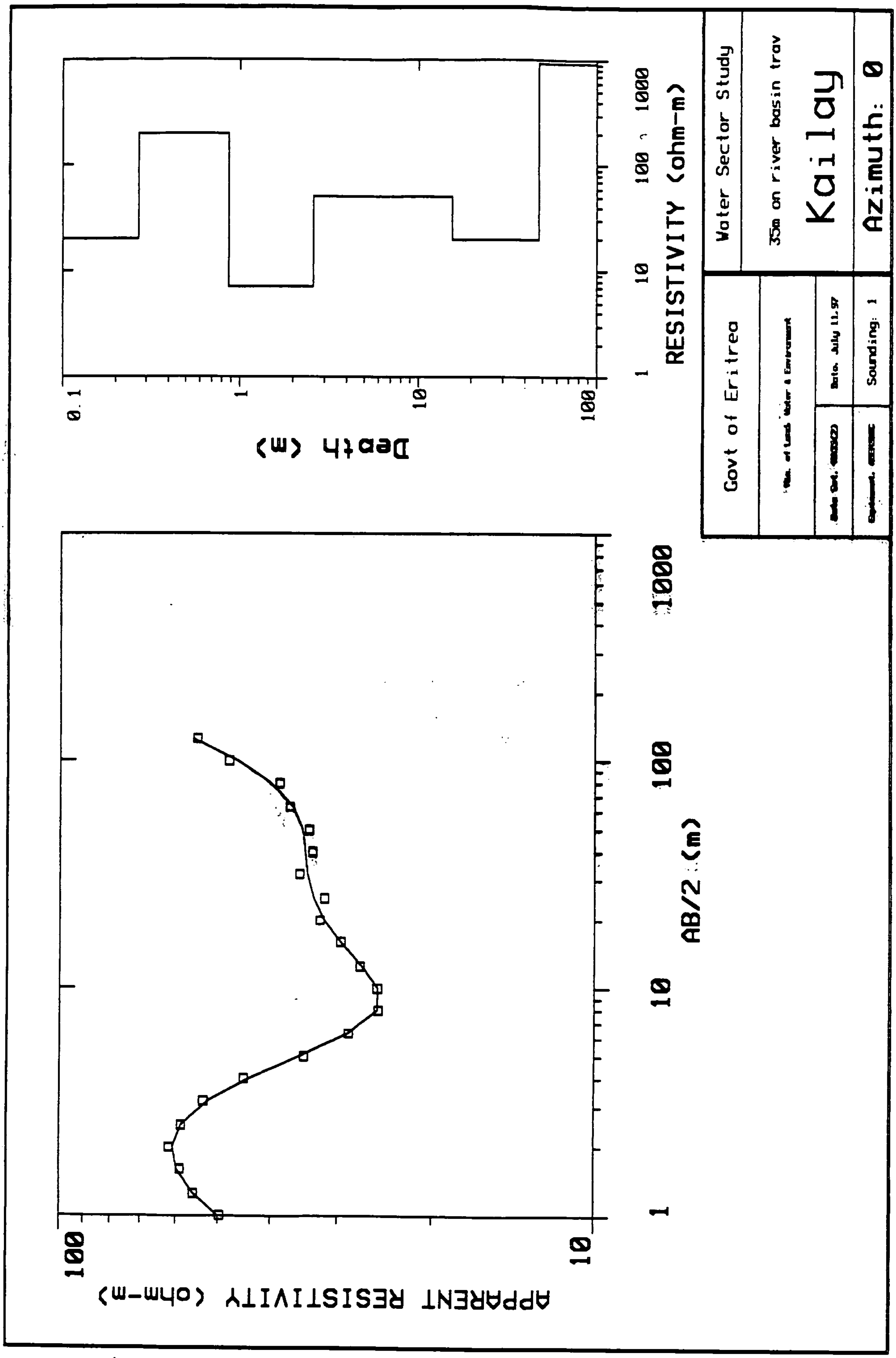


Fig. 3.4a_4 Kailay: DC sounding on Traverse 1 at 35 m

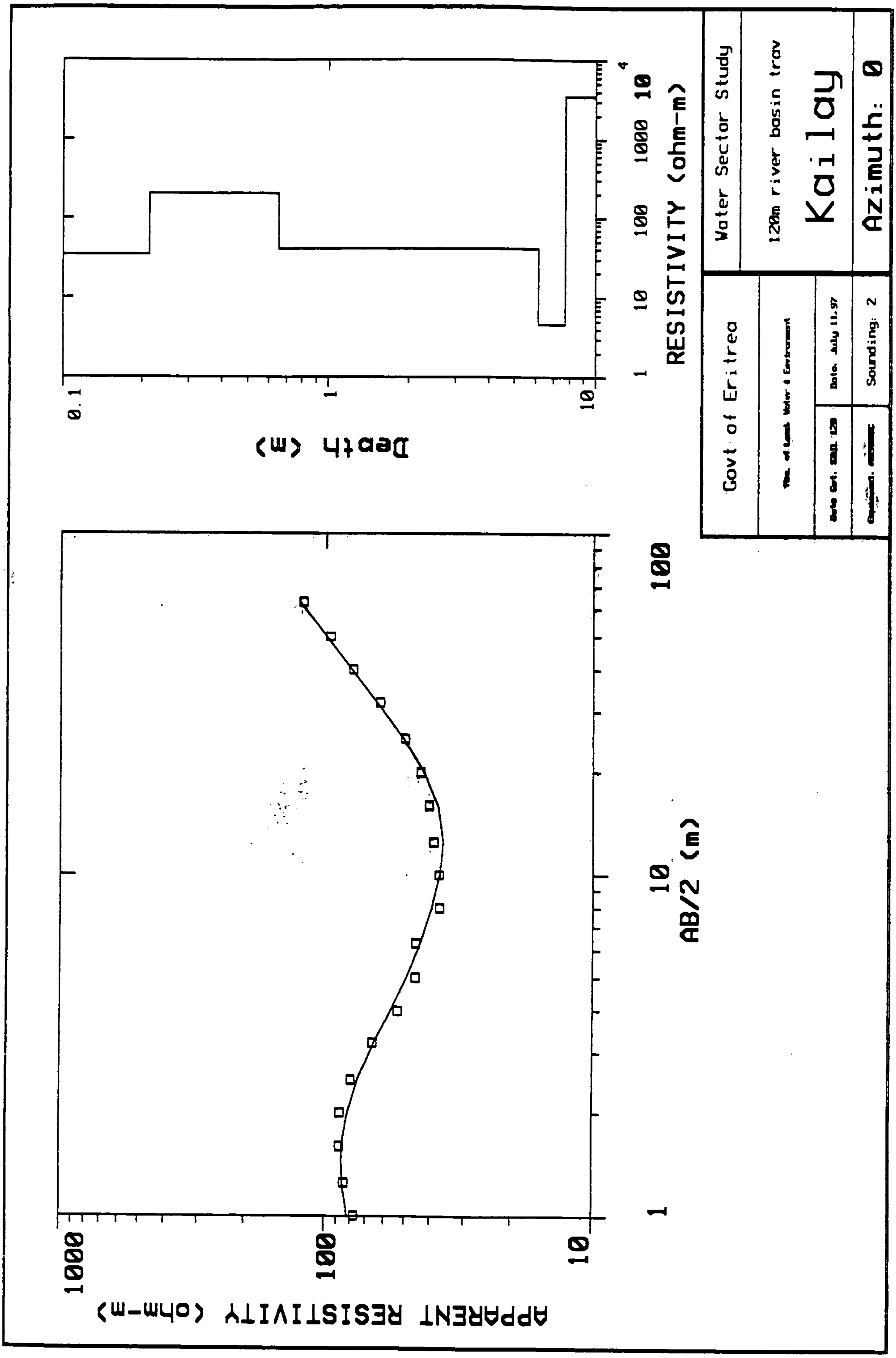


Fig. 3.4a_5 Kailay: DC sounding on Traverse 1 at 120 m

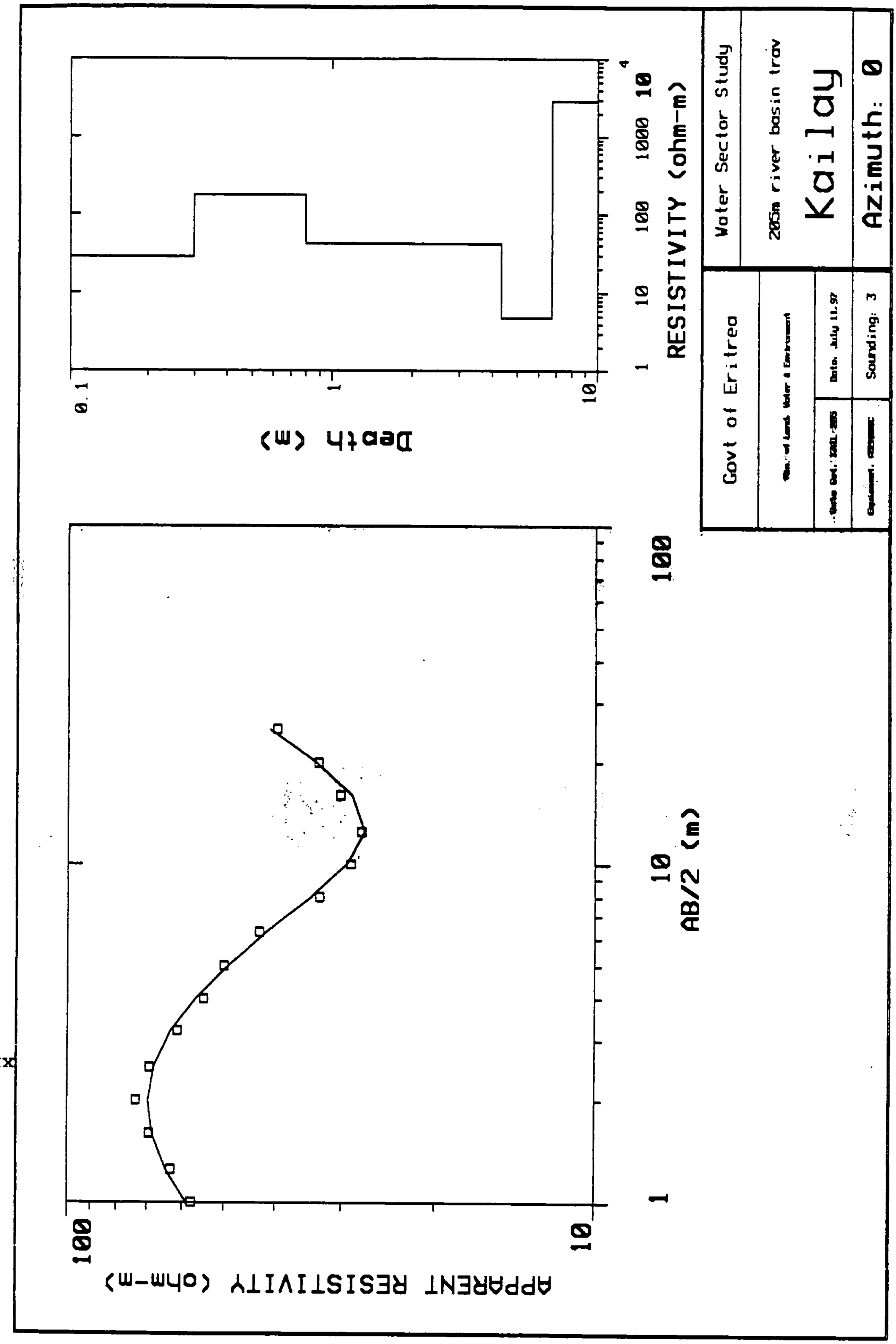


Fig. 3.4a_6 Kailay: DC sounding on Traverse 1 at 205 m

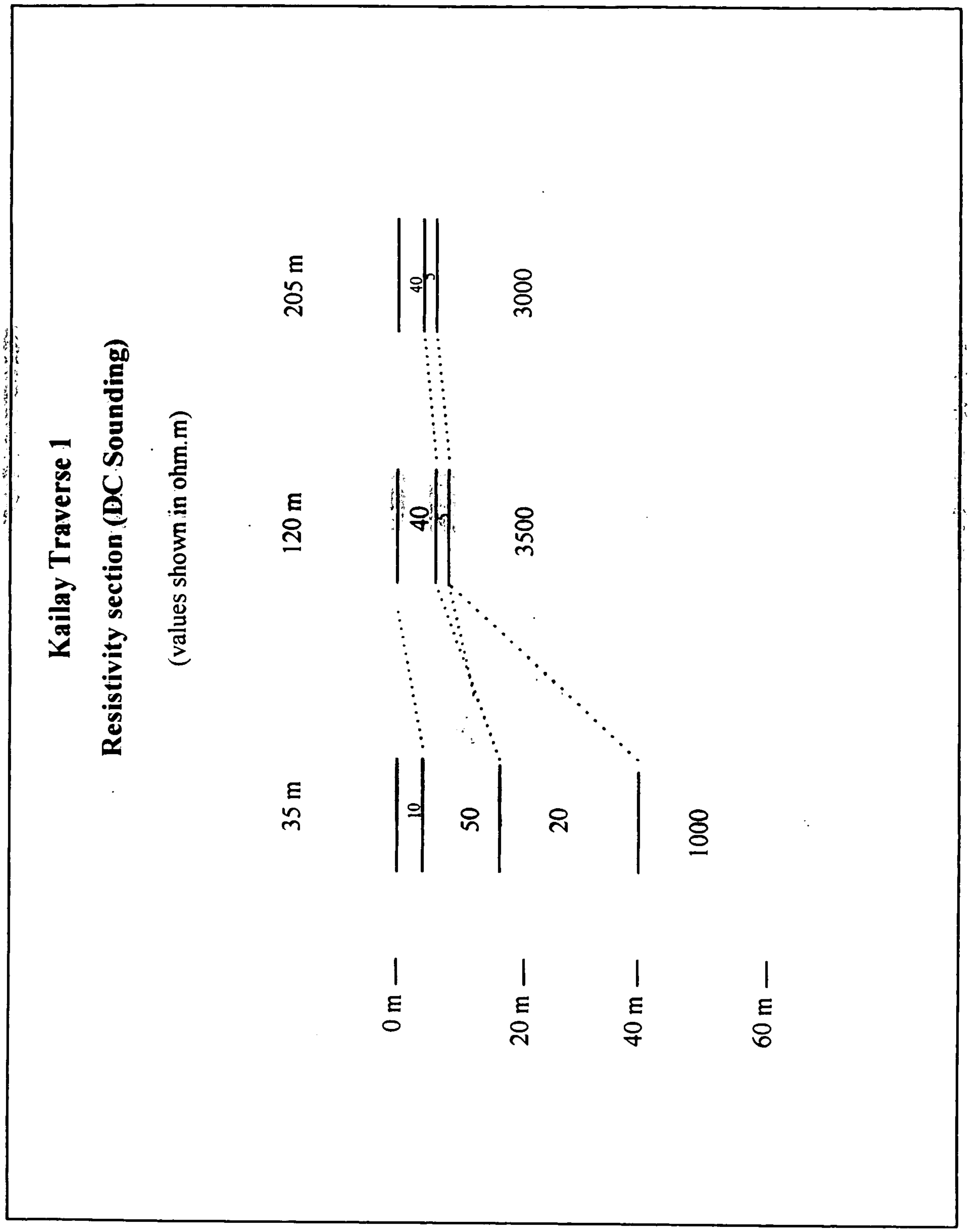


Fig. 3.4a_7 Kailay: Resistivity section traverse 1: DC sounding

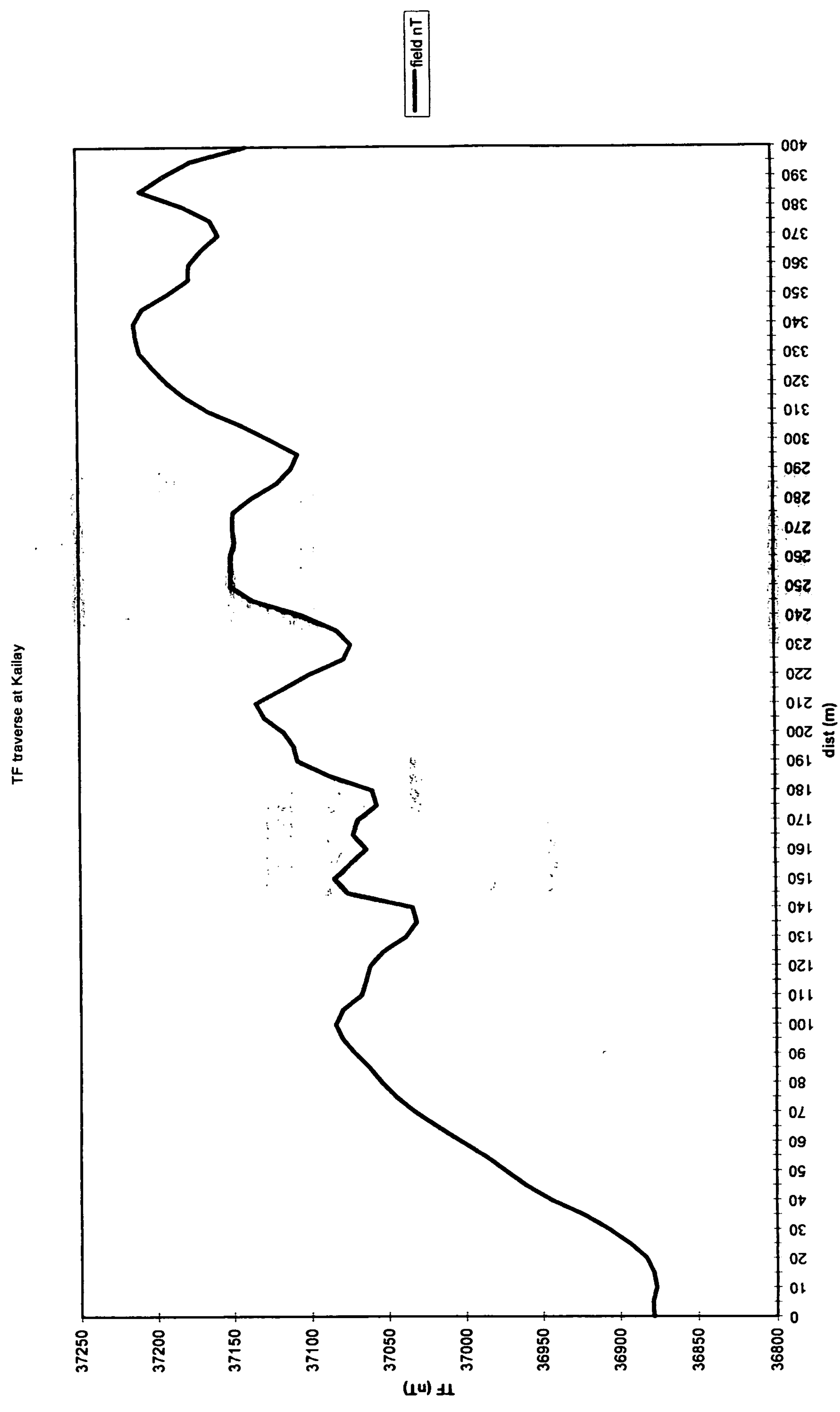


Fig. 3.4a_8 Kailay: Total field magnetic profile of Traverse 1

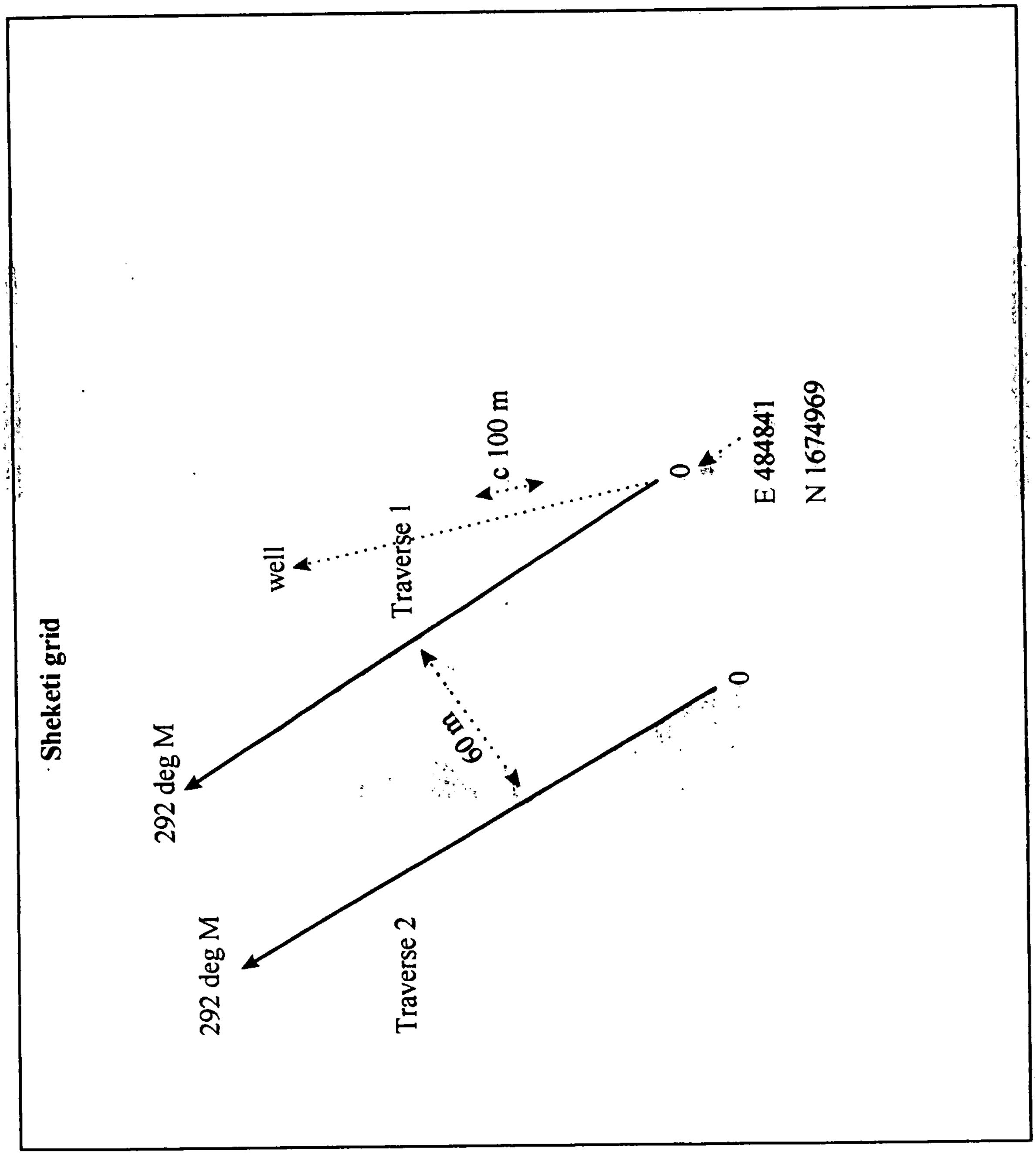


Fig. 3.5a_1 Sheketi: geophysical grid at Sheketi

ERITREA: SECTOR STUDY ON NATIONAL WATER RESOURCES AND IRRIGATION POTENTIAL

GROUNDWATER EXPLORATION

GEOPHYSICAL INVESTIGATIONS COMPLETED

SHEET No: **LOCATION:** SHEKETI **UTM Co-ords: E** 484841 **N** 1674969

Geology: Basement / dolerite dykes **Target:** Investigate "artesian" supply and relationship to dolerite dykes

GEOPHYSICAL TECHNIQUES				
	Used?	Line/Grid	cover m/No.	Comments
Conductivity EM34 40m				
Conductivity EM34 20m				
Conductivity EM34 10m				
TDEM 47 sounding (5m*5m)				
TDEM 47 sounding (40m*40m)				
TDEM47 sounding (100m*100m)				
TDEM 47 traversing (5m*5m)				
TDEM 47 traversing (40m*40m)				
TDEM 47 traversing (100m*100m)				
Resistivity (ABEM 300C) sounding				
Resistivity (ABEM 300C) traversing				
VLF (WADI) traversing				
Magnetometry (GEM) traversing	✓	L(2)	700m	
Gravimetry				
Seismic refraction				

Previous work:

Borehole sited ?: NO **Location:** **Project Bh No:**

Borehole drilled (date):

Result:

Fig. 3.5a_2 Sheketi: table summarising geophysical investigations

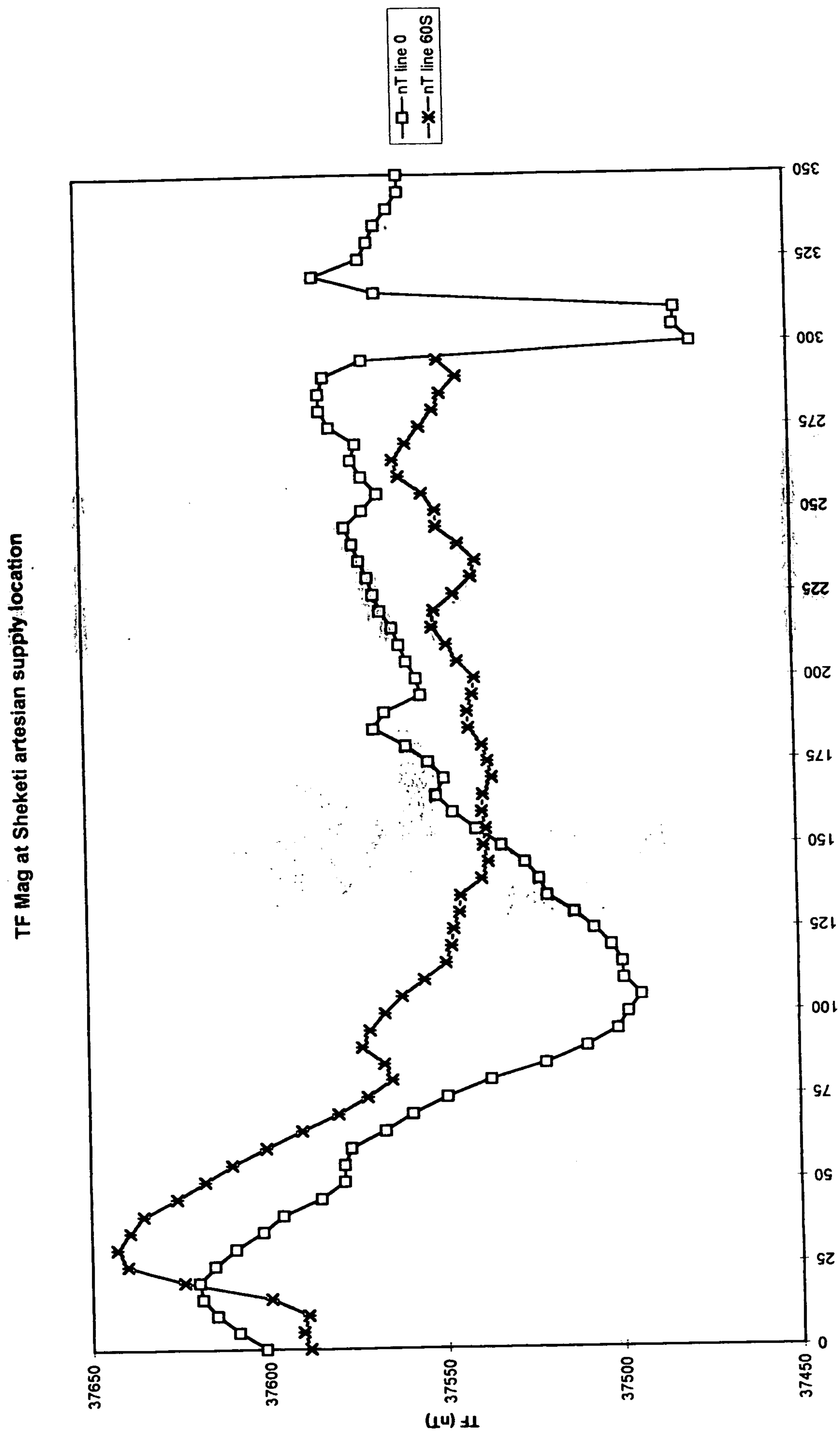


Fig. 3.5a_3 Sheketi: Total field magnetic profiles of Traverses 1 and 2

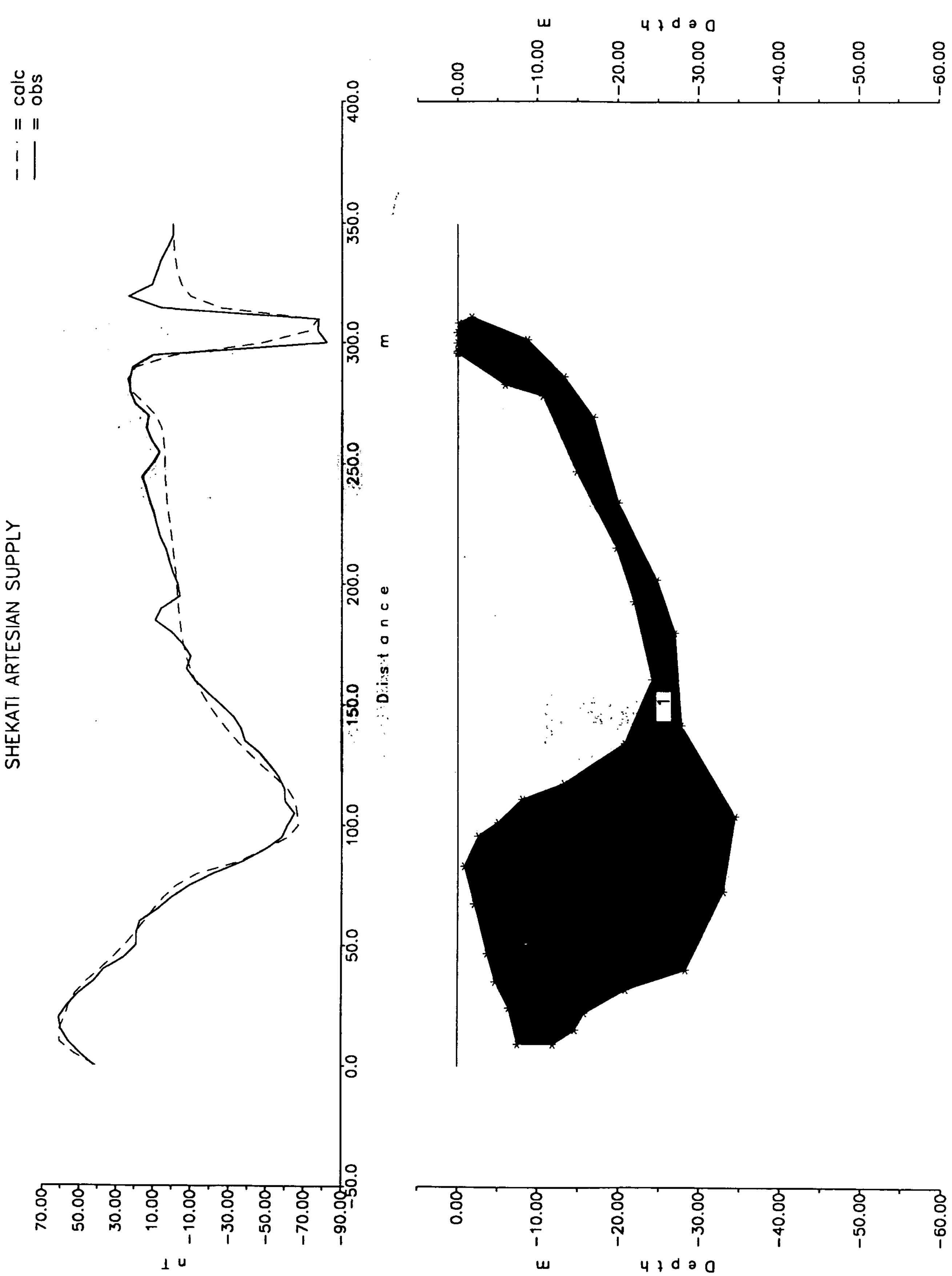


Fig. 3.5a_4 Sheketi: Modelled magnetic profile of Traverse 1

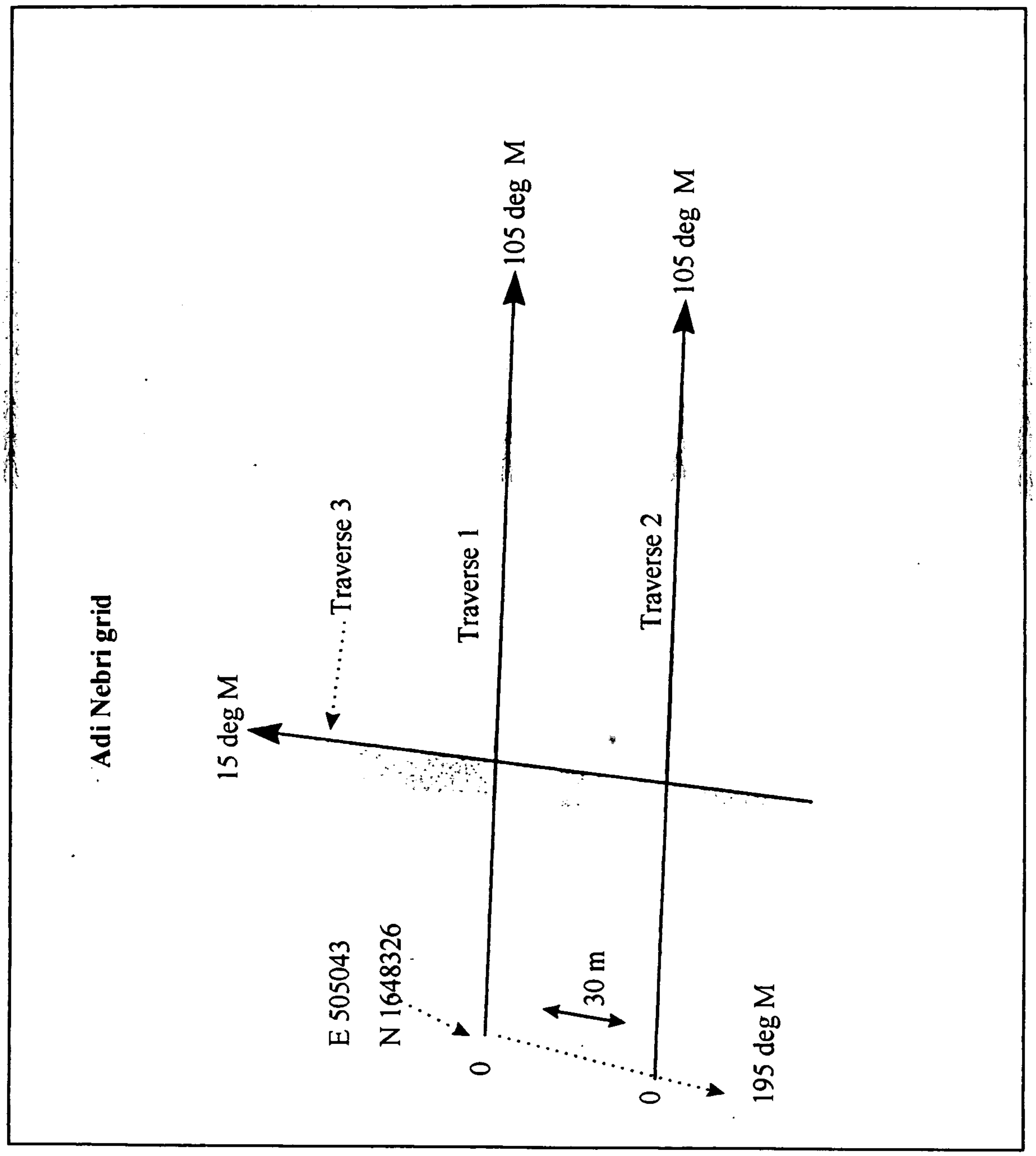


Fig. 3.5b_1 Adi Nebri: geophysical grid at Adi Nebri

(RJP)

ERITREA: SECTOR STUDY ON NATIONAL WATER RESOURCES AND IRRIGATION POTENTIAL

GROUNDWATER EXPLORATION

GEOPHYSICAL INVESTIGATIONS COMPLETED

SHEET No: **LOCATION:** Adi Nebri **UTM Co-ords: E** 505043 **N** 1648326

Geology: Basement (Adigrat sst. (steeply dipping - fault?) **Target:** Intersection 2 major satellite lineaments (N-S, W-E)

GEOPHYSICAL TECHNIQUES	Used?	Line/Grid	cover m/No.	Comments
Conductivity EM34 40m				
Conductivity EM34 20m	✓	L(3)	360m	2 ∥ lines, 1 at ⊥
Conductivity EM34 10m				
				Area physically
TDEM 47 sounding (5m*5m)				constrained + high
TDEM 47 sounding (40m*40m)				relief - not really
TDEM47 sounding (100m*100m)				suitable for geophysics.
TDEM 47 traversing (5m*5m)				
TDEM 47 traversing (40m*40m)				
TDEM 47 traversing (100m*100m)				
Resistivity (ABEM 300C) sounding				
Resistivity (ABEM 300C) traversing				
VLF (WADI) traversing				
Magnetometry (GEM) traversing				
Gravimetry				
Seismic refraction				

Previous work:

Borehole sited ?: NO (not by geophysics) **Location:** **Project Bh No:** BH 5

Borehole drilled (date):

Result:

Fig. 3.5b_2 Adi Nebri: table summarising geophysical investigations

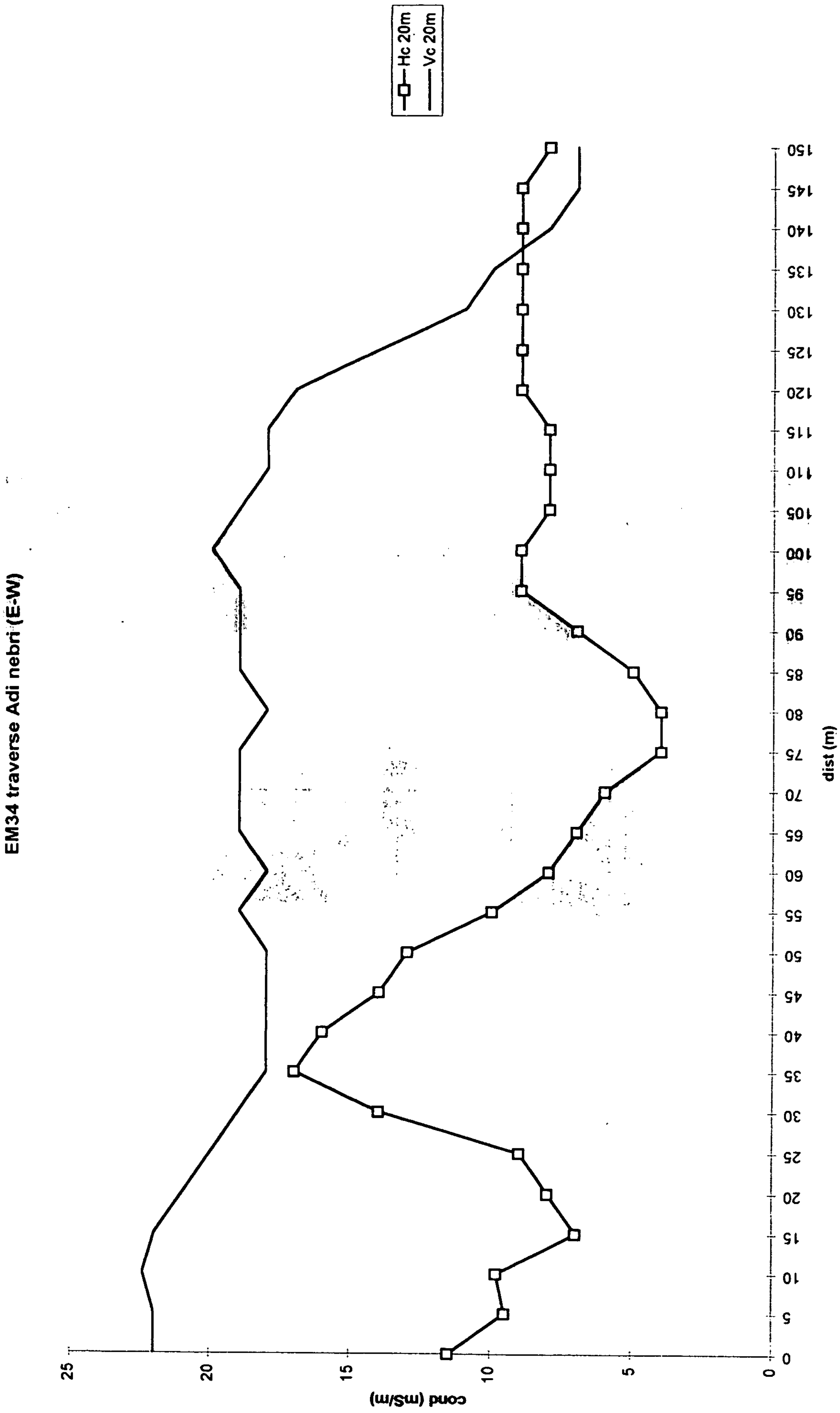


Fig. 3.5b_3 Adi Nebri: EM34 data of Traverse 1 (0 m to 150 m)

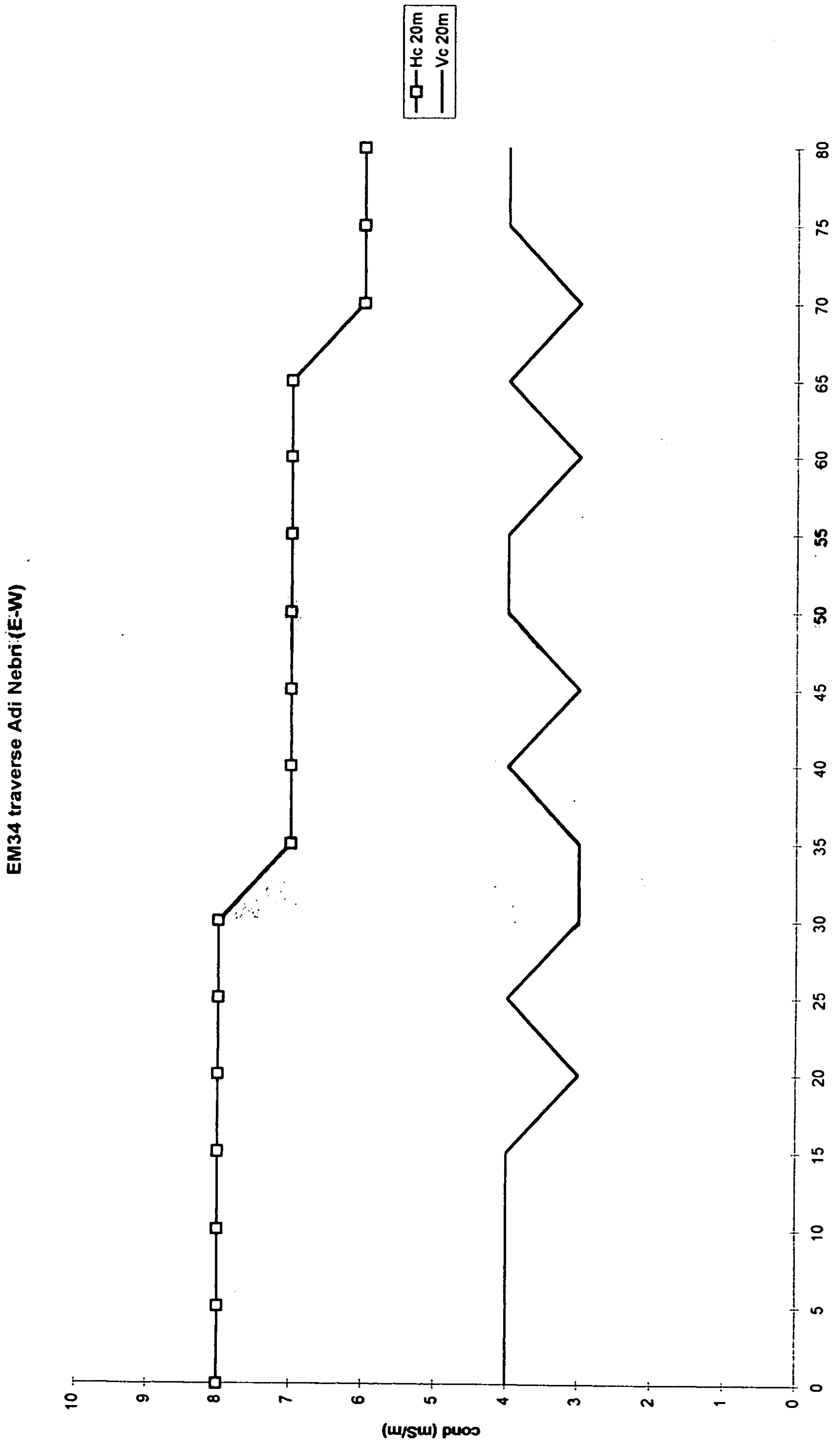


Fig. 3.5b_4 Adi Nebri: EM34 data of Traverse 2 (0 m to 80 m)

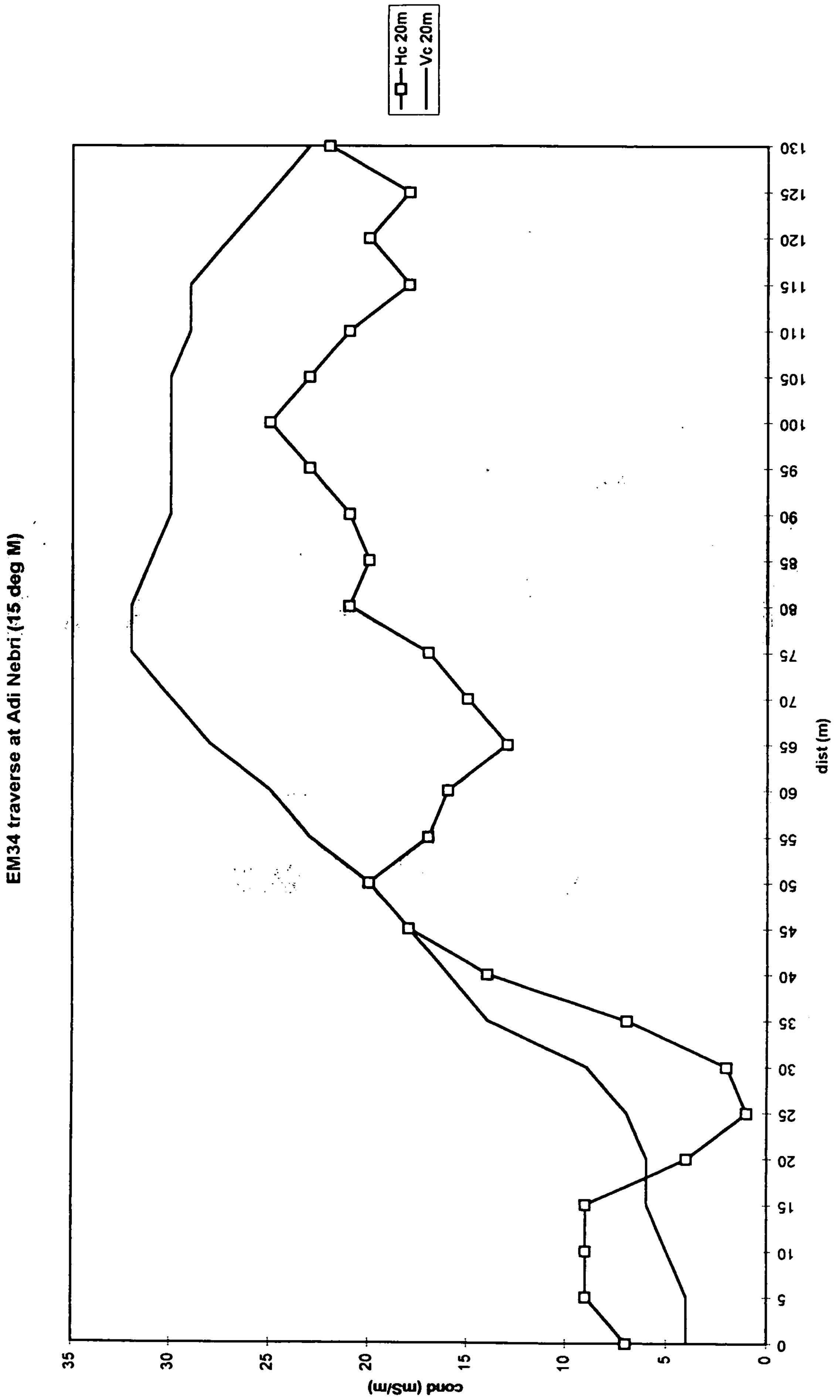


Fig. 3.5b_5 Adi Nebri: EM34 data of Traverse 3 (0 m to 130 m)

