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A WHOLE CRUST RESISTIVITY CROSS-SECTION ACROSS THE AE FOREST SOUTHERN UPLANDS

David Beamish

Bibliographic reference

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British Geological Survey, Keyworth, 1991

ABSTRACT

This report describes geoelectric modelling using data obtained from a reconnaissance MagnetoTelluric (MT) survey carried out as part of the Southern Upland mapping programme. The 8 site survey, along a 14 km NW-SE profile, was centred on the Ae forest area to the east of Thornhill and to the SW of Moffatt. The measurements were undertaken across one of the fault-bounded tract sequences of greywackes in the Central Belt. The purpose of the limited survey was to investigate the possibility of 'locally' detecting concealed tectonostratigraphic structure by virtue of its (possible) resistivity expression.

The MT method attempts to provide a resistivity cross-section, often through the whole crust. The sensors currently available restrict information to depths greater than several hundred metres. The present survey was carried out using a new 7-channel field instrument developed in-house by the BGS.

The present report provides information on the modelling of the survey data and presents both one-dimensional (1-D) vertical profiles and a final 2-D whole crustal geoelectric section. 1-D inversion of data from two sites within the Palaeozoic Lochmaben basin provide estimates of basin depth comparable with estimates obtained from gravity modelling. 2-D inversion of the profile data is undertaken using a new algorithm (OCCAM 2D) to provide a resistivity cross-section through the whole crust.

Resistivities greater than 1000 ohm.m, tentatively associated with Silurian greywackes, extend to a depth of about 12 km. A relatively conducting (resistivities < 100 ohm.m) lower crust occurs at depths greater than 15 km in keeping with previous, low frequency MT observations across the Southern Uplands. A major set of lateral resistivity gradients are found, centred on a depth of about 2.5 km, to the NW of the northern end of the profile. Underlying this anomaly a modification in lower crustal resistivity is apparent at depths greater than 15 km. The resistivity cross-section suggests that a form of whole crustal modification occurs to the NW of the survey profile. The location of the main anomaly remains speculative since the reconnaissance survey was of limited length.

INTRODUCTION

Detailed information on the MT survey has been described in an initial report by Beamish and Wallis (1991), referred to here as Paper 1. Paper 1 describes the survey purpose, quality control and the sounding data obtained. The initial report also undertook a basic appraisal of survey penetration depths, dimensional characteristics and geoelectric strike azimuths.

The location of the reconnaissance MT survey is shown in Figure 1. The 14 km profile comprises data from the 8 sounding locations shown in Figure 2. Site coordinates are given in Table 1. The 8 site NW-SE profile provides information on the crustal resistivity section from depths of several hundred metres through to depths greater than 30 km. Of the 8 soundings obtained only one sounding (site 005) appears to suffer a high degree of static distortion.

As expected from the outcrop geology along the profile, the two sites (007 and 008) to the SE of the profile detect what amounts to an 'at-surface' conductive layer associated with the upper Palaeozoic sandstones of the basin around Lochmaben.

In terms of overall sounding characteristics (discussed in paper 1) the data along the profile form 3 groups. Sites 007 and 008 define the first group largely by virtue of the near-surface conductive effect. These soundings are also the most 1-D through the upper crustal section. Sites 002 to 006 form the second group of sites with similar data characteristics. A major transition, in terms of overall data character, takes place between sites 001 and 002.

All sites display a transition from approximate 1-D behaviour within the upper crustal section through to 2-D by mid to lower crustal depths. Basically sites 002 to 008 are underlain by a relatively conducting (initial estimate of 100 ohm.m or less) mid to lower crustal layer. This deep seated 2-D 'structure' is responsible for the regional geoelectric anisotropy and the stable geoelectric strike directions discussed later. The major crustal dislocation in resistivity structure that takes place between sites 001 and 002 (an along profile distance of 2.2 km) must also require a 2-D interpretation.

GEOELECTRIC STRIKE AZIMUTHS

The MT tensor can be rotated (or decomposed) to provide a horizontal azimuth which corresponds to a direction of maximum (or minimum) resistivity. The azimuth, so obtained, is equivalent to the geoelectric strike direction which is assumed 2-D. The geoelectric strike directions for all sites at high frequencies (50 to 10 Hz) are shown in Figure 3a. All azimuths refer to grid north and are quoted as positive degrees east of north. From site 1, in the NW, to site 8, in the SW, there is a form of progression through 90 degrees from NE to NW. The azimuth 'spread' at site 4 may mark the response as 'intermediate'. Such a 90 degree progression can be interpreted (in 2-D structural terms) as an indication that a structural boundary has been traversed (see below).

The strike directions at low frequencies (0.065 to .021 Hz or 15 to 50 sec) are shown in Figure 3b. At low frequencies no 'along-profile' progressive rotation is observed which means that the structural boundary implied by the rotations at high frequencies is confined to shallow (upper crustal) depths. The relatively stable geoelectric strike directions at low frequencies indicate a deep-crustal regional geoelectric anisotropy which influences all the sounding data. The azimuths in Figure 3b are not identical. At site 002 the regional low frequency azimuth is +45 degrees and is found to rotate to +50 to +60 degrees by sites 003 and 004. At sites 006, 007 and 008 the regional strike is between +60 and +70 degrees.