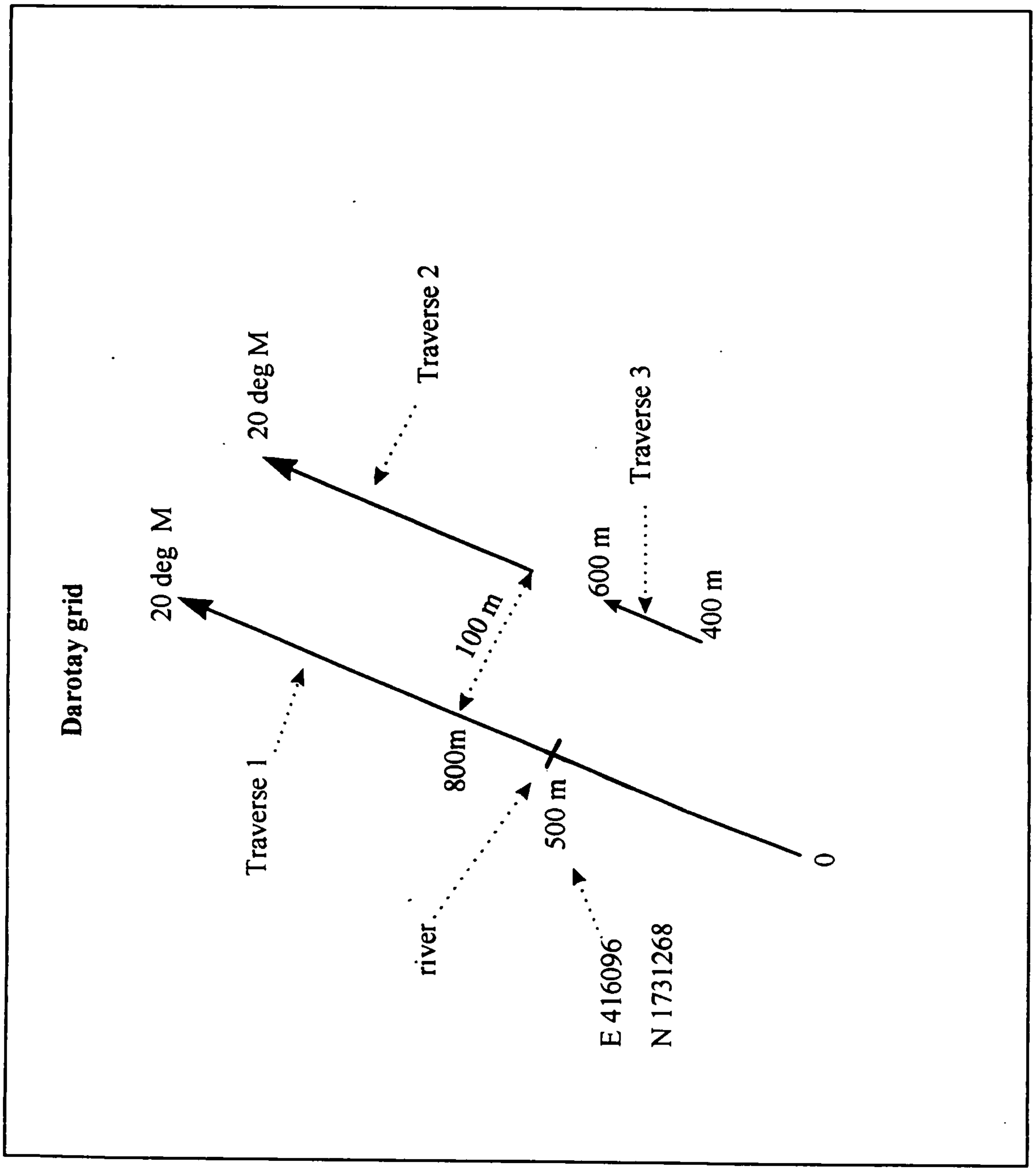


Fig. 3.3a_1 Darotay: geophysical grid at Darotay

ERITREA: SECTOR STUDY ON NATIONAL WATER RESOURCES AND IRRIGATION POTENTIAL

GROUNDWATER EXPLORATION

GEOPHYSICAL INVESTIGATIONS COMPLETED

SHEET No: **LOCATION:** DAROTAY **UTM Co-ords:** E416096 N1731268 (500m stn. Line 1, beside river)

Geology: Basement / granite **Target:** Tensional fracture (Tertiary) of Drury (satellite image)

GEOPHYSICAL TECHNIQUES				
	Used?	Line/Grid	cover m/No.	Comments
Conductivity EM34 40m	✓	L	1600 m	
Conductivity EM34 20m	✓	L	140 m	
Conductivity EM34 10m	✓	L	140 m	
TDEM 47 sounding (5m*5m)				
TDEM 47 sounding (40m*40m)	✓	L	2 (No.)	
TDEM47 sounding (100m*100m)				
TDEM 47 traversing (5m*5m)				
TDEM 47 traversing (40m*40m)				
TDEM 47 traversing (100m*100m)				
Resistivity (ABEM 300C) sounding				
Resistivity (ABEM 300C) traversing	✓	L	650 m	Dipole-dipole a 10m n 1 to 6
VLF (WADI) traversing	✓	L (3)	2400 m	
Magnetometry (GEM) traversing	✓	L (3)	2400 m	
Gravimetry				
Seismic refraction				

Previous work: Well in river bed c. 40m of line TD 9.8m WT 8.45m
Evidence high degree fracturing / broken pegmatite etc. N of river (ie 700m+)
highly varied geology (slate/granite/gneiss rubble)

Borehole sited ?: YES (2) **Location:** ~~550m~~ ~~1140 m~~ 560 m 1160 m Traverse 1 **Project Bh No:**

Borehole drilled (date):

Result:

Fig. 3.3a_2 Darotay: table summarising geophysical investigations

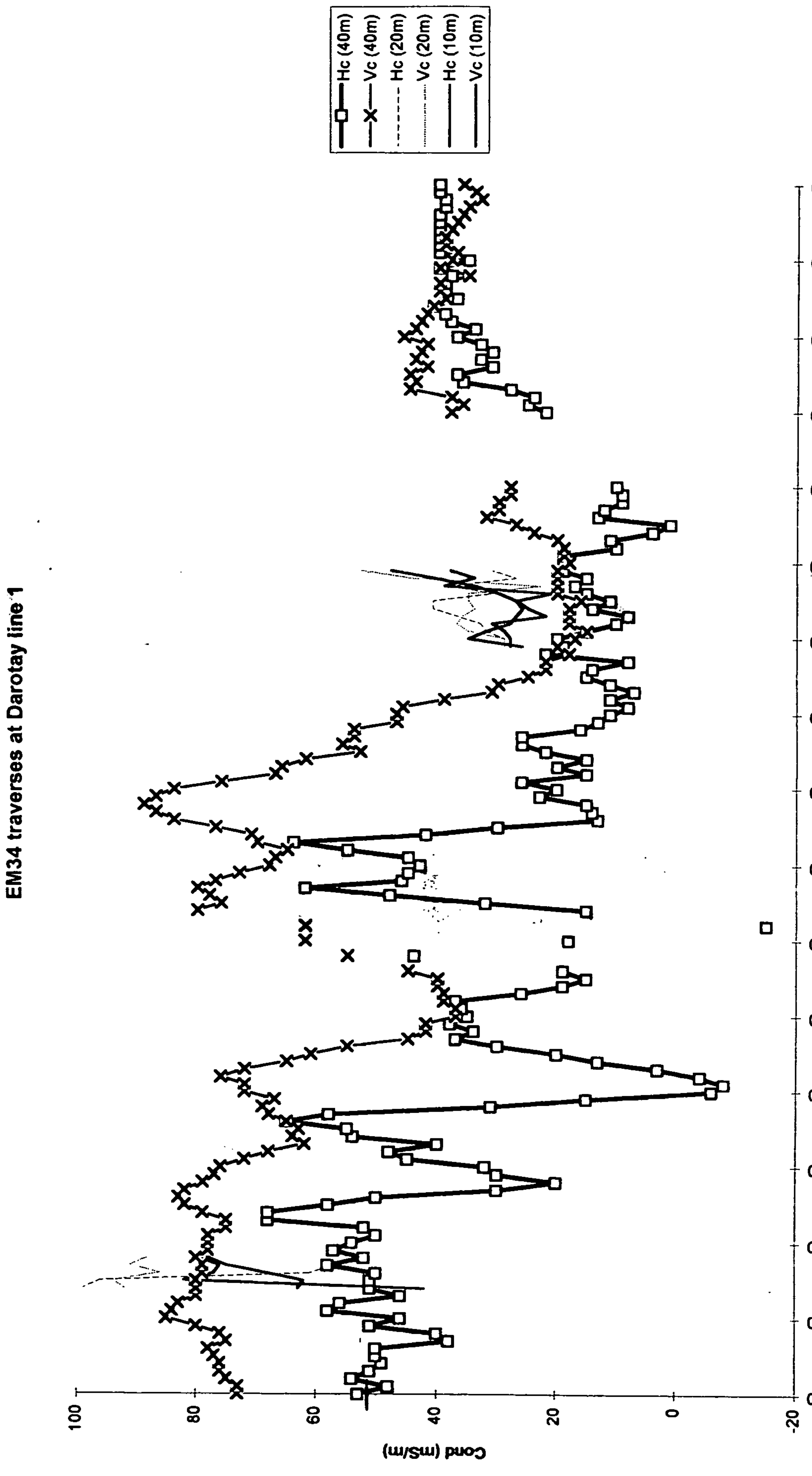


Fig. 3.3a_3 Darotay: EM34 data on Traverse 1

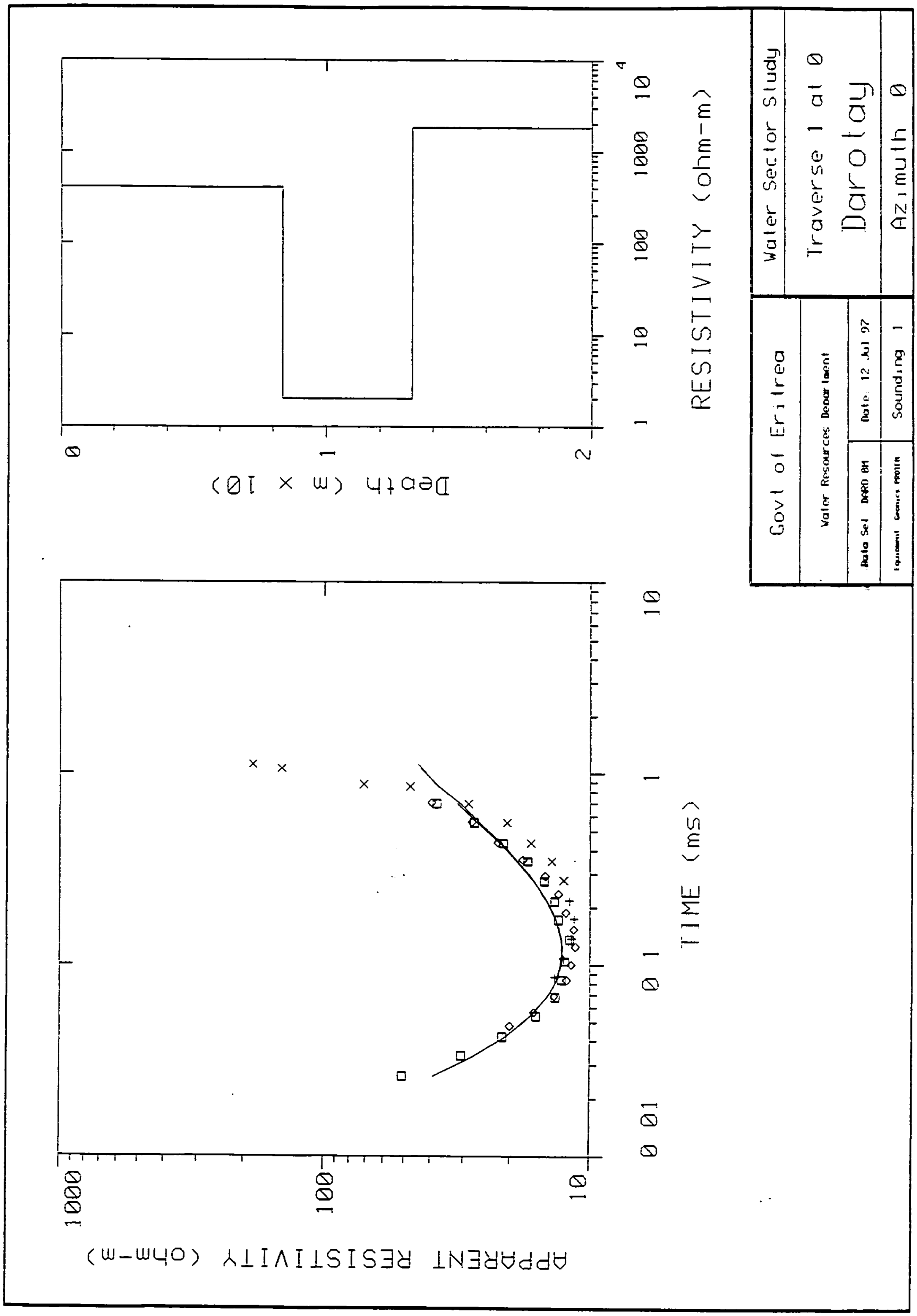


Fig. 3.3a_4 Darotay: TDEM sounding at 0 m Traverse 1

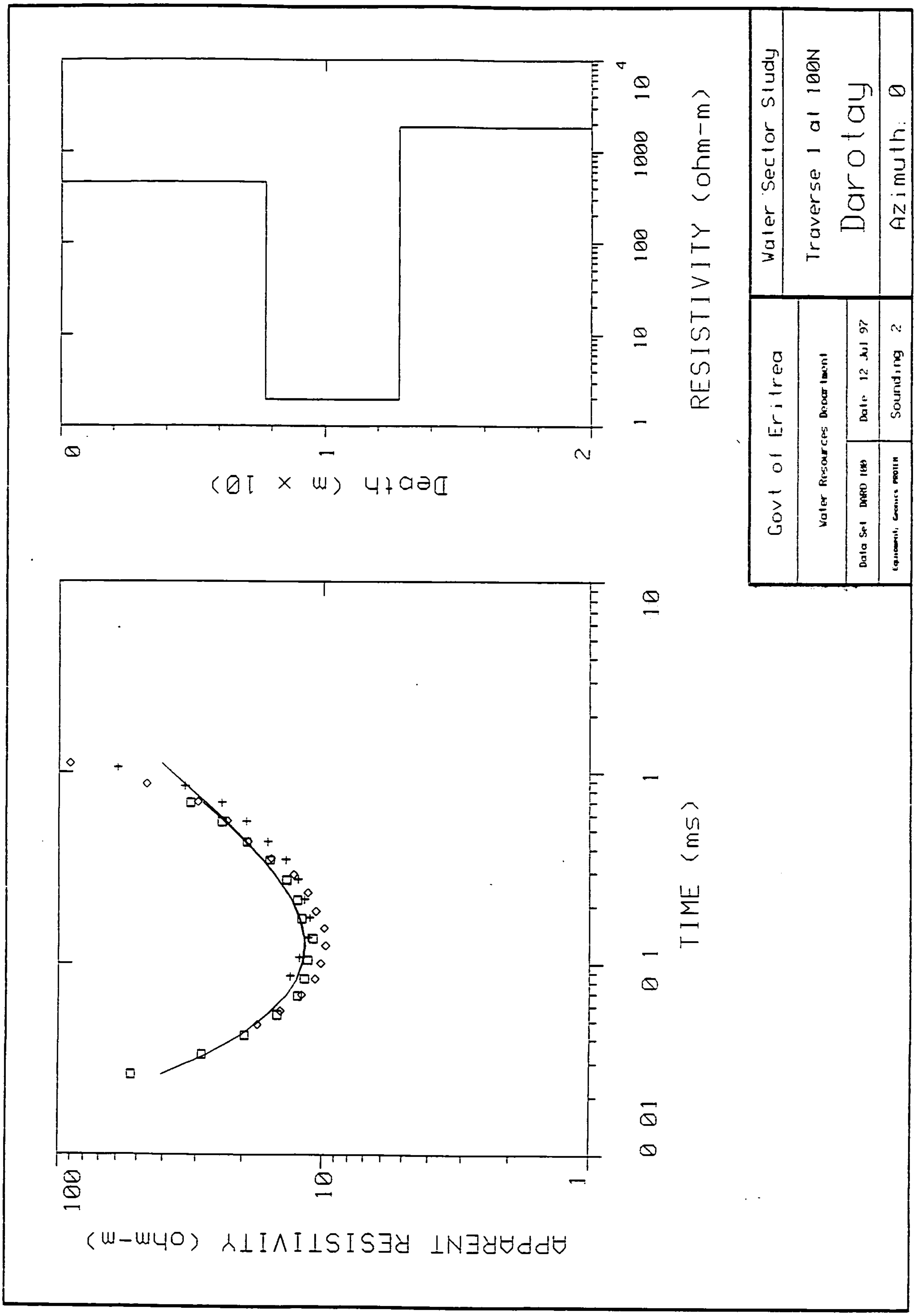


Fig. 3.3a_5 Darotay: TDEM sounding at 100 m Traverse 1

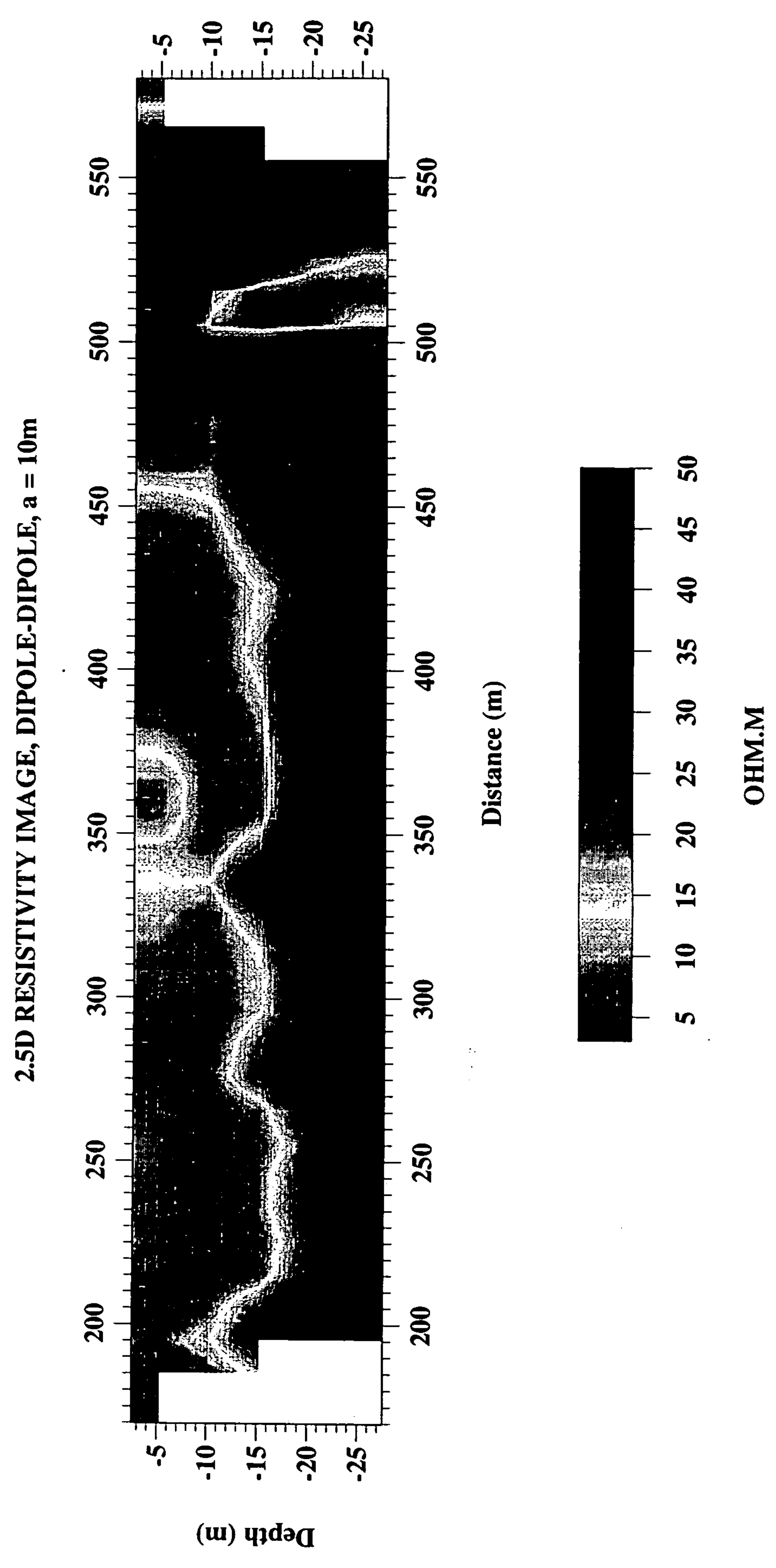


Fig. 3.3a_6 Darotay: Modelled dipole-dipole data (200m to 550m Traverse 1)

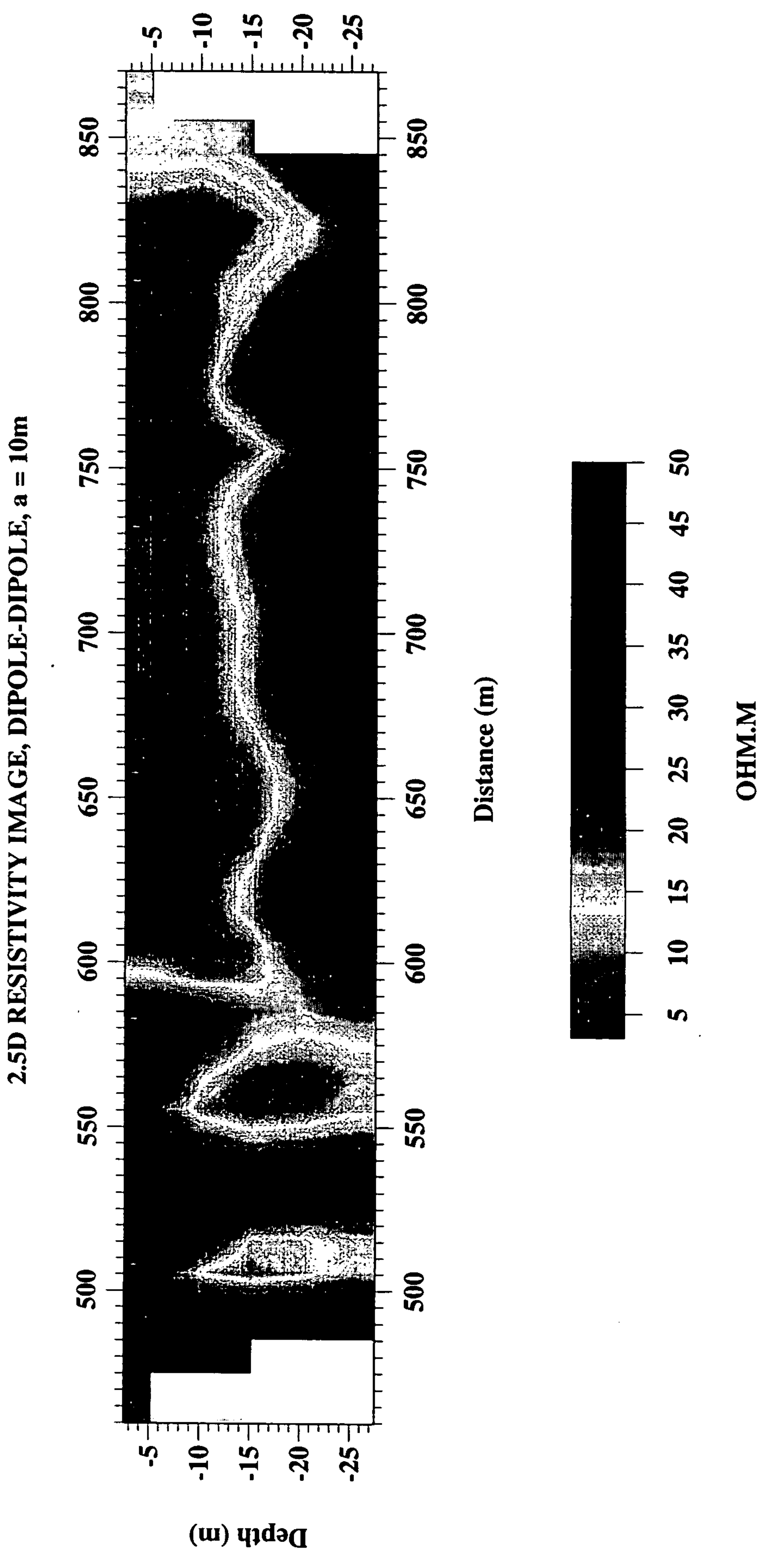


Fig. 3.3a_7 Darotay: Modelled dipole-dipole data (500m to 850m Traverse 1)

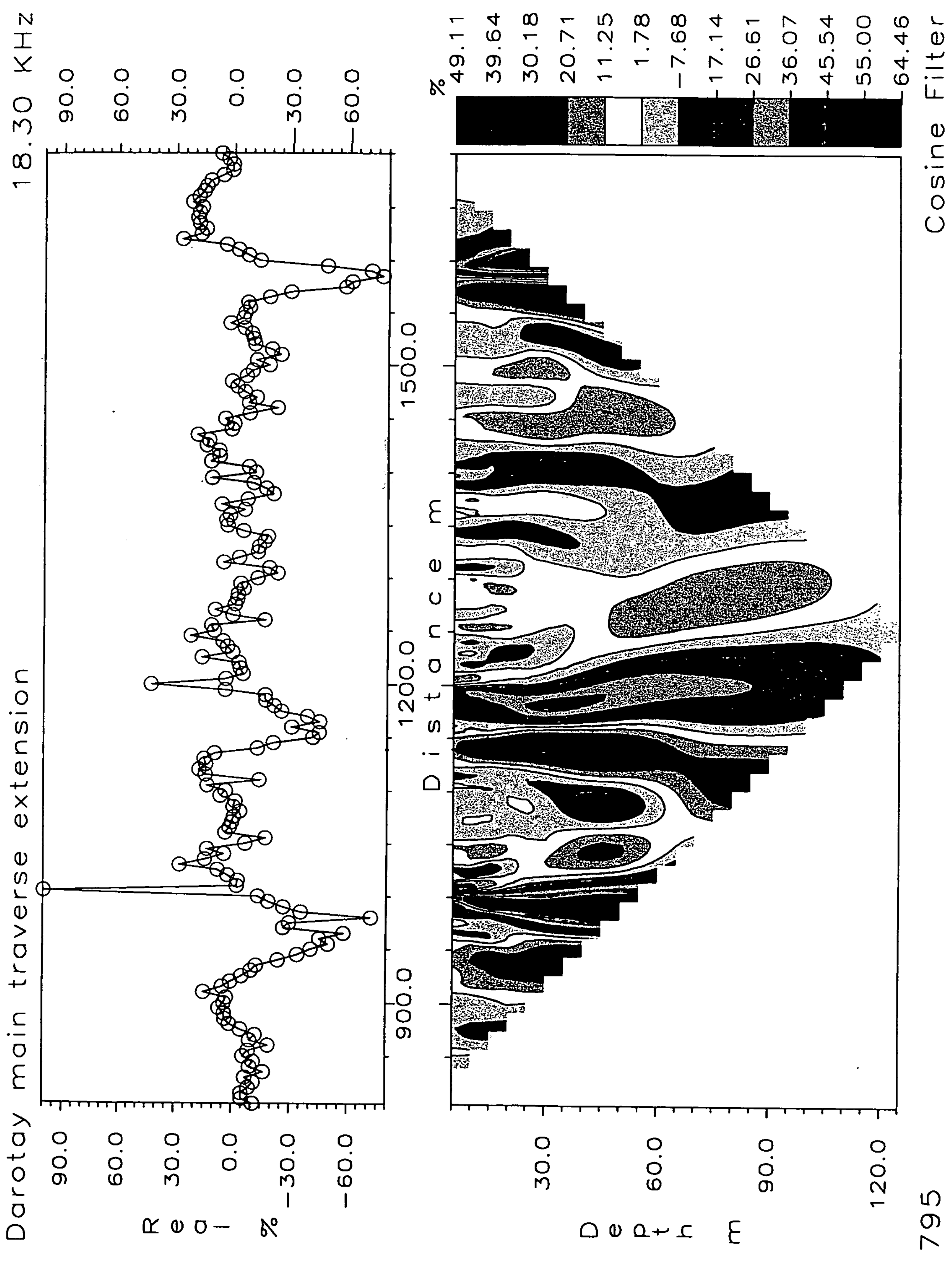


Fig. 3.3a_9 Darotay: VLF in phase data and Karous-Hjelt filter result: Traverse 1(b)

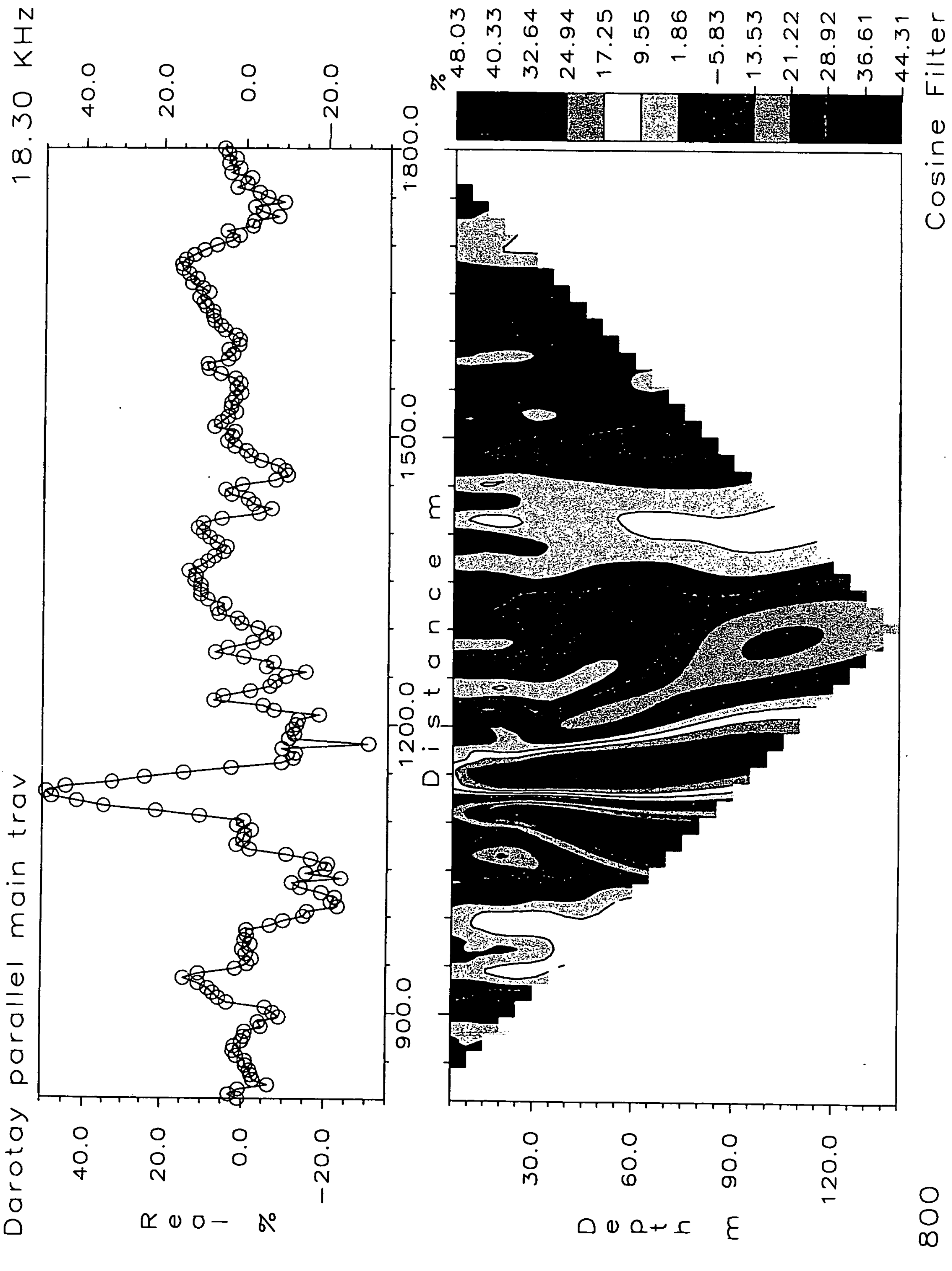


Fig. 3.3a_10 Darotay: VLF in phase data and Karous-Hjelt filter result:Traverse 2

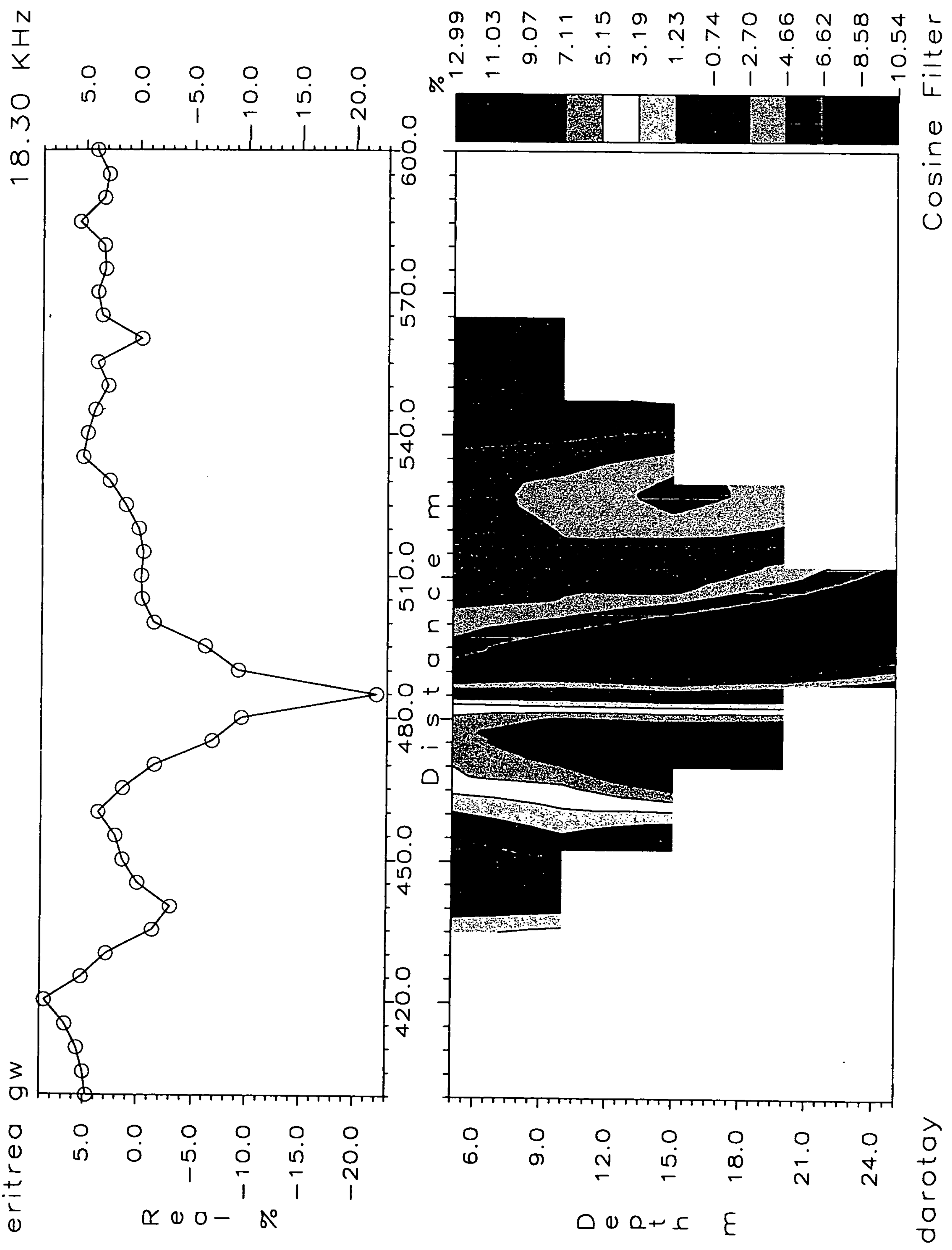
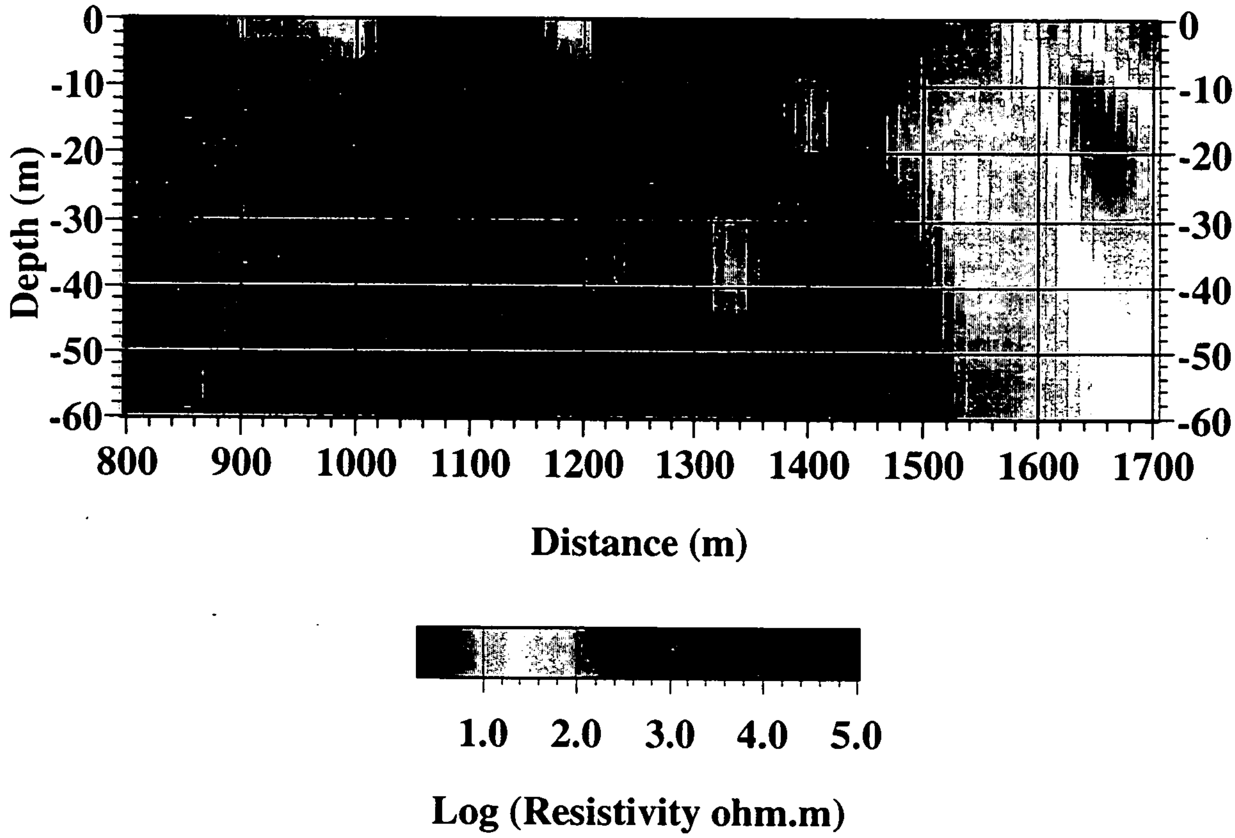


Fig. 3.3a_11 Darotay: VLF in phase data and Karous-Hjelt filter result:Traverse 3

Eritrea VLF. DAR Line 1.

2d Occam resistivity cross-section, rms=1.7 (10%), Hz-TE mode

DAR LINE 1



DAR LINE 1

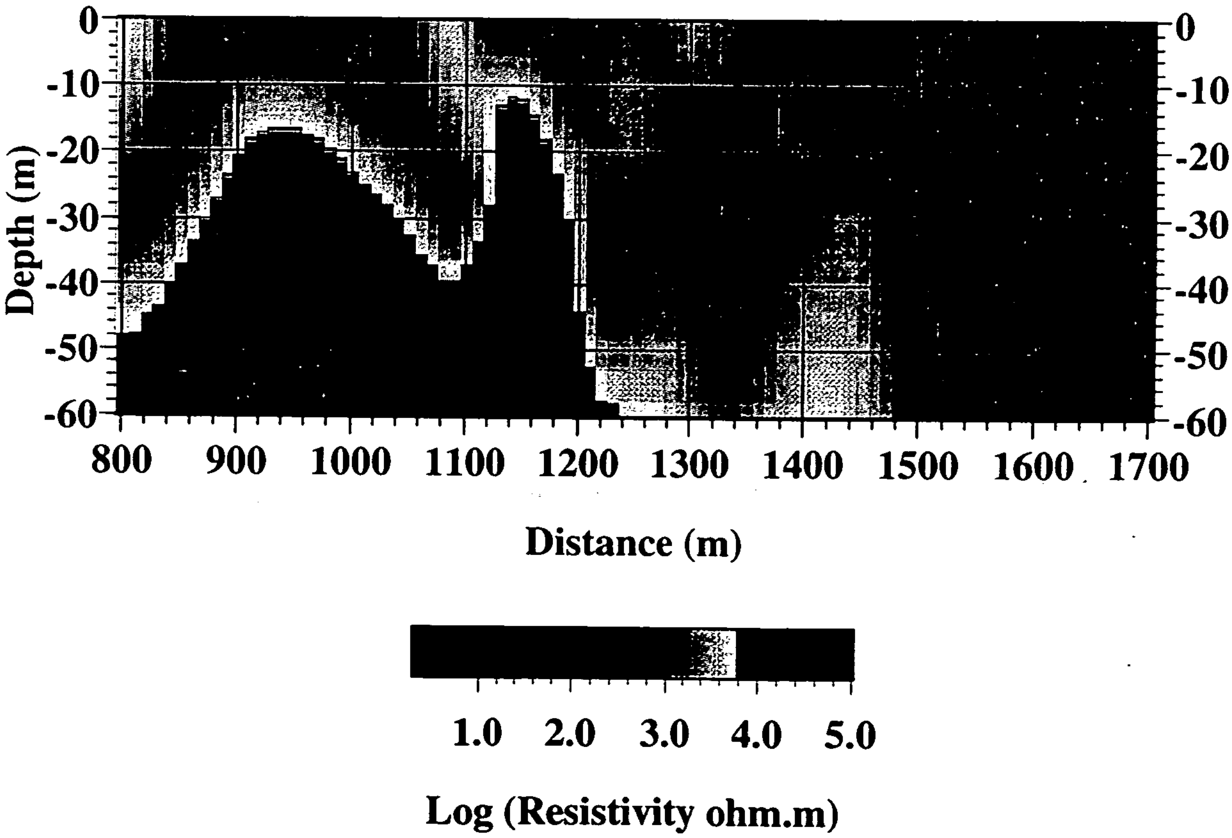
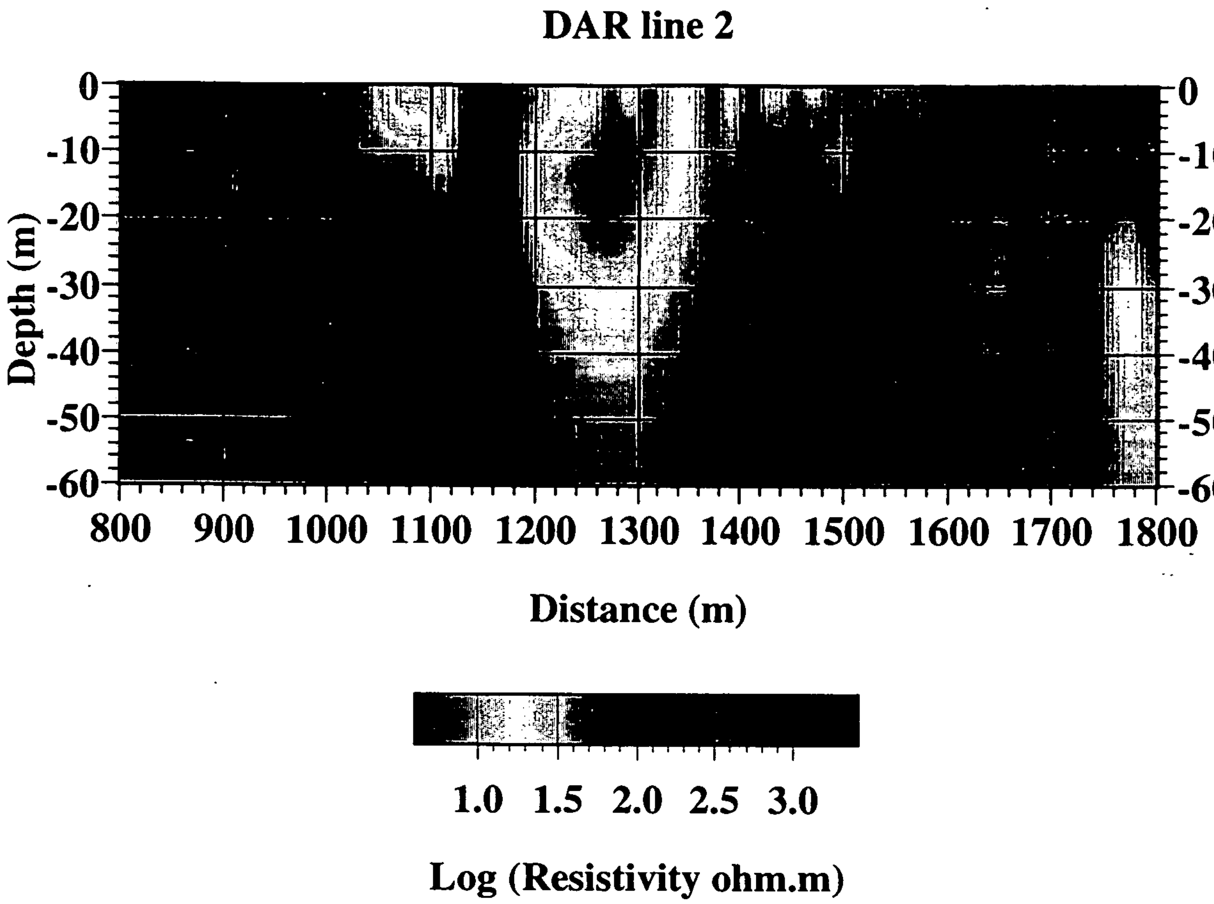


Fig. 3.3a_12 Darotay: VLF smooth model : Traverse 1(b)

Eritrea VLF. DAR Line 2.