In order to assess and model the data within a 2-D framework the data need to be rotated to the geoelectric azimuths discussed above. In a strictly 2-D (and no noise) situation the principal azimuths would be identical at all sites and all frequencies. In order to generate an appropriate 2-D coordinate system the tensor data have been rotated to the two orthogonal directions of +50 and +140 degrees. These two directions are consistent with the general attitude of the principal geoelectric strike azimuths *at both high and low frequencies* shown in Figure 3. The data rotated to 50 degrees will be referred to as TE-mode (electric field parallel to strike) data and the data rotated to 140 degrees will be referred to as TM-mode (magnetic field parallel to strike) data.

The azimuthal behaviour at high frequencies (Fig. 3a) results from the variation in the ratio of the apparent resistivities of the two orthogonal modes. At high frequencies we find the TM-mode apparent resistivities are significantly greater than those of the TE-mode at sites 001 to 005 but at sites 006 to 008 the inequality is reversed. The same behaviour is also obtained from the response of the 2-D model developed later. At sites 006 and 007, the ratio of the TM-mode apparent resistivity to that of the TE-mode is only slightly less than unity while at site 008 the ratio is significantly less than unity. In strike azimuth terms, this behaviour results in the azimuths 'transferring' between the two orthogonal modes across the profile.

THE ROTATED DATA

The sounding data rotated to the principal directions are shown in Figure 4. Figure 4a shows the TE mode response and Figure 4b shows the TM mode response at all 8 sites. The data at different sites are 'grouped' according to the plotting symbol used. The data at sites 007 and 008 are shown with open circles. They are highly consistent between the two sites *and* between the two orthogonal modes. As indicated previously this behaviour confirms that these sites are the most 1-D in character. The main differences between the two modes at these sites occur at low frequencies.

The data from site 5 are shown by open crosses since this site suffers static distortion and may be influenced by 3-D effects. The data from sites 002, 002, 004 and 006 are shown by the continuous lines. The different response behaviour between the two modes at these sites is indicative of 2-D behaviour with the greatest differences between sites occuring in the TM-mode (Fig. 4b). The distinct and individual response, particularly in the phase behaviour, observed at site 001 is shown by the solid symbols. Such behaviour can only be accomodated by a major (2-D) resistivity transition in the vicinity of the north-western end of the profile.

The data rotated to the principal geoelectric coordinates and shown in Figure 4 form the data set which has to be modelled in the form of a crustal resistivity section.

1-D INVERSION

Prior to 2-D modelling it is instructive to consider the vertical resistivity profile revealed by 1-D inversion at sites 007 and 008. These two sites are both situated within the Palaeozoic basin around Lochmaben. The data from these two locations are also the the most 1-D in character although the degree of one-dimensionality decreases with decreasing frequency (increasing depth).

Four-layer inversions of the scalar, rotationally-invariant response at the two sites are shown in Figure 5. Four-layer inversions appear adequate since the r.m.s. misfit errors between the data and models are 1.0 at site 007 and 0.95 at site 008. The upper crustal portion of the inverse solutions is probably well-represented by the 1-D models however the rather extreme behaviour in the vicinity of the mid-crustal conductor through to the lower crust is probably an inadequate representation. If we associate the initial conductive layer (about 100 ohm.m) with the Palaeozoic sandstones then the more resistive layer 2 would represent the main Silurian greywacke formation. Following this argument we would estimate the basin depth as 850 metres at site 007 and 1100 metres at site 008. These depth estimates compare favourably with the depth of the Lochmaben basin estimated from gravity modelling by Rollin (1991, unpublished manuscript). In the Dumfries area, a single-density modelling procedure indicated a minimum depth of the basin to be 1200 metres as shown in Figure 6 (after Rollin, 1991). The survey profile line (140 degrees east) and the location of sites 007 and 008 are superimposed. Site 007 is located in the region of strong gradients and lies on the approximate 700 metre contour. Site 008 lies close to the depocentre and is approximately located on the 1100 metre contour.

2-D INVERSION

A rather special 2-D inversion scheme has recently been introduced by deGroot-Hedlin and Constable (1990). The algorithm is referred to as OCCAM 2D. The approach of OCCAM 2D is to find models fitting the data which are extreme in the sense of having the minimum possible structure (roughness). The reasoning behind the approach is that most gridded models are highly overparameterised (in relation to the data) and conducting least-squares inversion often leads to solutions which contain large oscillations. The OCCAM approach is to conduct a *regularised* inversion.

Although the 'most-smooth' OCCAM models are not necessarily closer to the truth than any other models which fit the data, they give *lower-bounds* on the amount of structure required. It is then likely that the 'true' section is at least as rough as the models.

The cross-section profile for 2-D modelling was discussed previously. The profile shown in Figure 7 is defined along 140 degrees east and is perpendicular to the assumed geoelectric strike of 50 degrees east. The data rotated to +50 and +140 degrees define the TE- and TM-mode data respectively. These are the data used as input to the inversion algorithm.

In practice a reduced data set is used. The frequency axis of each sounding is resampled at a number of representative frequencies spaced uniformly in log(frequency). For the present data the 8 frequencies of 75.0, 23.7, 7.5, 2.4, 0.75, 0.24, 0.075 and 0.024 Hz were used. The reduced data retains the main turning points in the original sounding data. Since localised (near-surface) 3-D effects may influence the response at site 005 these data were not included in the modelling procedure. The remaining 7 sites provide 2 response data (apparent resistivity and phase), in each of the 2 modes and at each frequency. The data set used in the modelling procedure therefore provides 7 x 4 x 8 = 224 degrees of freedom. Site locations in model (profile) coordinates are 001(-7.2 km), 002(-4.975 km), 003(-3.225 km), 004(-2.25 km), 006(+1.1 km), 007(+3.375 km) and 008 (+6.225 km).