2d Occam resistivity cross-section, rms=1.0 (10%), Hz-TE mode



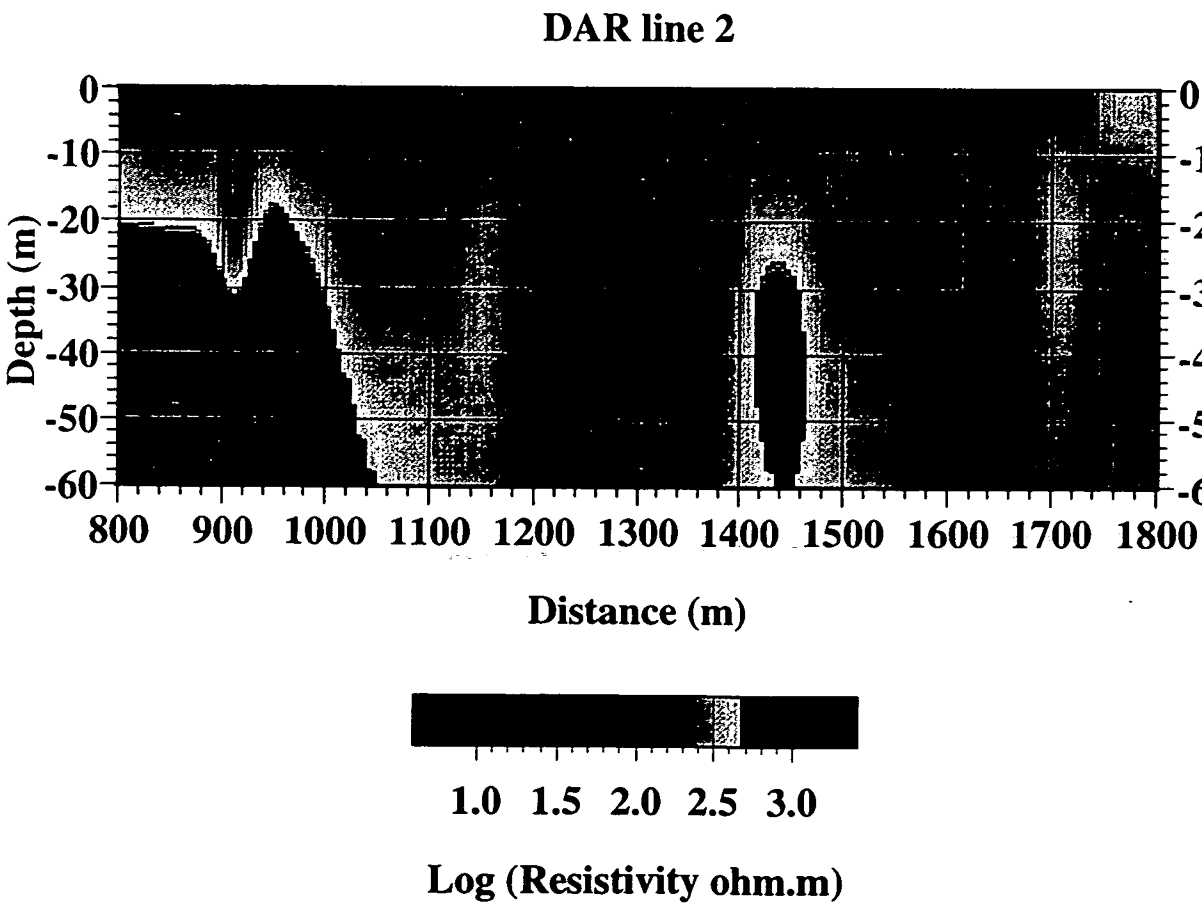


Fig. 3.3a_13 Darotay: VLF smooth model : Traverse 2

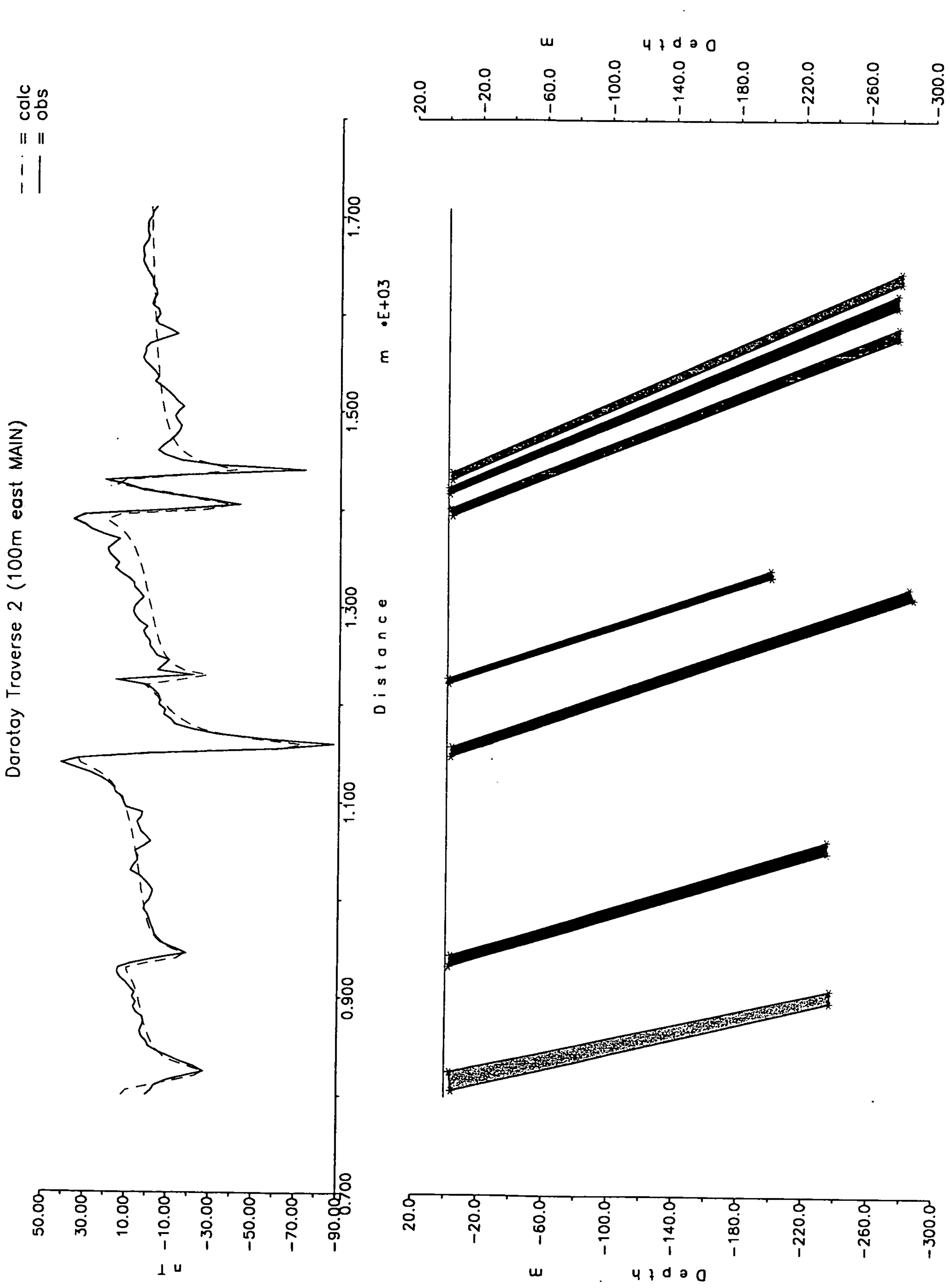


Fig. 3.3a_16 Darotay: Modelled Total Field magnetic profile: Traverse 2

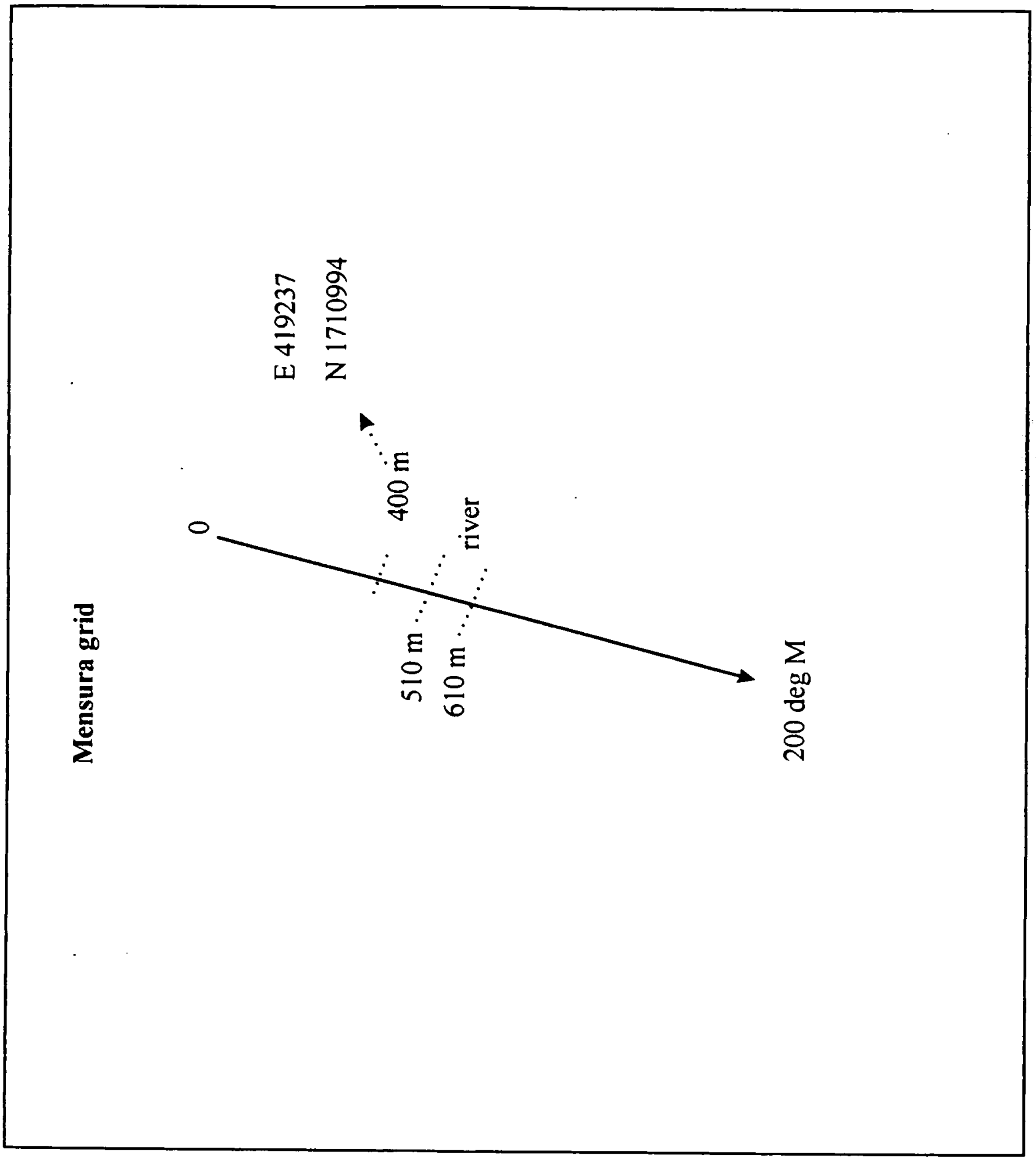


Fig. 3.3c_1 Mensura: geophysical grid at Mensura

ERITREA: SECTOR STUDY ON NATIONAL WATER RESOURCES AND IRRIGATION POTENTIAL

GROUNDWATER EXPLORATION

GEOPHYSICAL INVESTIGATIONS COMPLETED

SHEET No: **LOCATION:** MENSURA **UTM Co-ords: E** 0419237 **N** 1710994

Geology: Basement / granite **Target:** Dilational (pull-apart) tension fracture (Tertiary) of Drury et al

GEOPHYSICAL TECHNIQUES				
	Used?	Line/Grid	cover m/No.	Comments
Conductivity EM34 40m				
Conductivity EM34 20m	✓	L		Gully relief S of river too
Conductivity EM34 10m			200 m	steep for drilling rig
				∴ survey abandoned.
TDEM 47 sounding (5m*5m)				
TDEM 47 sounding (40m*40m)				
TDEM47 sounding (100m*100m)				
TDEM 47 traversing (5m*5m)				
TDEM 47 traversing (40m*40m)				
TDEM 47 traversing (100m*100m)				
Resistivity (ABEM 300C) sounding				
Resistivity (ABEM 300C) traversing				
VLF (WADI) traversing				
Magnetometry (GEM) traversing	✓	L	1000 m	
Gravimetry				
Seismic refraction				

Previous work: Numerous boreholes sited in apparently favourable locations (beside river, highly weathered granites, in shear zone) but disappointing yields (< 1 l/s) (T.D. > 60 m).

Borehole sited ?: YES (2) **Location:** ~~115 m~~ 128 m **Project Bh No:**

Borehole drilled (date): ~~190 m~~ 320 m × check for man made source

Result:

Fig. 3.3c_2 Mensura: table summarising geophysical investigations

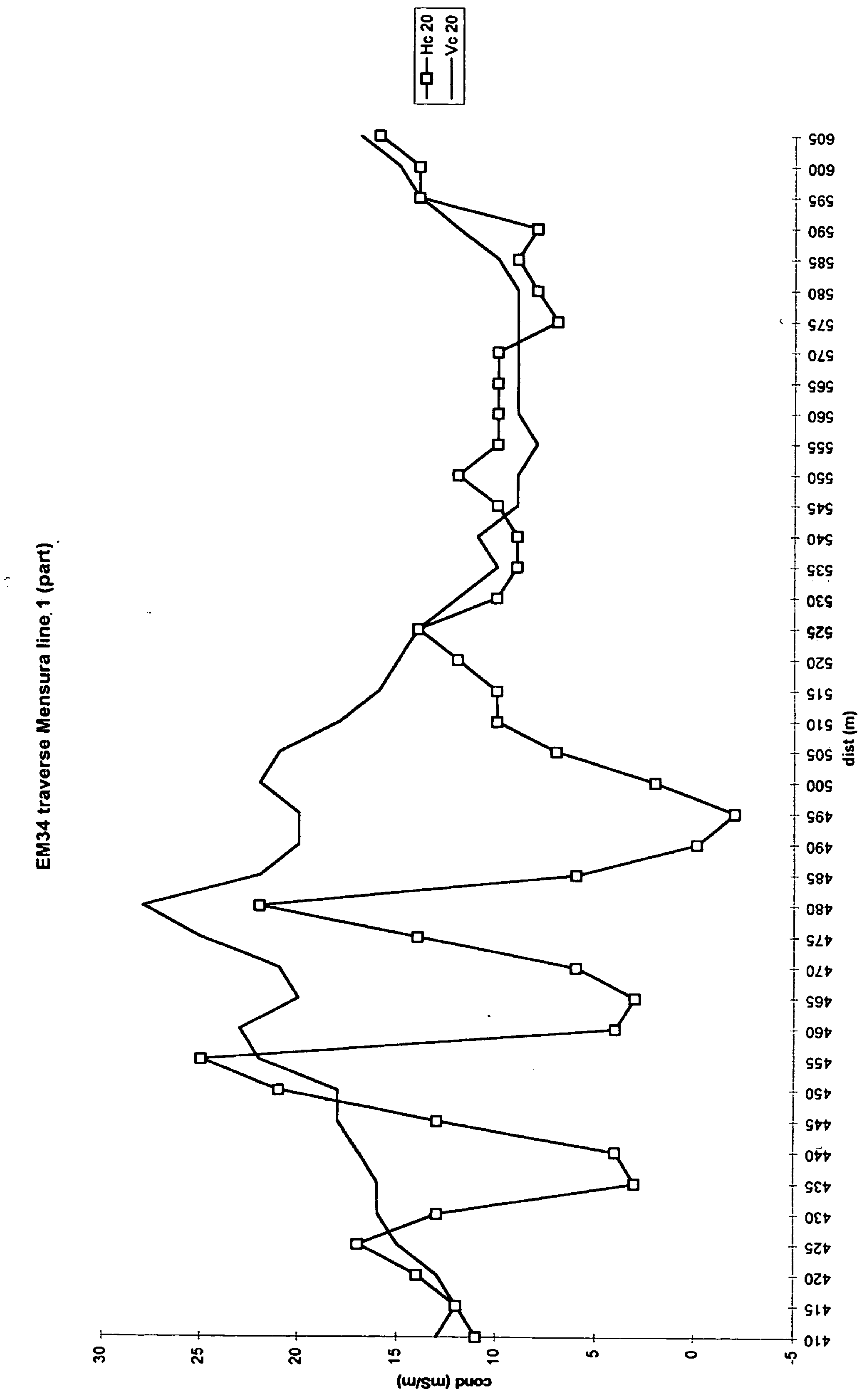


Fig. 3.3c_3 Mensura: EM34 data of Traverse 1 (410m to 605m)

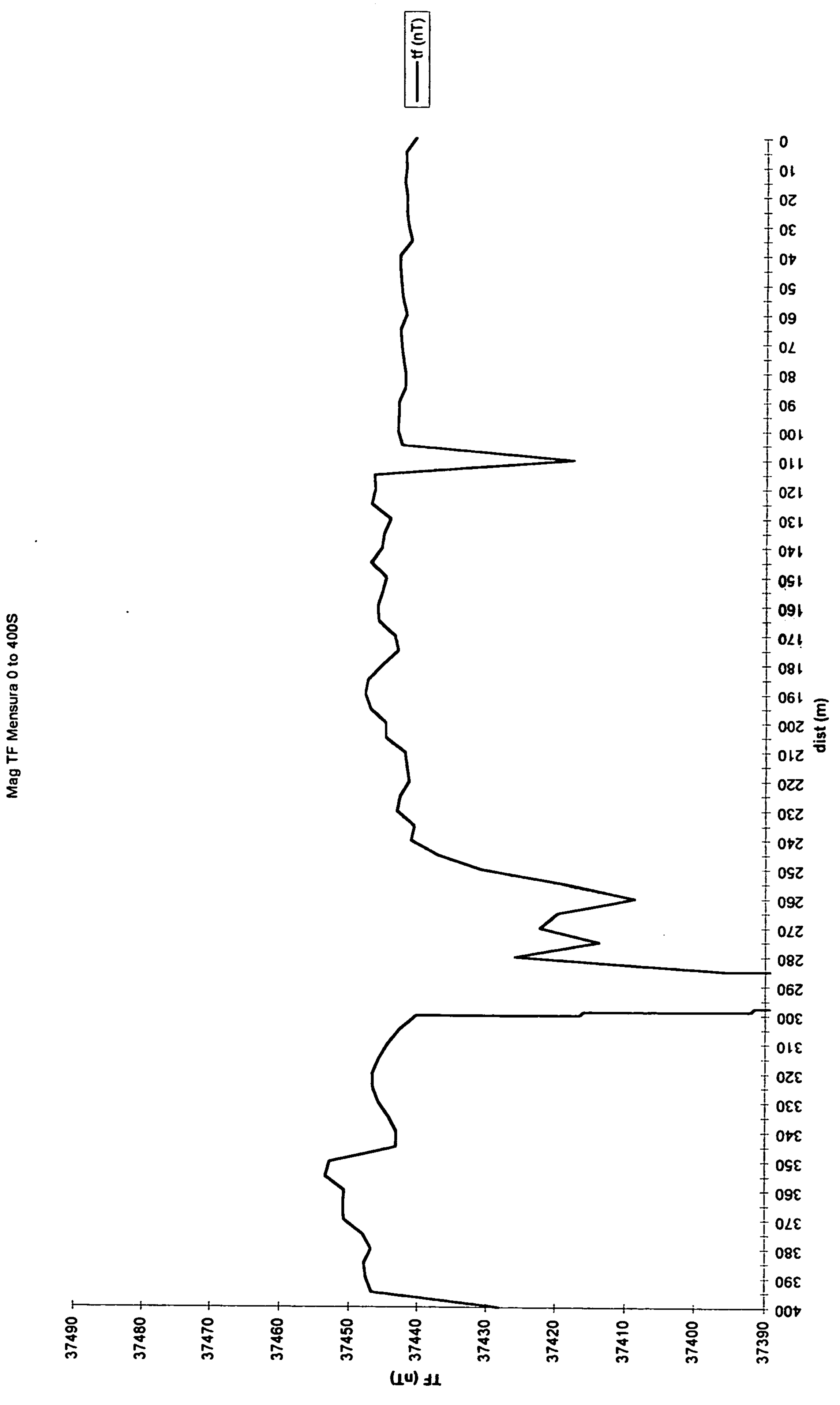


Fig. 3.3c_4 Mensura: Total field magnetic profile of Traverse 1 (0 m to 400 m)

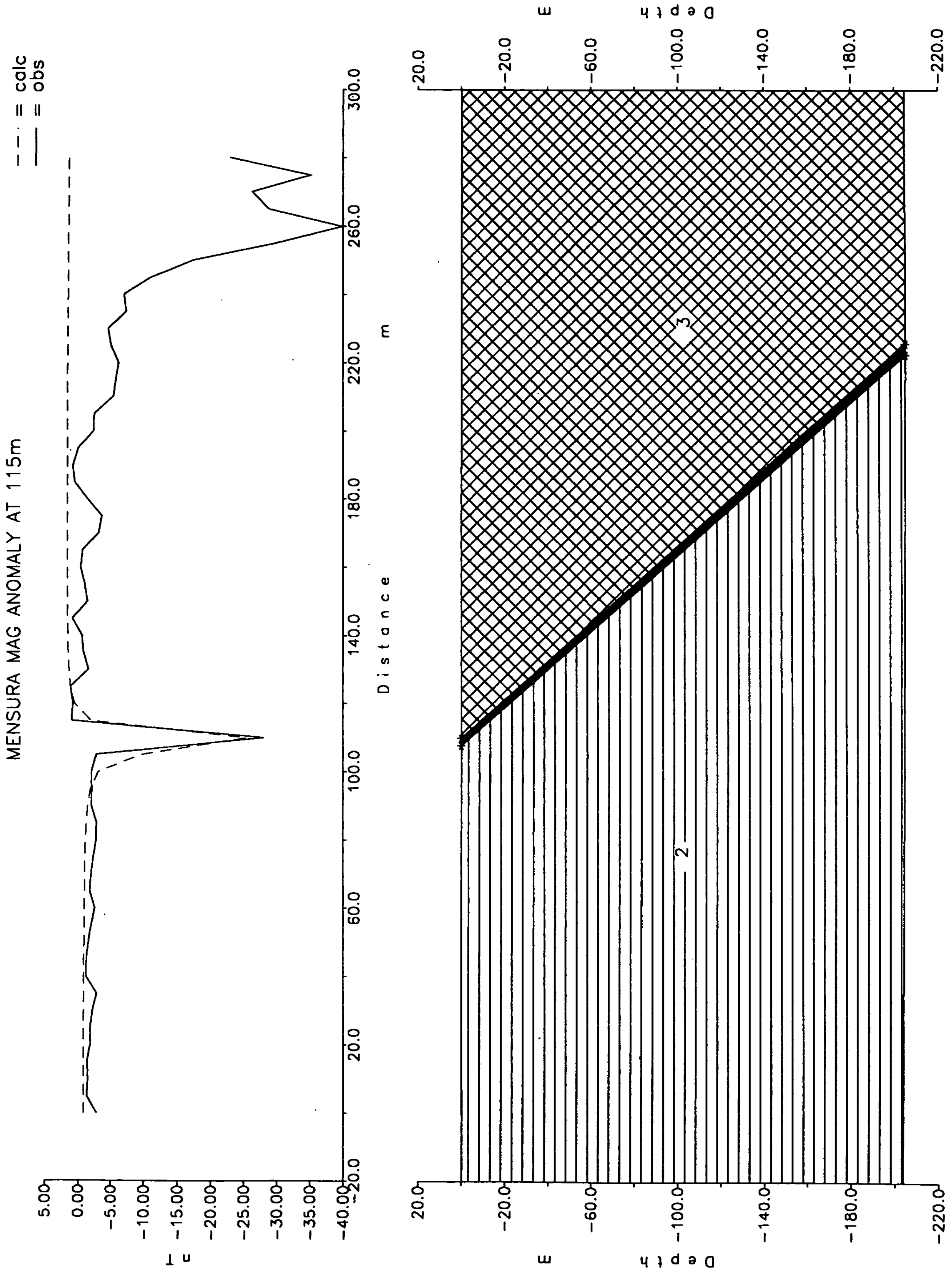


Fig. 3.3c_4x Mensura: modelled magnetic anomaly (c. 115 m traverse 1)

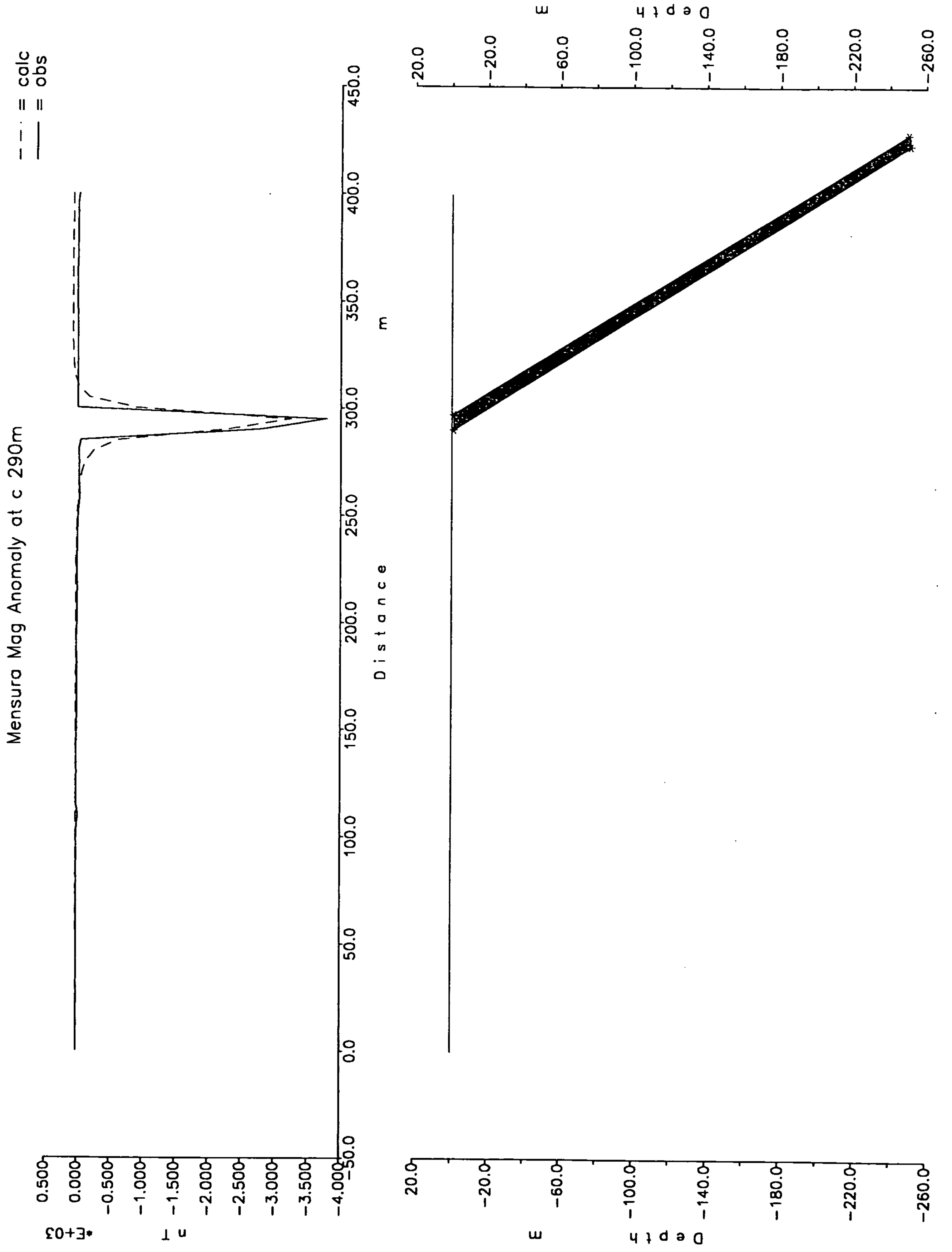


Fig. 3.3c_4xx Mensura: modelled magnetic anomaly (c. 290 m traverse 1)

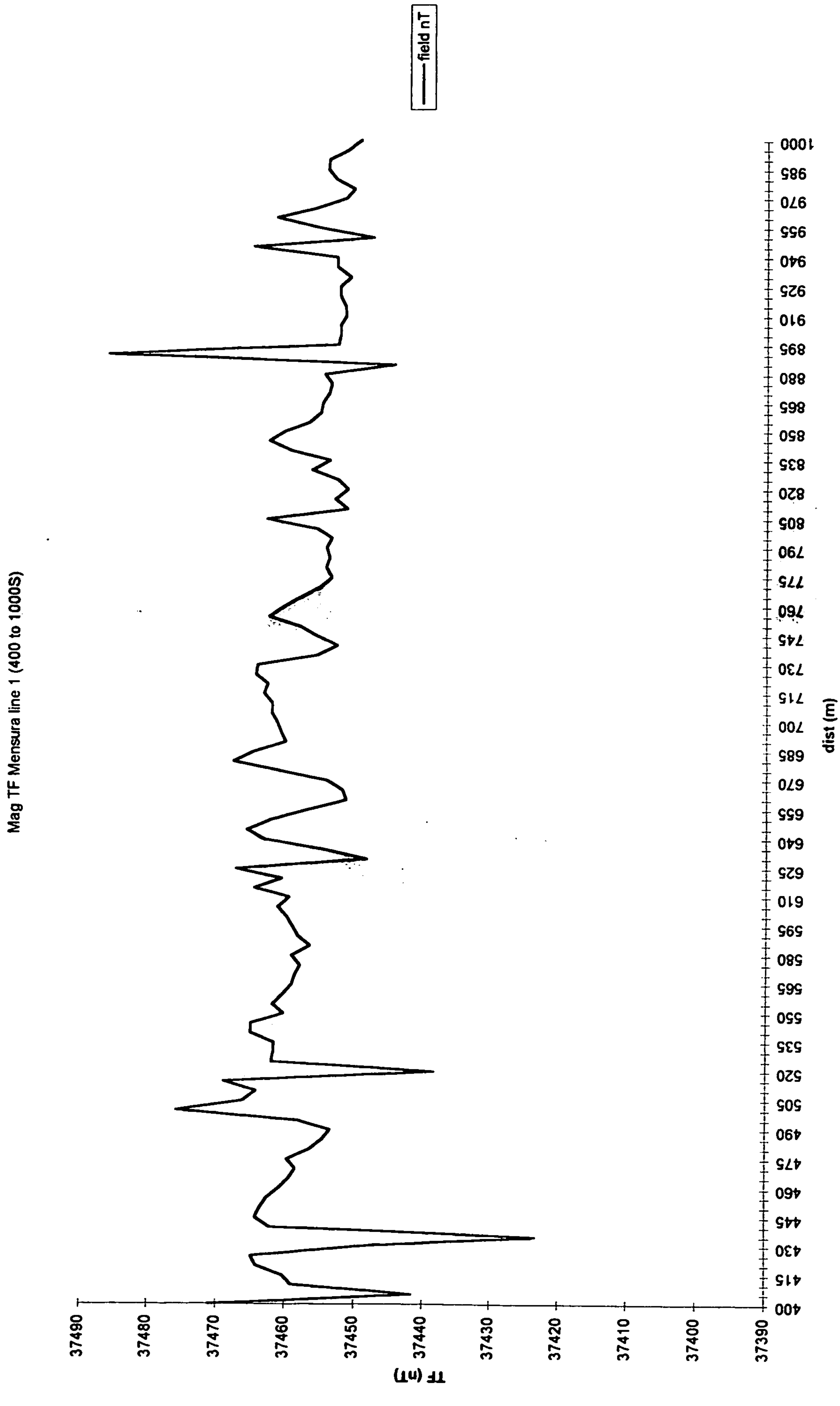


Fig. 3.3c_5 Mensura: Total field magnetic profile of Traverse 1 (400 m to 1000 m)

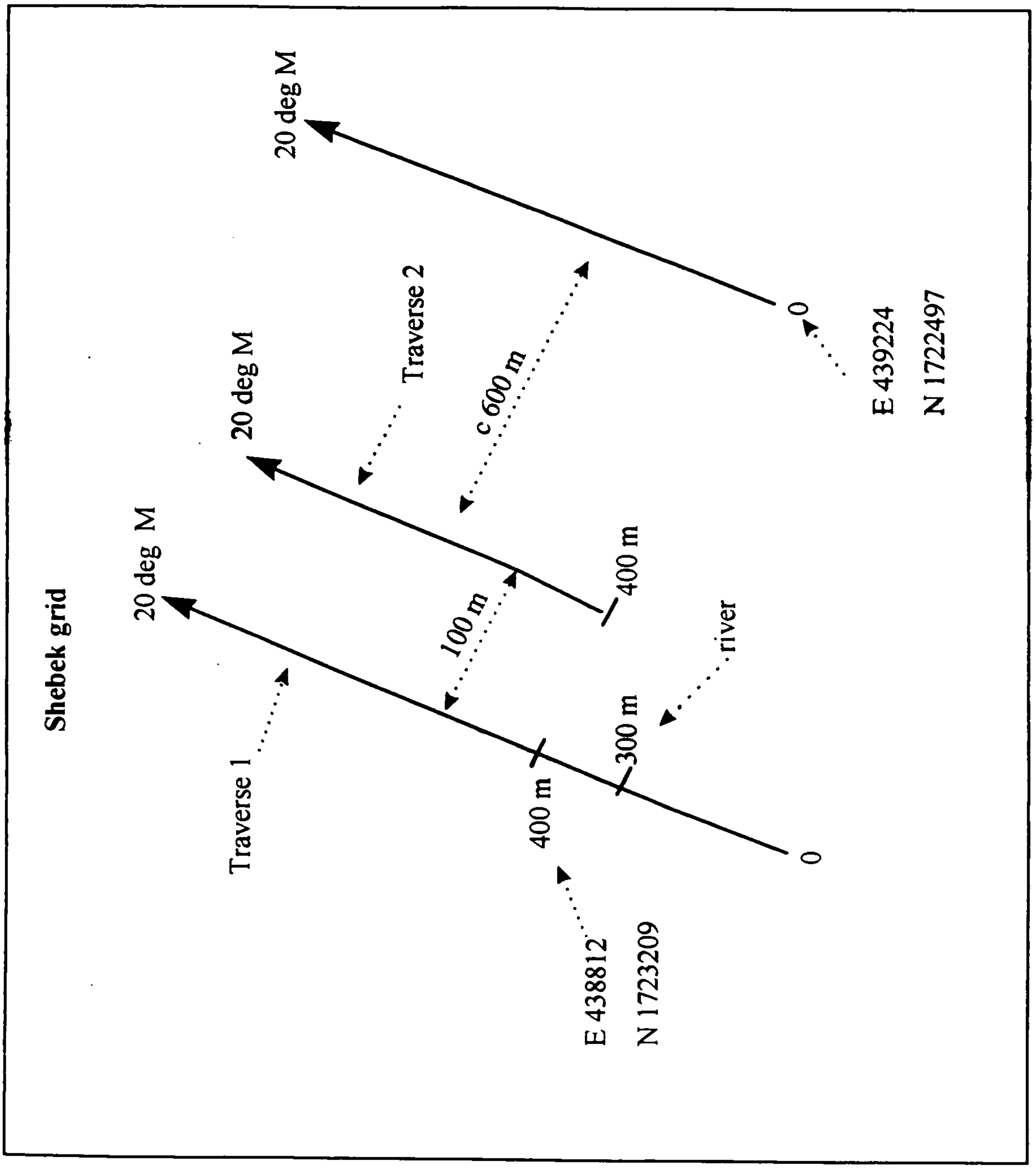


Fig. 3.3b_1 Shebek: geophysical grid at Shebek

ERITREA: SECTOR STUDY ON NATIONAL WATER RESOURCES AND IRRIGATION POTENTIAL

GROUNDWATER EXPLORATION

GEOPHYSICAL INVESTIGATIONS COMPLETED

Stn 400N (trav 1) 0433312 1723209

SHEET No: **LOCATION:** SHEBAK **UTM Co-ords: E** 0439224 **N** 1722497
(0 of Line 3, c. 600m E Line 1)

Geology: Basement / granite **Target:** Dilational / Tensional Tertiary shear zone of Drury et al.

GEOPHYSICAL TECHNIQUES				
	Used?	Line/Grid	cover m/No.	Comments
Conductivity EM34 40m	✓	L	280m	Abandoned due flooding
Conductivity EM34 20m	✓	L		
Conductivity EM34 10m			350m ↑	
TDEM 47 sounding (5m*5m)				
TDEM 47 sounding (40m*40m)				
TDEM47 sounding (100m*100m)				
TDEM 47 traversing (5m*5m)				
TDEM 47 traversing (40m*40m)				
TDEM 47 traversing (100m*100m)				
Resistivity (ABEM 300C) sounding				
Resistivity (ABEM 300C) traversing				
VLF (WADI) traversing		L (3)	2230m	
Magnetometry (GEM) traversing		L (3)	2800m	
Gravimetry				
Seismic refraction				

Previous work: BH at c 670m on traverse 3: WS 28m TD 60m
Yield reported good (BH now only partly serviceable)

Borehole sited ?: YES (2) **Location:** **Project Bh No:**

Borehole drilled (date): ~~370m~~ Tr. 1 350m
~~655m~~ (Tr. 600m East) 400m traverse 3

Result:

Fig. 3.3b_2 Shebek: table summarising geophysical investigations

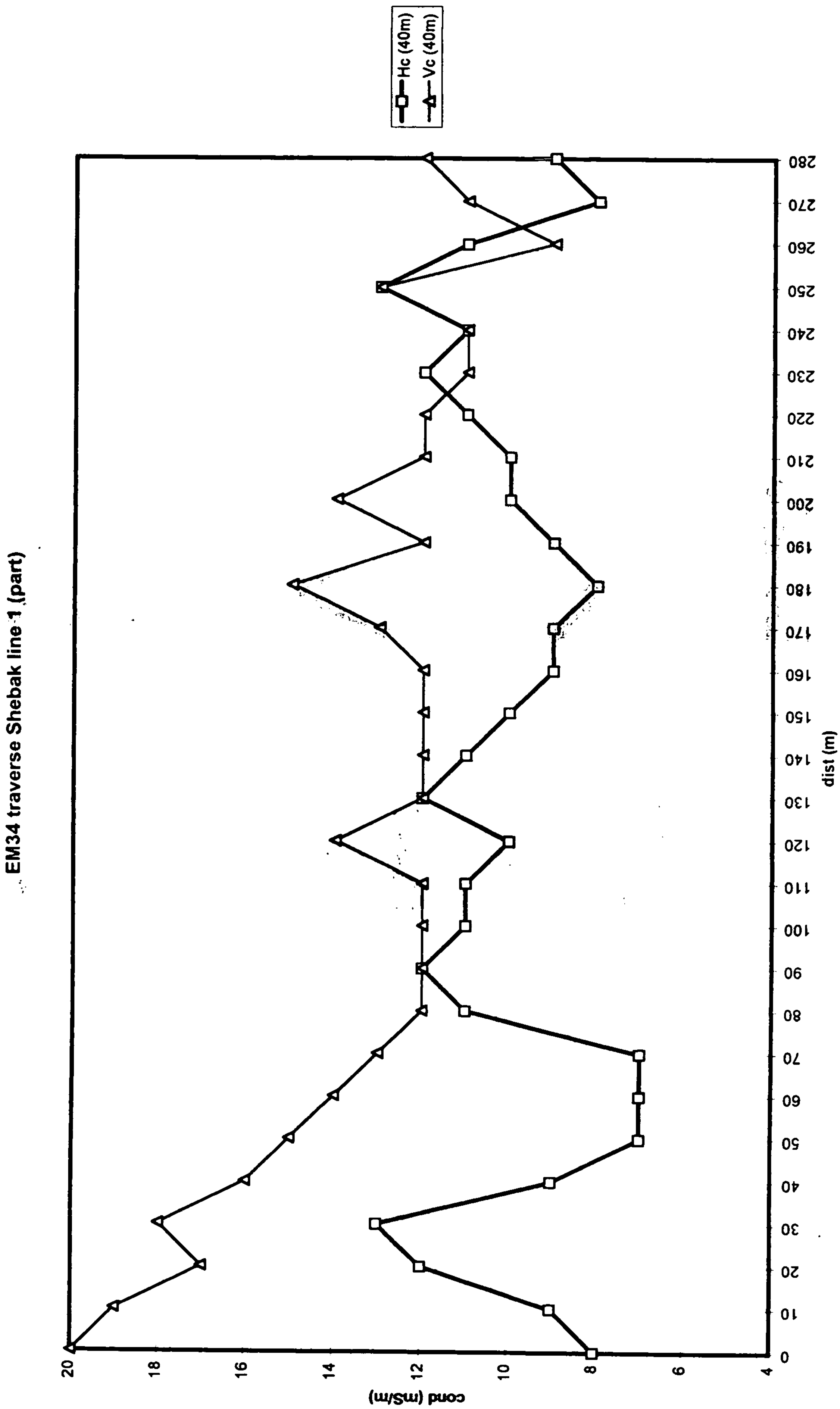


Fig. 3.3b_3 Shebek: EM34 data of Traverse 1 (0m to 280m)

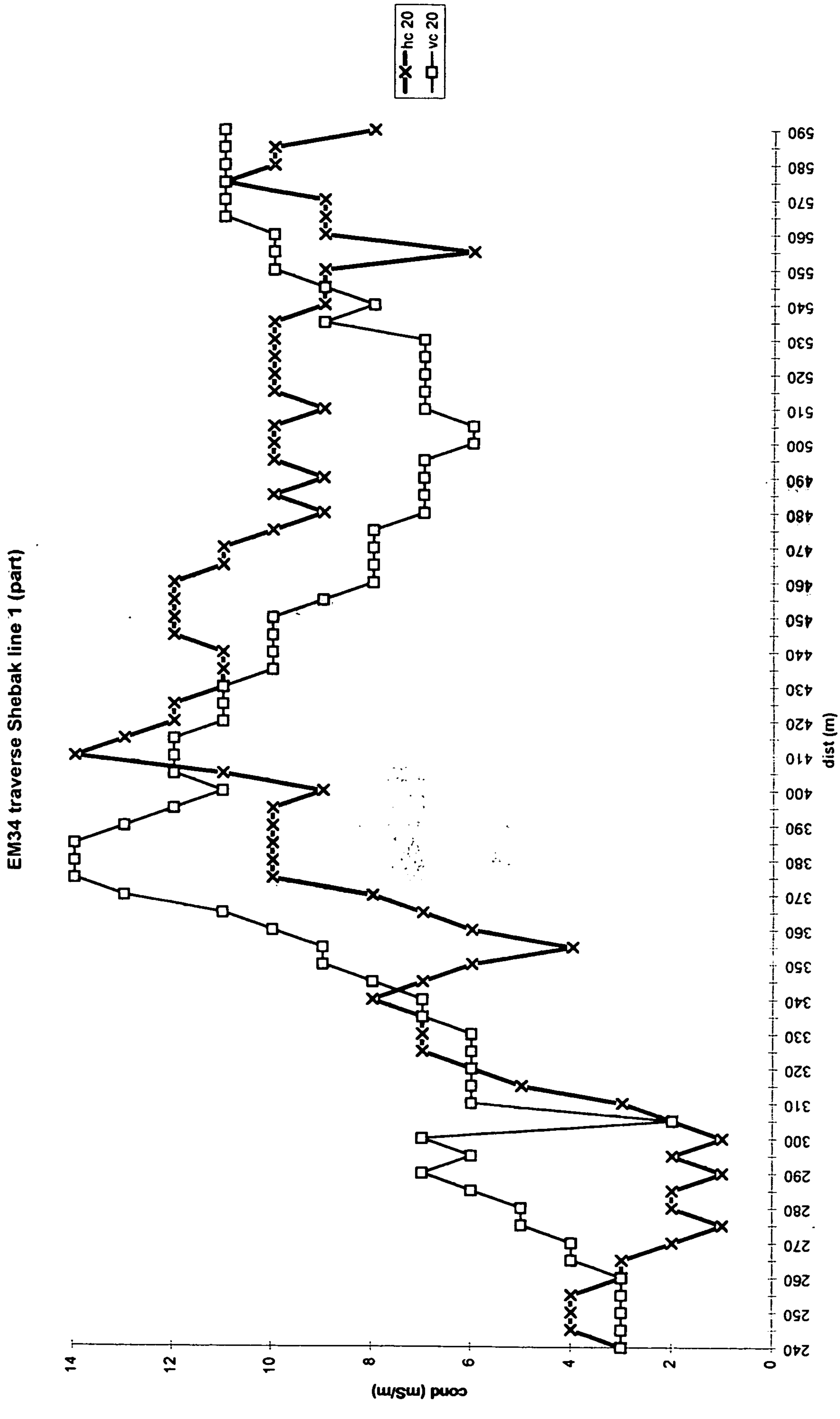


Fig. 3.3b_4 Shebek: EM34 data of Traverse 1 (240m to 590m)