For modelling purposes the centre of the profile was defined at 301.6,591.3 km. The model itself is defined on a regularisation grid. In the present case the regularisation grid had 20 columns (x-axis) made up of 14 layers (z-axis). Within the regularisation grid, a rectangular finite element mesh allows expansion and contraction of both the lateral and vertical scale to accomodate the boundary condition requirements of EM modelling. The modelling algorithm uses a logarithmic depth scaling in keeping with the exponential decay of EM fields (within a half-space).

2-D INVERSION RESULTS

A number of inversion experiments were carried out on the data using the OCCAM 2D algorithm. In each case the initial model consisted of a uniform half-space of 315 ohm.m. This aspect is particularly important as it allows an unprejudiced regularised search for the global minimum inverse solution. Since some of the data had small error bars which may be unrealistic in the case of the 2-D approximation (deGroot-Hedlin and Constable, 1990), minimum errors were increased to 5% for all data.

The inversion first produced a model with an overall rms misfit of 4.2. This corresponds to fitting all 224 data to within 4.2 standard errors. The model is shown in Figure 8. The seven site locations are indicated by dots. Although the observational profile length is only about 14 km, it should be understood that wavefield penetrations exceed 10 km at low frequencies (below about 0.7 Hz for these data). These penetrations apply, in the 2-D case here considered, both laterally and vertically. Resistivity gradients which are significantly beyond the observational profile cannot, however, be considered 'well-constrained.'

A further feature of OCCAM 2D is its ability to perform a regularised inversion which solves for resistivitities and static shifts simultaneously and which produces the smoothest model. The philosophy followed in this approach is that there is no reason to model structure at depth if it can be shown that variations in the data may be due to near-surface inhomogeneities. Then one may presume that any resistivity anomalies remaining in the model are also present in the real Earth and are not artifacts of static shifted data. This form of OCCAM 2D inversion produced a model with a reduced rms misfit of 2.5 as shown in Figure 9. A comparison of Figures 8 and 9 shows that the broad form of the resistivity cross-section is similar in the two cases. The allowance for static distortion has produced a model (Figure 9) in which the gradients of the major anomaly to the NW of site 1 have been translated to slightly greater depth. The static shift parameters at the 7 sites produced by the inversion are shown in Figure 10. Overall the inversion shown in Figure 9 is preferred for the reasons outlined above.

The overall rms misfit level produced by the model of Figure 9 is 2.5. To further describe the fit of the model, examples of individual response data are shown in Figures 11 and 12. Figure 11 shows observed (line) and modelled (symbol) data for the TM-mode at sites 001 and 008. Figure 12 shows observed and modelled data for the TE-mode at sites 003 and 006. A further comparison between observed and modelled data is shown in the form of pseudo-sections in Figures 13 and 14. Here the eight selected frequencies along the 7 site profile are used and the comparison uses the TM-mode response. Figure 13 shows the comparison in apparent resistivity (logarithmic scale) and Figure 14 is a comparison of phase. Overall the agreement between data and model is excellent.

SUMMARY

It should be noted that the final geoelectric model (Figure 9) produced by the OCCAM 2D inversion possesses minimum structure. This means that sharp (stepwise) discontinuities are not imaged and the gradients present are likely to represent significant 'stucture'. The largest gradients occur through the upper crustal interval and are centred on a depth of about 2.5 km to the NW of site 001. Elsewhere through the upper crustal interval the resistivities above 1000 ohm.m are presumably associated with the main Silurian greywacke formation. The lower resistivities associated with the Lochmaben basin are represented in block model fashion by the at-surface decrease in resistivity centred on +3 km.

Through the 'normal' greywacke sequence between -3 and 9 km, resistivities in excess of 1000 ohm.m are maintained down to about 12 km. The resistivities are then found to decrease through to values of less than 100 ohm.m by the lower crust. These values for the middle and lower crust are compatible with previous estimates from MT data across the Southern Uplands (Hutton *et al.*, 1980; Ingham and Hutton, 1982; Beamish, 1986). A significant feature of the model in Figure 9 is the lateral gradients through the lower crust (below 15 km) that occur *beneath* the location of the main upper crustal anomaly. The image of Figure 9 indicates a whole crustal resistivity anomaly centred on a line of about -10 km in model coordinates.

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deGroot-Hedlin, C. and Constable, S., 1990. Occam's inversion to generate smooth, two-dimensional models from magnetotelluric data, *Geophysics*, 55, 1613-1624.

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Ingham, M.R. and Hutton, V.R.S., 1982. Crustal and upper mantle electrical conductivity in southern Scotland, *Geophys. J. R. astr. Soc.*, 69, 579-594.

Rollin, K.E., 1991. Gravity models of the upper Palaeozoic deposits near Dumfries, *British Geological Survey*, unpublished manuscript.

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FIGURE CAPTIONS.

Figure 1. Location of MT survey profile (+ to +) on geological map of the Southern Uplands after Stone *et al* (1987).

Figure 2. Detailed site locations of the MT survey. Sites are referred to as 001 to 008 in the text. Centre (dotted) line defines a model centre coordinate of 301.6, 591.3 km.