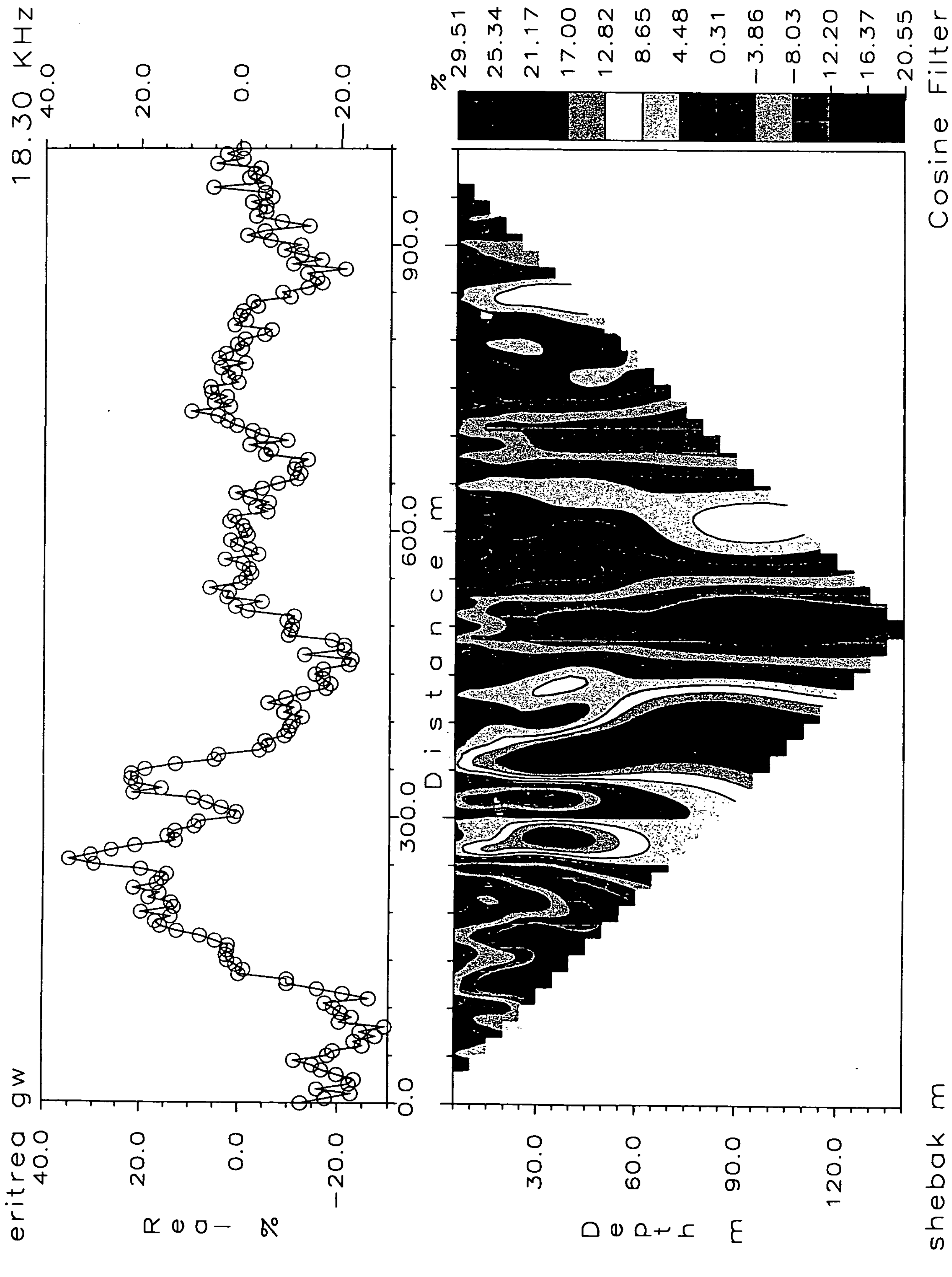


Fig. 3.3b_5 Shebek: VLF in phase data and Karous-Hjelt filter result:Traverse 1

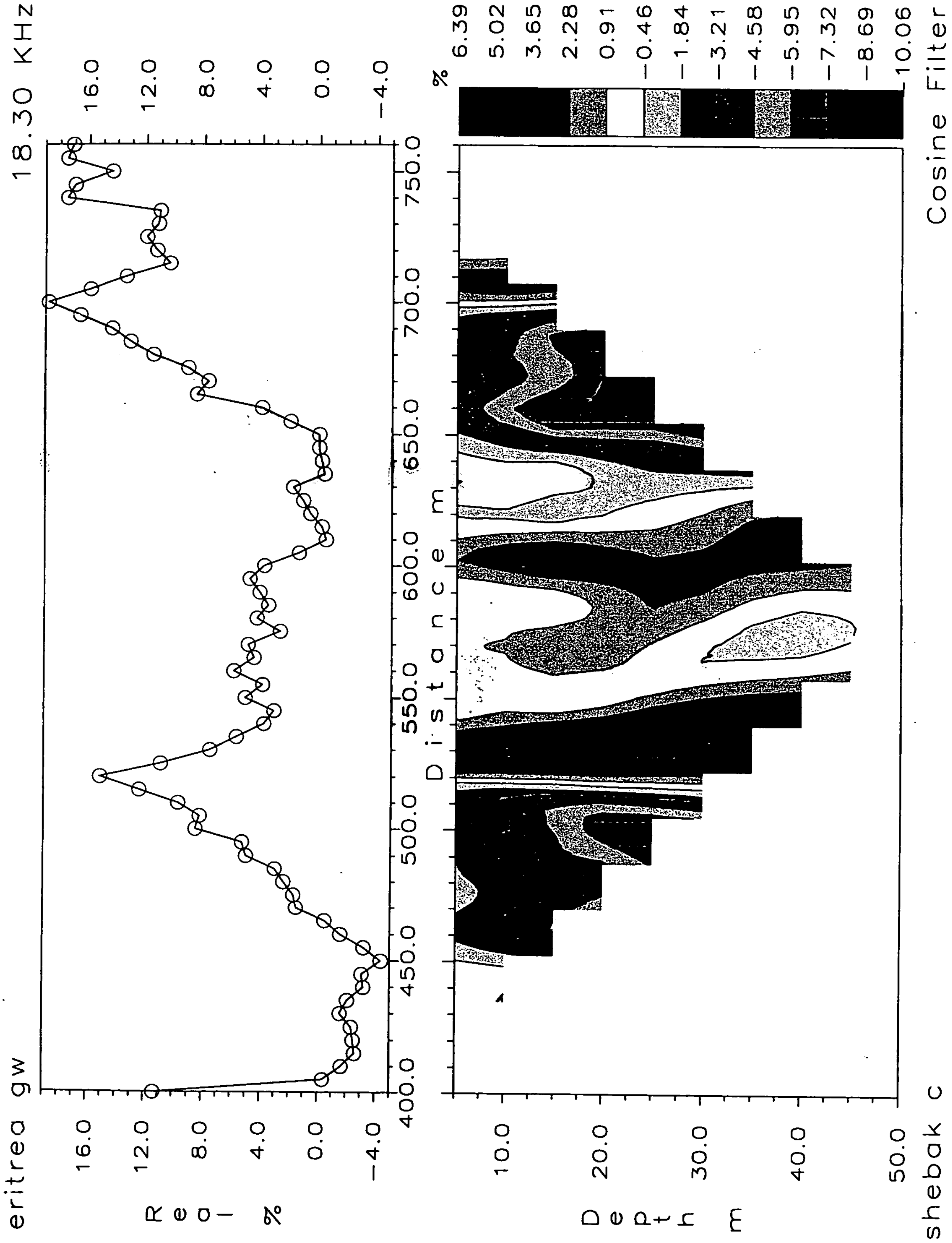


Fig. 3.3b_6 Shebek: VLF in phase data and Karous-Hjelt filter result:Traverse 2

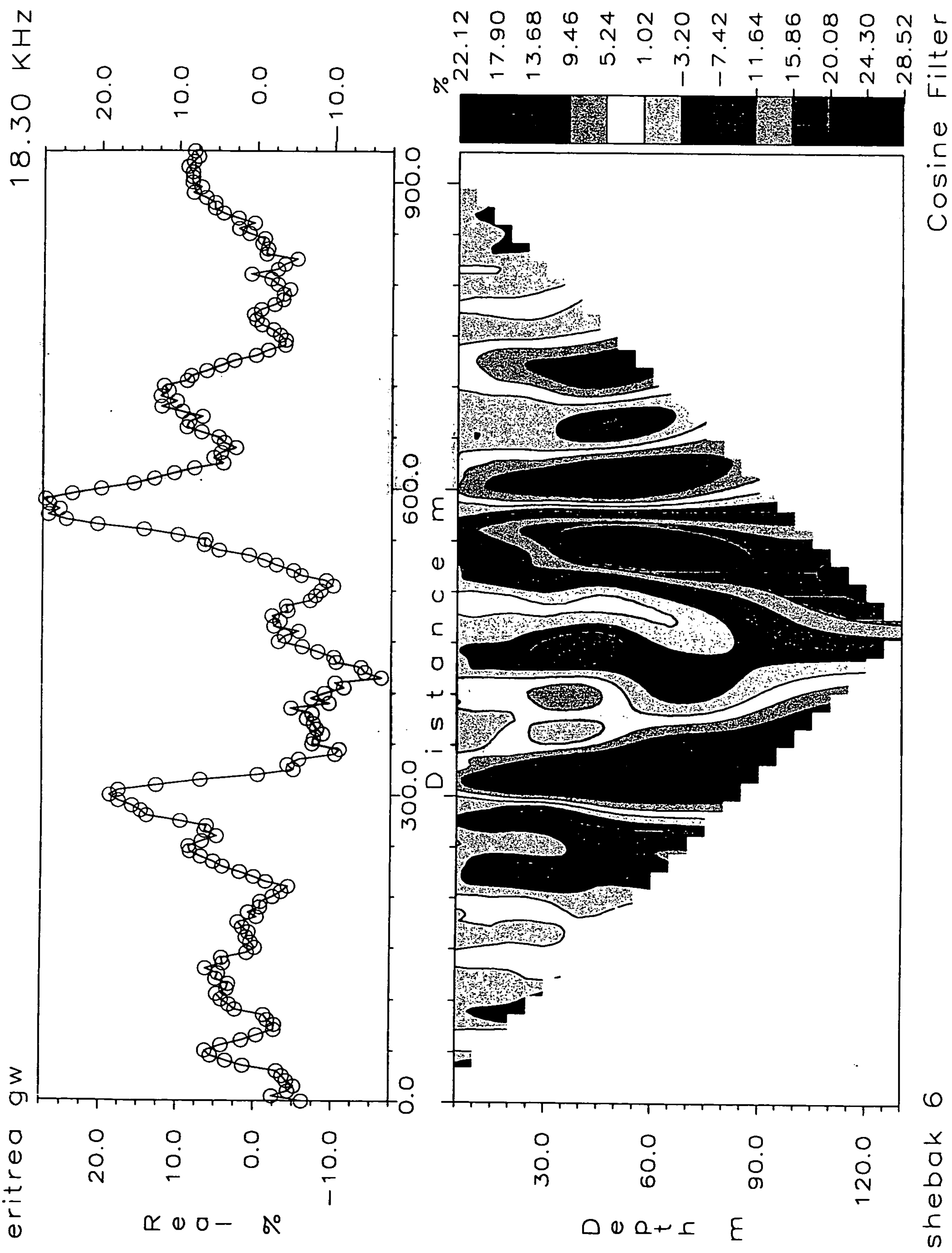
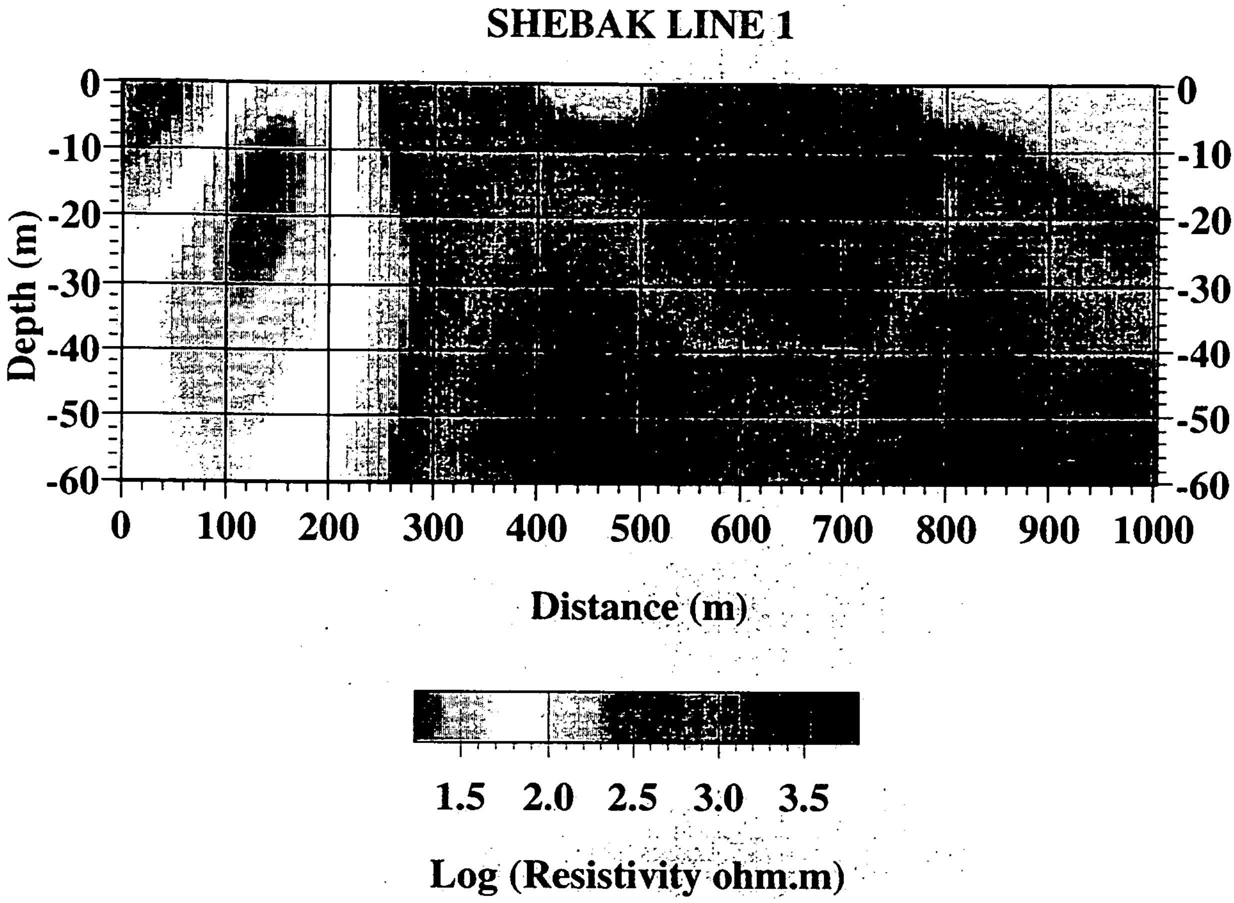


Fig. 3.3b_7 Shebek: VLF in phase data and Karous-Hjelt filter result:Traverse 3

Eritrea VLF. SHEBAK Line 1.

2d Occam resistivity cross-section, rms=1.0 (10%), Hz-TE mode



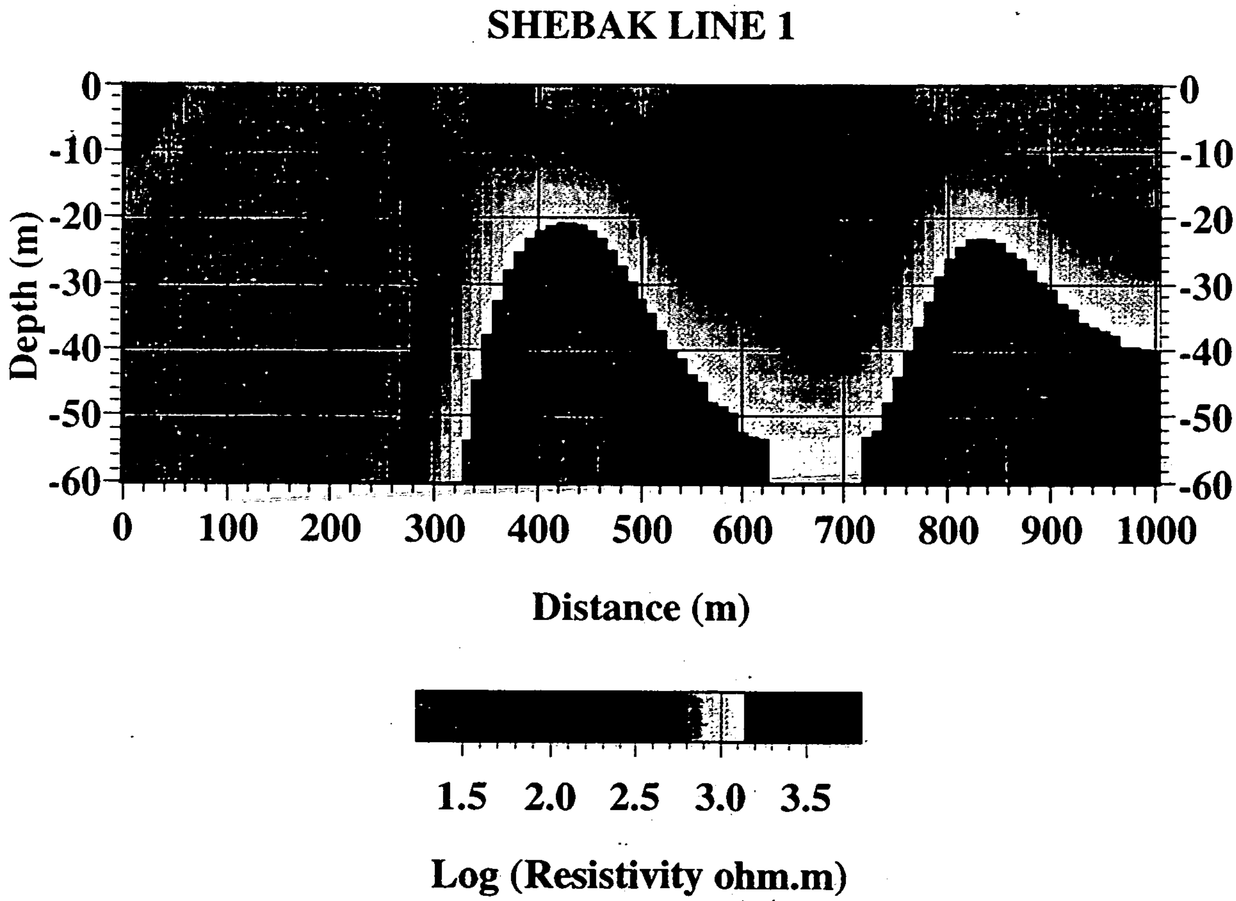
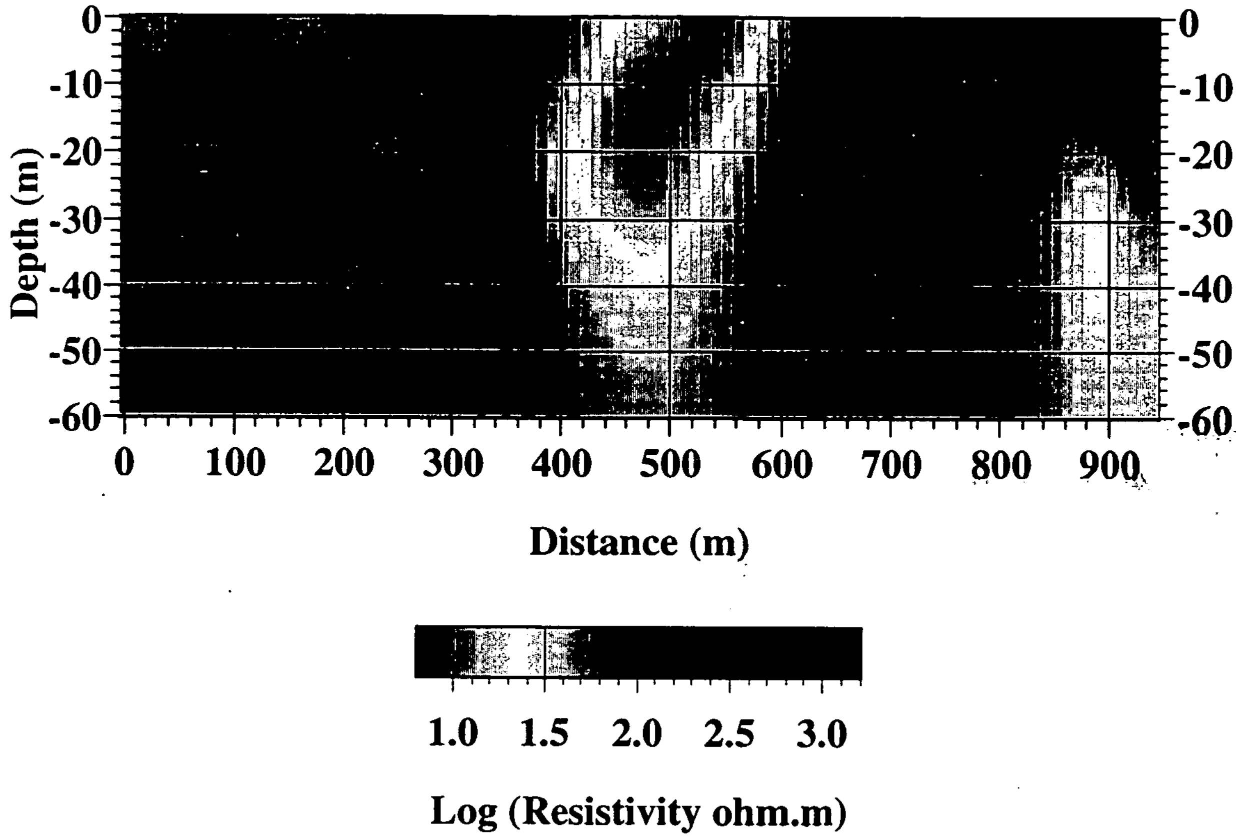


Fig. 3.3b_8 Shebek: VLF smooth model : Traverse 1

Eritrea VLF. SHEBAK Line 3.

2d Occam resistivity cross-section, rms=1.0 (10%), Hz-TE mode

LINE 3, rms=1.0%, start=3000 ohm.m



LINE 3, rms=1.0%, start=3000 ohm.m

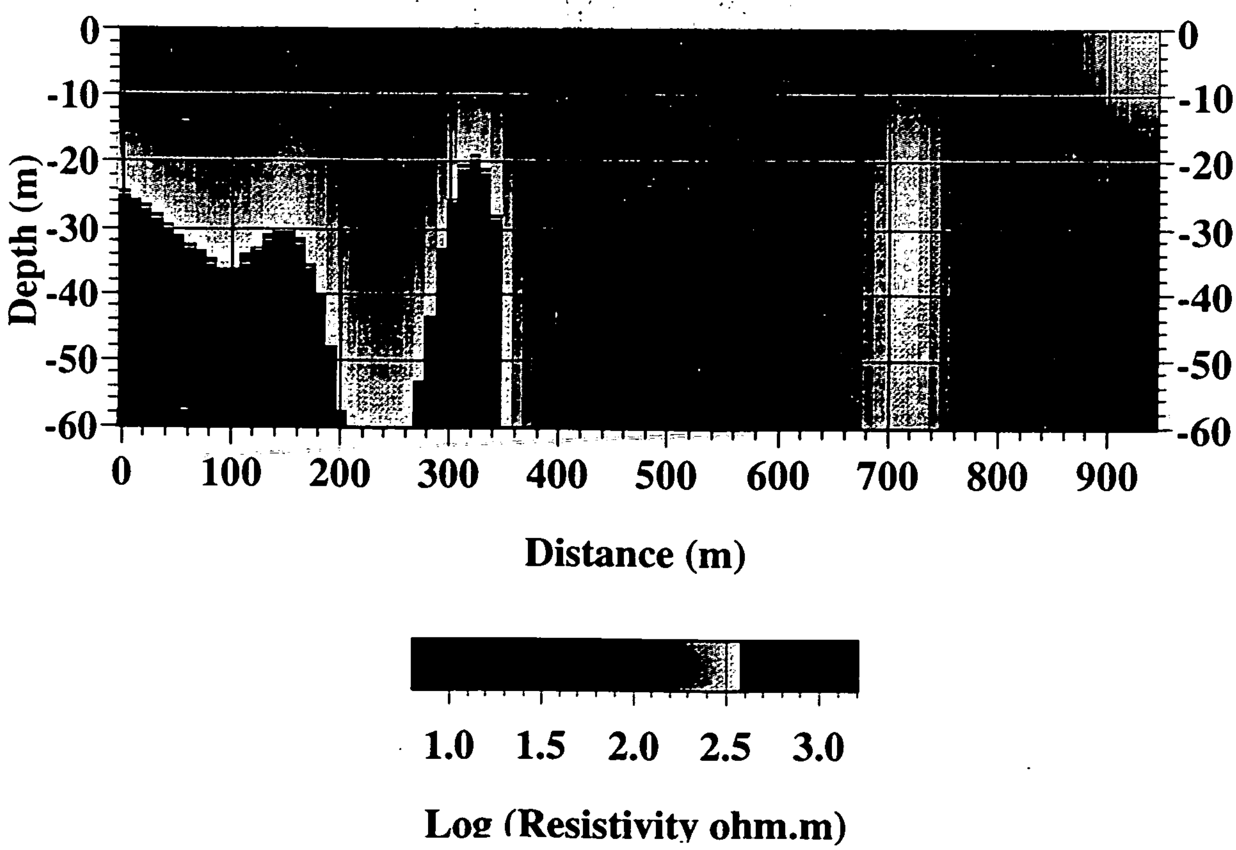


Fig. 3.3b_9 Shebek: VLF smooth model : Traverse 3

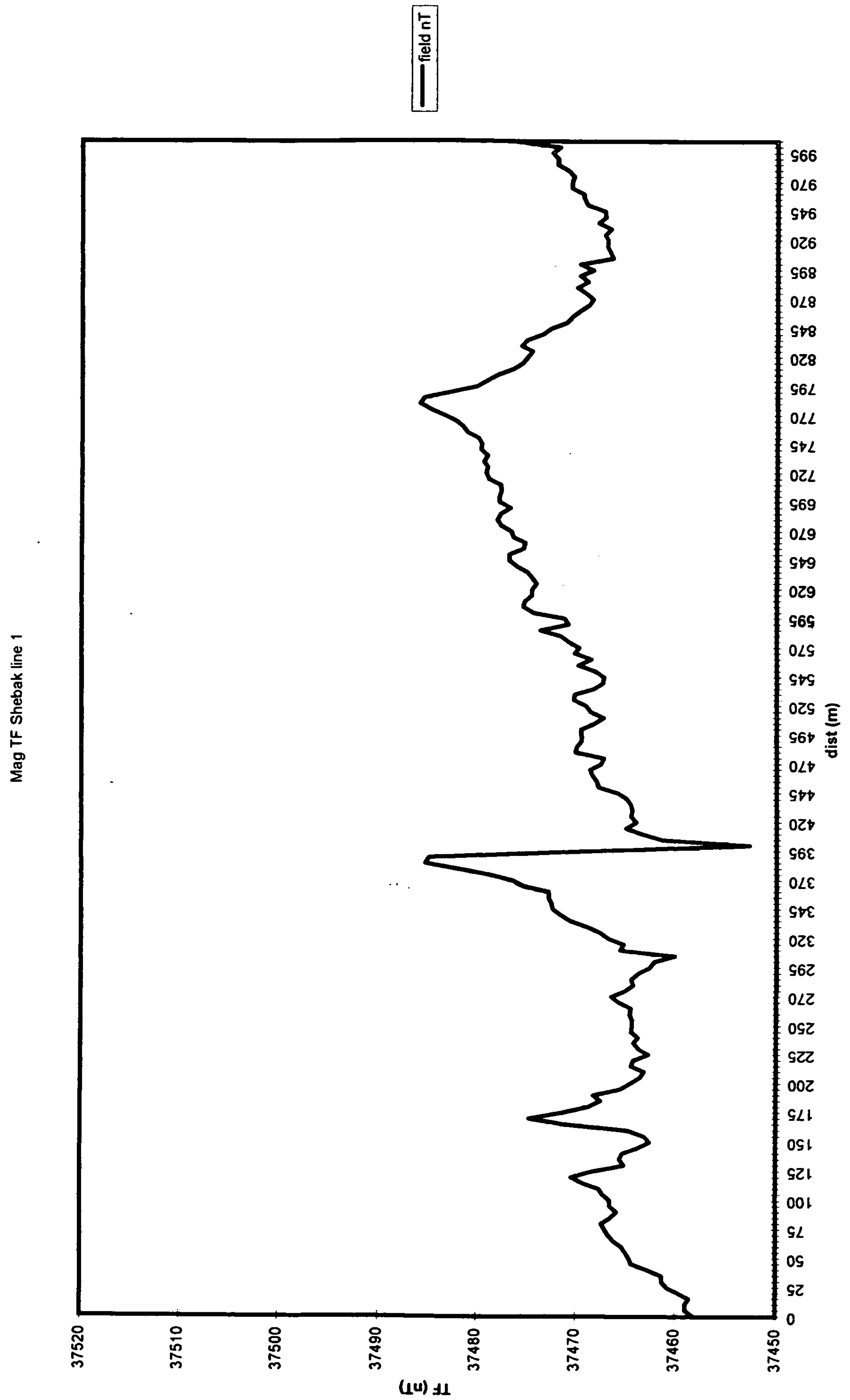


Fig. 3.3b_10 Shebek: Total field magnetic data of Traverse 1

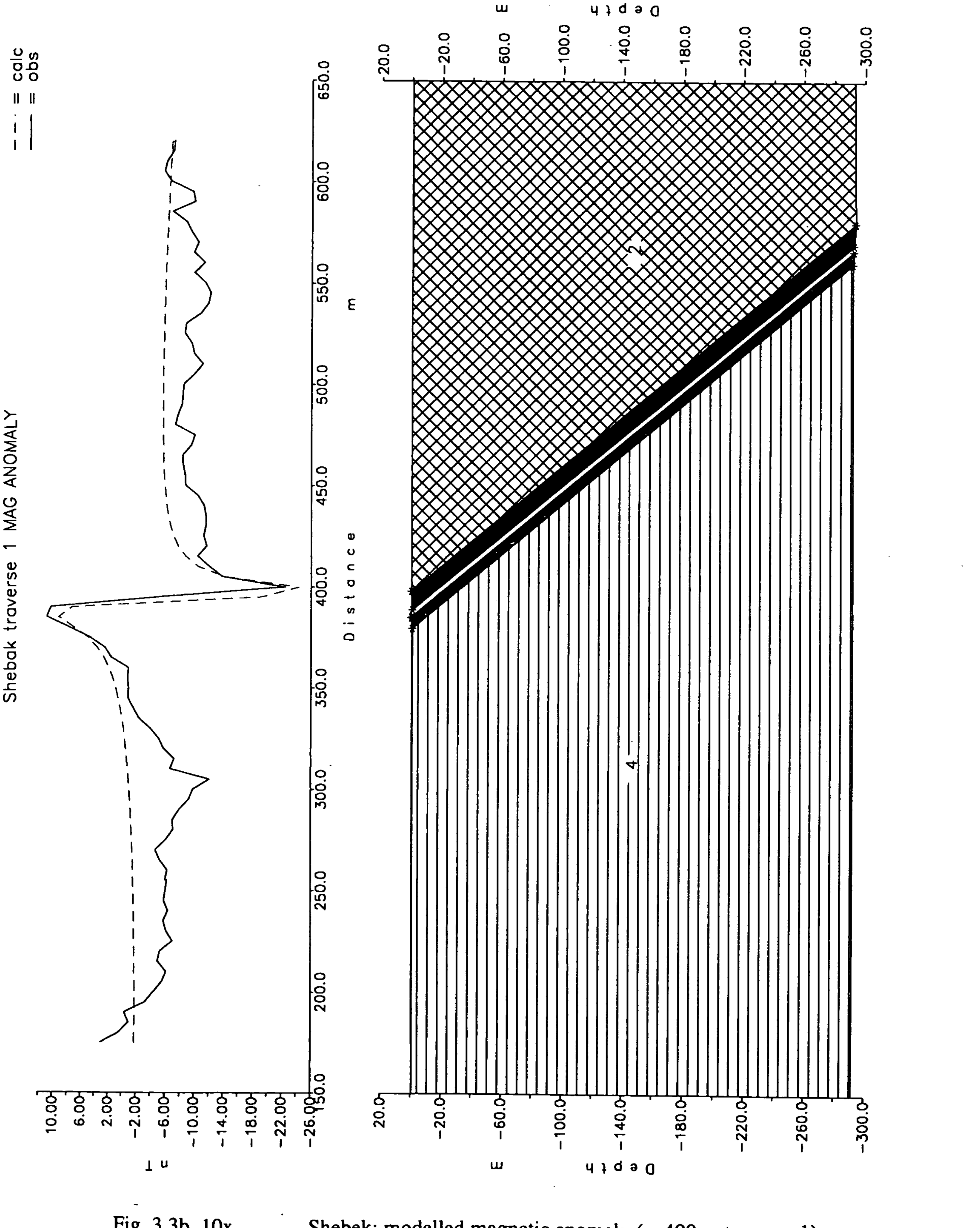


Fig. 3.3b_10x Shebek: modelled magnetic anomaly (c. 400 m traverse 1)

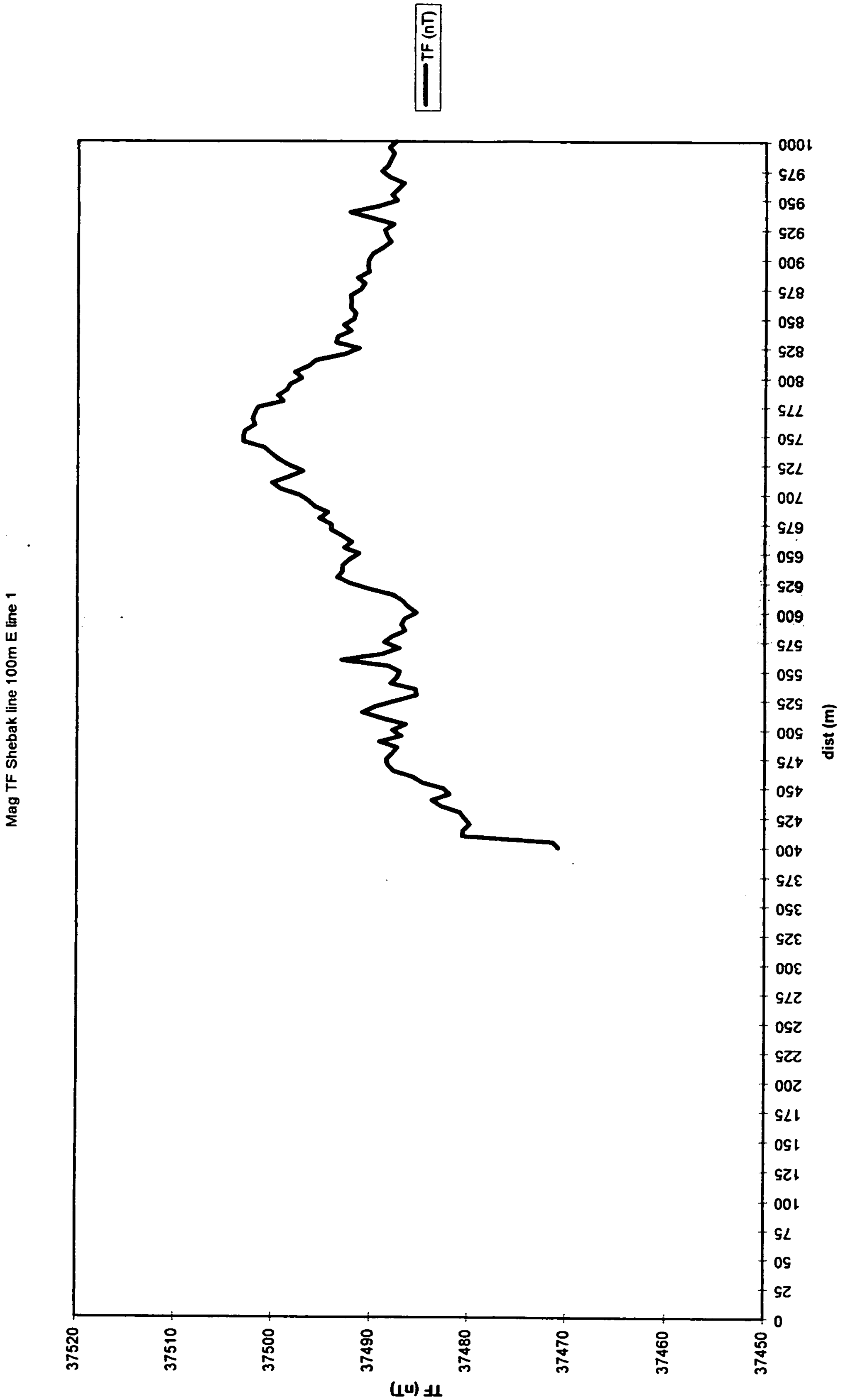


Fig. 3.3b_11 Shebek: Total field magnetic data of Traverse 2

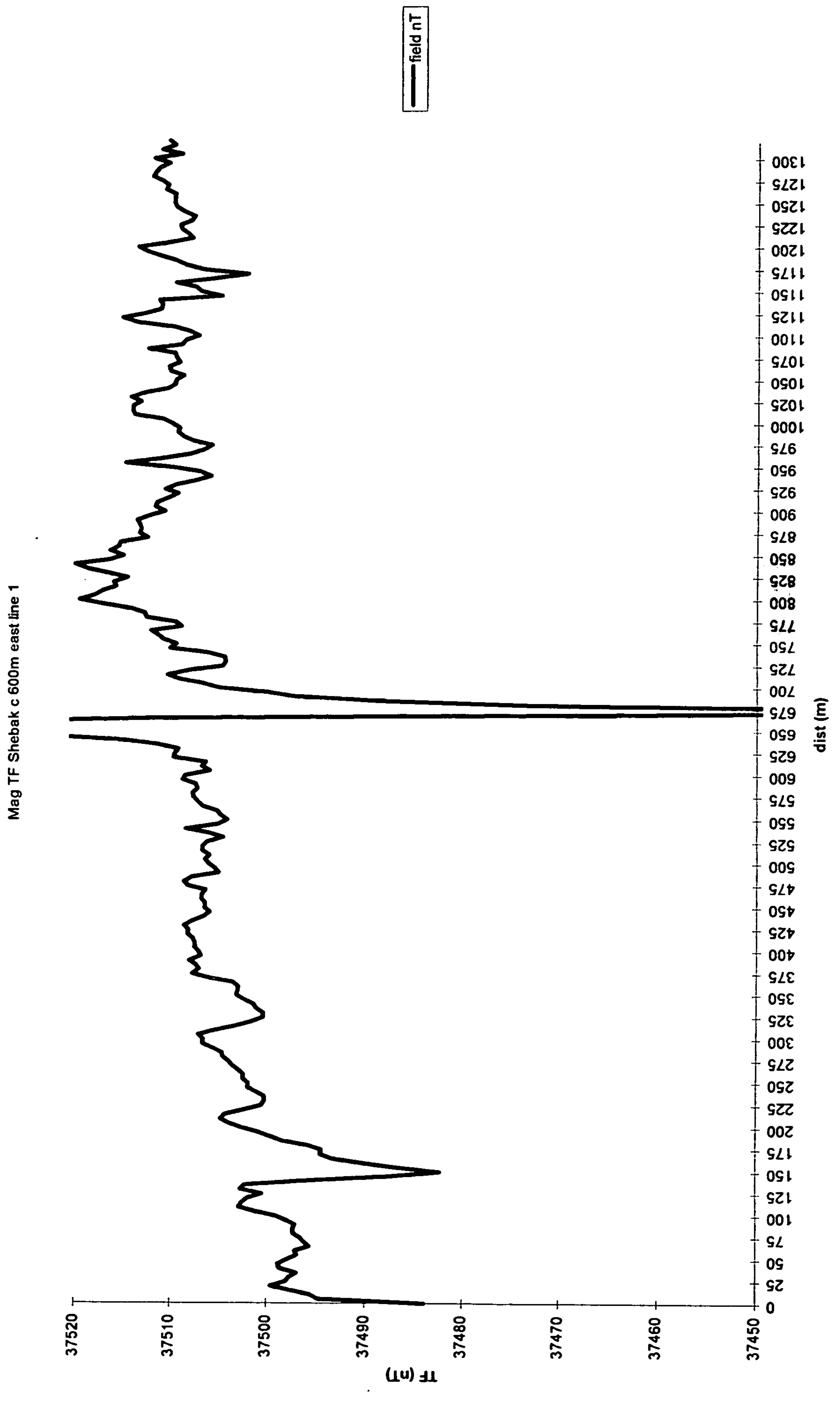


Fig. 3.3b_12 Shebek: Total field magnetic data of Traverse 3

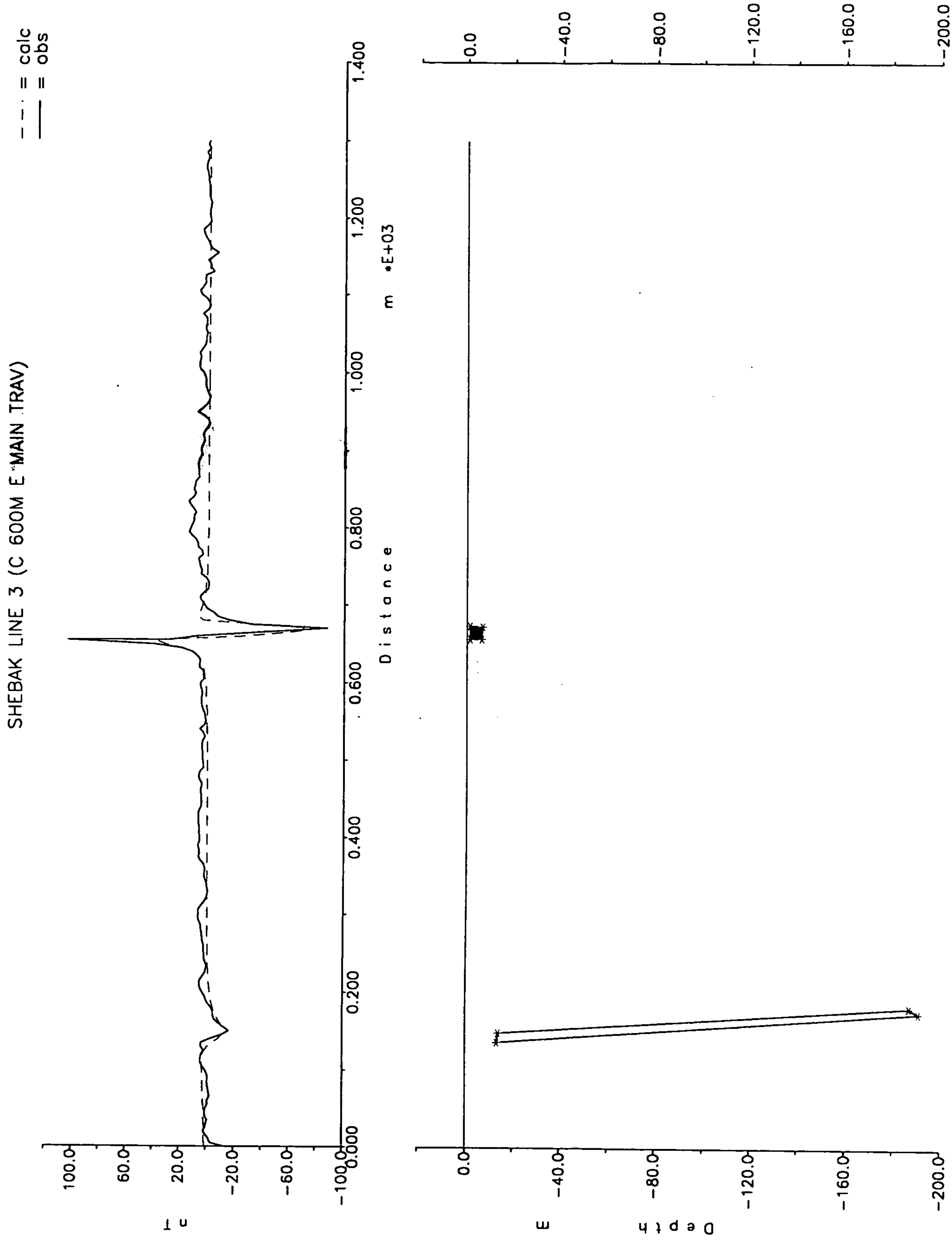


Fig. 3.3b_13 Shebek: Modelled Total Field magnetic profile: Traverse 3

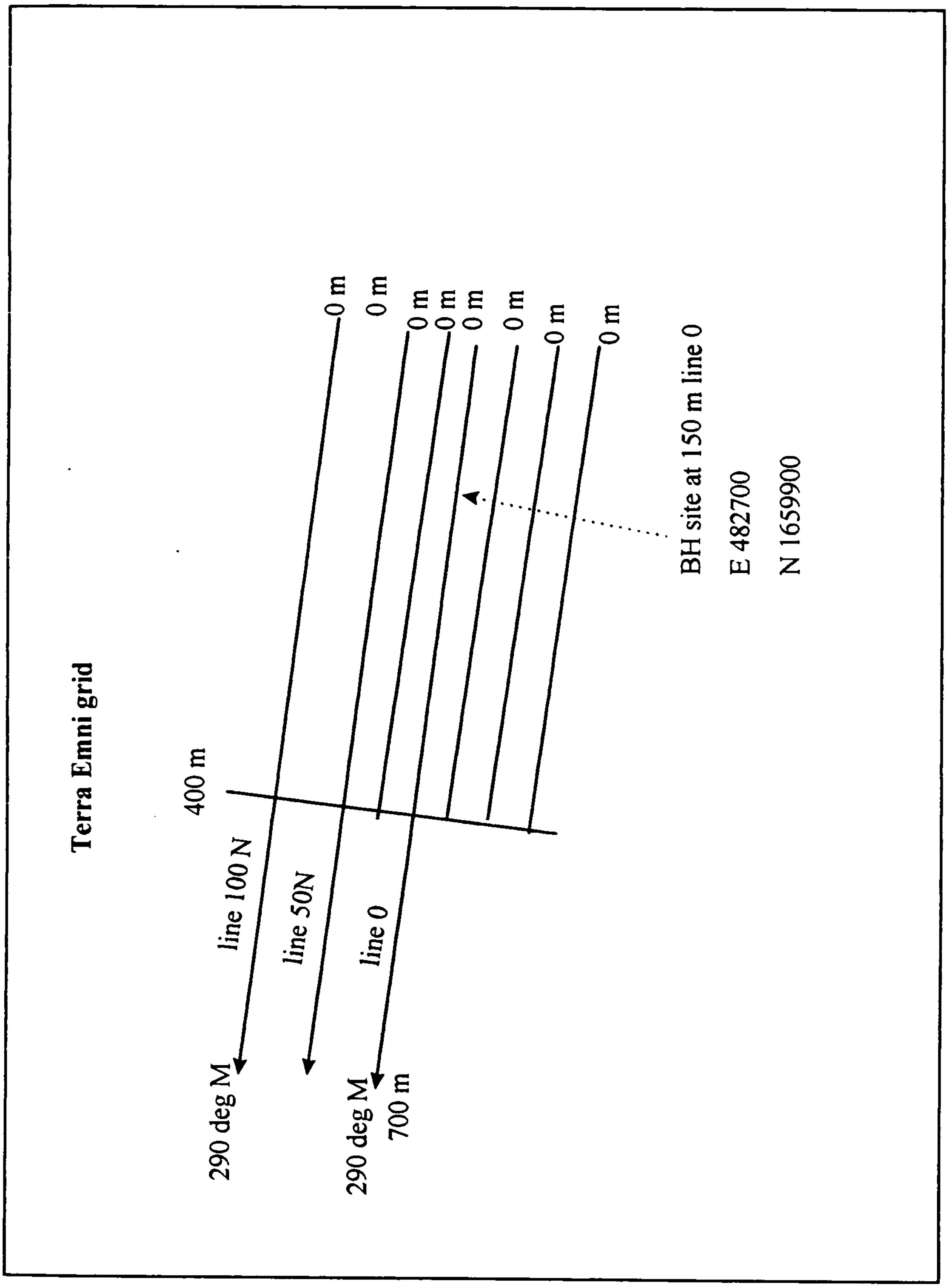


Fig. 3.2a_1 Terra Emni: geophysical grid at Terra Emni

ERITREA: SECTOR STUDY ON NATIONAL WATER RESOURCES AND IRRIGATION POTENTIAL

GROUNDWATER EXPLORATION

GEOPHYSICAL INVESTIGATIONS COMPLETED

SHEET No: **LOCATION:** Terra Emni **UTM Co-ords: E** **N**

Geology: Basalt **Target:** Fractures / thin basalt o/l weathered Basement

GEOPHYSICAL TECHNIQUES				
	Used?	Line/Grid	cover m/No.	Comments
Conductivity EM34 40m	✓	L	700 m	
Conductivity EM34 20m	✓	L	700 m	
Conductivity EM34 10m	✓	L	380 m	
TDEM 47 sounding (5m*5m)				
TDEM 47 sounding (40m*40m)	✓	L	4 No.	
TDEM47 sounding (100m*100m)				
TDEM 47 traversing (5m*5m)				
TDEM 47 traversing (40m*40m)				
TDEM 47 traversing (100m*100m)				
Resistivity (ABEM 300C) sounding	✓	L	7 No	
Resistivity (ABEM 300C) traversing				
VLF (WADI) traversing				
Magnetometry (GEM) traversing	✓	G	3700 m	
Gravimetry				
Seismic refraction				

Previous work:

Borehole sited ?: YES **Location:** 150 m Traverse 1 **Project Bh No:**

Borehole drilled (date):

Result:

Fig. 3.2a_2 Terra Emni: table summarising geophysical investigations

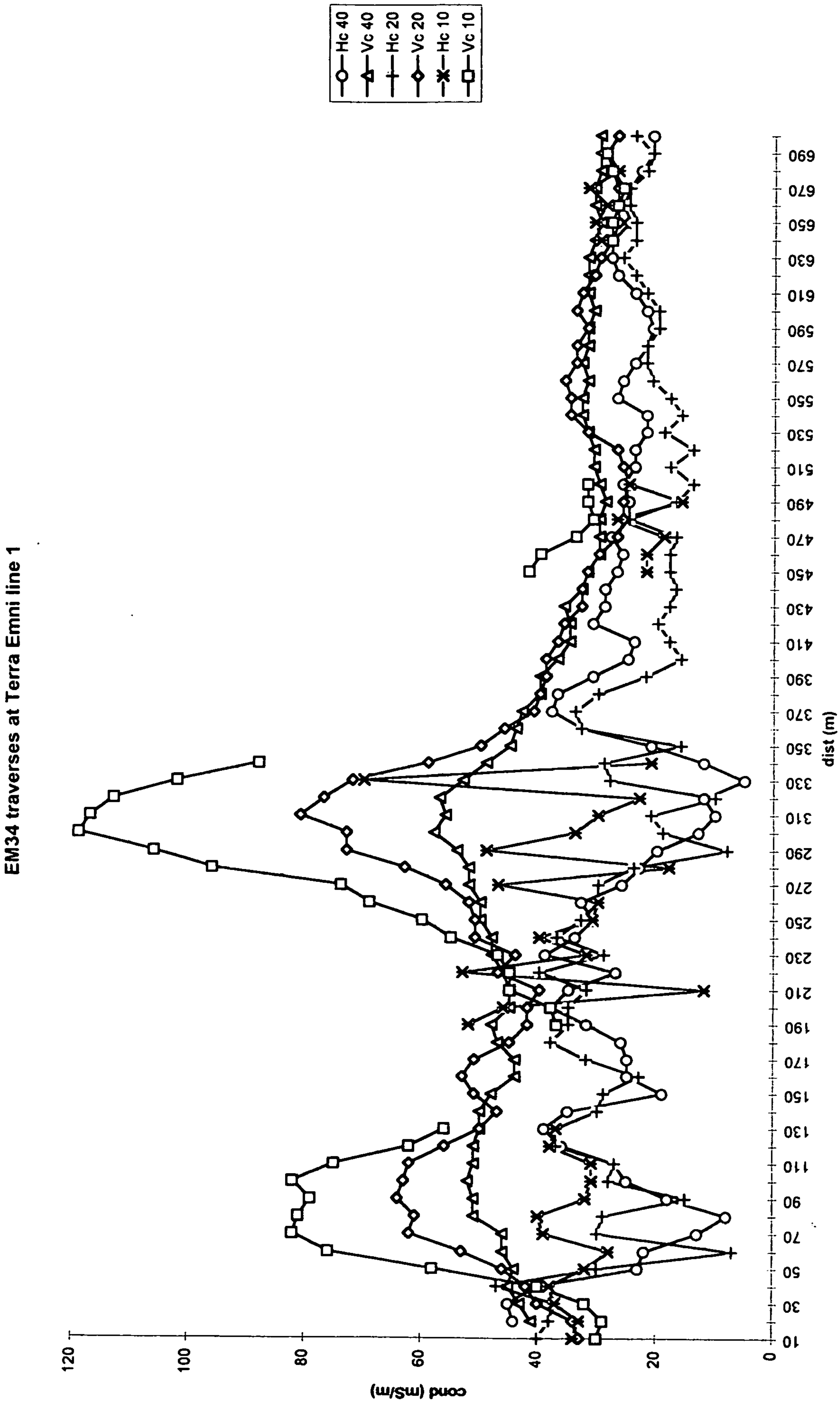


Fig. 3.2a_3 Terra Emni: EM34 data on Traverse 1 (Line 0)