Figure 3. Geoelectric strike azimuths defining the direction of maximum or minimum resistivity. (a) Upper. High frequencies, from 50 to 10 Hz. (b) Lower. Low frequencies, from .065 to .021 Hz.

Figure 4. Sounding data rotated to principal geoelectric strike direction. Site 1 (solid dots). Sites 002, 003, 004 and 006 (continuous lines). Site 005 (open crosses). Sites 007 and 008 (open circles). (a) Upper. TE-mode, + 50 degrees. (b) Lower, TM-mode, +140 degrees.

Figure 5. Four layer 1-D inversions of the rotationally-invariant response at sites 007 (single line) and 008 (line with infill). Left frame shows results in logarithmic depth and right frame shows results in linear depth scale.

Figure 6. Taken from Rollin (1991, Fig.4). Computed depths in km below OD to the base of the sedimentary basins in the Dumfries area, using a single density contrast. In the Lochmaben basin, the model represents the *minimum* thickness of Permian rocks needed to explain the gravity residuals. Location of sites 007 and 008, together with profile (+140 degrees) are superimposed.

Figure 7. Profile coordinates for 2-D modelling. Centre (dotted lines) is at 301.6, 591.3 km. Line at +50 degrees defines TE-mode direction (geoelectric strike). Orthogonal line at +140 degrees defines TM-mode direction.

Figure 8. OCCAM 2D solution (no static shift option) shown as true-scale crustal cross-section in log (resistivity). RMS misfit is 4.2. The 7 site locations used are shown by dots.

Figure 9. OCCAM 2D solution (with static shift option) shown as true-scale crustal cross-section in log (resistivity). RMS misfit is 2.5. The 7 site locations used are shown by dots.

Figure 10. Static shift parameters obtained from the OCCAM 2D inverse model of Figure 9.

Figure 11. Examples of the fit between observed sounding data (continuous lines) and modelled data (symbols) achieved by the OCCAM 2D model of Figure 9. TM mode results. (a) Upper. Data at site 001. (b) Lower. Data at site 008.

Figure 12. Examples of the fit between observed sounding data (continuous lines) and modelled data (synbols) achieved by the OCCAM 2D model of Figure 9. TE-mode results. (a) Upper. Data at site 003. (b) Lower. Data at site 006.

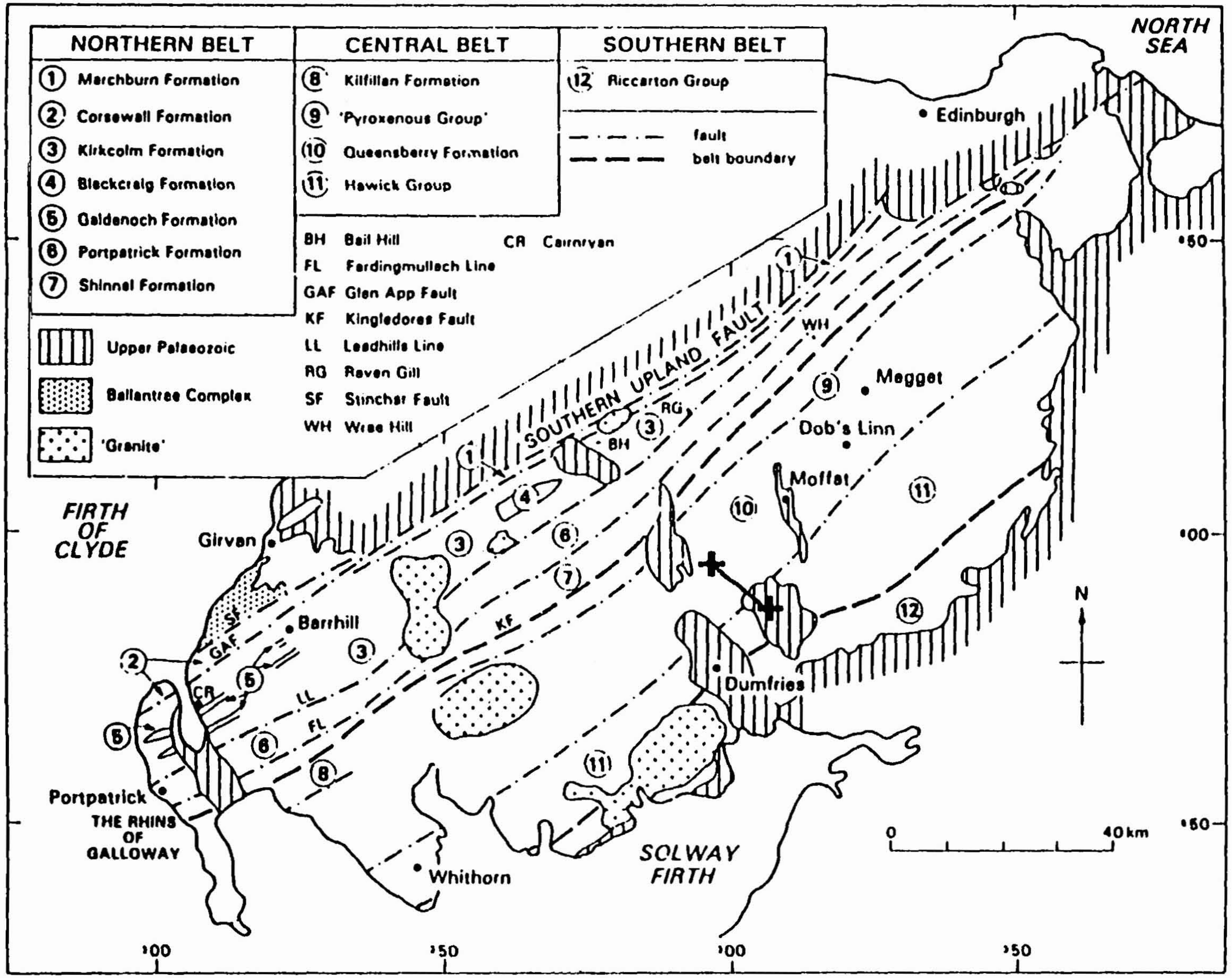
Figure 13. Example of the fit between observed sounding data and that of the modelled response. 7-site pseudo-sections in apparent resistivity (logarithmic scale).