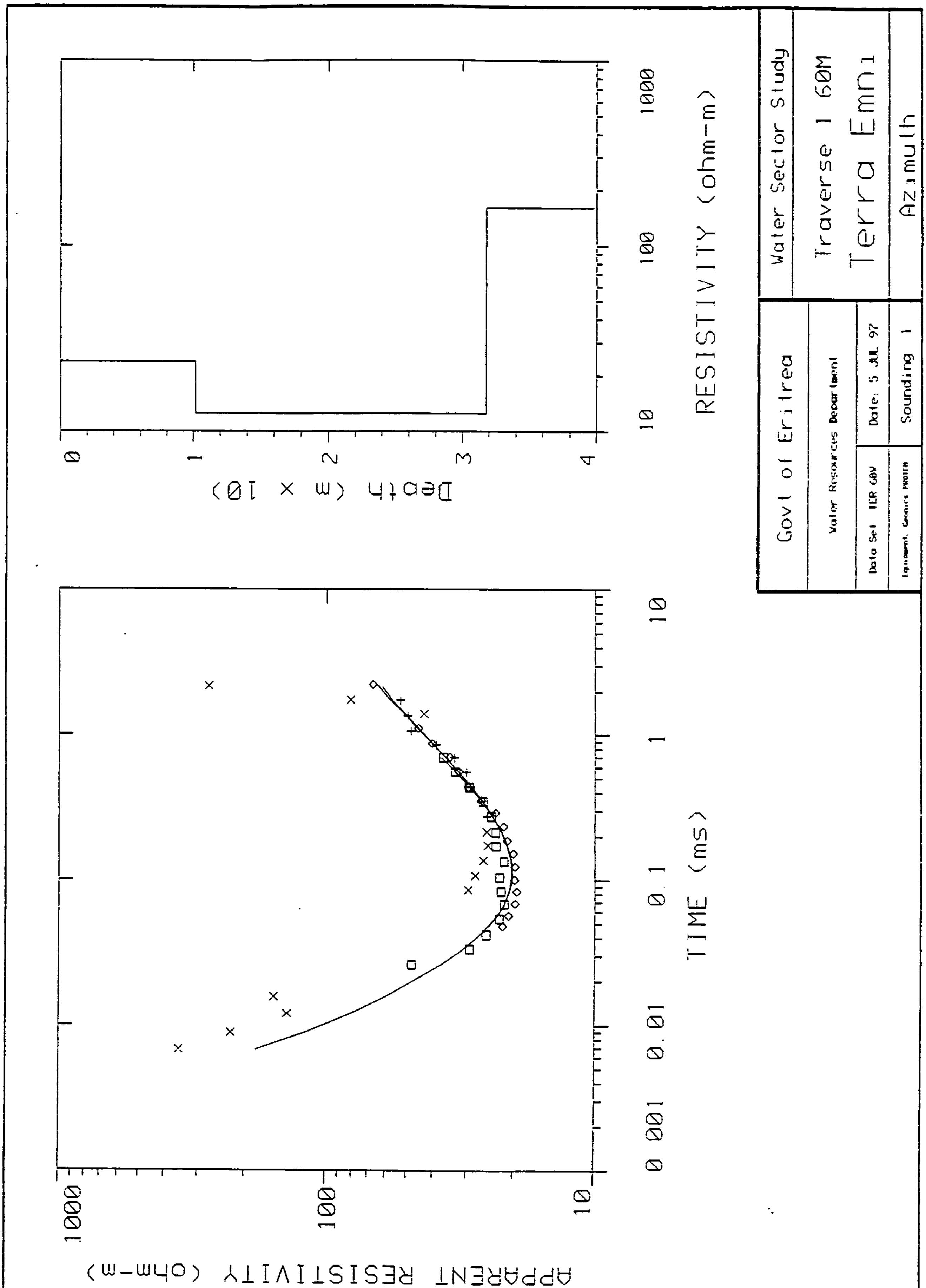


Fig. 3.2a_4 Terra Emni: TDEM sounding at 60 m Traverse 1

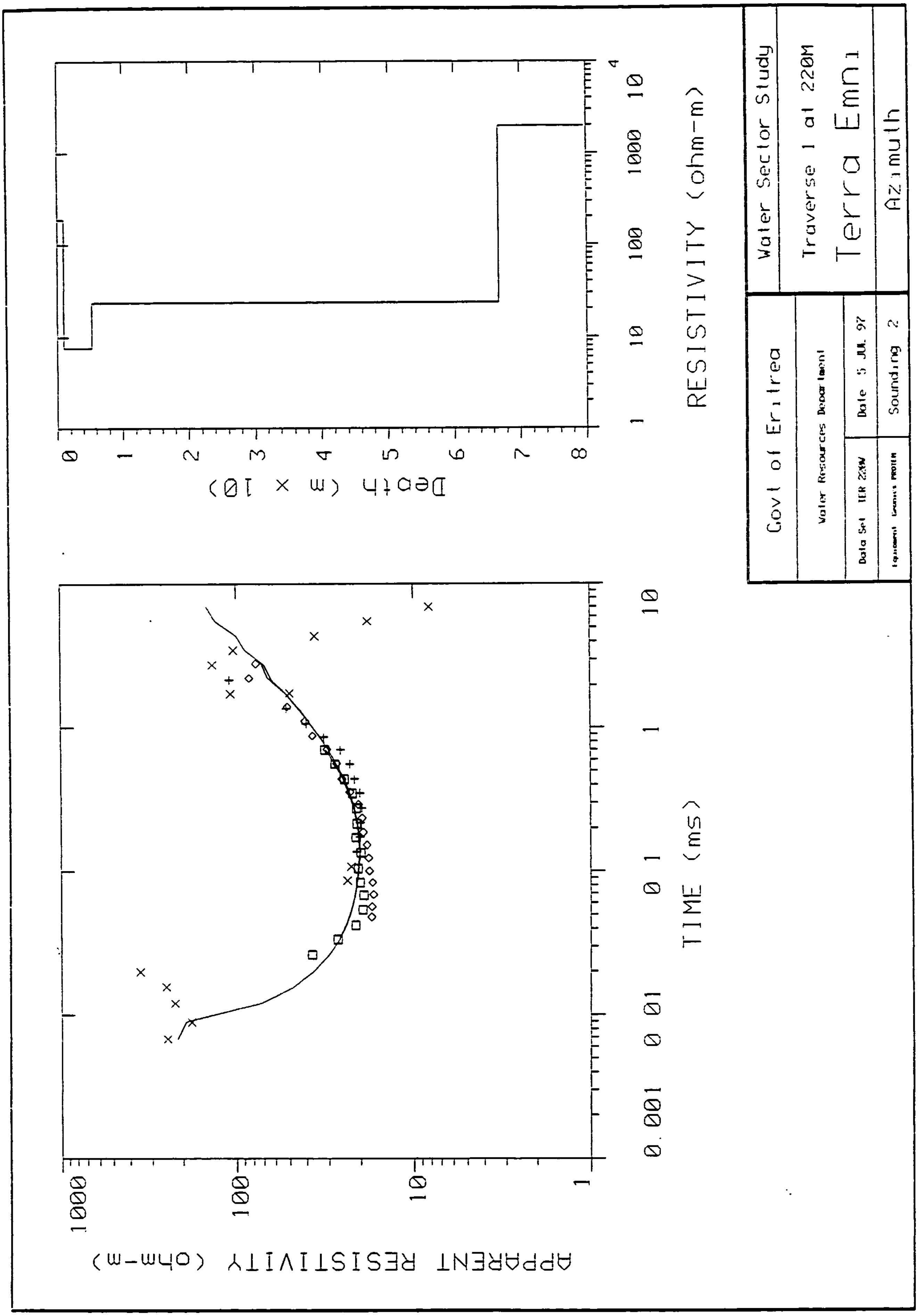


Fig. 3.2a_5 Terra Emni: TDEM sounding at 220 m Traverse 1

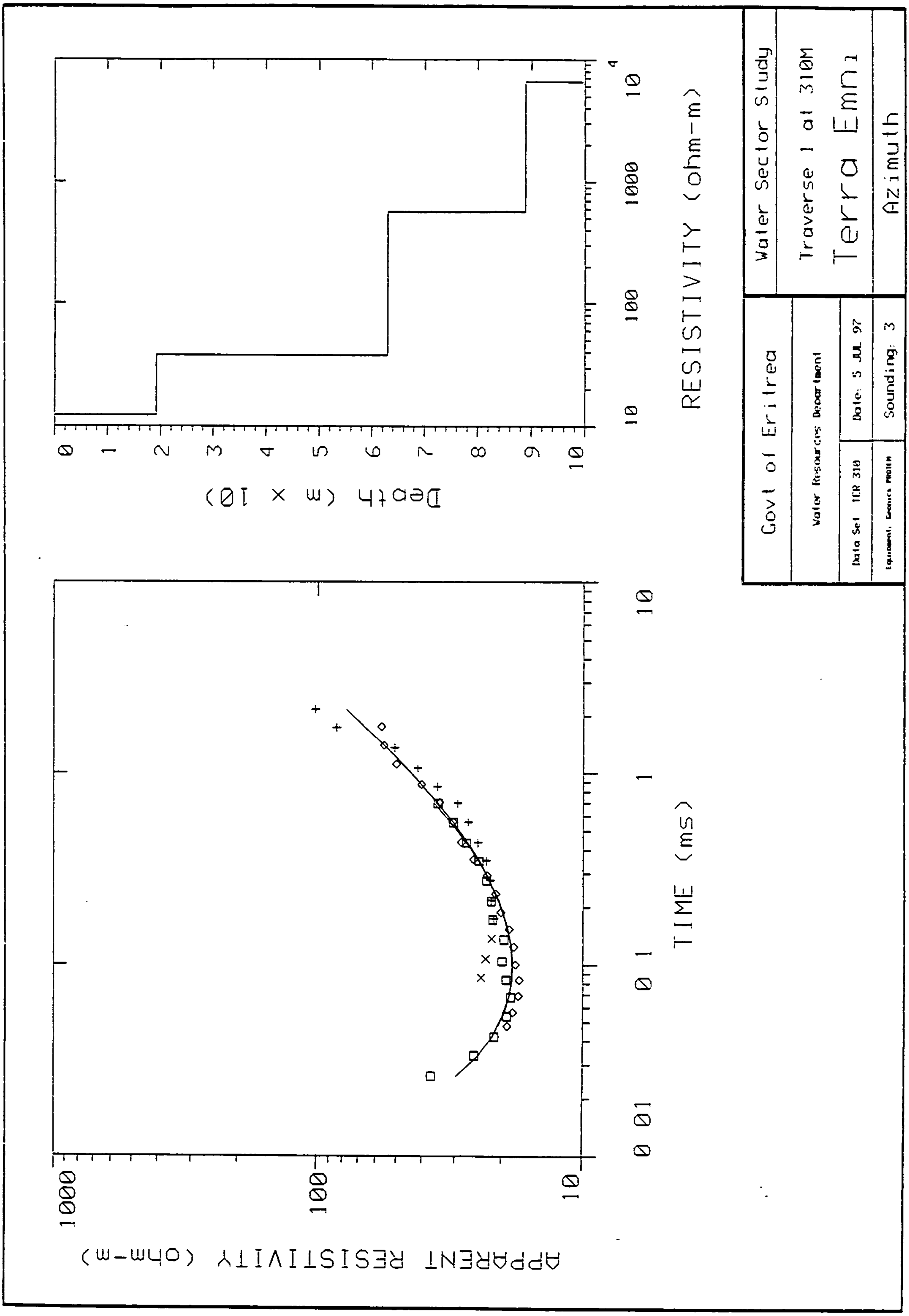


Fig. 3.2a_6 Terra Emni: TDEM sounding at 310 m Traverse 1

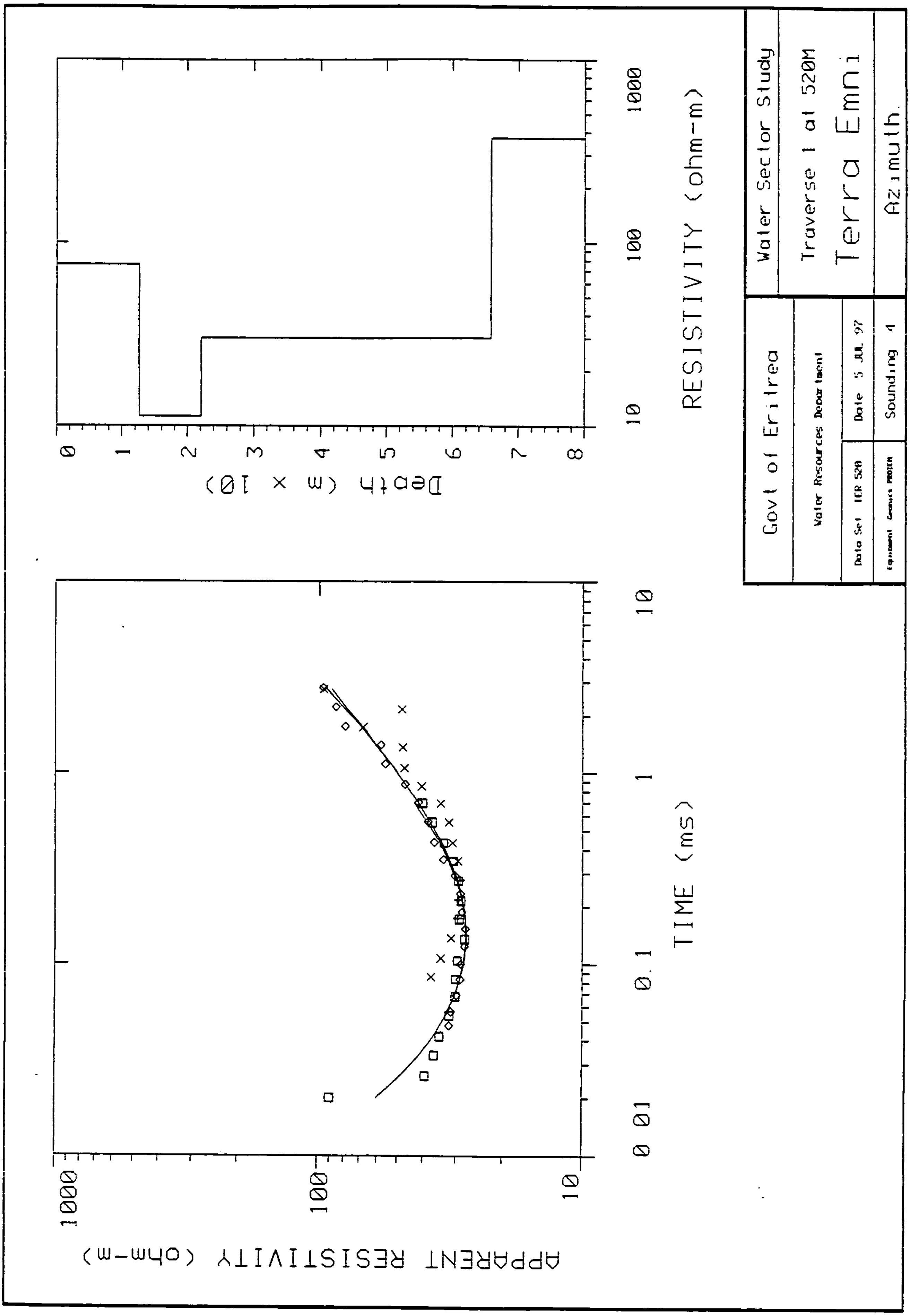


Fig. 3.2a_7 Terra Emni: TDEM sounding at 520 m Traverse 1

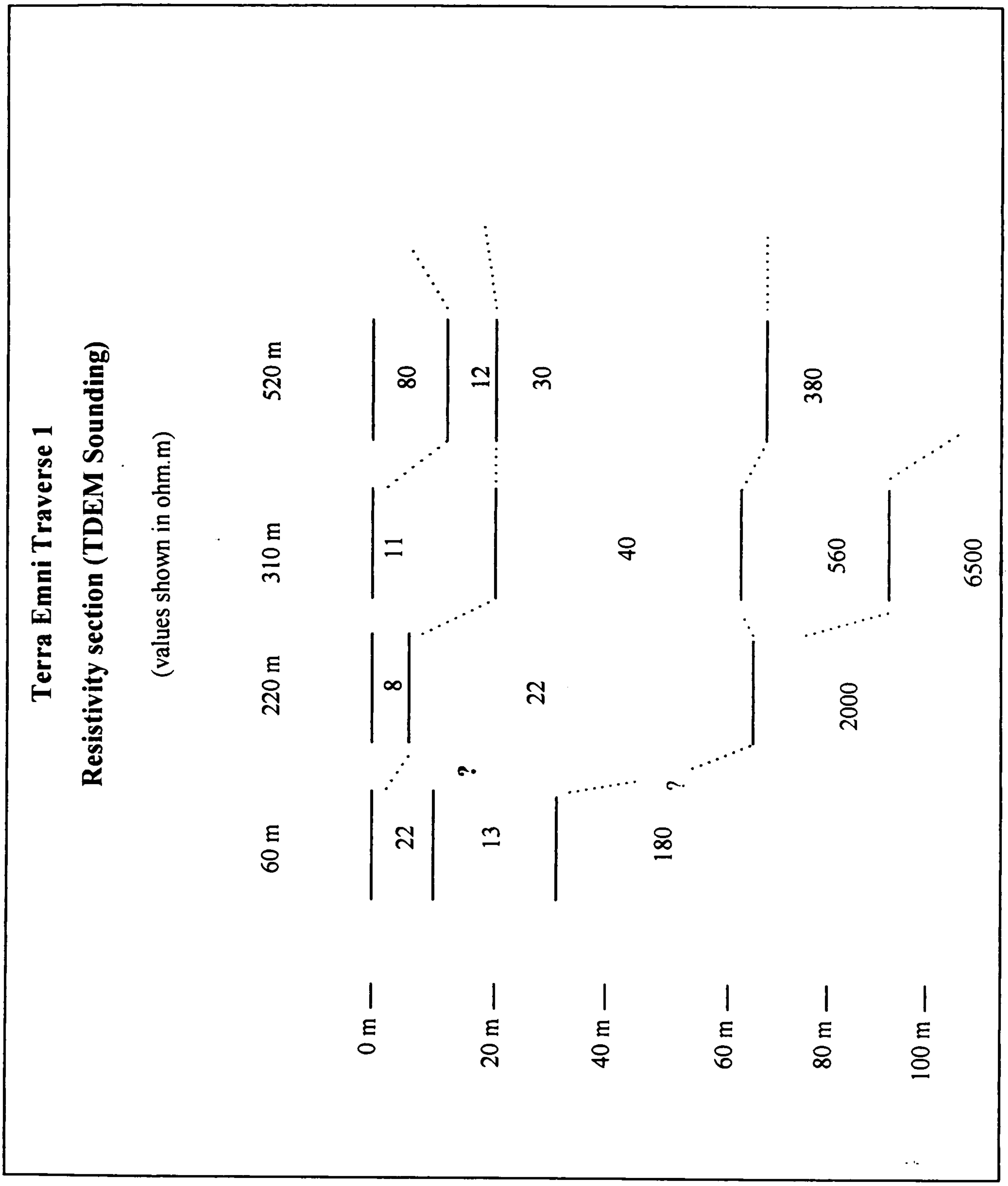


Fig. 3.2a_8 Terra Emni: Resistivity section Traverse 1: TDEM sounding

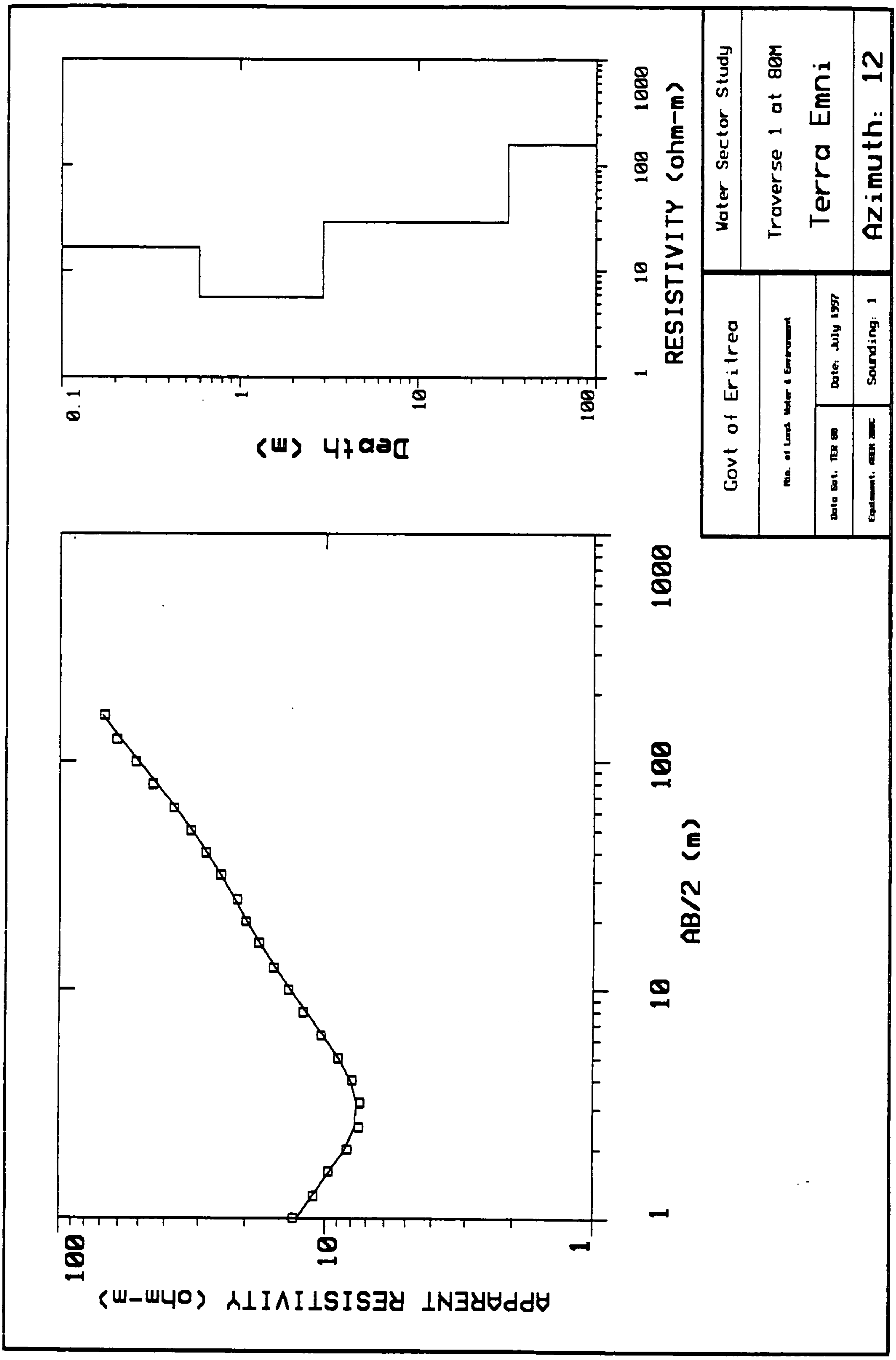


Fig. 3.2a_9 Terra Emni: DC sounding at 80 m Traverse 1

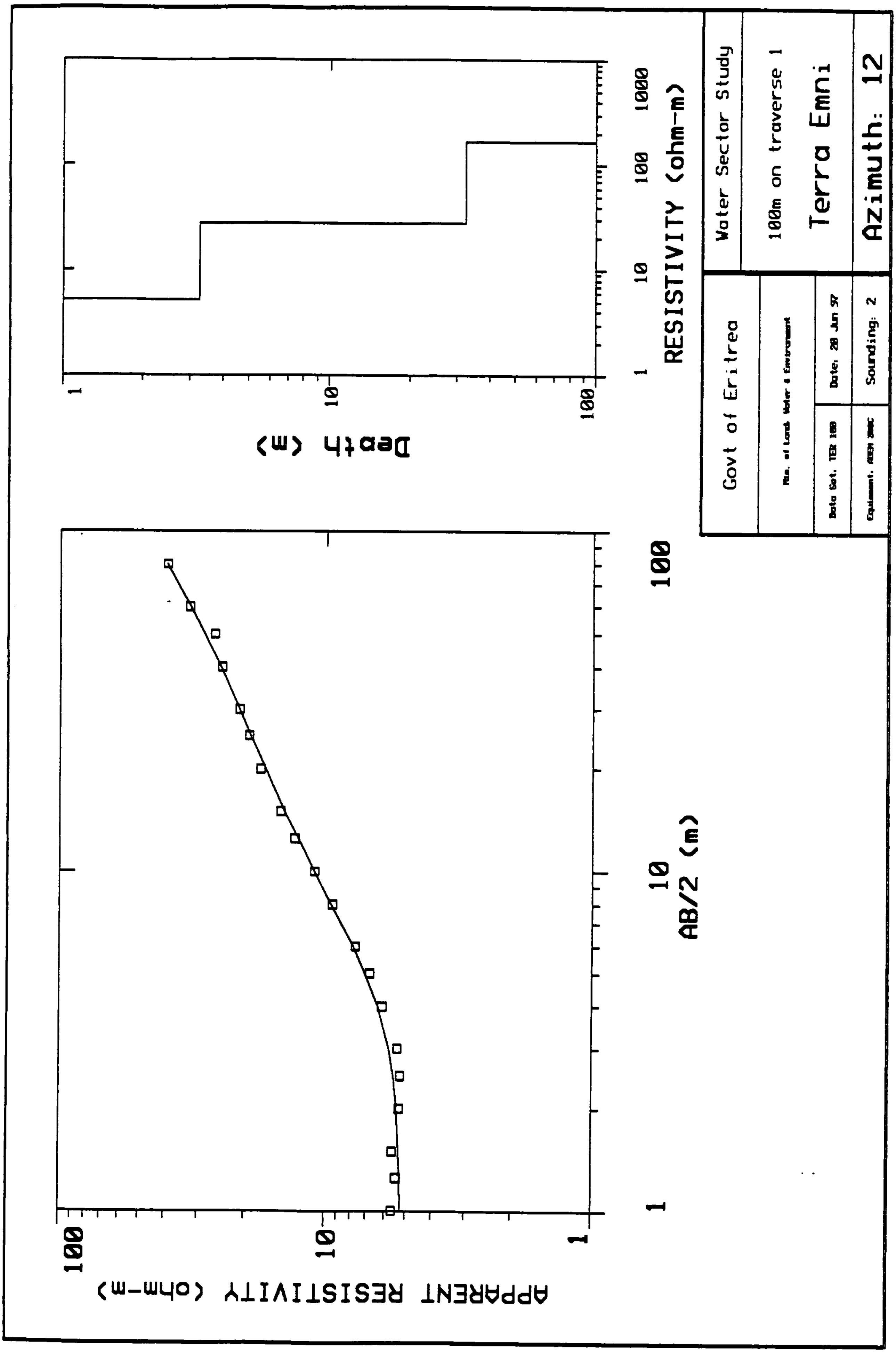


Fig. 3.2a_10 Terra Emni: DC sounding at 100 m Traverse 1

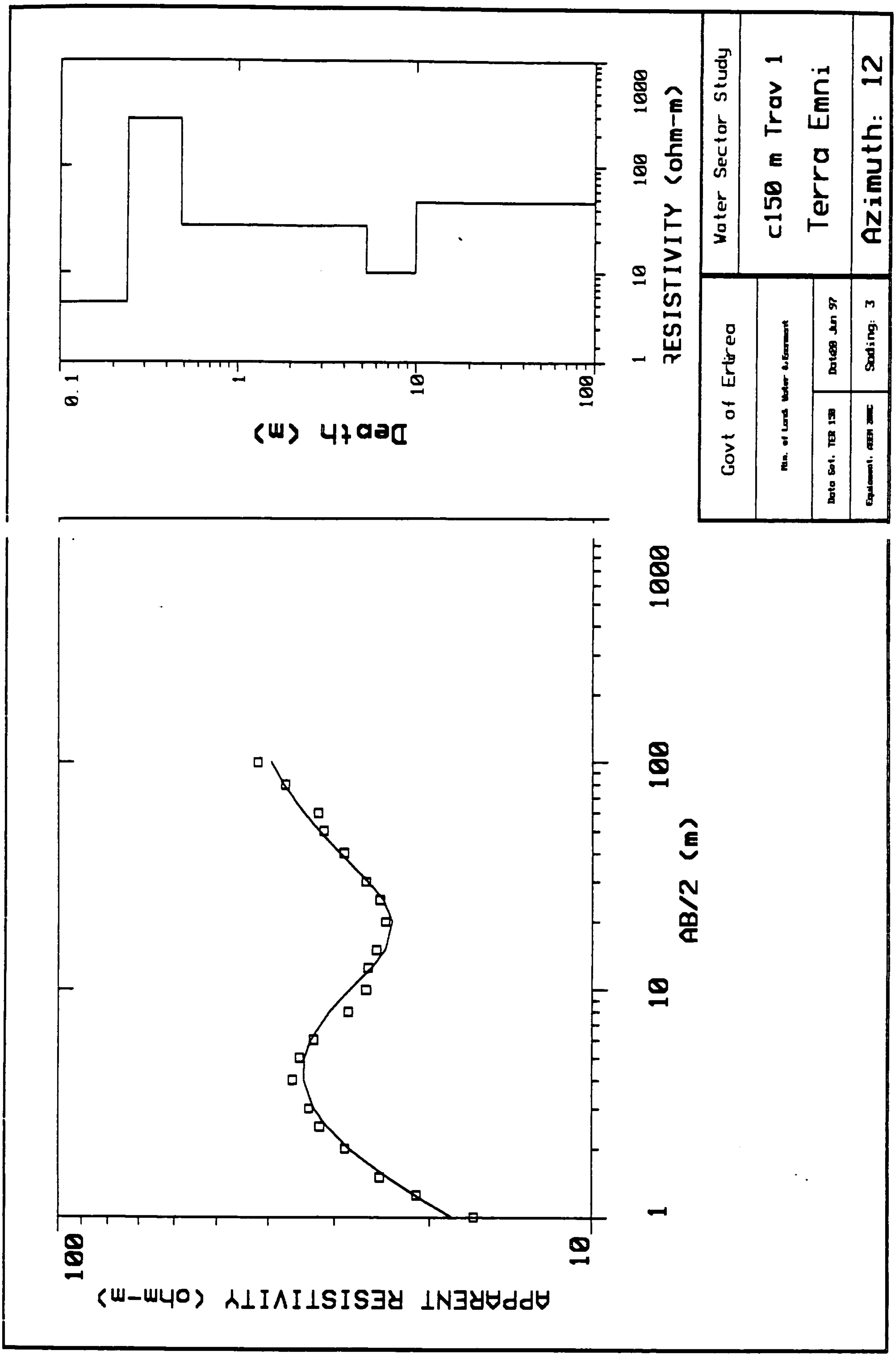


Fig. 3.2a_11 Terra Emni: DC sounding at c. 150 m Traverse 1

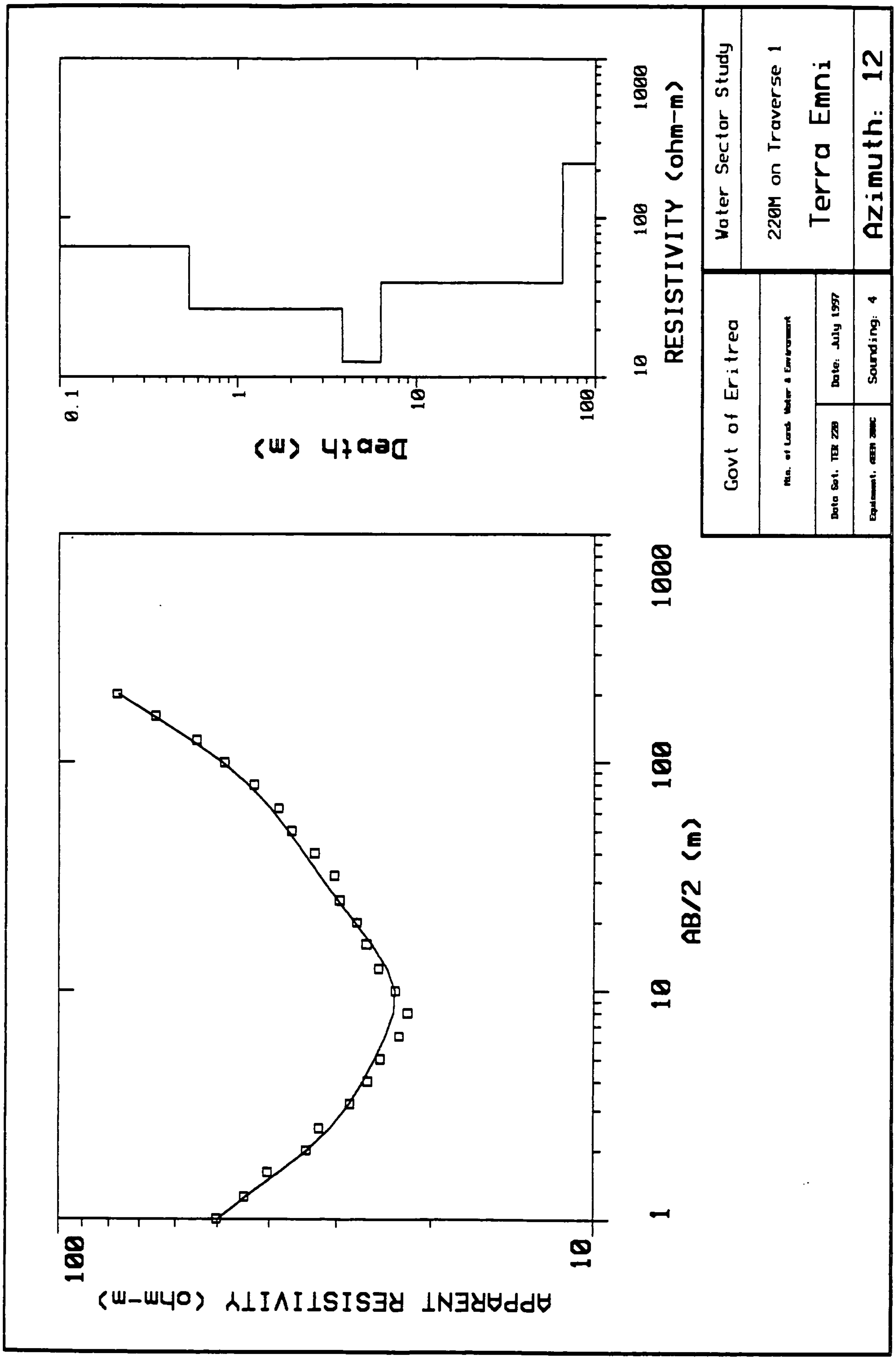


Fig. 3.2a_12 Terra Emni: DC sounding at 220 m Traverse 1

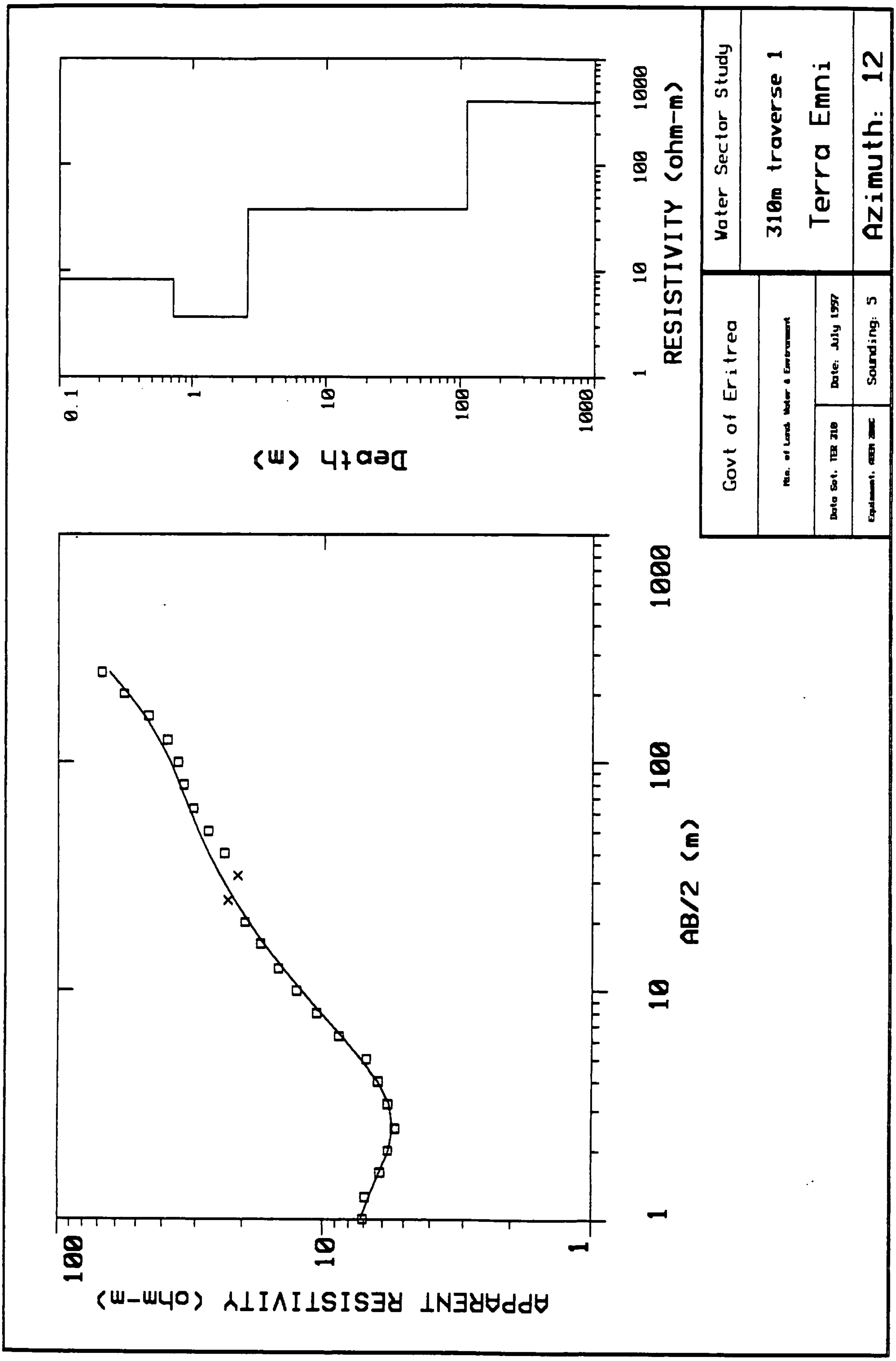


Fig. 3.2a_13 Terra Emni: DC sounding at 310 m Traverse 1

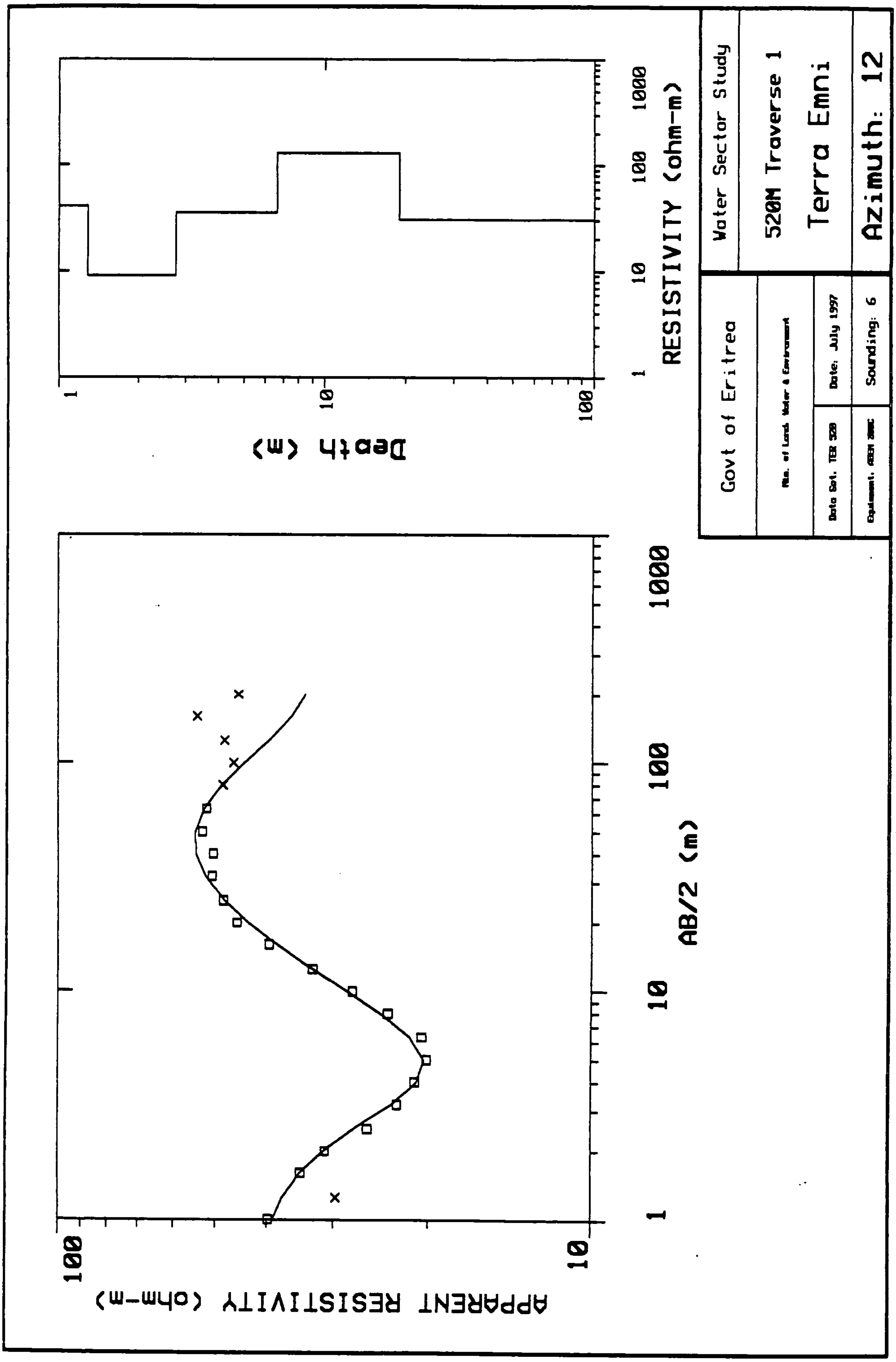


Fig. 3.2a_14 Terra Emni: DC sounding at 520 m Traverse 1

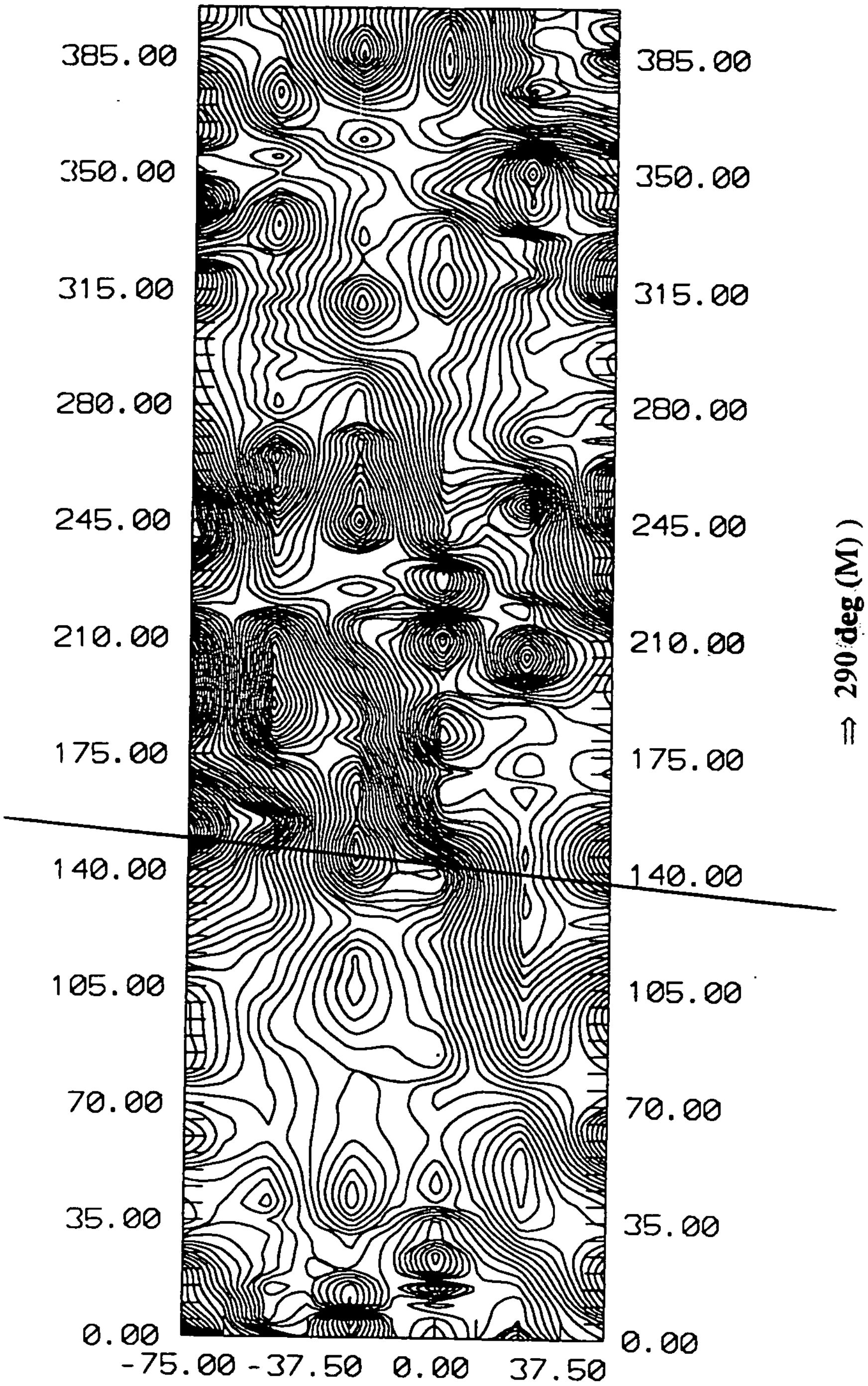


Fig. 3.2a_17 Terra Emni: Total field magnetic contours (uncorrected data)

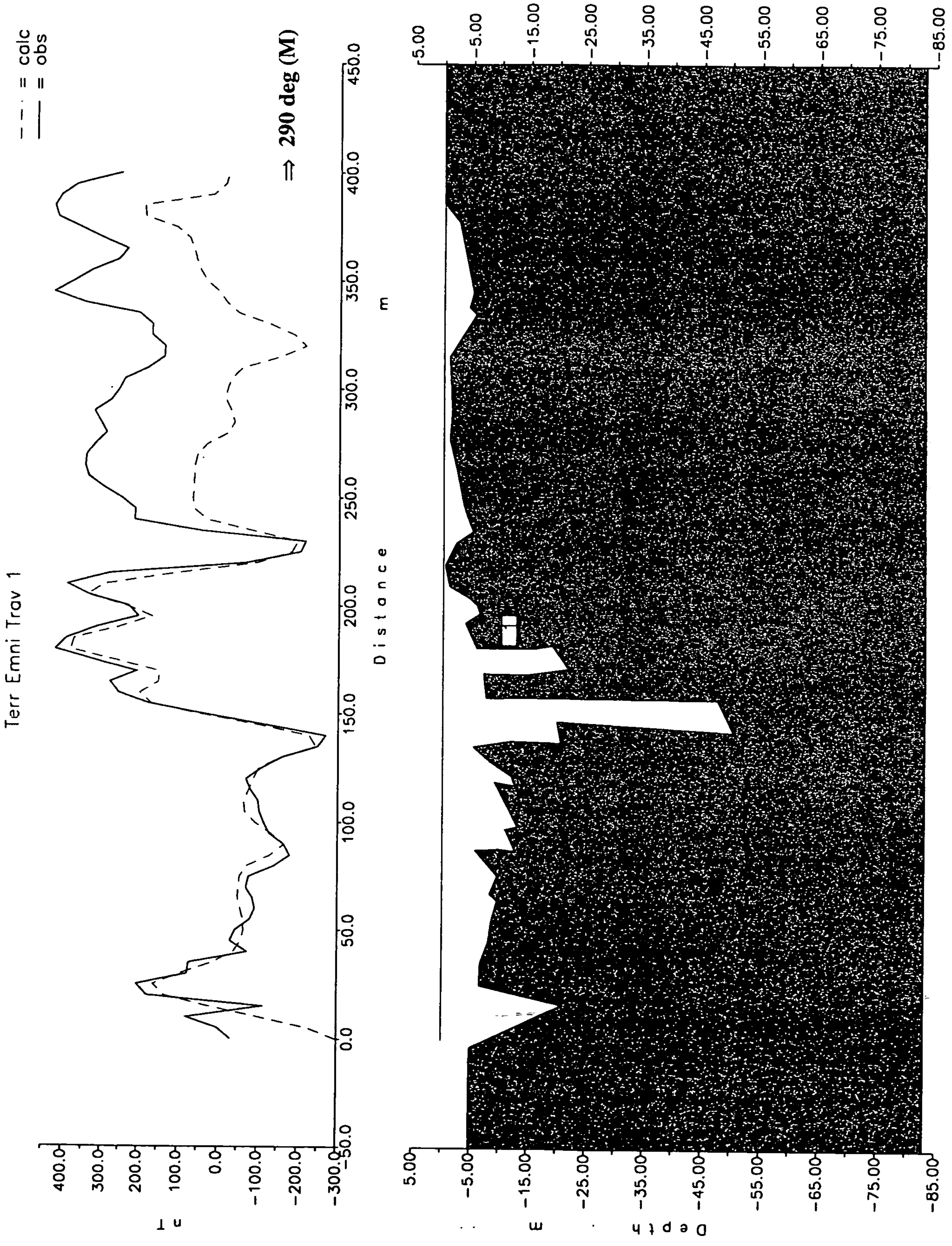


Fig. 3.2a_18 Terra Emni: Partially modelled magnetic profile of Traverse 1

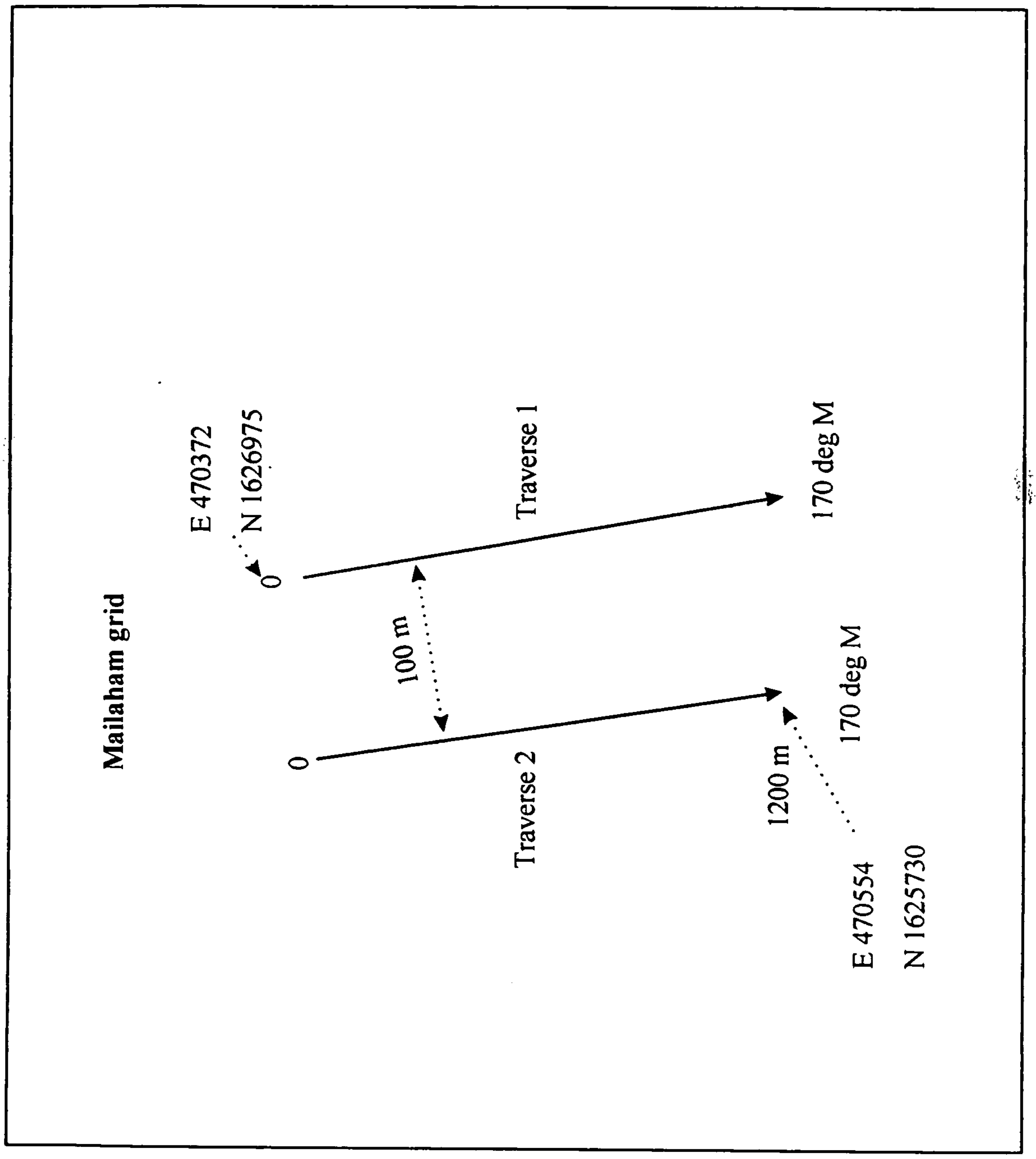


Fig. 3.2b_1 Mailaham: geophysical grid at Mailaham

ERITREA: SECTOR STUDY ON NATIONAL WATER RESOURCES AND IRRIGATION POTENTIAL

GROUNDWATER EXPLORATION

GEOPHYSICAL INVESTIGATIONS COMPLETED

SHEET No: **LOCATION:** Mailaham **UTM Co-ords: E** 470372 **N** 1626975

Geology: Basalt / dolerite dykes **Target:** Satellite lineament (Dury) – Tertiary normal faults (↓ to S)