Figure 14. Example of the fit between observed sounding data and that of the modelled response. 7-site pseudo-sections in phase.

TABLE 1. AE FOREST MT SURVEY. SITE DETAILS.

The 8 sites comprising the Ae forest survey are listed 001-008. The profile consists of a NW-SE traverse with site 001 defining the northern-most site and site 008 defining the southern-most site. The FIELD-ID is a field (data file) code which also refers to the chronological order of the survey (i.e. 111 to 888). Date refers to site occupation. National Grid coordinates and elevations (from 1:10000 O.S. maps) are given in metres.

SITE CODE	FIELD ID	DATE	EASTING (m)	NORTHING (m)	HEIGHT (m)
001	444	13-09-91	296590	596420	220
002	333	12-09-91	298590	595355	280
003	222	11-09-91	299730	594000	290
004	555	14-09-91	299820	592740	340
005	111	10-09-91	300920	592140	249
006	666	15-09-91	302340	591000	297
007	777	16-09-91	303770	588690	82
008	888	17-09-91	306100	587050	58



Geological map of the Southern Uplands showing lithostratigraphic divisions, major faults, boundaries between the belts and localities mentioned in the text.

Fig.1

Fig.2

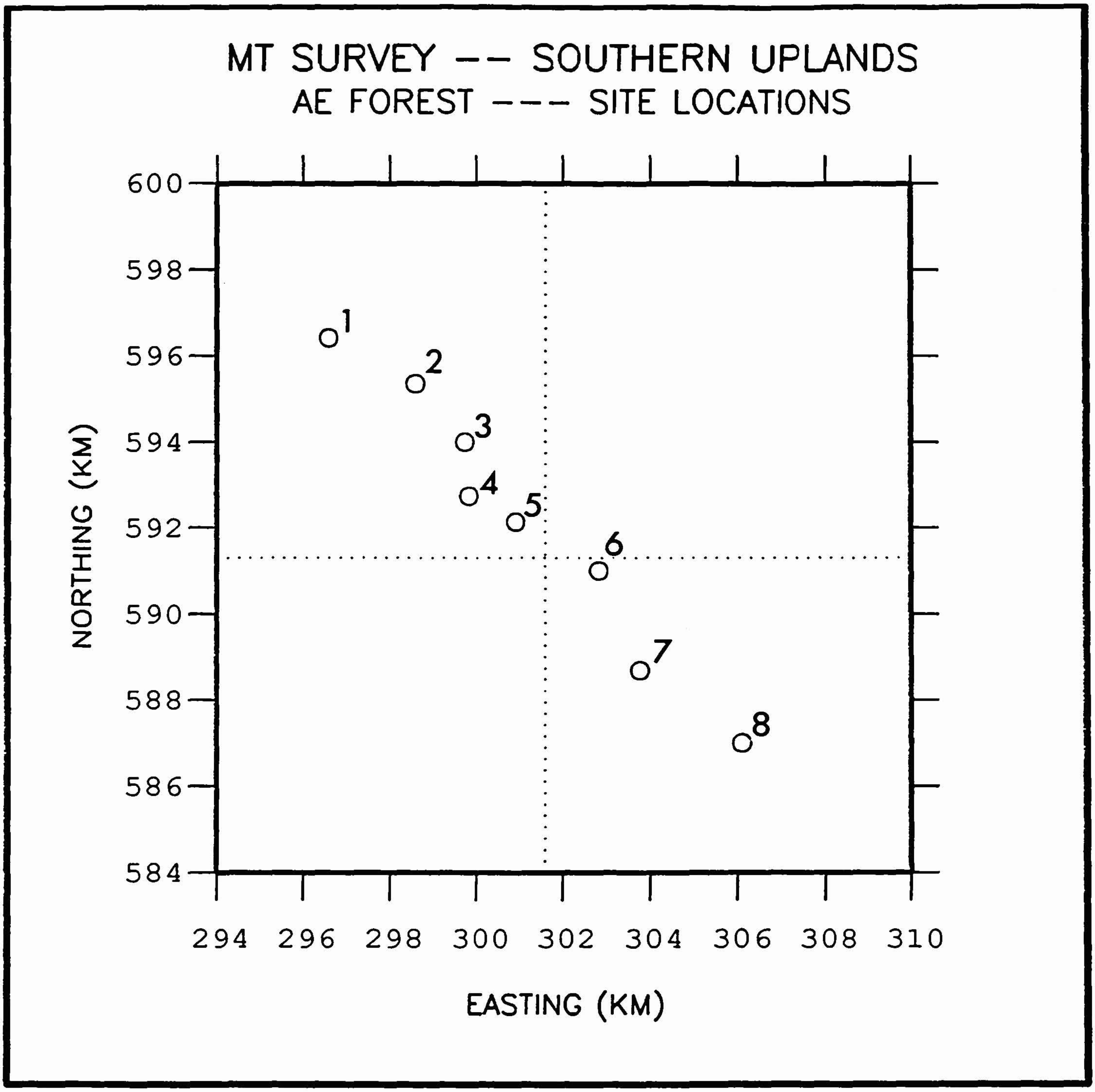
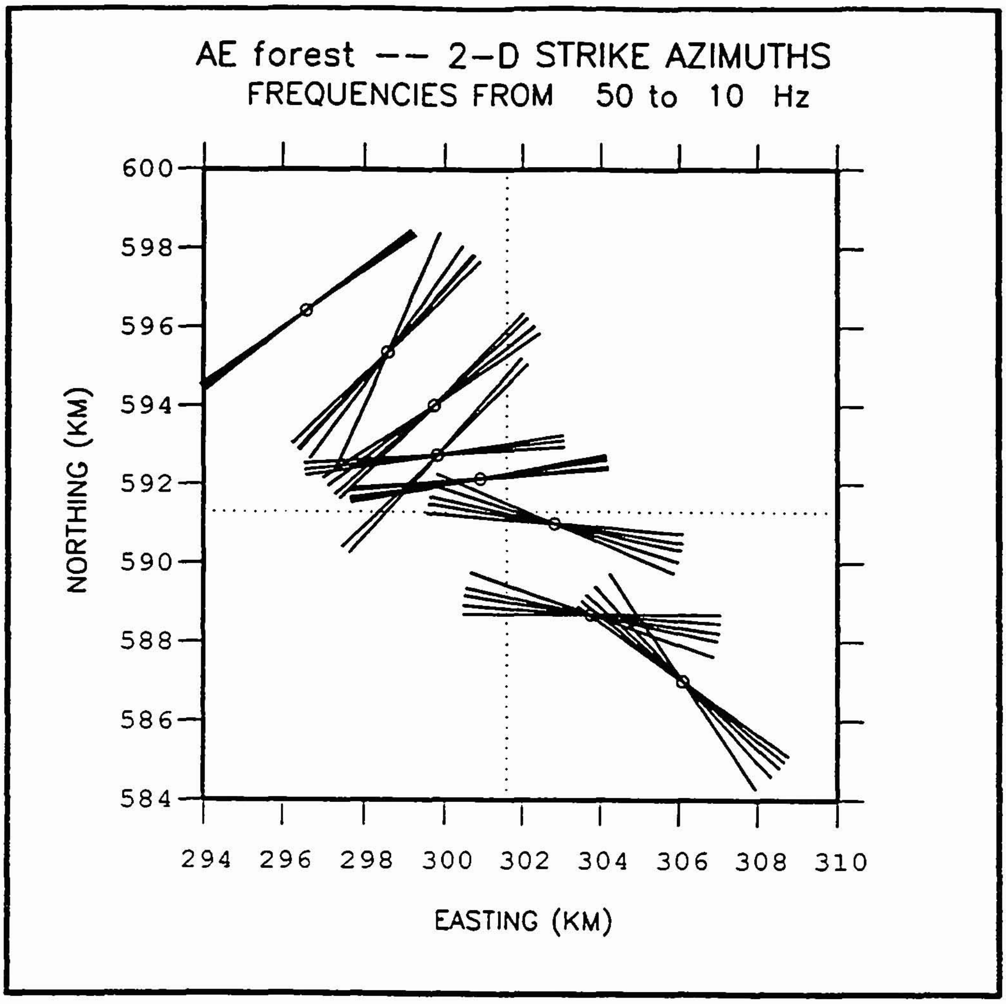
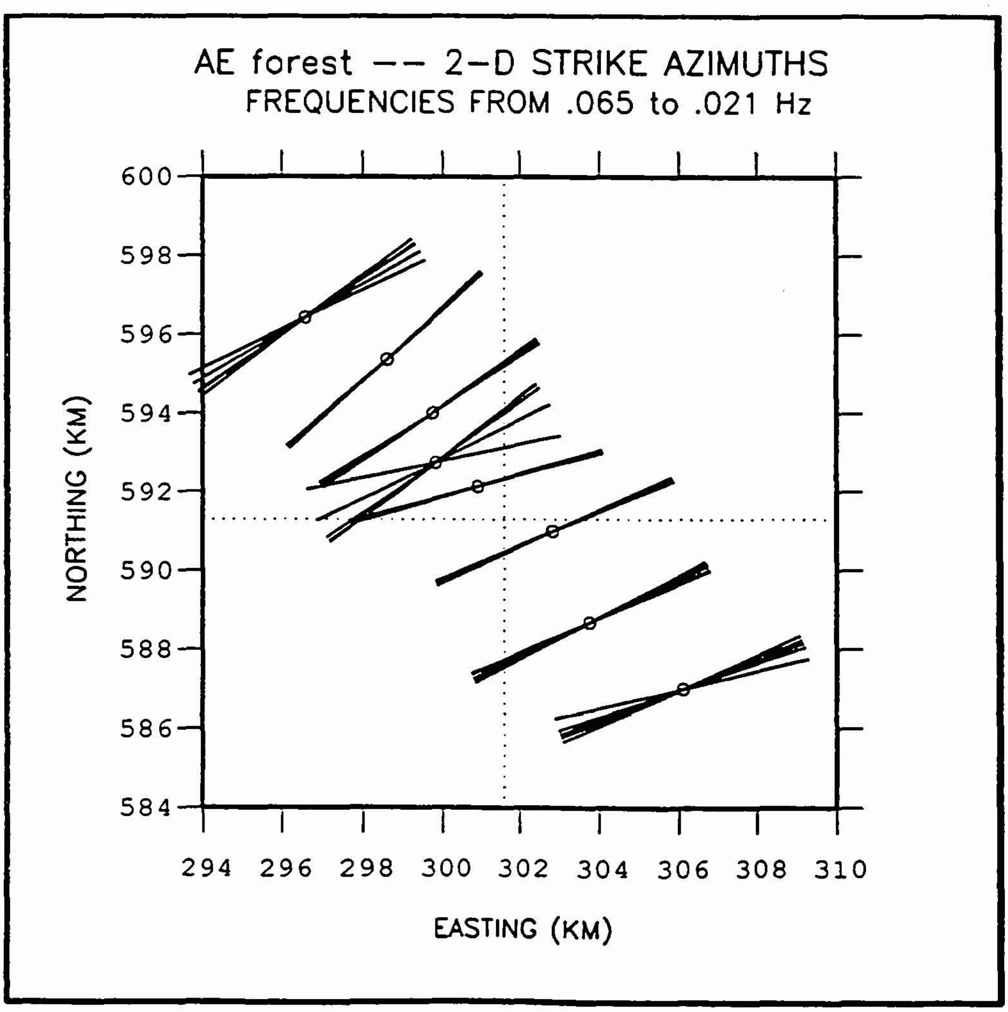