GEOPHYSICAL TECHNIQUES	Used?	Line/Grid	cover m/No.	Comments
Conductivity EM34 40m	✓	L	530 m	
Conductivity EM34 20m	✓	L	180 m	
Conductivity EM34 10m	✓	L	180 m	
TDEM 47 sounding (5m*5m)				
TDEM 47 sounding (40m*40m)				
TDEM47 sounding (100m*100m)				
TDEM 47 traversing (5m*5m)				
TDEM 47 traversing (40m*40m)				
TDEM 47 traversing (100m*100m)				
Resistivity (ABEM 300C) sounding				
Resistivity (ABEM 300C) traversing				
VLF (WADI) traversing	✓	L (6)	3000 m	19.8 + includes 100 m 'Box' to East
Magnetometry (GEM) traversing	✓	L (6)	3000 m	
Gravimetry				
Seismic refraction				

Previous work:

Borehole sited ?: YES **Location:** 330 m (Line 1) **Project Bh No:**

Borehole drilled (date):

Result:

Fig. 3.2b_2 Mailaham: table summarising geophysical investigations

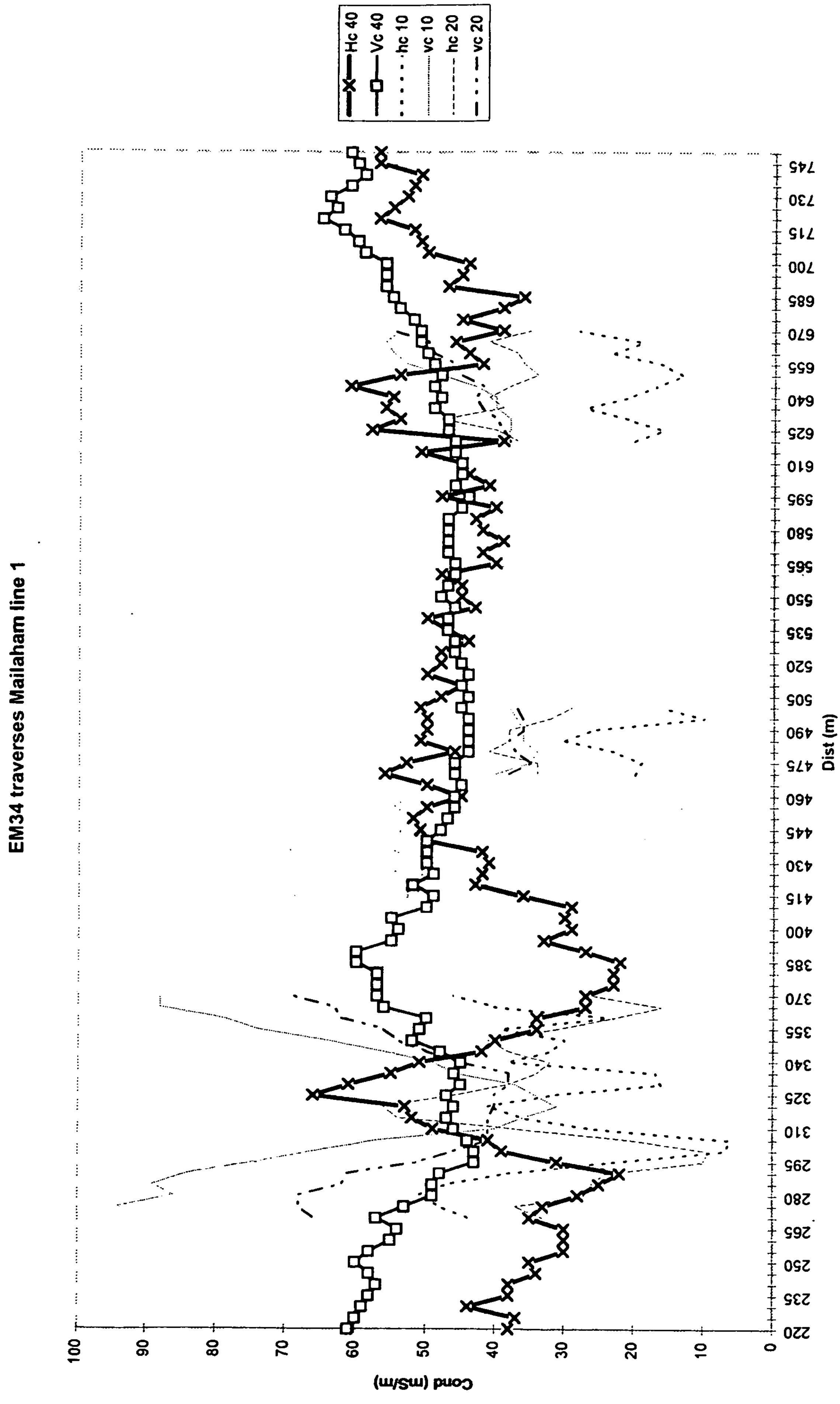


Fig. 3.2b_3 Mailaham: EM34 data on Traverse 1

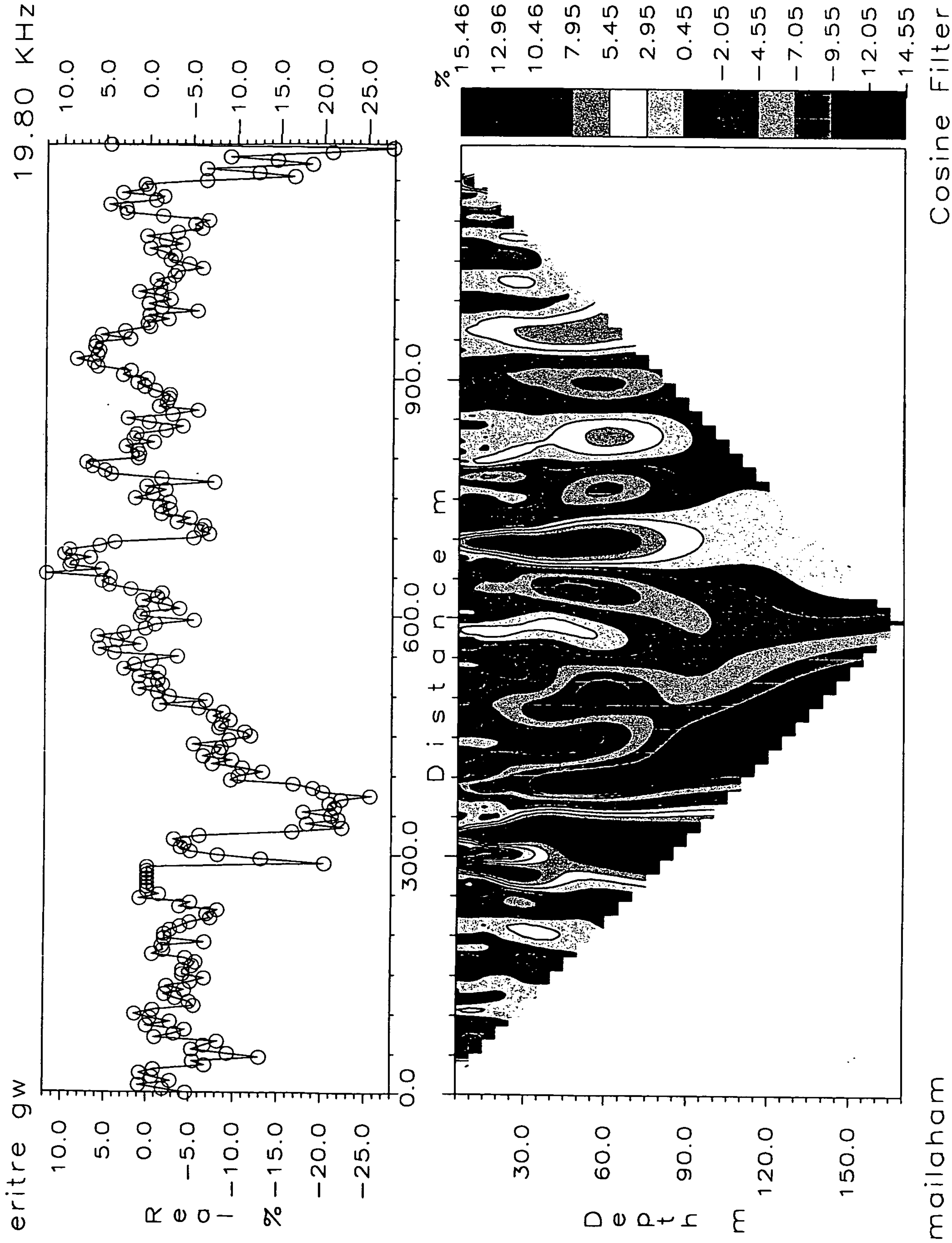


Fig. 3.2b_5 Mailaham: VLF in phase data and Karous-Hjelt filter result of Traverse 2

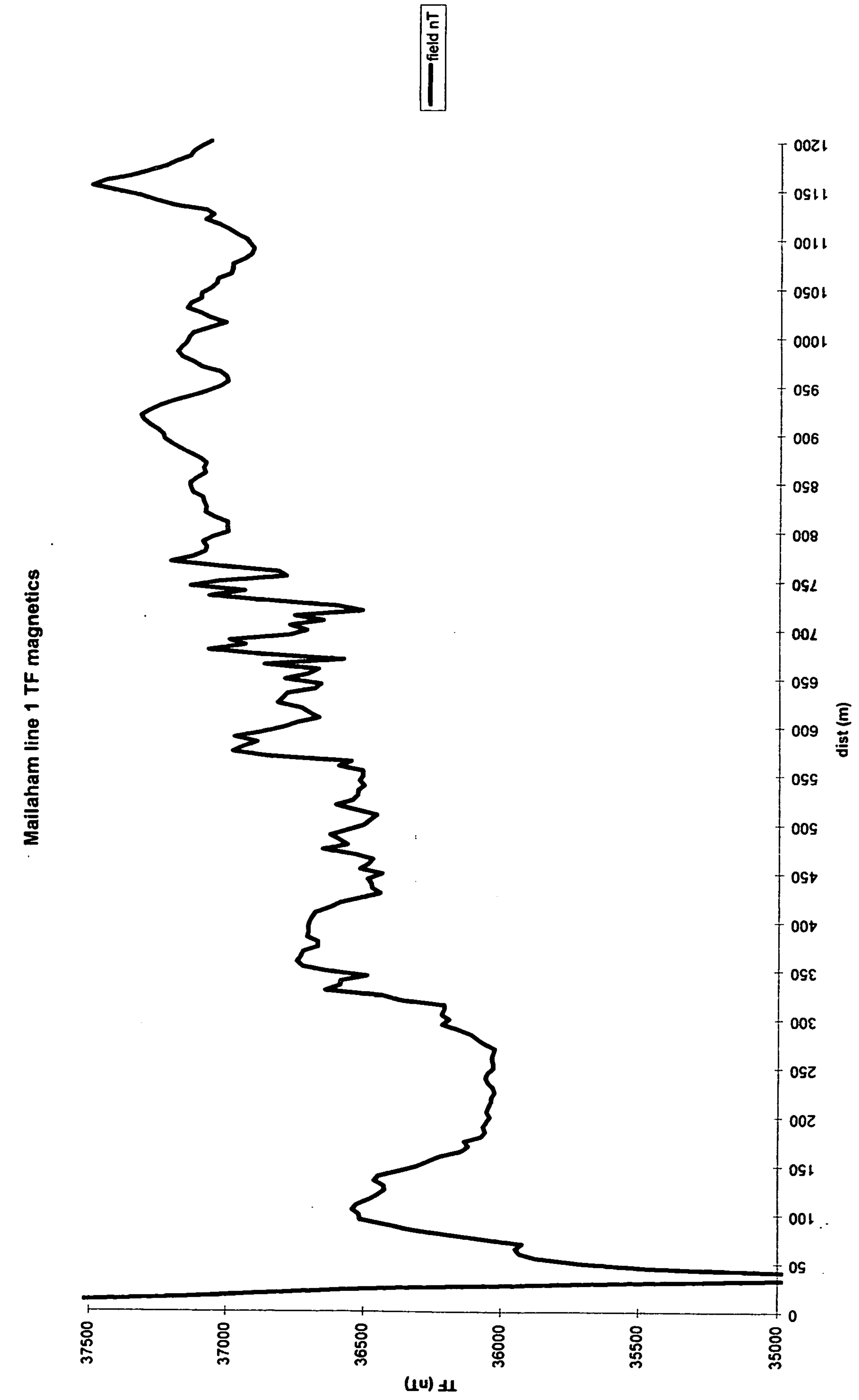


Fig. 3.2b_6 Mailaham: Total field magnetic data of Traverse 1

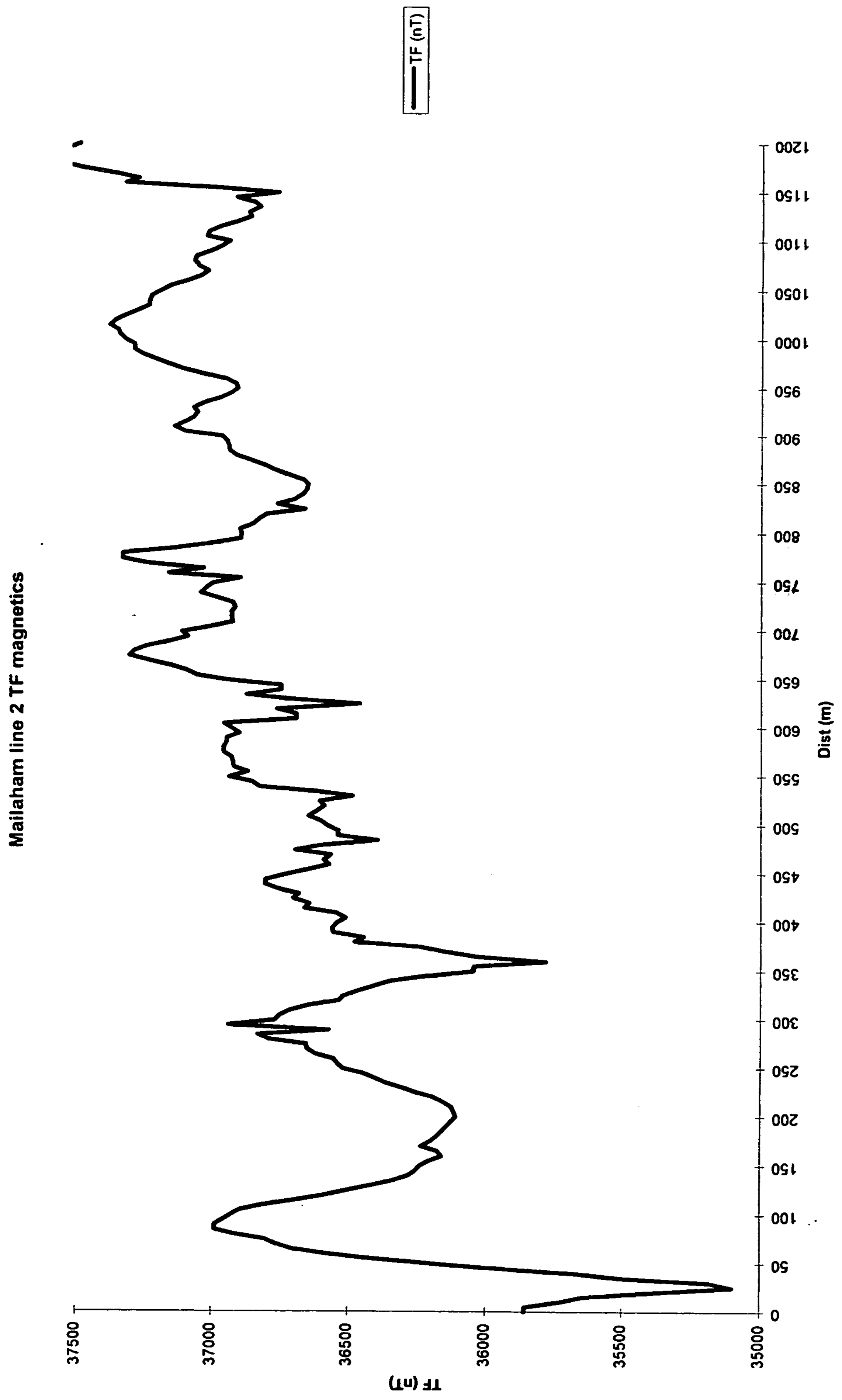


Fig. 3.2b_7 Mailaham: Total field magnetic data of Traverse 2

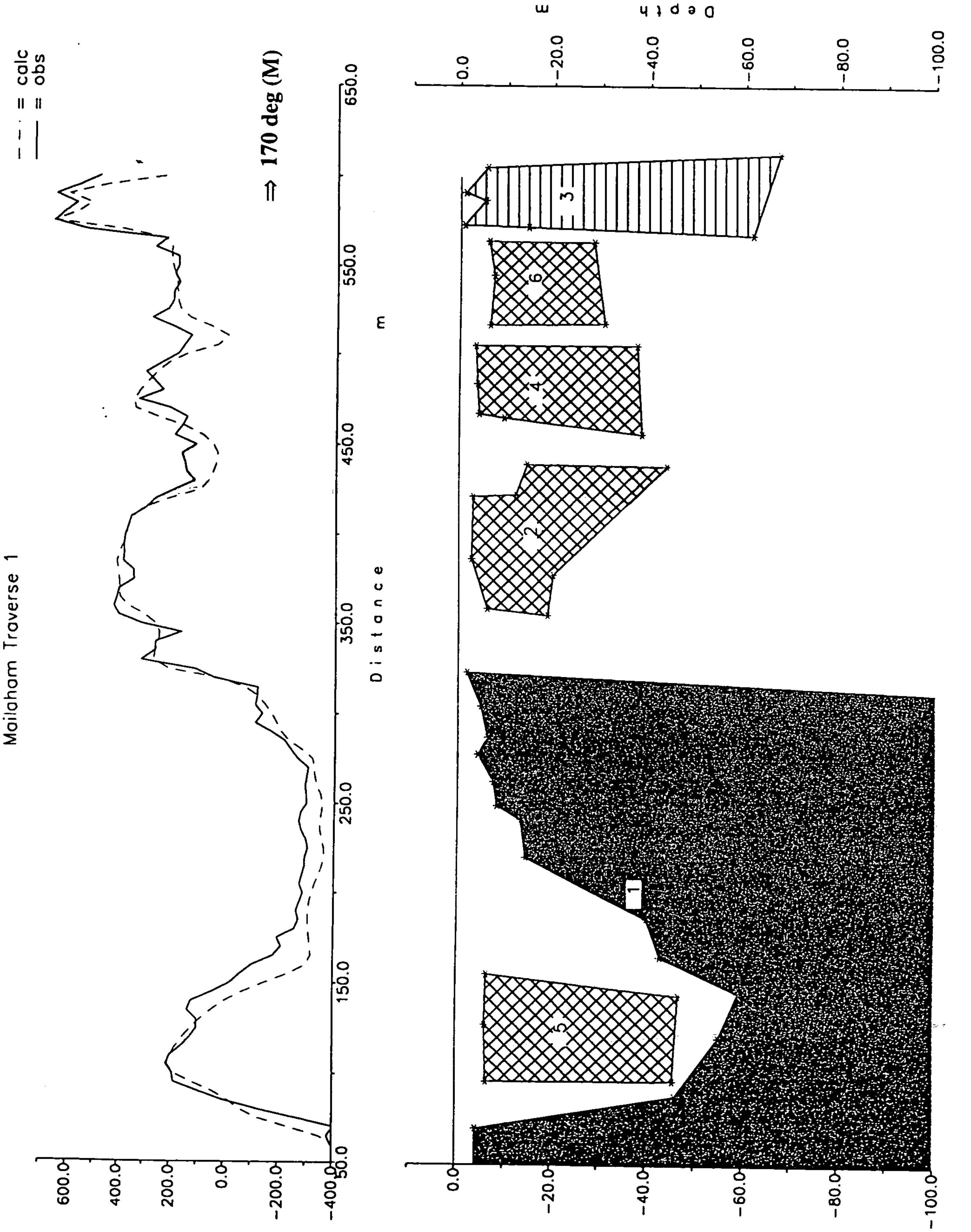


Fig. 3.2b_8 Mailaham: Modelled magnetic profile of Traverse 1

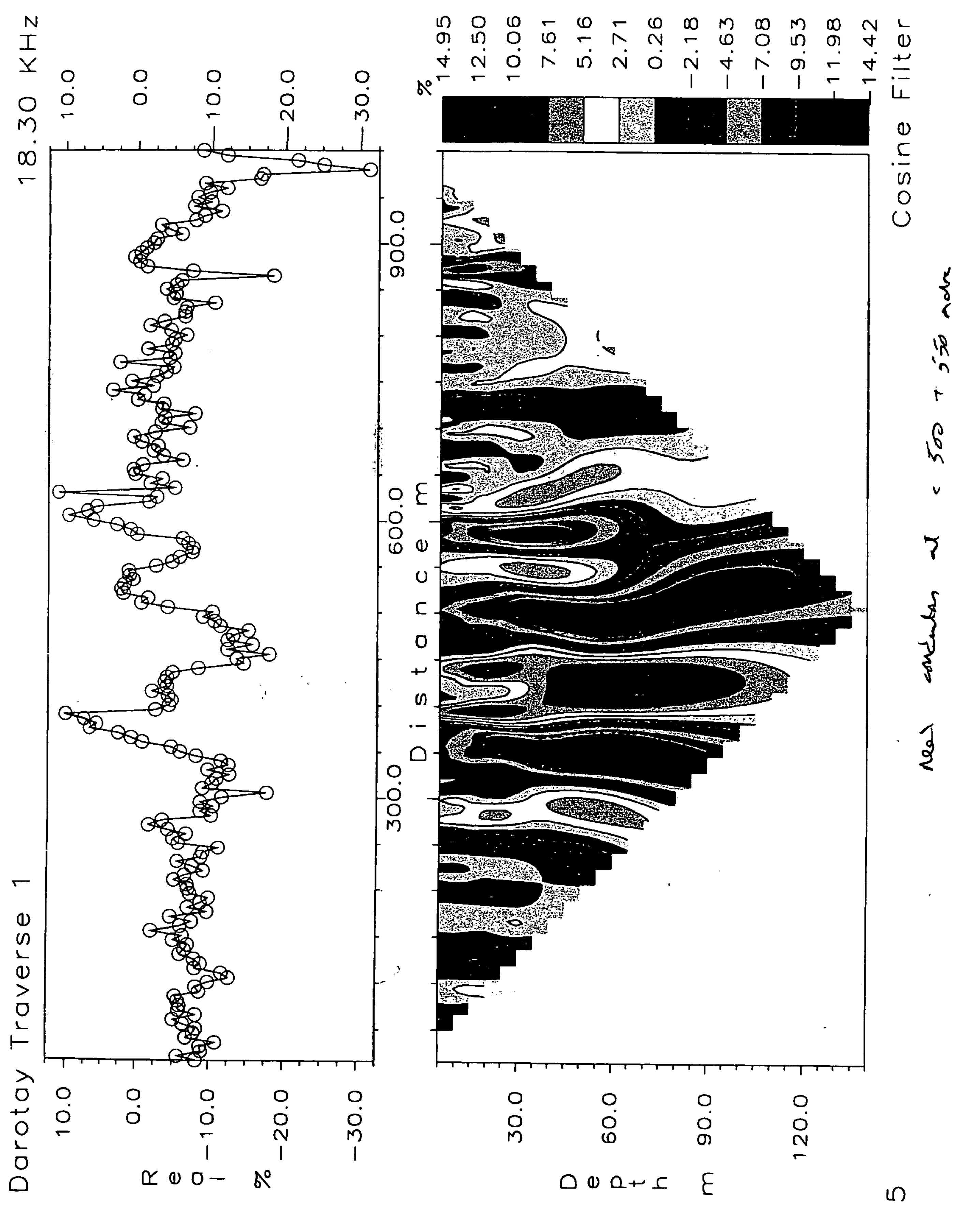


Fig. 3.3a_8 Darotay: VLF in phase data and Karous-Hjelt filter result: Traverse 1(a)

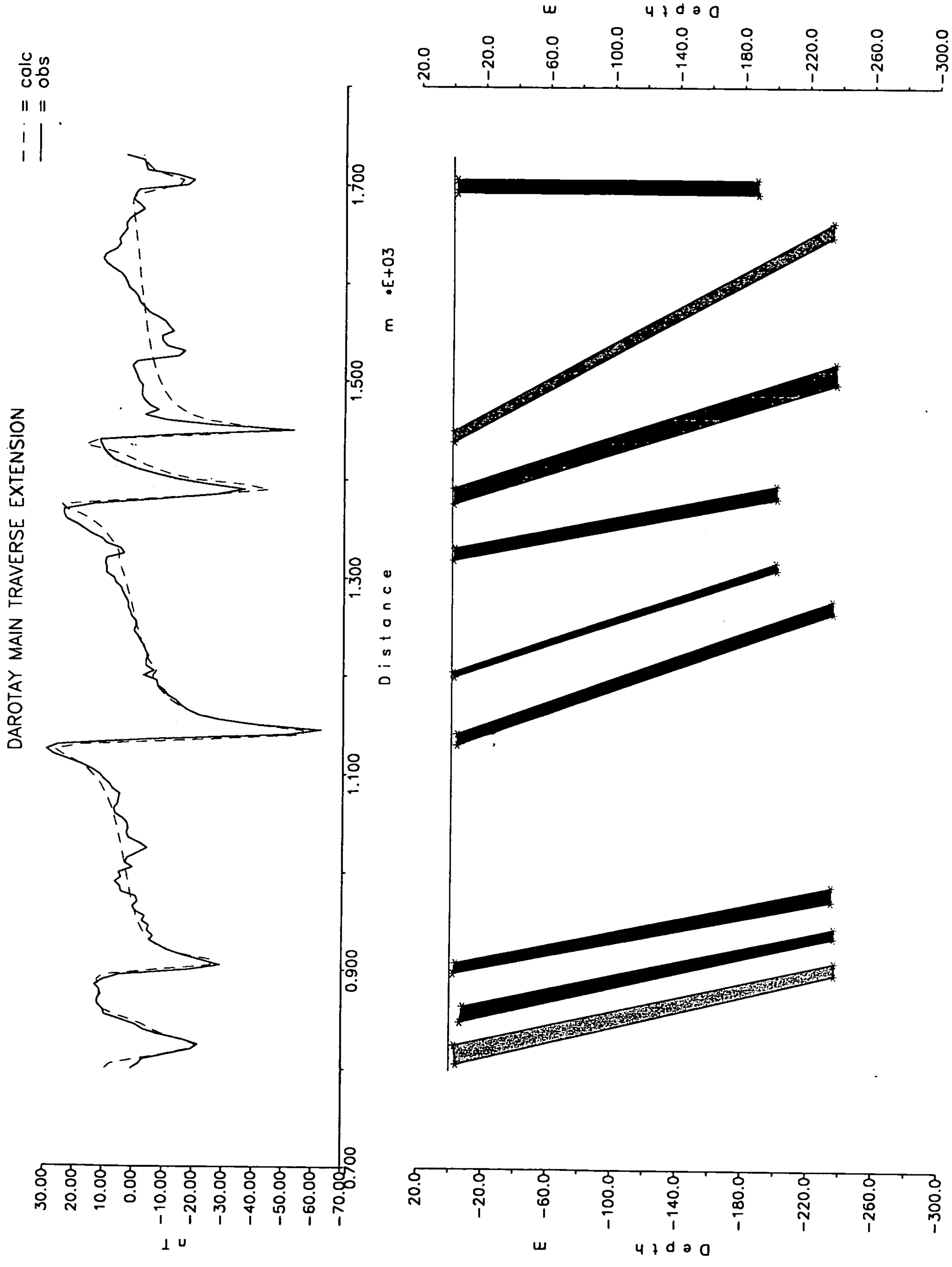


Fig. 3.3a_15 Darotay: Modelled Total Field magnetic profile: Traverse 1(b)

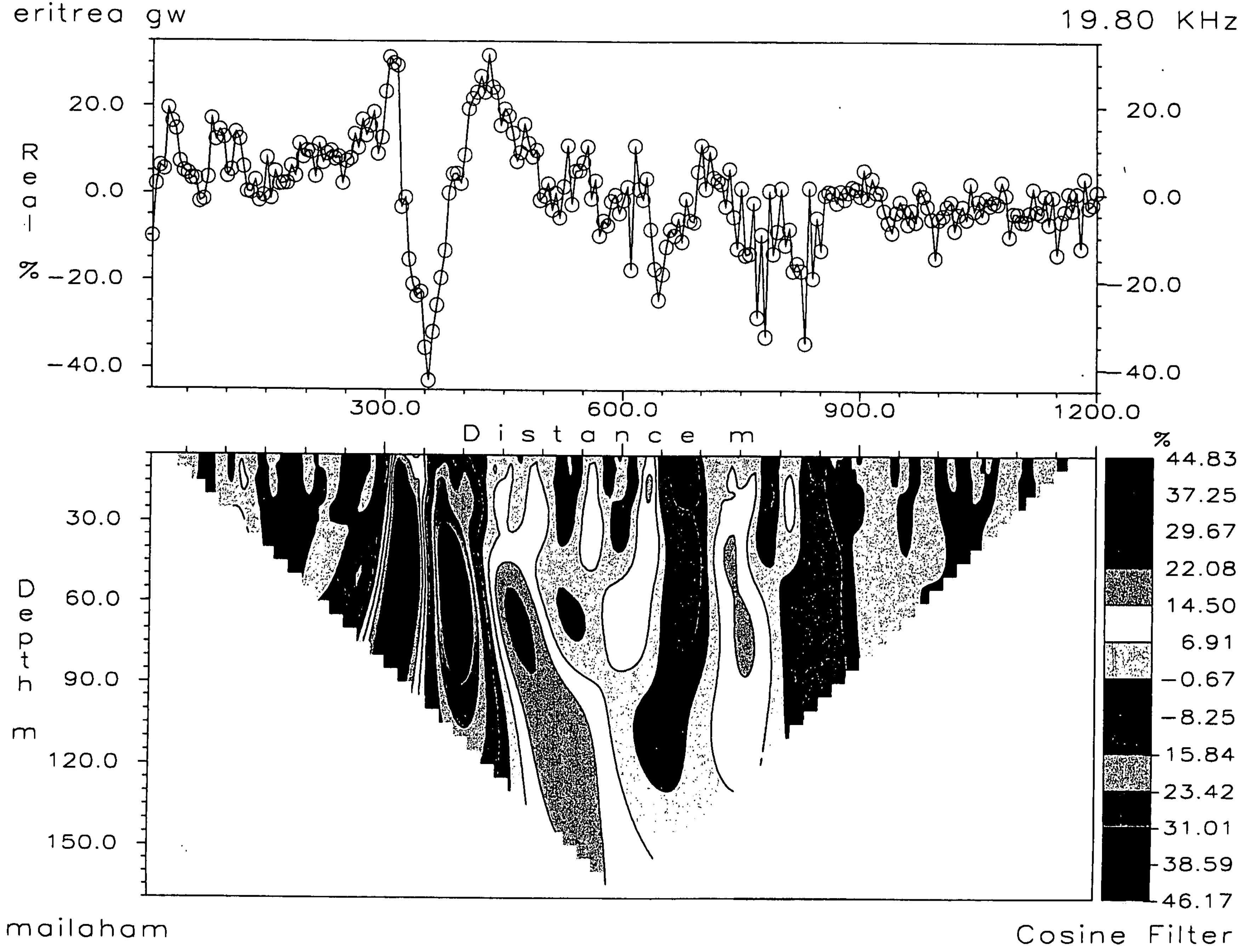


Fig. 3.2b_4 Mailaham: VLF in phase data and Karous-Hjelt filter result of Traverse 1

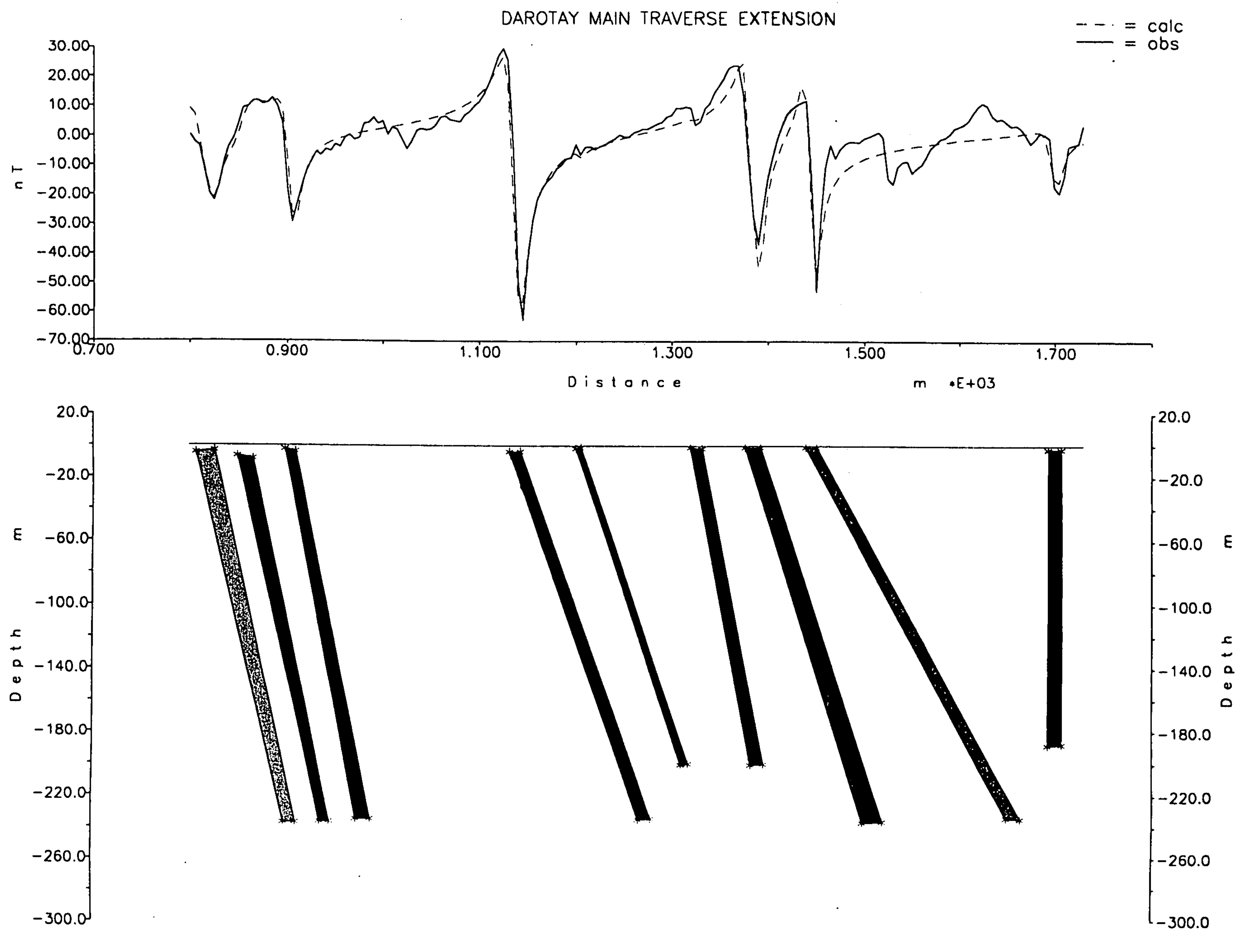


Fig. 3.3a_15 Darotay: Modelled Total Field magnetic profile: Traverse 1(b)

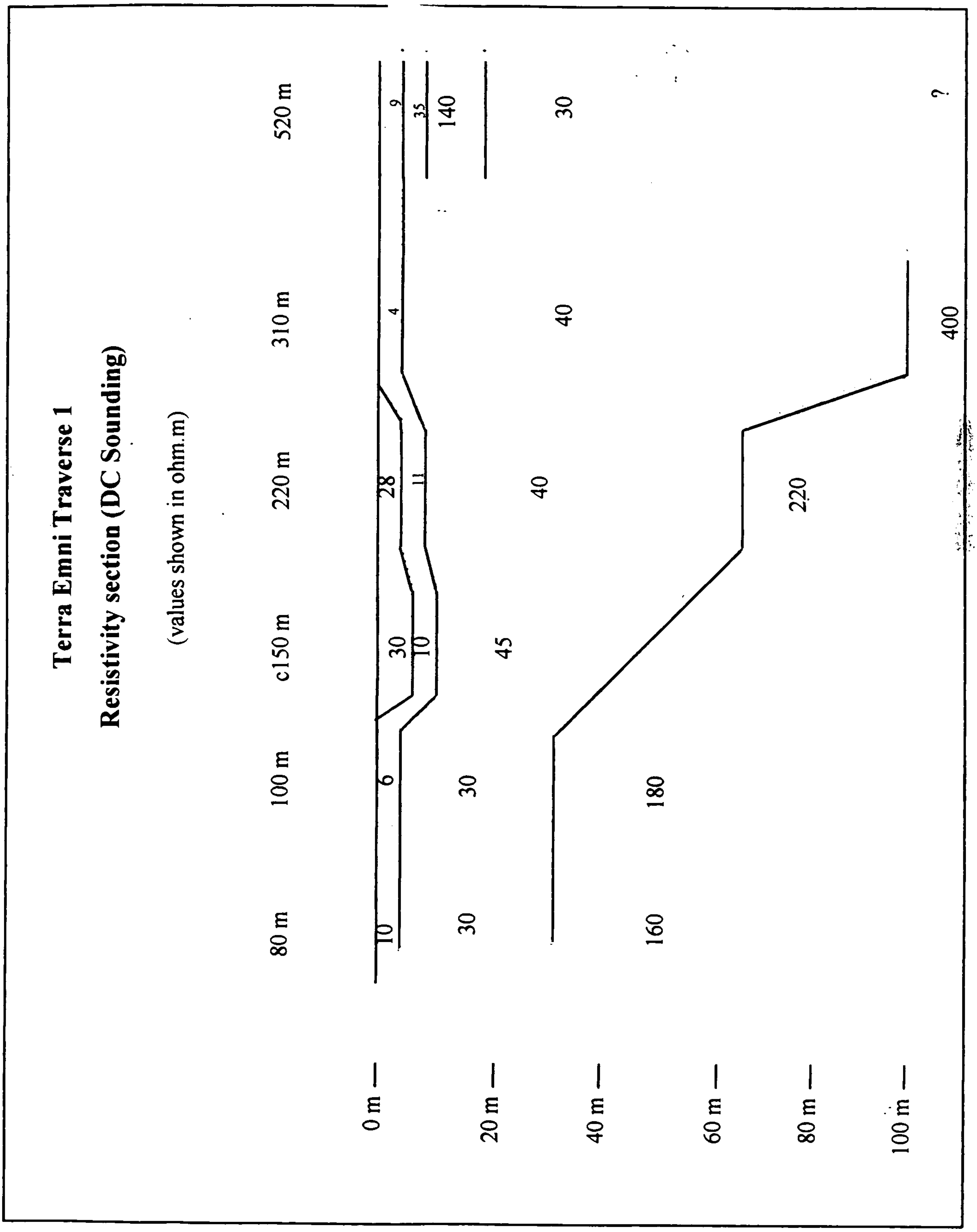


Fig. 3.2a_15 Terra Emni: Resistivity section Traverse 1: DC sounding

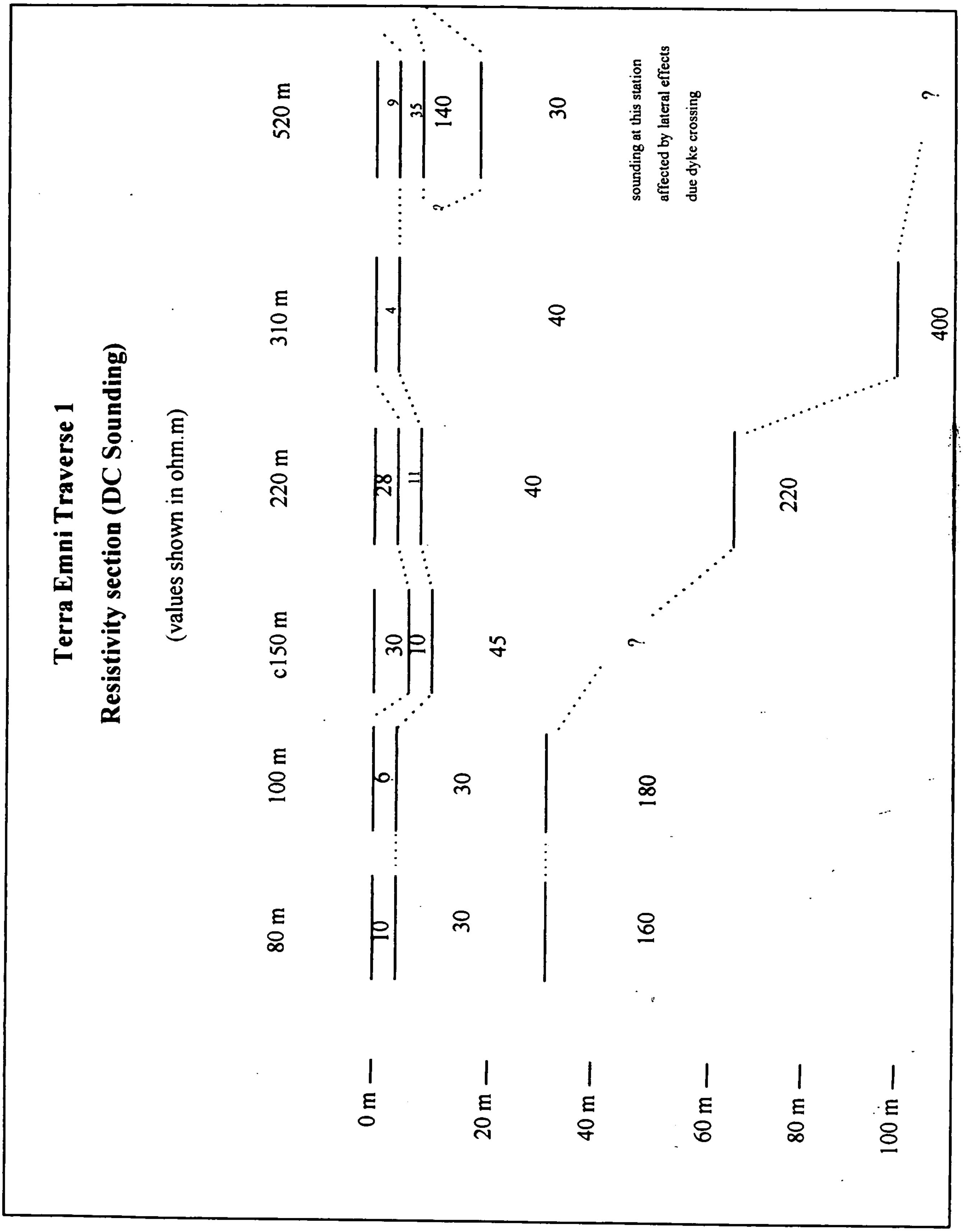


Fig. 3.2a_15 Terra Emni: Resistivity section Traverse 1: DC sounding

ERITREA: SECTOR STUDY ON NATIONAL WATER RESOURCES AND IRRIGATION POTENTIAL

CORRELATION OF SURFACE GEOPHYSICAL DATA WITH SUBSEQUENT BOREHOLE CONTROL

March 1998

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CONTENTS

FIGURES ENCLOSED

Abbreviations used in this Report

DC	direct current
EM	electromagnetic
EM34	conductivity measuring equipment
GPS	global positioning system
mbgl	metres below ground level
rwl	rest water level
SP	spontaneous potential (geophysical log)
swl	standing water level
TDEM	time domain electromagnetics (a method of sounding)
VES	vertical electrical sounding (also known as DC sounding)
VLF	very low frequency electromagnetics
wth	weathered

1 INTRODUCTION

The Project's surface geophysics input is designed to assist in the characterisation of Eritrea's various hydrogeological environments. The first half input of the geophysics specialist (June 17 to August 13, 1997) was focused on the location of fracture zones in hard and otherwise hydrogeologically 'tight' lithologies. Typically these fracture zones were identified on 1:250 000 scale satellite imagery and/or described in published papers (eg by Drury et al, 1994). They were then located approximately in the field using GPS and one or more long (usually in excess of 1km) geophysical traverses were made normal to their strike direction. EM34 Conductivity, magnetometry and Very Low Frequency (VLF) EM techniques were found to be particularly useful in these studies. A total of 12 sites were investigated and eleven promising borehole sites were recommended. Full details of this work are included in 'Report on first half input of surface geophysics specialist (17 June to 13 August 1997) (revised version) (February 1998).

Of the eleven borehole sites recommended, only three were subsequently drilled (Decamhare (Bh 6), Terra Emni (Bh 7) and Kailay (Bh 12)). Limited surface geophysical observations were made at two other Project borehole sites: a single time domain EM sounding near the Mai Aini borehole (Bh 4) (in progress) for calibration purposes and limited EM34 traverses at the topographically constrained site at Adi Nebri (Bh 5). A further Project borehole was drilled 'somewhere' on our main geophysical traverse at Darotay (Bh 11) but not, unfortunately, at the recommended site.

In this report I attempt to correlate the surface geophysical data with subsequent borehole control (occasionally supplemented by geophysical logging). This exercise should indicate (in spite of limited statistics) which geophysical technique (or combination of techniques) has been most successful in locating fracture zones. It should also allow refinement of the range of physical parameters (principally resistivity/conductivity) associated (locally) with productive aquifers.

For each borehole site a brief description of the geology and nature of the target is given; then follows both the original (uncontrolled) and refined (controlled) geophysical interpretation.

2. CORRELATION OF DATA

2.1 At Project boreholes sited following geophysical survey

2.1.1 Decamhare (borehole 6) (at 580 m on traverse 1) (E 504355 N1662469)

Target: a regional-scale N-S trending satellite lineament, probably reflecting a major fault zone in this predominantly granitic terrain.

Geophysical indications: a major, exceptionally well defined conductivity anomaly was detected with all coil separations and orientations on the initial traverse between stations 510 and 690 (Fig 1). The conductivity profiles indicate an abrupt thickening of conductive material and thus probably reflect in-situ weathering products within a fracture zone rather than regular alluvial deposition. A VES made at 526 m (Fig. 2) indicated favourable resistivities (13 – and 30 ohm.m) to some 40 m depth. The reported typical thickness of regolith in this area is some 7 m only.

The borehole at 580 m (Fig 3) proved various grades and mixtures of sand to 42 m depth, bottoming in weathered granite at 49 m. The water table at this site is some 2.5 mbgl (as proved in the adjacent river bed) and yet the borehole is reported as being dry. Fig 4 shows the VES at 526 m re-interpreted to include the lithological contacts defined by drilling (ie 12-, 16- and 42 m). This has necessitated only minor modification to the specific resistivities of the relatively conductive layers (13-, 16- and 33 ohm.m).

Comments: An exceptional thickness of sands has been proved at the site of borehole 6 where the water table is known to be shallow. The range of specific resistivity of these sands (13 – to 33 ohm.m) would normally indicate promising aquiferous conditions and yet the borehole is dry. Is it possible that the drilling/development techniques caused a local reduction of porosity/permeability?