MT SURVEY -- SOUTHERN UPLANDS
AE FOREST --- SITE LOCATIONS
NORTHING (KM)
EASTING (KM)
600
598
596
594
592
590
588
586
584
294
296
298
300
302
304
306
308
310
1
2
3
4
5
6
7
8

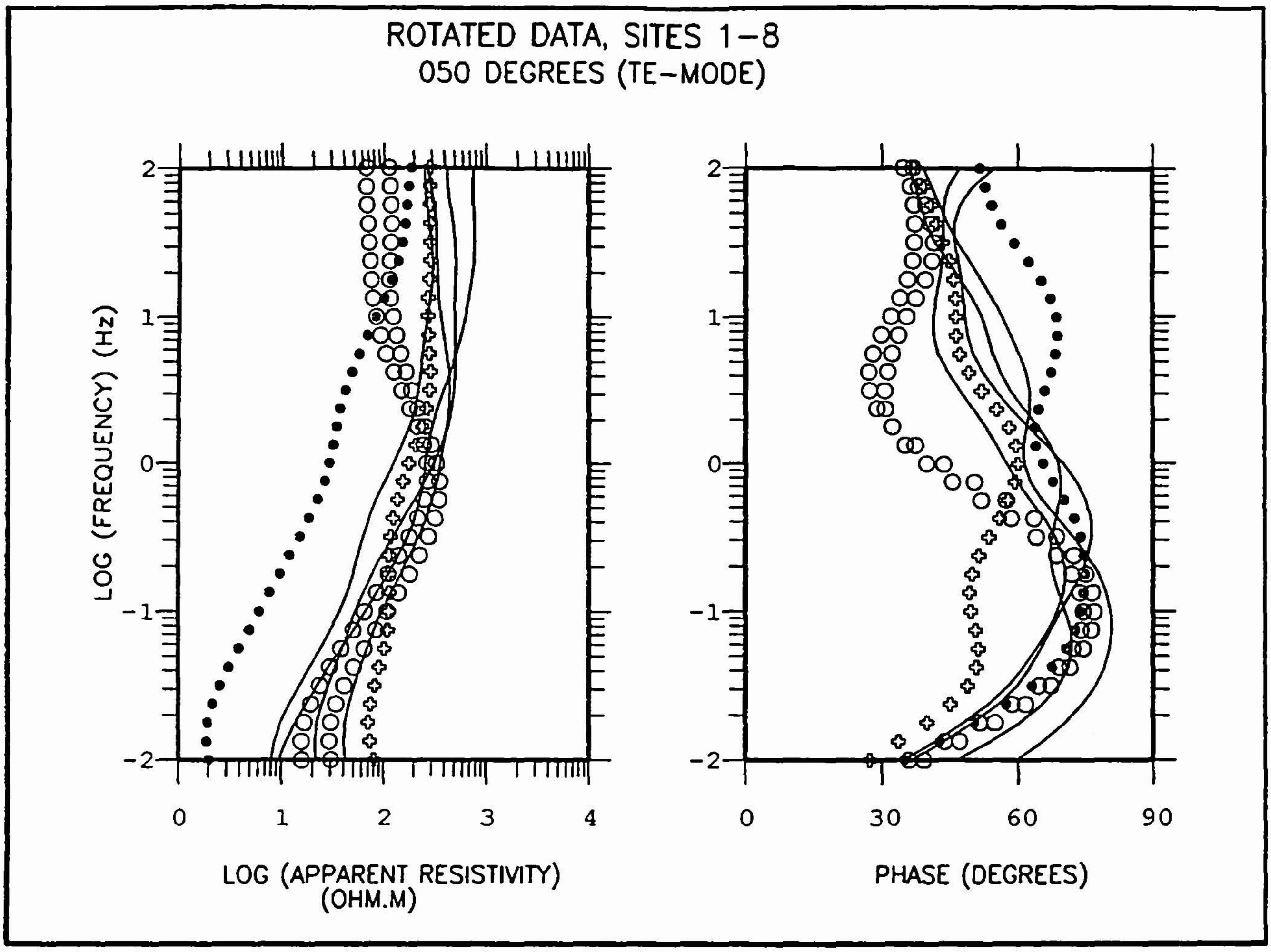
Fig.3



AE forest -- 2-D STRIKE AZIMUTHS
FREQUENCIES FROM 50 to 10 Hz
600
598
596
594
592
590
588
586
584
NORTHING (KM)
294 296 298 300 302 304 306 308 310