2.1.2 Terra Emni (borehole 7) (at 150 m on traverse 1) (482700 E 1659900 N)

Targets: a) fault/fracture zone in flood basalt terrain
b) permeable intraflow sediments
c) thin basalt cover/shallow indurated basement contact

Geophysical indications: magnetometer traversing revealed a step feature (of c 600 nT amplitude) between stations 150 m and 410 m on traverse 1; adjacent traverses showed this feature to have significant strike extent (Fig 5). Partial modelling of the traverse 1 profile (Fig 6) suggests a fracture zone centred at station 150 m, about which the basalt cover has suffered vertical displacement. Mutually consistent resistivity sections of traverse 1 derived from VES and TDEM soundings (Figs 7 and 8) suggest an abrupt deepening of hydrogeological basement (ie values in excess of c 150 ohm.m) in the vicinity of station 150. The VES at 150 m (Fig 9) suggests a considerable thickness (in excess of 50 m) of favourable resistivity (45 ohm.m); it should be noted, however, that a sounding made directly above a fracture zone will suffer some distortion. This sounding has been re-interpreted to include the lithological boundaries proved by drilling (Figs 10 and 11); the resulting specific resistivities for the various units are as follows:

silty clay (7- and 52 ohm.m)
laterite (13 ohm.m)
upper weathered basalt (31 ohm.m)
weathered tuff (26 ohm.m)
lower weathered basalt (plus weathered basement?) (52 ohm.m)

The interpreted resistivities are low for all units below the surficial clay. This implies either (or both) a high degree of weathering (reflecting close proximity to a fracture zone) or the presence of highly conductive groundwaters. The relatively resistive units in this sequence (ie the upper and lower weathered basalts) are also clearly defined by the point resistance log of borehole 7 (Fig 12). Minor negative-going excursions of this log possibly indicate additional fractures (eg at about 24 m depth, where a water strike was reported).

Comments: borehole 7, drilled to only 29 m, proved highly successful. Transmissivity at this site was calculated as 205 m^2/d, a value approaching two orders of magnitude greater than the previous best Project borehole drilled in similar basalt terrain but without the benefit of geophysical siting. Similarly, its measured yield/drawdown (2.1 l/s/m) is approaching some two orders of magnitude greater than the previous best basalt borehole. The estimated safe yield is some 8 l/s while the various variable discharge pump tests conducted showed little evidence of de-watering of the fissures encountered in the borehole.

2.1.3 Kailay (borehole 12) (at 35 m on traverse 1) (E366889 N1702551)

Target: We were drawn to investigate this site by the possibility of E-W fracturing traversing a river basin, as suggested by the abrupt termination of an upstanding dyke swarm immediately north of the river.

Geophysical indications: VES were made at three characteristic locations identified by conductivity traversing. The VES at 35 m indicated an anomalous thickness of favourable resistivities (ie 50- and 20 ohm.m to about 40 m depth) (Figs 13 and 14).

Comments: borehole 12 proved sand and gravel/cobbles to 24 m depth, underlain by granite (Fig 15). The VES at this site has been re-interpreted (Fig 16) incorporating this borehole control. The indicated specific resistivities are:

silty clay (22- , 206- and 3.5 ohm.m)
sand (137 ohm.m)
gravels/cobbles (10 ohm.m)
granite (weathered) (860 ohm.m)

The borehole was dry, in spite of the anomalous thickness of gravel/cobbles and the proximity to a river course. If the drilling/development techniques were not at fault, it must be assumed that the low resistivity value for the gravel/cobbles (10 ohm.m) indicates a high clay content resulting in diminished porosity/permeability.

2.2 At Project boreholes sited **without** the benefit of geophysical survey

2.2.1 Hazemo (Mai Aini) (Project borehole 4)

Target: a calibration/test TDEM sounding was made about 150 m north of the Project borehole being drilled in the centre of an extensive plain to test the thickness and aquifer properties of both alluvials and the underlying Mesozoic Adigrat Sandstone.

Geophysical indications: Fig 17 shows an uncontrolled interpretation of the TDEM sounding, indicating potential aquifer conditions (resistivity in the range 25- to 130 ohm.m) between depths of about 23 m to 72 m.

Comments: Borehole 4 (Fig 18) proved 11 m of dry alluvials overlying Adigrat

Sandstone to total depth (102 m). Water was struck at 52 m and 82 m with rest level at 33.5 mbgl. The point resistance log of this borehole (Fig 19) confirms the deep water table and suggests the presence of two discrete conductive zones below this, with a boundary at about 70 m, the lower zone extending to at least 94 m. Since it has not proved possible to increase the TDEM sounding modelled depth to basement significantly below about 72 m it is assumed that basement shallows towards the north. The high value of specific resistivity indicated for the Adigrat Sandstone (c 130 ohm.m) suggests that it is of low porosity. Indeed, the main groundwater contributors to the borehole were discrete strikes at 52 m and 82 m (some evidence of which are seen on the point resistance- and SP logs (Figs. 19 and 20) suggesting that the Adigrat Sandstone here is predominantly a secondary aquifer.

2.2.2 Adi Nebri (Project borehole 5) (E505043 N1648326)

Target: the intersection of regional-scale NS and EW satellite lineaments, promising a highly fractured and permeable zone.

Geophysical indications: the three short conductivity traverses made near this borehole site did not reveal any consistent features reflecting structure at depth.

Comments: the borehole was drilled to 64 m at which stage it was abandoned due to severe collapse problems (suggesting intense fracturing?) (Fig 21). The point resistance and SP borehole logs (Figs 22 and 23) suggest a water level at about 28 mbgl at the time of logging; both logs are of poor quality (showing erratic excursions and unrealistically high values), possibly reflecting inadequate earthing of the reference electrode or a dirty tool. Some of the coincident excursions may reflect conductive fractures (eg at 33 mbgl). The natural gamma log (Fig 24) is also sub-standard; it appears that the time constant was too short and the logging speed too fast.

2.3 Miscellaneous borehole

2.3.1 Darotay (borehole 11) ('somewhere on traverse 1')(E416096 N1731268)

Target: a regional-scale dilational (tensional) fracture zone, possibly including 'clastic dykes' as reported by Drury et al (1994), affecting predominantly granitic basement.

Geophysical indications: numerous discrete conductive fracture zones were located on traverse 1, with some displaying strike extent of at least 100 m. Magnetic modelling suggests that many of these fractures dip at a high angle towards the north. A regolith thickness of about 13 m to 20 m is suggested by both Dipole-Dipole resistivity inversion and TDEM sounding. Closer correlation between surface observations and borehole control (see below) will be attempted when the exact traverse position of this borehole has been established.

Comments: borehole 11 was drilled to 45 m, encountering variably fractured and weathered granodiorite and granite between 4 m and 43 m (Fig 25). Water strikes were made at 29 m and 35 m and the calculated safe yield of this borehole is 3.66 l/s. The point resistance and SP logs (Figs 26 and 27) confirm the swl at about 10 m. The point resistance log indicates three discrete units below this; the centralmost (resistive) feature (between 21 m and 31 m) being coincident with the upper part of the logged granite. Numerous minor excursions on both logs may indicate additional conductive fractures.

3. CONCLUSIONS

Of the eleven promising borehole sites located by geophysical survey only three have been tested by drilling. Two of these (Decamhare (Bh 6) and Terra Emni (Bh 7)) were drilled to test fracture zones. The Decamhare borehole proved an exceptional thickness (42 m) of regolith but yielded no water. The controlled interpretation of a VES near this borehole site indicated favourable specific resistivities for the regolith (in the range 13- to 33 ohm.m); thus it is considered possible that the drilling/development techniques employed at this site have locally diminished the formation porosity/permeability.

The Terra Emni borehole proved fractured and weathered basalts and tuffs to its total depth of only 29 m. This borehole is highly successful. Both the calculated transmissivity (m^2/d) and yield/drawdown (l/s/m) at this site approach two orders of magnitude greater than at the best Project borehole drilled in similar basalt terrain, sited *without* the benefit of geophysical survey. Variable discharge pump tests showed no significant dewatering of the fractures/fissures and a safe yield of at least 8 l/s is estimated.

The third promising site tested was at Kailay where an anomalous thickness of regolith identified by conductivity traversing and subsequent electrical sounding was tested by borehole 12. The uncontrolled VES interpretation here indicated a thickness of some 40 m of regolith while the borehole proved only some 24 m of alluvials overlying granite. Such over-estimation results from the problem of equivalence (whereby numerous different arrangements of layer resistivities and thicknesses yield an identical sounding curve). The problem is best overcome by the inclusion of borehole control. However, even in the absence of such control, a series of VES can still be interpreted to indicate the thickest development of a particular layer (provided its resistivity remains constant) even if its absolute thickness/depth cannot be forecast. The Kailay borehole is also dry. The controlled interpretation of the VES at this site indicates a specific resistivity of about 10 ohm.m for the alluvials. Provided the drilling/development techniques were appropriate at this site, then it must be assumed that these alluvials contain a high clay content resulting in low porosity/permeability.

Limited surface measurements were made at two further Project boreholes that had been sited without the benefit of geophysical survey. The Adigrat Sandstone tested at Mai Aini (Hazemo) (borehole 4) displays a relatively high specific resistivity (about 130 ohm.m); this suggests that the intrinsic porosity/permeability of this sandstone is rather low. The main water contributions at this borehole appear to be from deep fissures. Conductivity traverses at the Adi Nebri site (borehole 5) did not reveal any consistent trends reflecting deep structure.

Project borehole 11 was drilled at an unknown location on geophysical traverse 1 at Darotay where we investigated a regional-scale tensional shear identified on satellite imagery. This borehole proved variously weathered granodiorite and granite to 43 m and encountered several fractures/fissures, yielding some 3.66 l/s. Had the borehole been drilled at one of the two recommended locations (where large conductive fractures had been identified) we could anticipate a considerably greater yield.

Magnetometry and conductivity traversing (supplemented by VES) have been especially useful in locating fracture zones to date. Since these fracture zones generally have little or no surface expression (when viewed in the field) it is essential to employ geophysics for their efficient detection. They are also generally narrow features and it is important that boreholes are drilled within a couple of metres of the recommended sites.

It should be emphasised that geophysical techniques do not *directly* indicate the presence of available groundwater, but rather indicate where conditions are favourable for its occurrence. For instance, we can detect a thick sequence of alluvials displaying favourable resistivity (in the range, say, 20 to 100 ohm.m) but cannot guarantee a successful borehole.

4. REFERENCES

Drury, S A, Kelley, S P, Berhe, S M, Collier, R E and Abraha, M. 1994. Structures related to Red Sea evolution in northern Eritrea. TECTONICS, Vol 13, No 6 pp 1371-1380

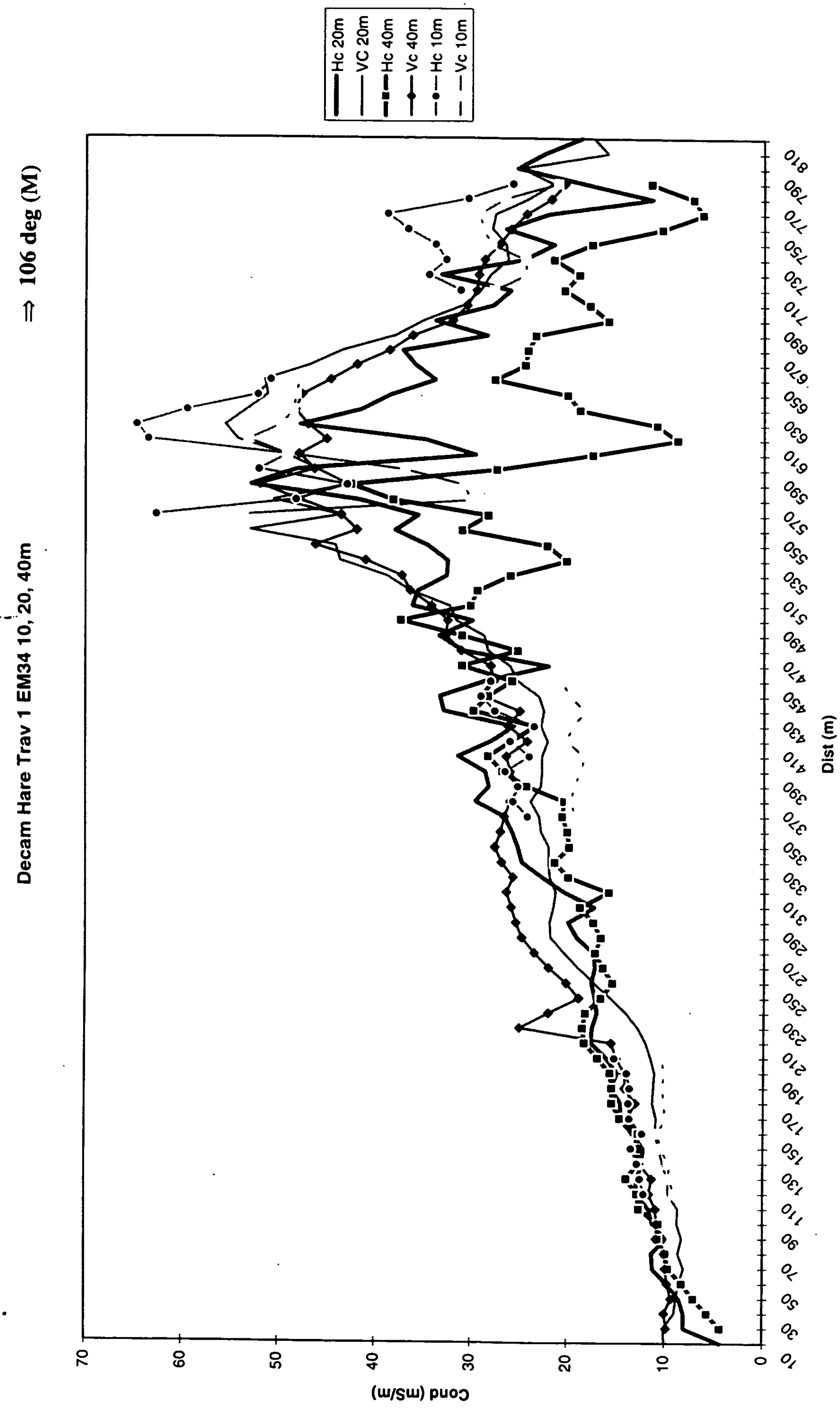


Figure 1 Decamhare: EM34 conductivity data of traverse 1

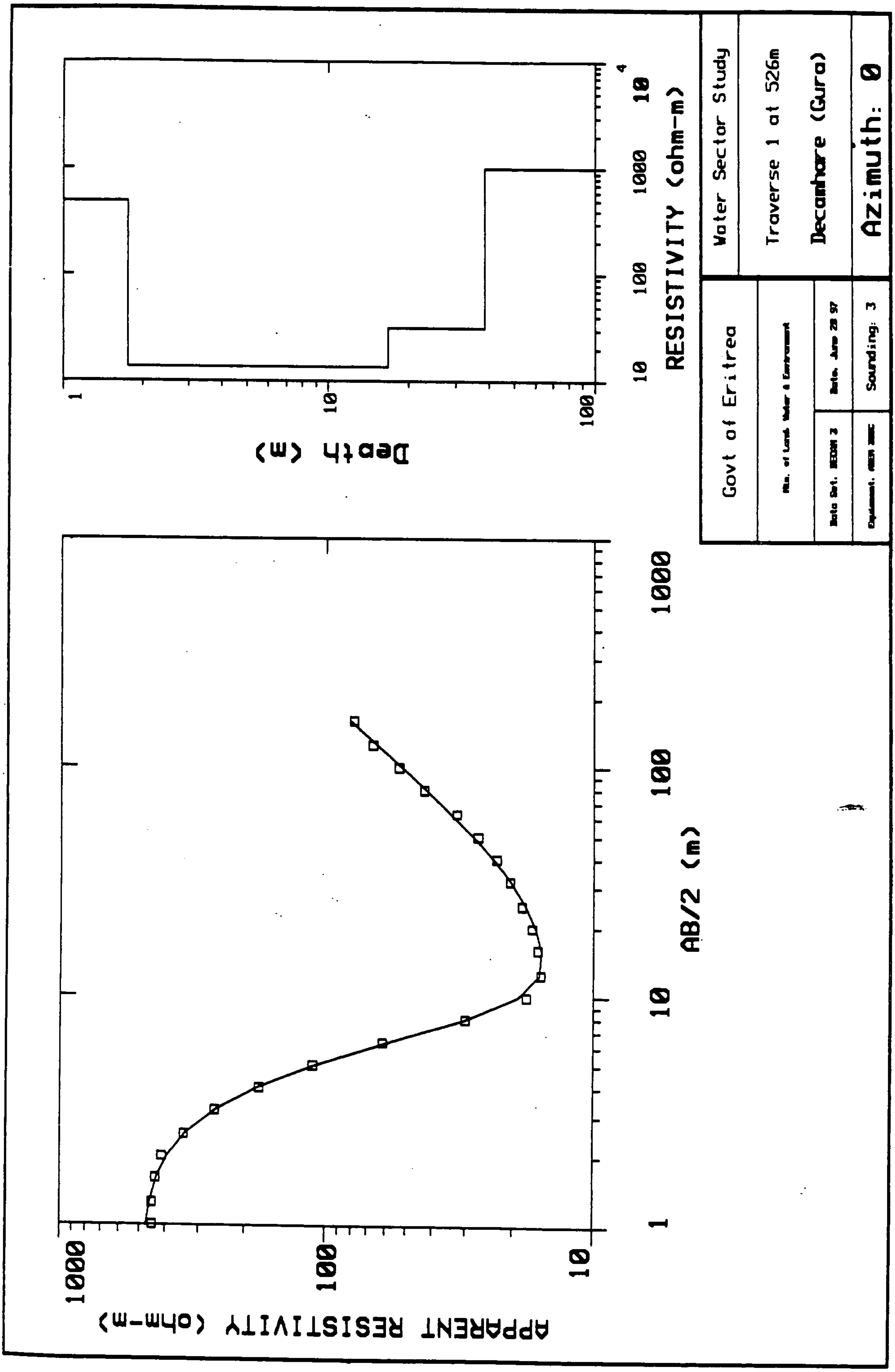
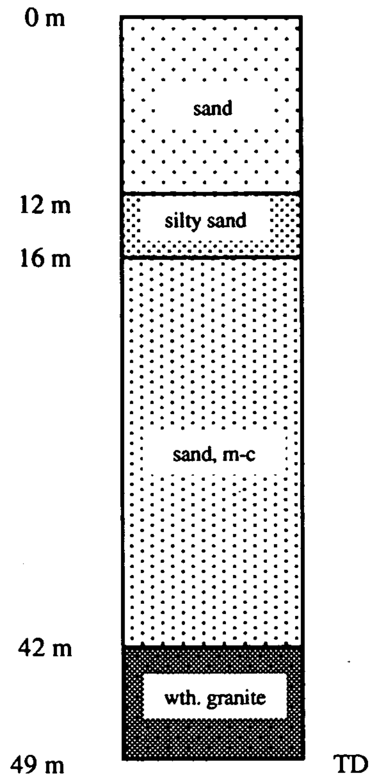


Figure 2 Decamhare: DC sounding at 526 m on traverse 1

Decamhare (Project borehole 6)



Hydrogeology:

Dry borehole

Figure 3 Decamhare: log of Project borehole 6

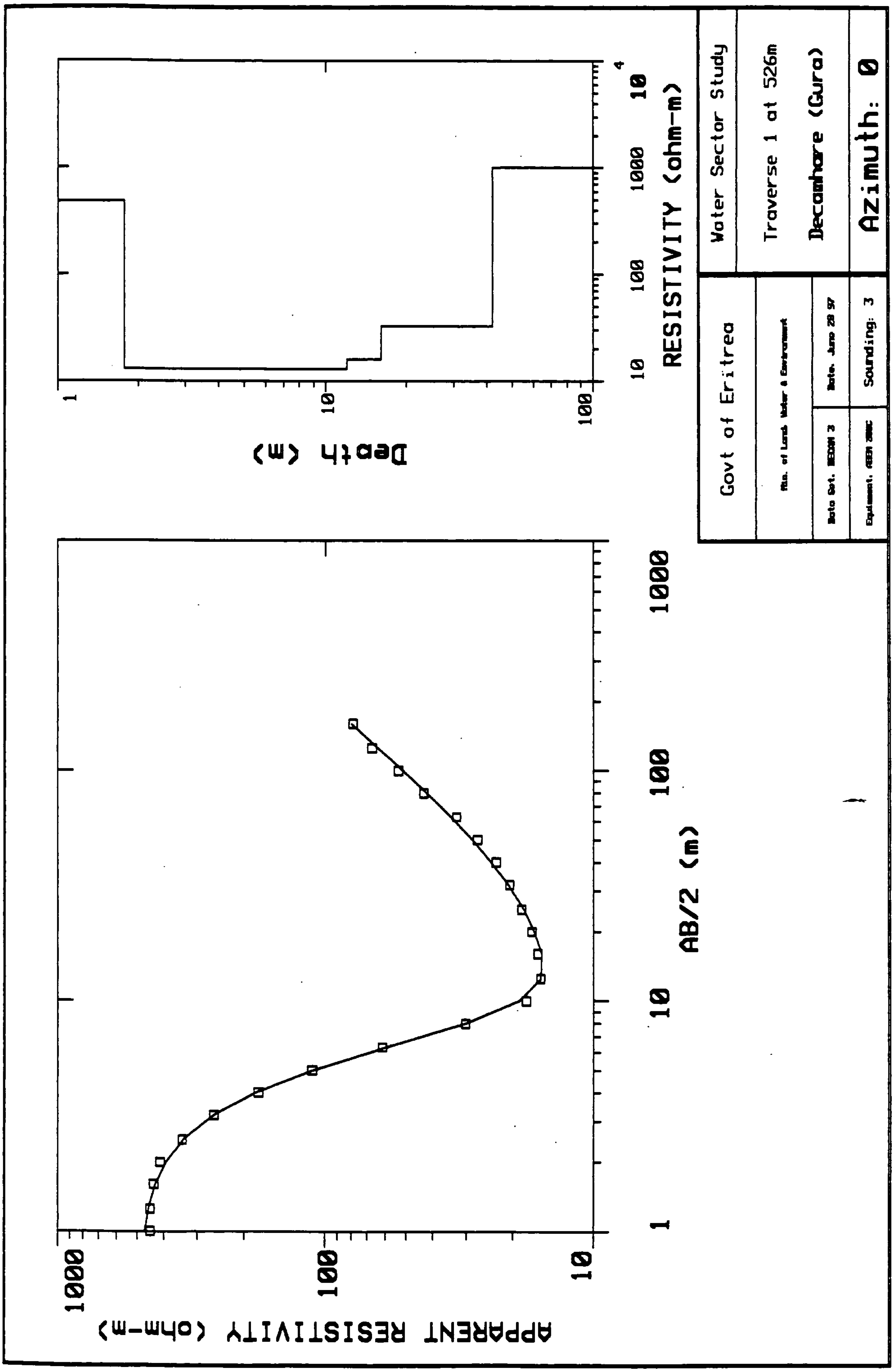


Figure 4 Decamhare: controlled interpretation of VES at 526 m on traverse 1

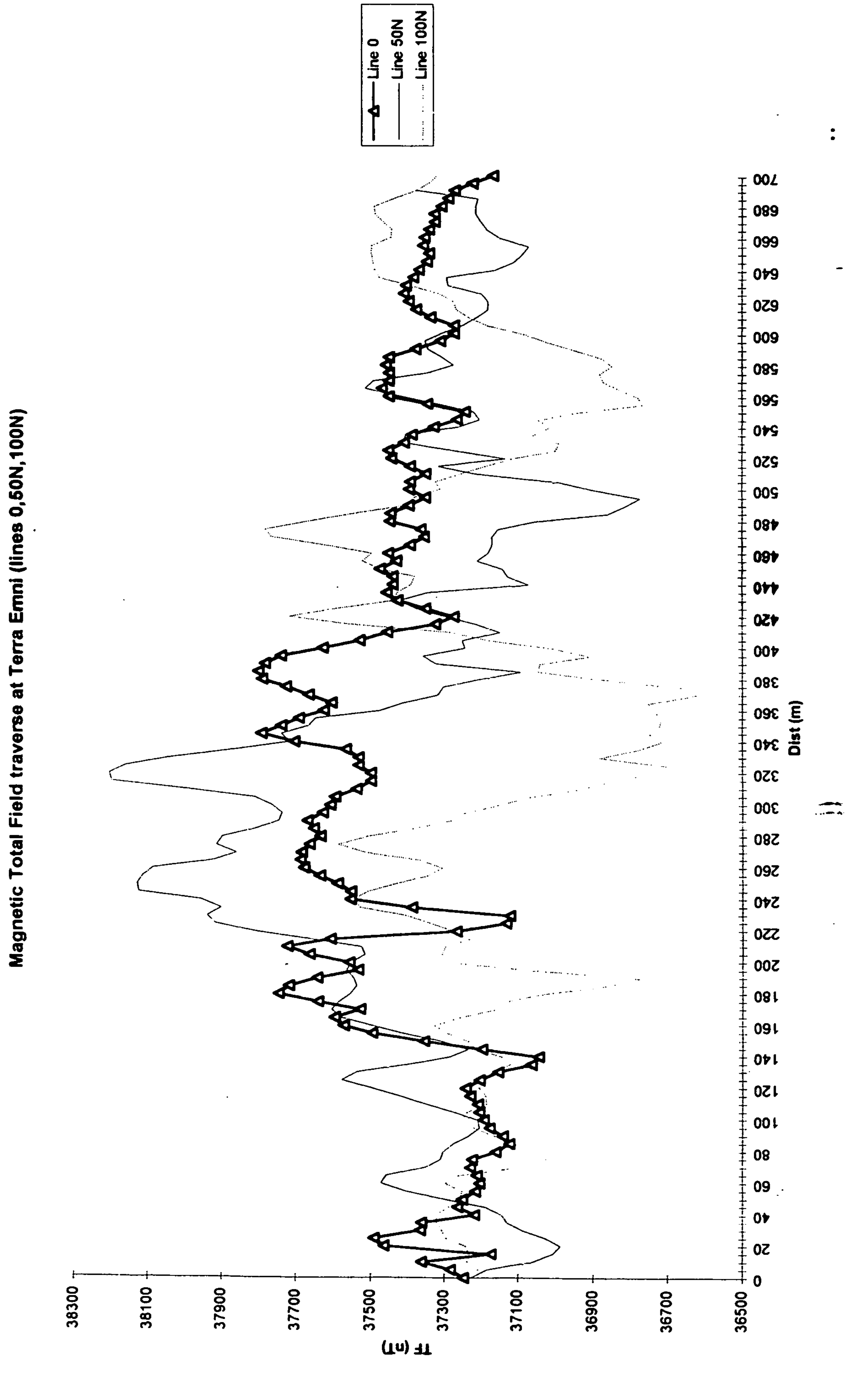


Figure 5 Terra Emni: Total field magnetic data of lines 0, 50 N and 100 N

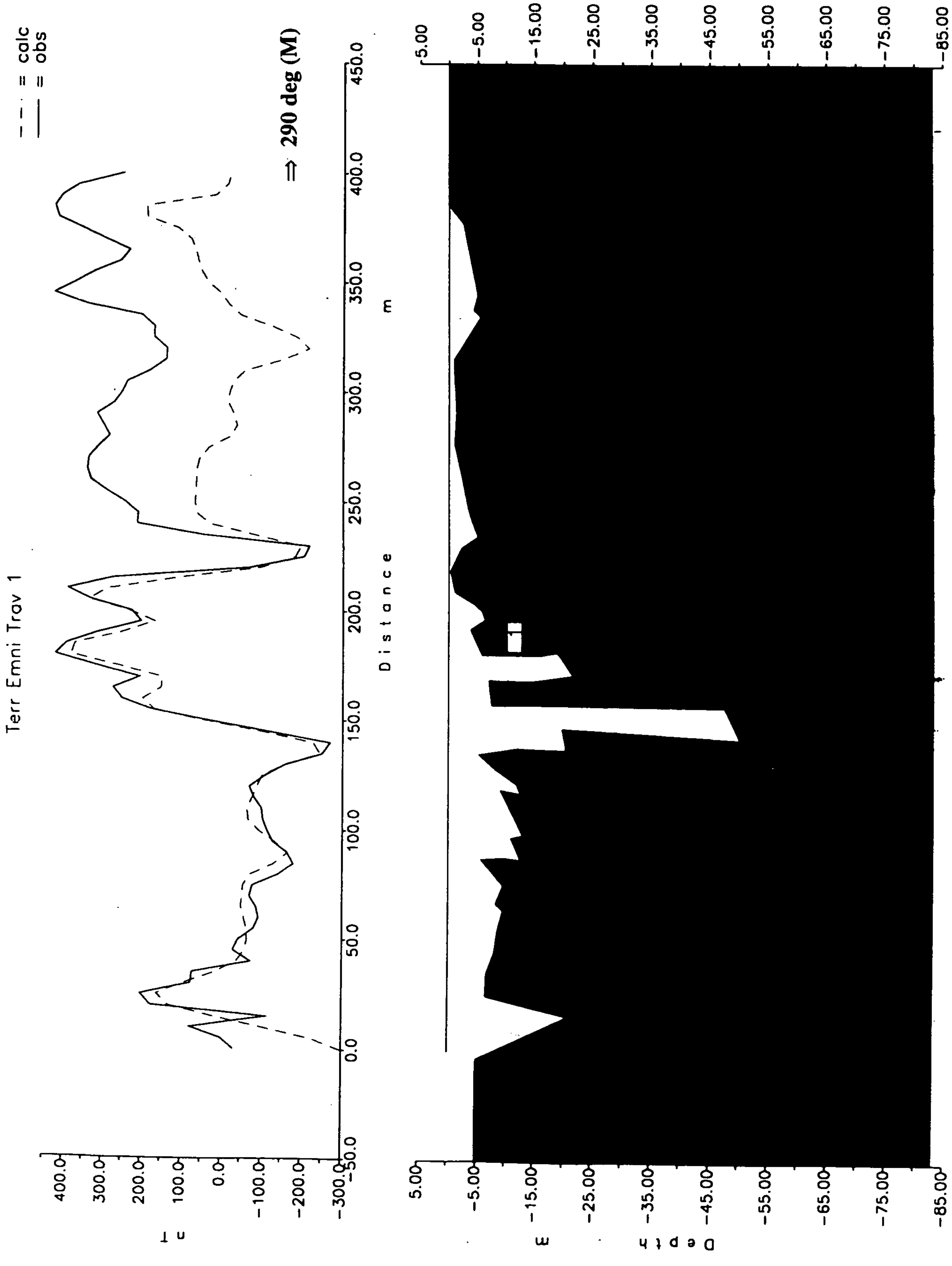


Figure 6 Terra Emni: partially modelled magnetic profile of traverse 1

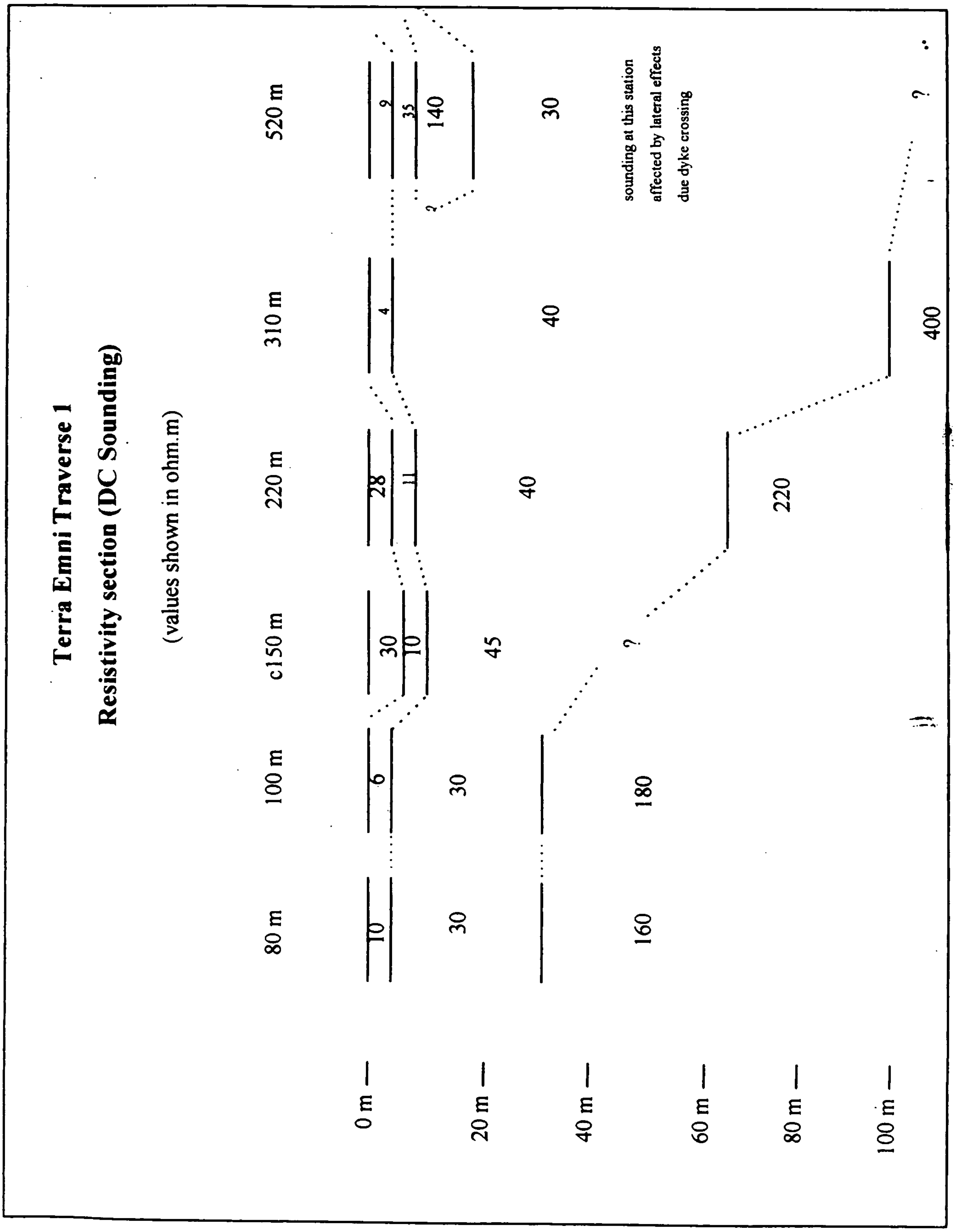


Figure 7 Terra Emni: resistivity cross section of traverse 1 (DC sounding)

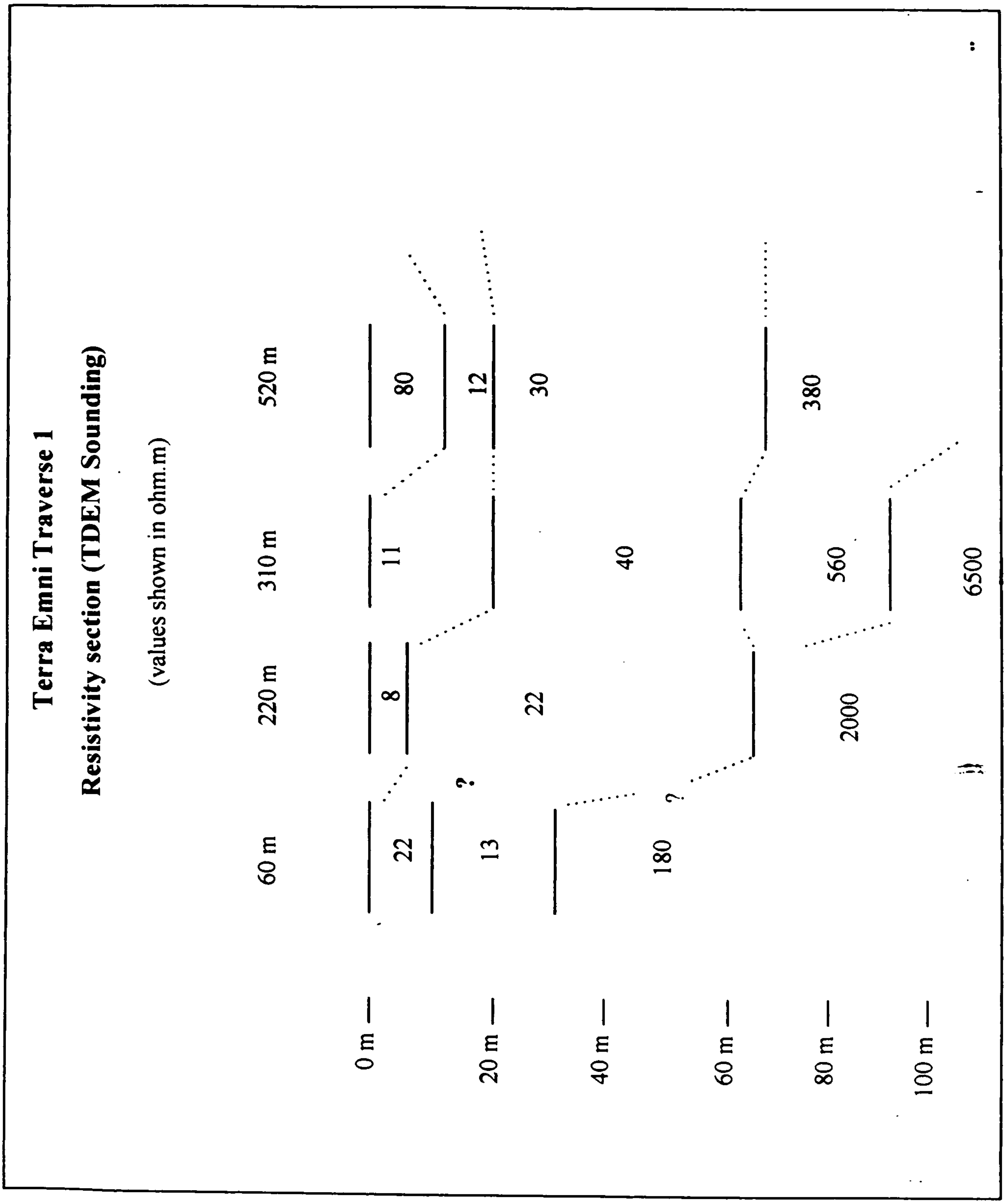


Figure 8 Terra Emni: resistivity cross section of traverse 1 (TDEM sounding)

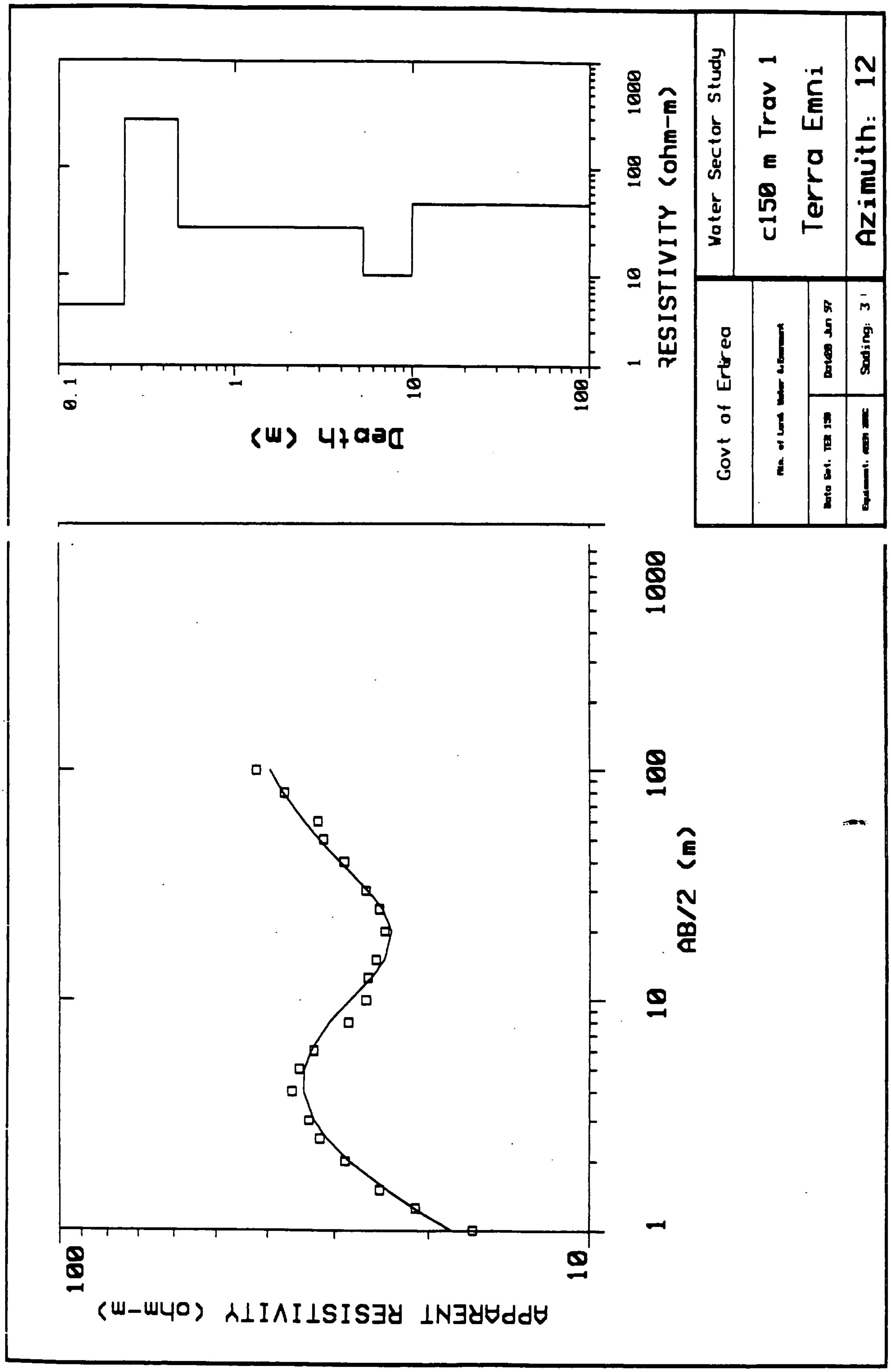
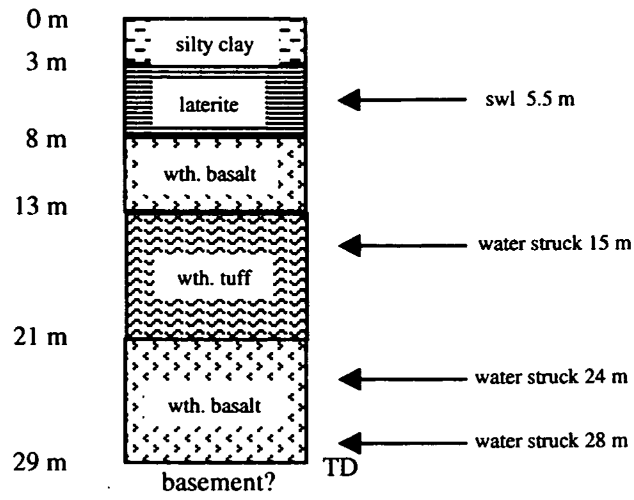


Figure 9 Terra Emni: DC sounding at c 150 m traverse 1

Terra Emni (Project borehole 7)



Hydrogeology:

Transmissivity: 205 m^2/d

yield: 8 l/s

drawdown: 2.1 l/s/m

Figure 10 Terra Emni: log of Project borehole 7

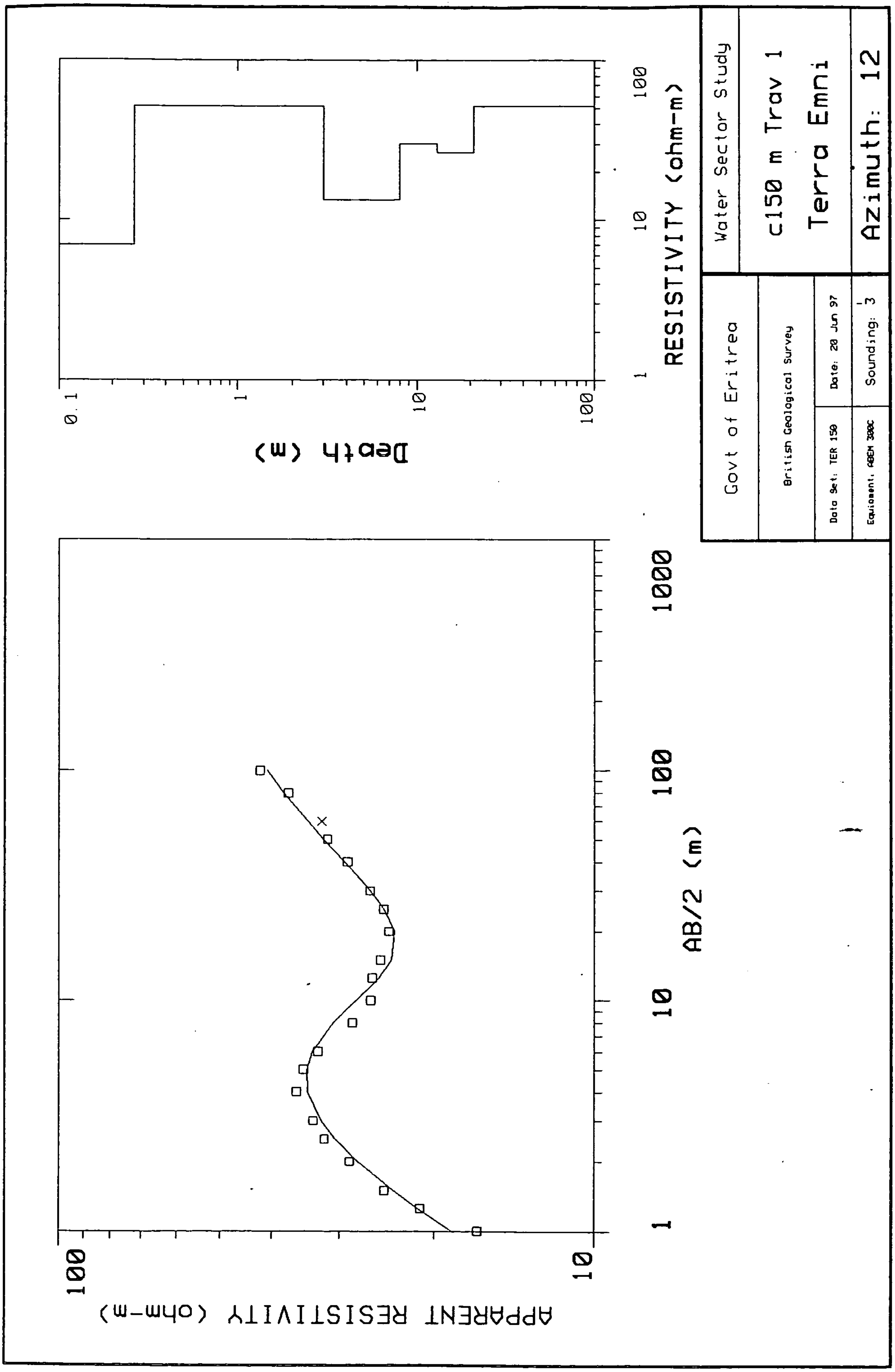


Figure 11 Terra Emni: controlled interpretation of VES at c 150 m on traverse 1

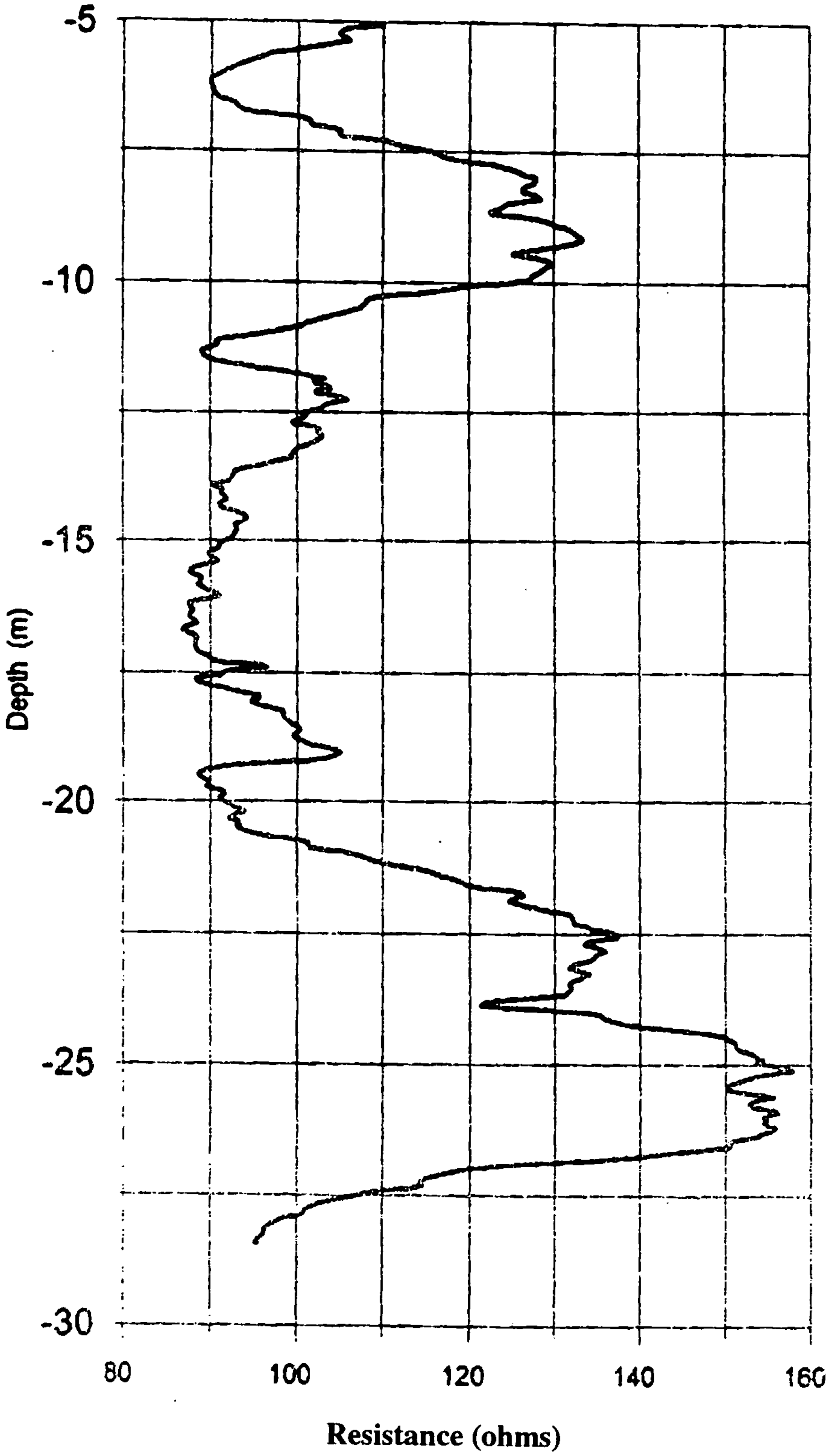


Figure 12 Terra Emni: point resistance log of Project borehole 7

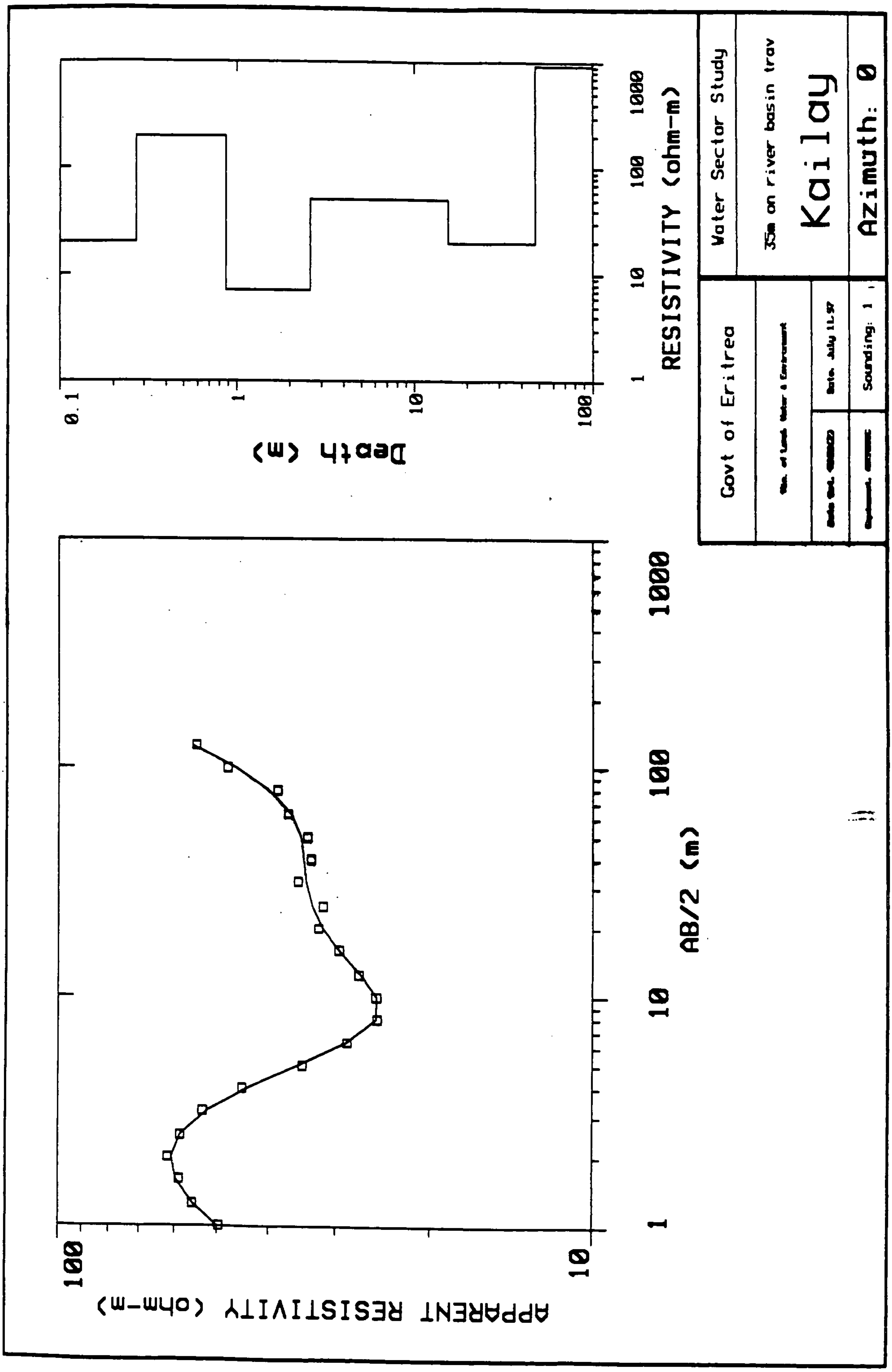


Figure 13 Kailay: VES at 35 m on traverse 1

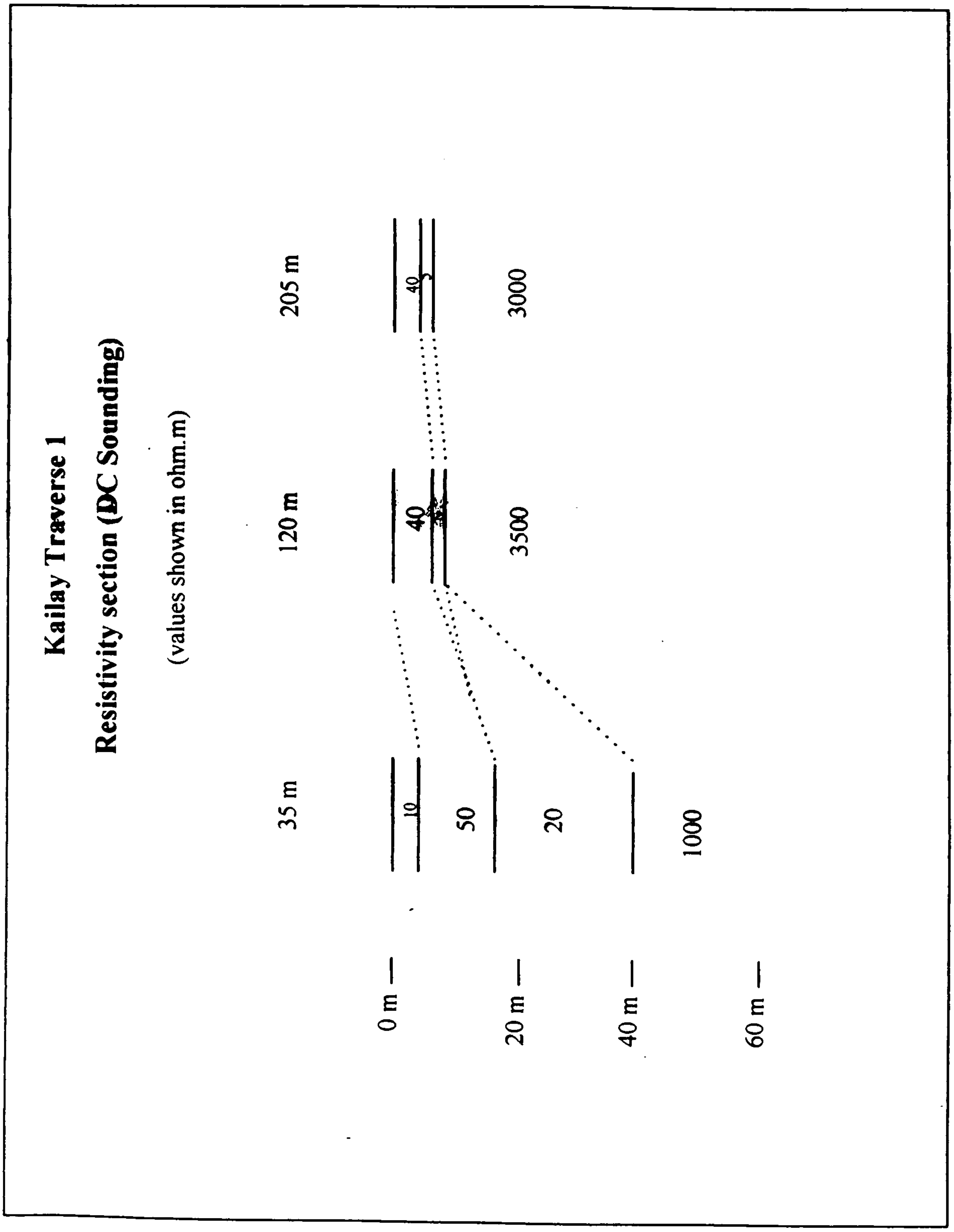
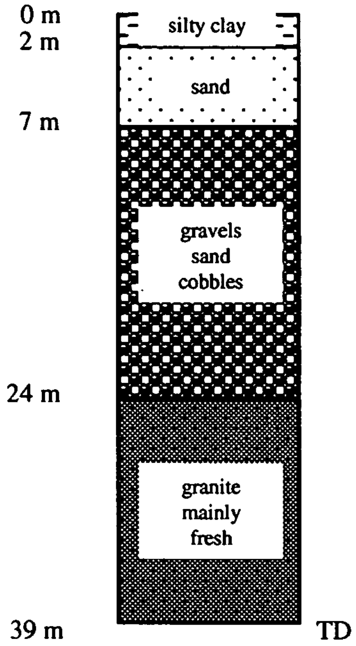


Figure 14 Kailay: resistivity cross section of traverse 1 (DC sounding)

Kailay (Project borehole 12)



Hydrogeology:

Dry borehole

Figure 15 Kailay: log of Project borehole 12

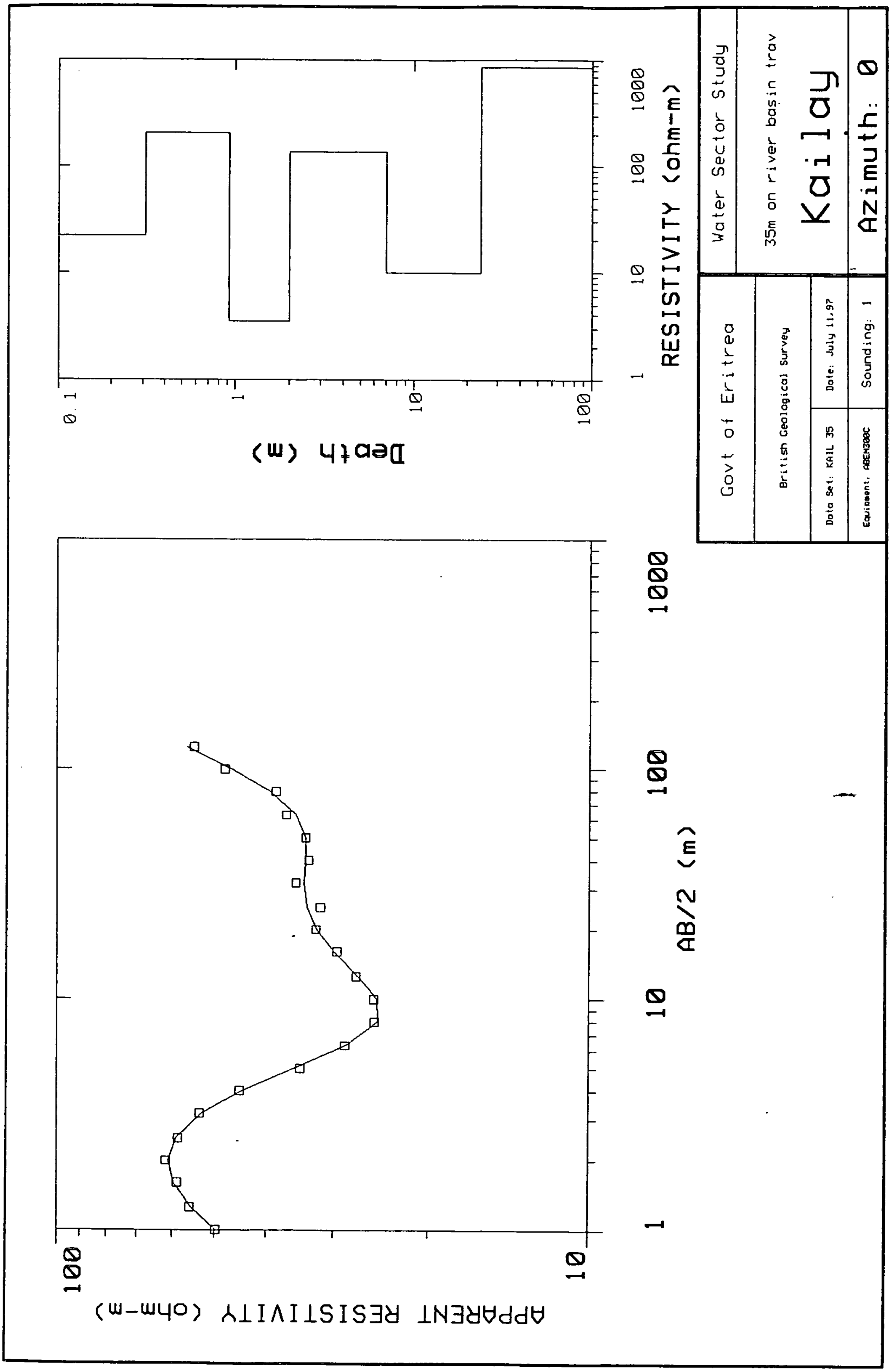


Figure 16 Kailay: controlled interpretation of VES at 35 m on traverse 1

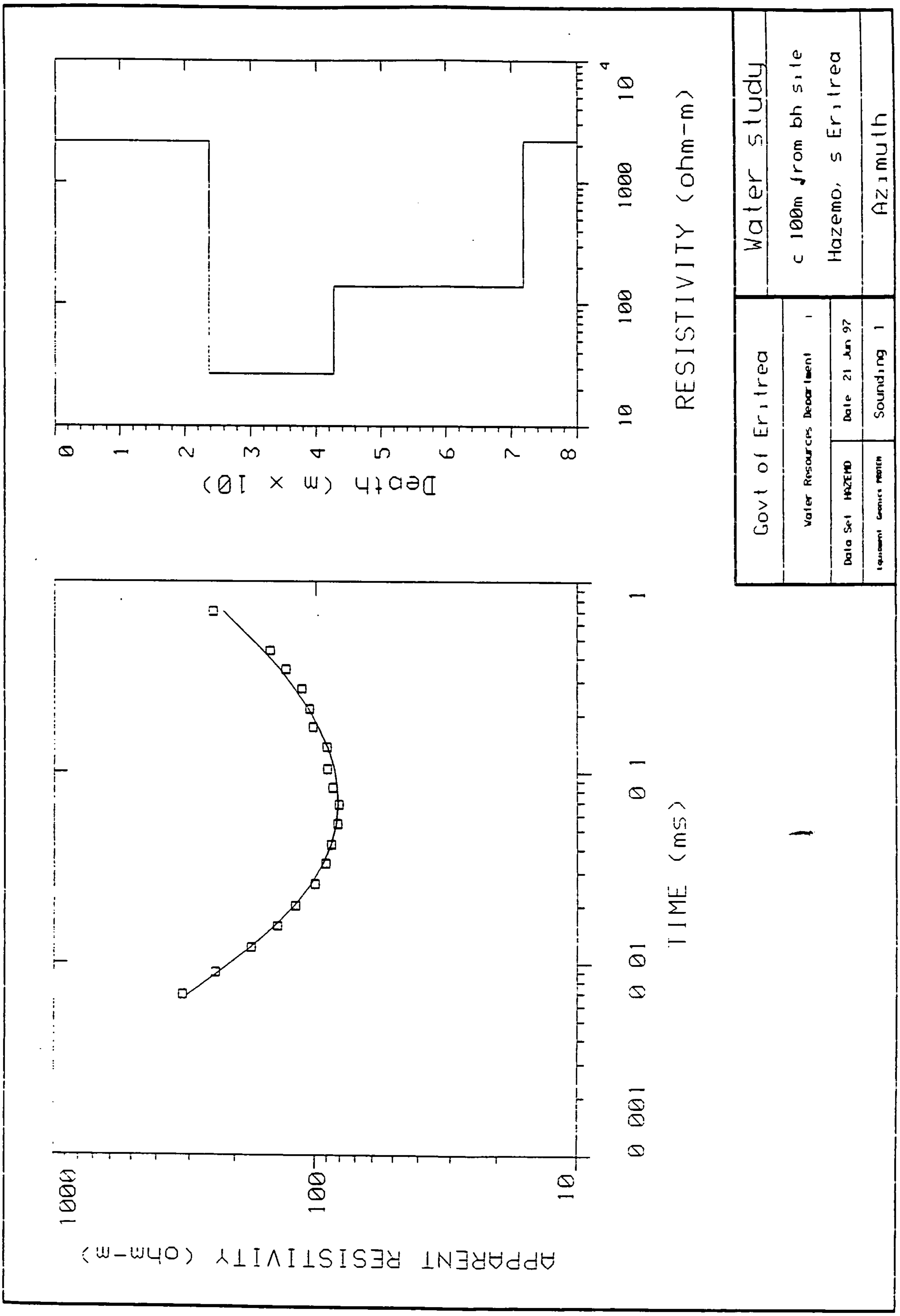
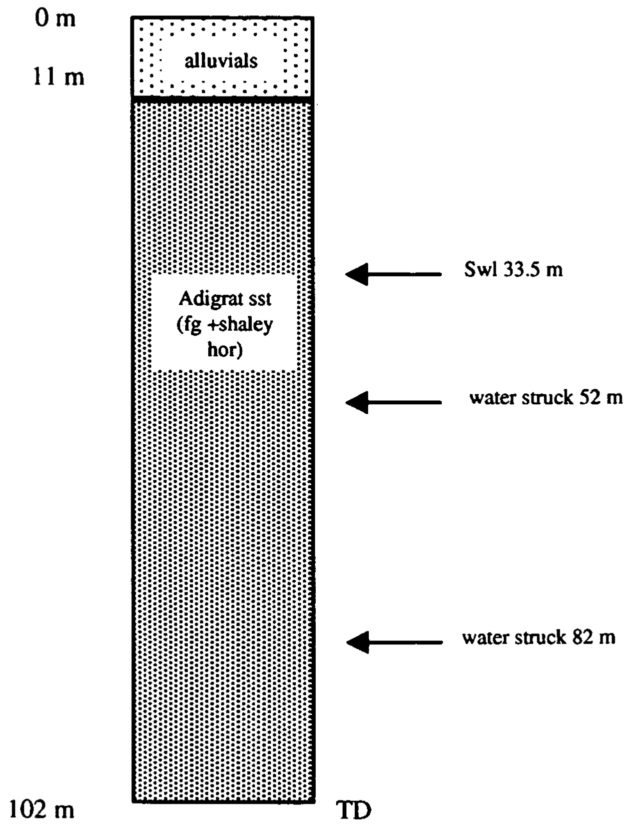


Figure 17 Mai Aini: TDEM sounding c 150 m N of Project borehole 4

Mai Aini (Hazemo)

(Project borehole 4)



Hydrogeology:

Max yield 3 l/s

Transmissivity 20 m^2/d

Figure 18 Mai Aini: log of Project borehole 4

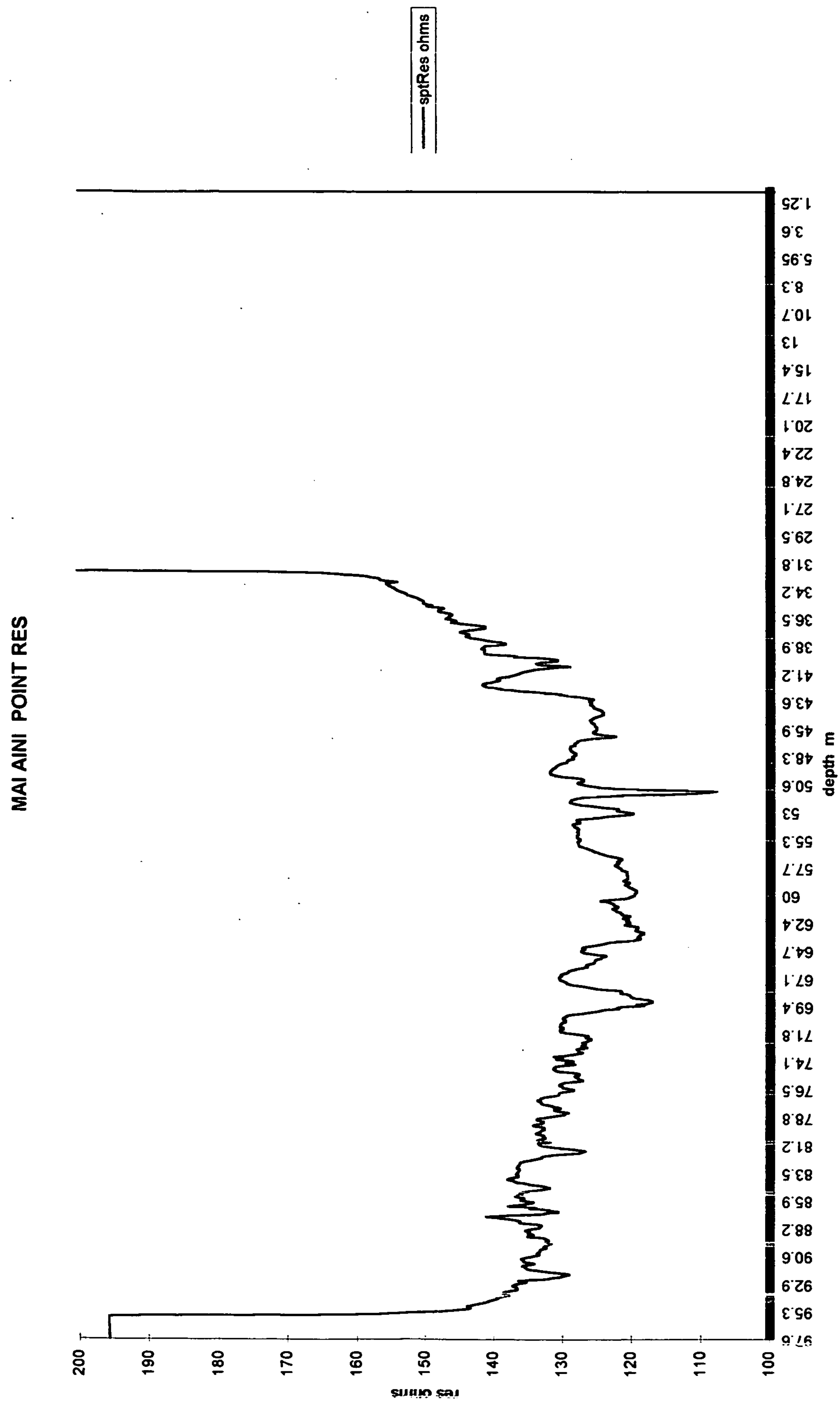


Figure 19 Mai Aini: point resistance log of Project borehole 4

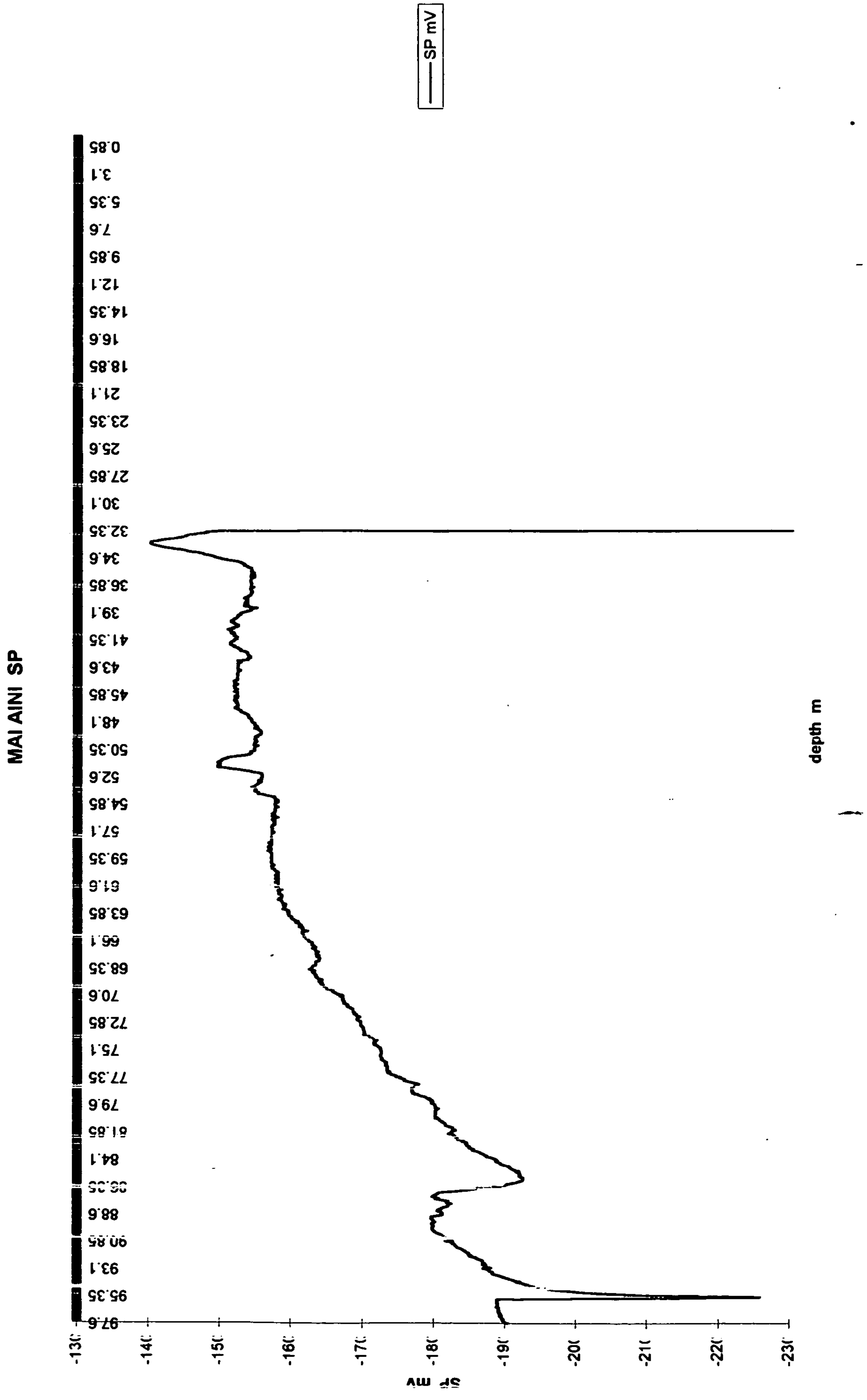
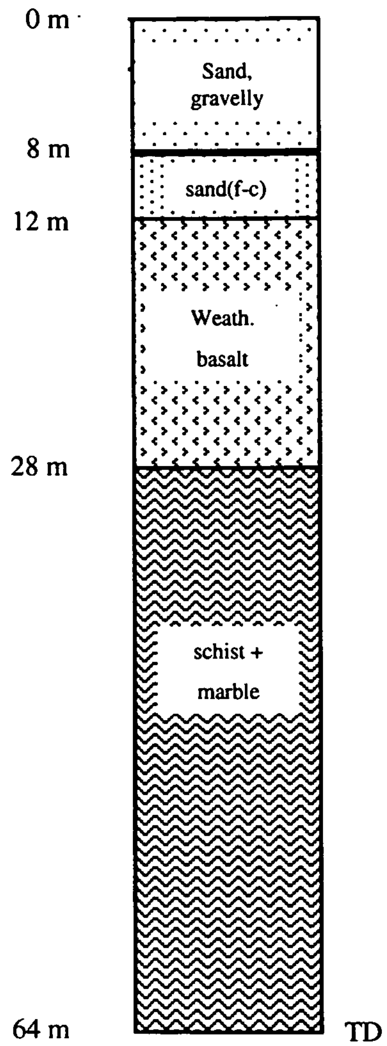


Figure 20 Mai Aini: SP log of Project borehole 4

Adi Nebri (Project borehole 5)



Hydrogeology:

Borehole collapsed above WT

no pump test undertaken

Figure 21 Adi Nebri: log of Project borehole 5

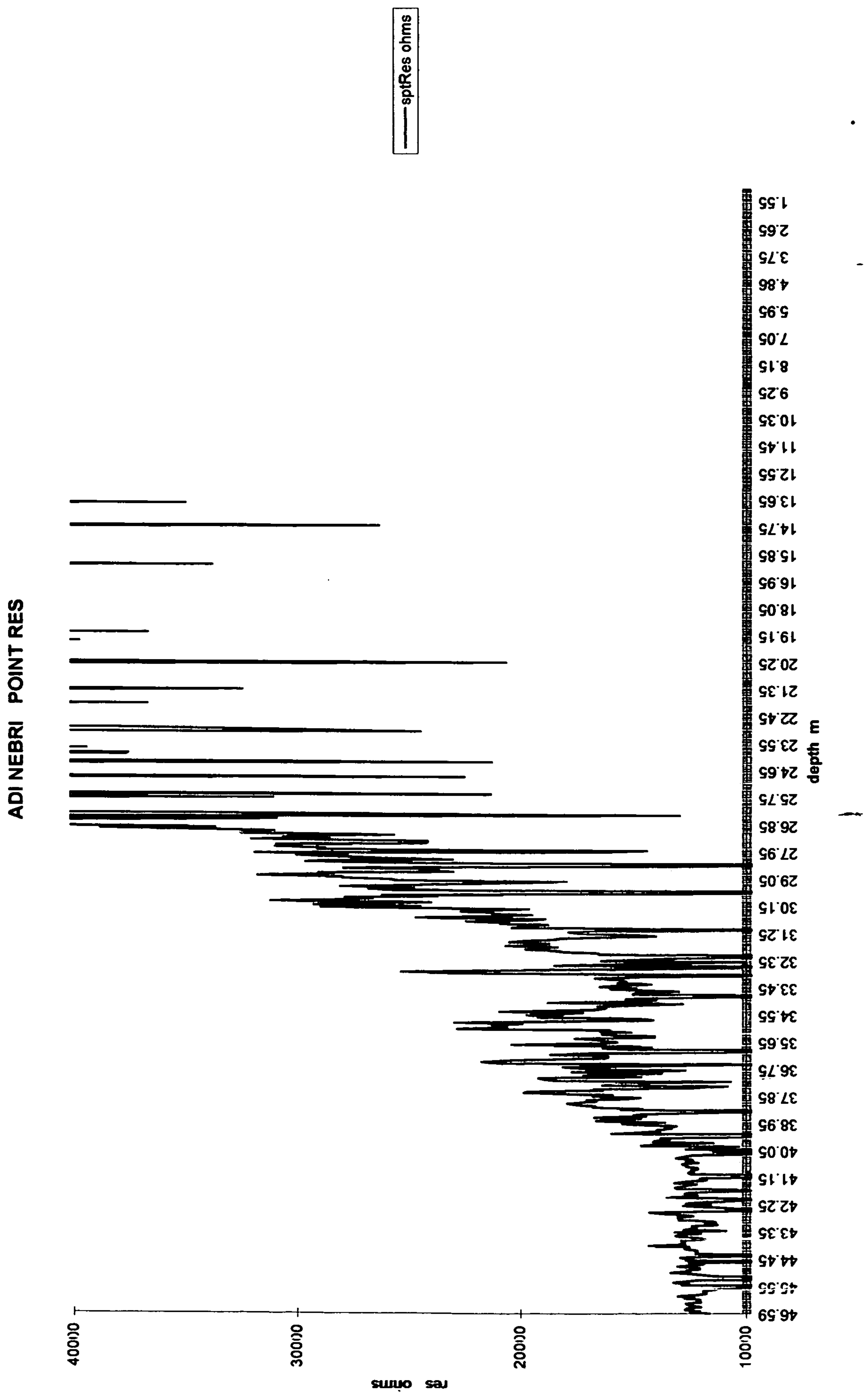


Figure 22 Adi Nebri: point resistance log of Project borehole 5

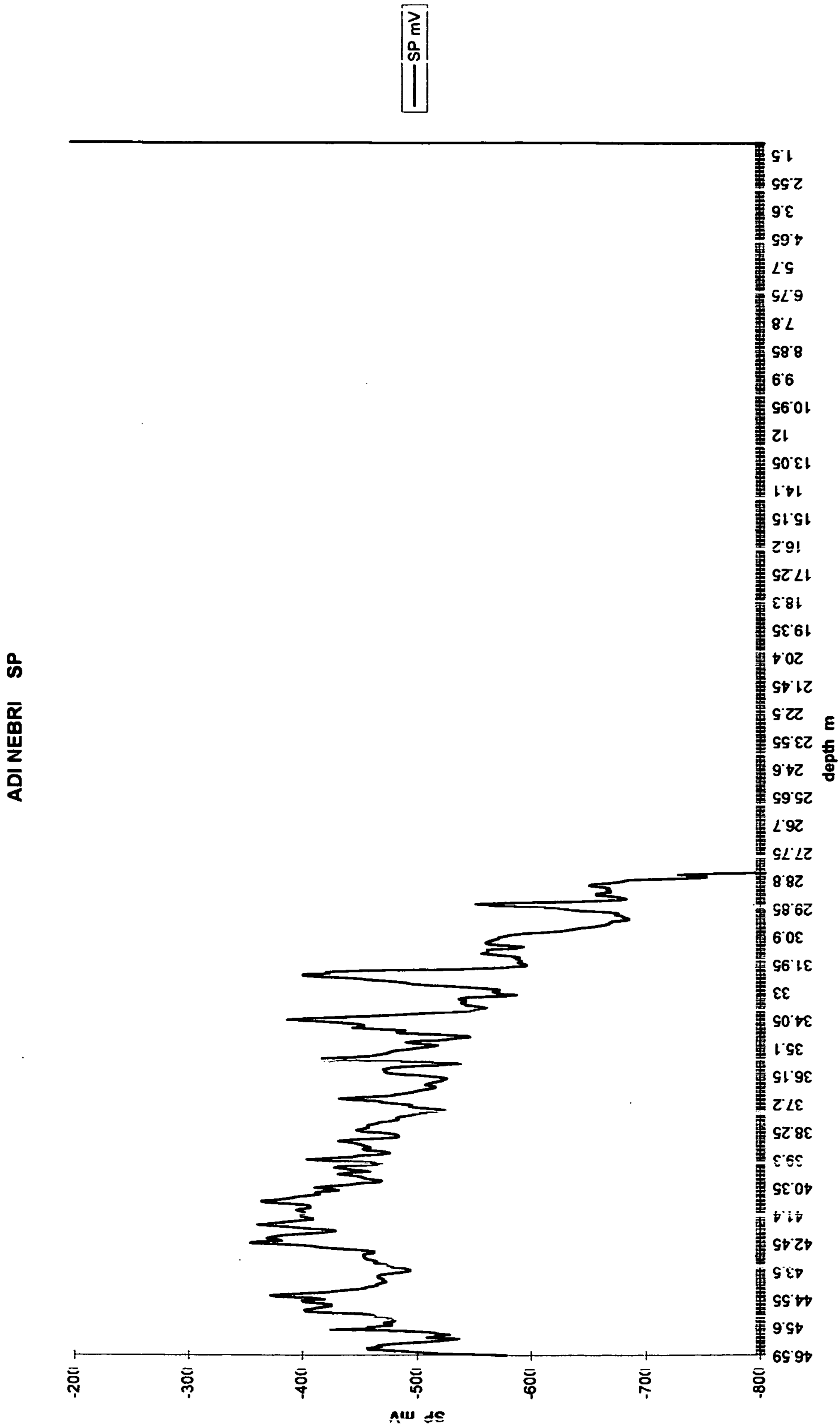


Figure 23 Adi Nebri: SP log of Project borehole 5

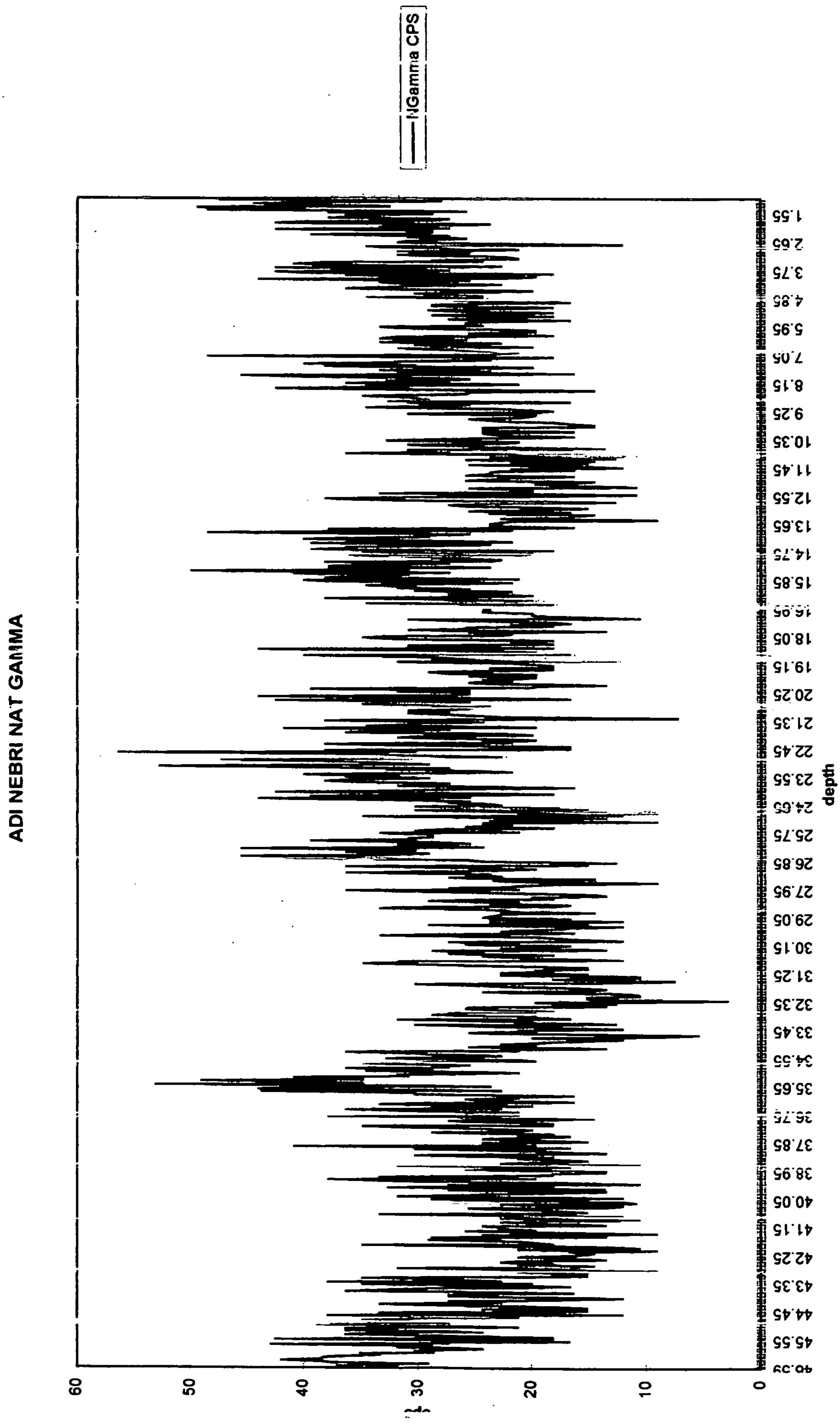
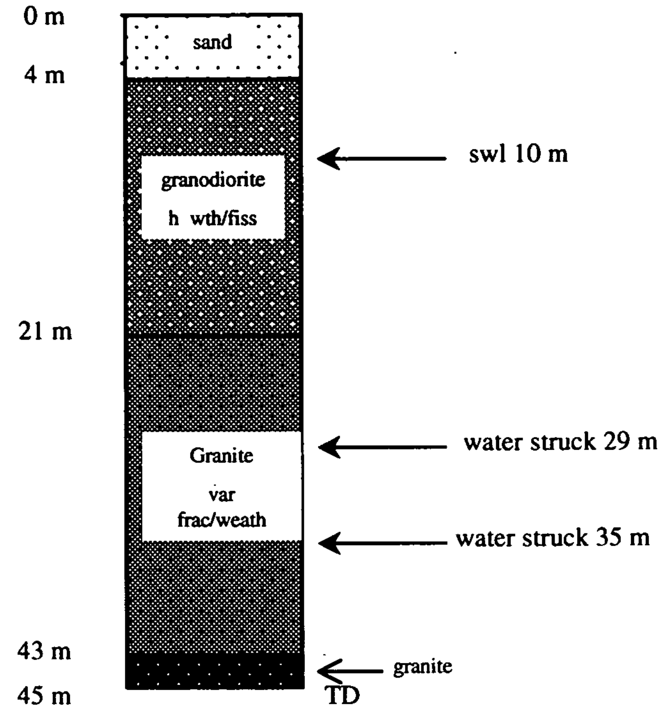


Figure 24 Adi Nebri: natural gamma log of Project borehole 5

Darotay (Project borehole 11)



Hydrogeology

Yield 3.66 l/s

Figure 25 Darotay: log of Project borehole 11

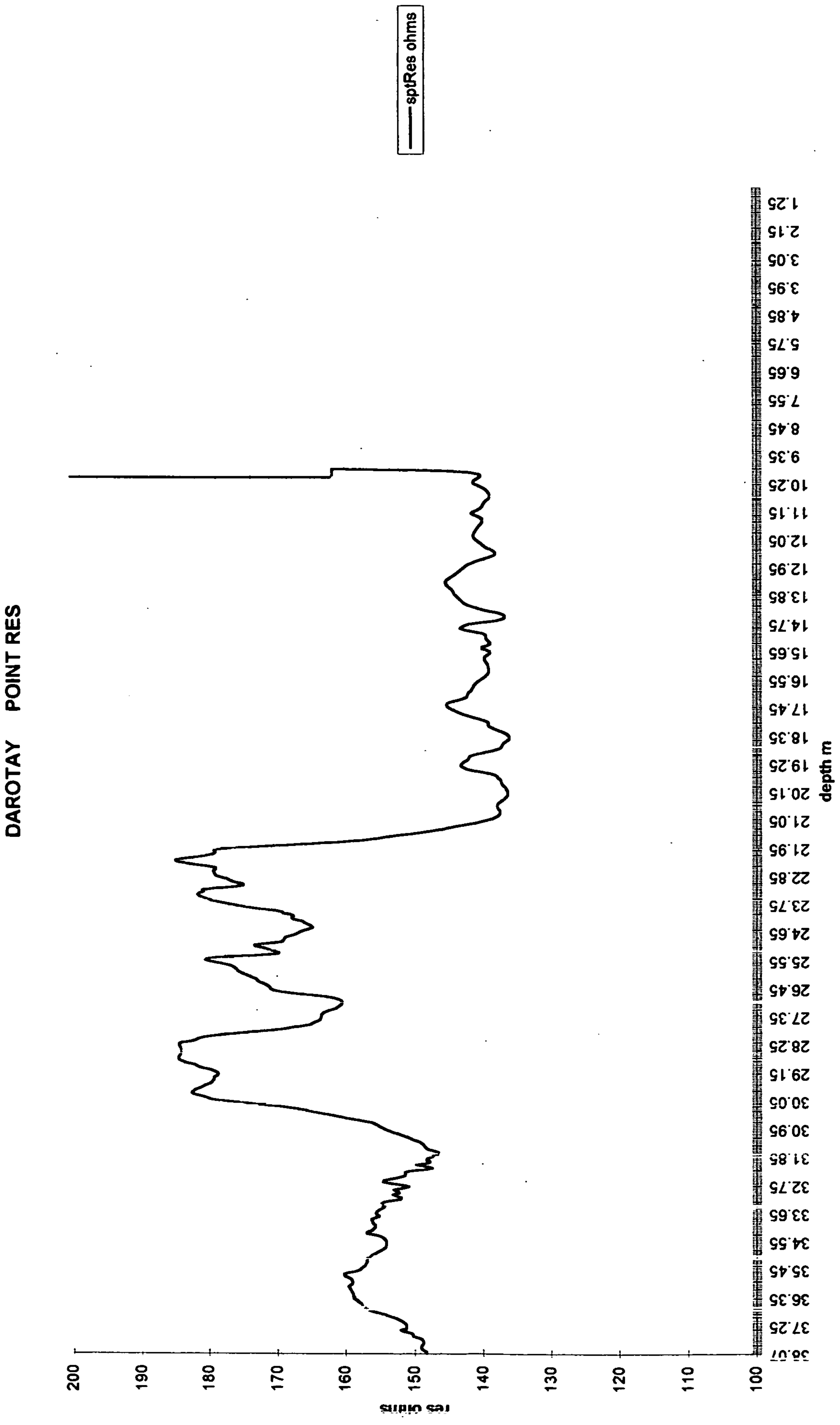


Figure 26 Darotay: point resistance log of Project borehole 11

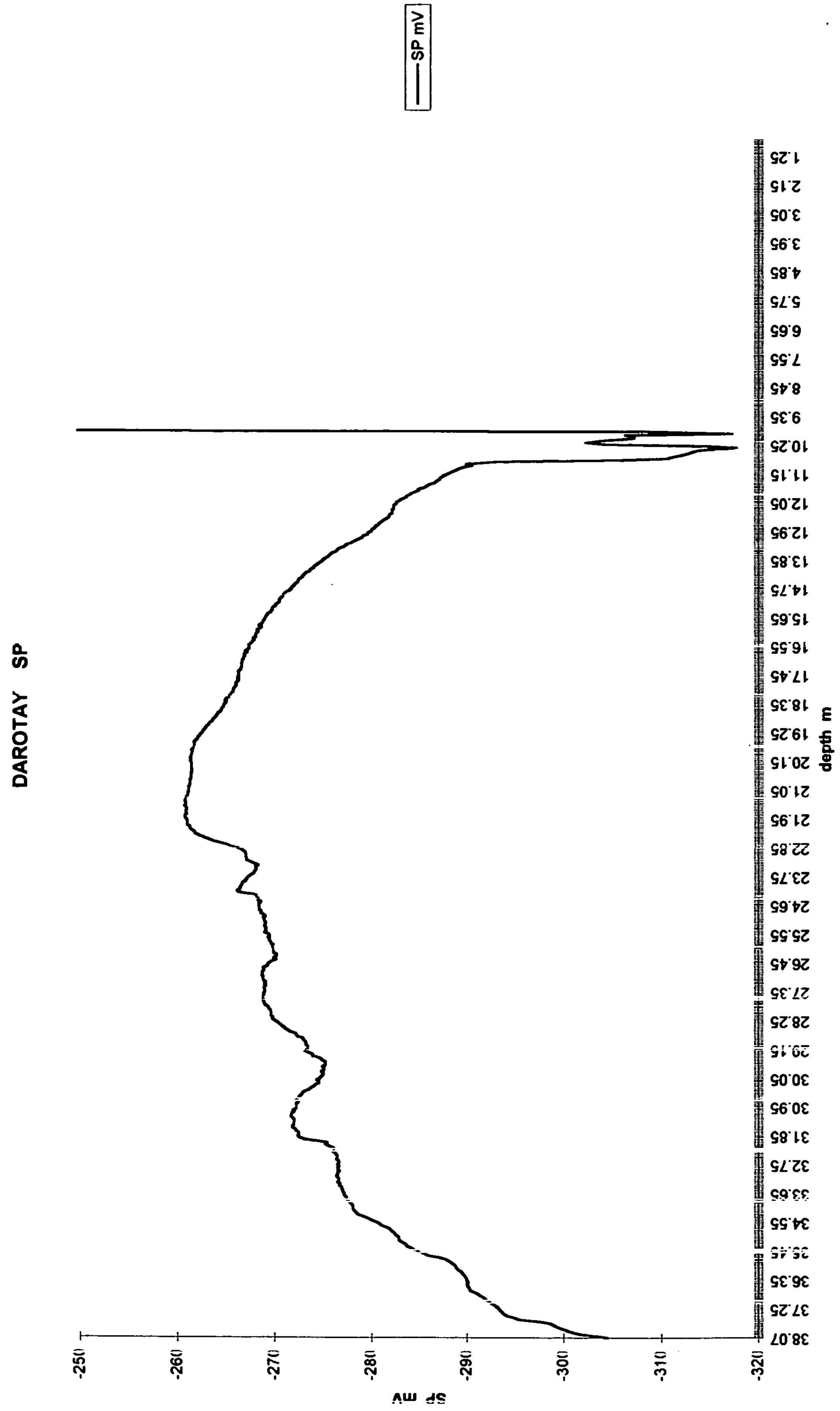


Figure 27 Darotay: SP log of Project borehole 11