EASTING (KM)



AE forest -- 2-D STRIKE AZIMUTHS
FREQUENCIES FROM .065 to .021 Hz
600
598
596
594
592
590
588
586
584
NORTHING (KM)
294 296 298 300 302 304 306 308 310
EASTING (KM)


ROTATED DATA, SITES 1-8
050 DEGREES (TE-MODE)
LOG (FREQUENCY) (Hz)
LOG (APPARENT RESISTIVITY) (OHM.M)
PHASE (DEGREES)
2
1
0
-1
-2
0
1
2
3
4
0
30
60
90

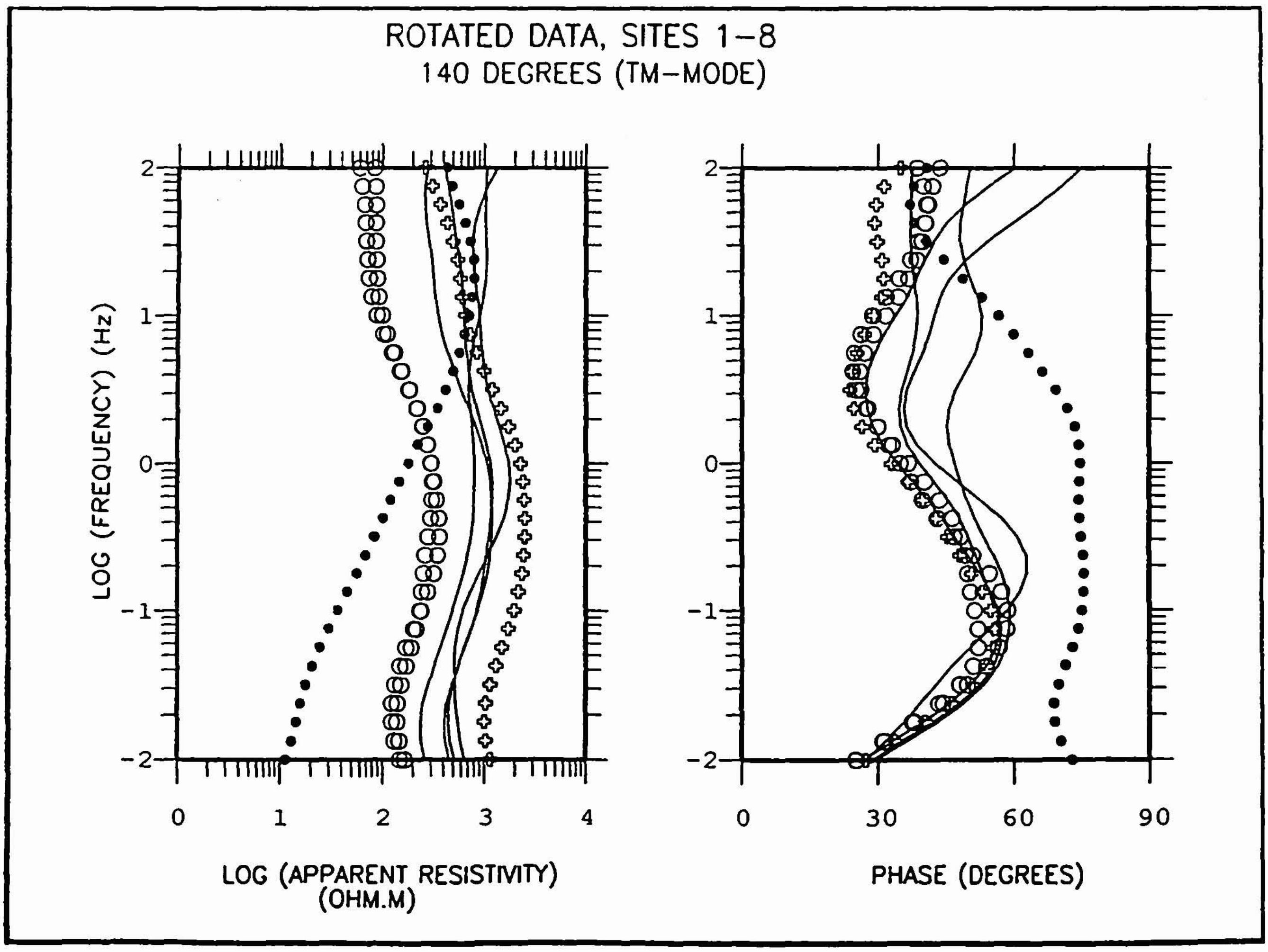
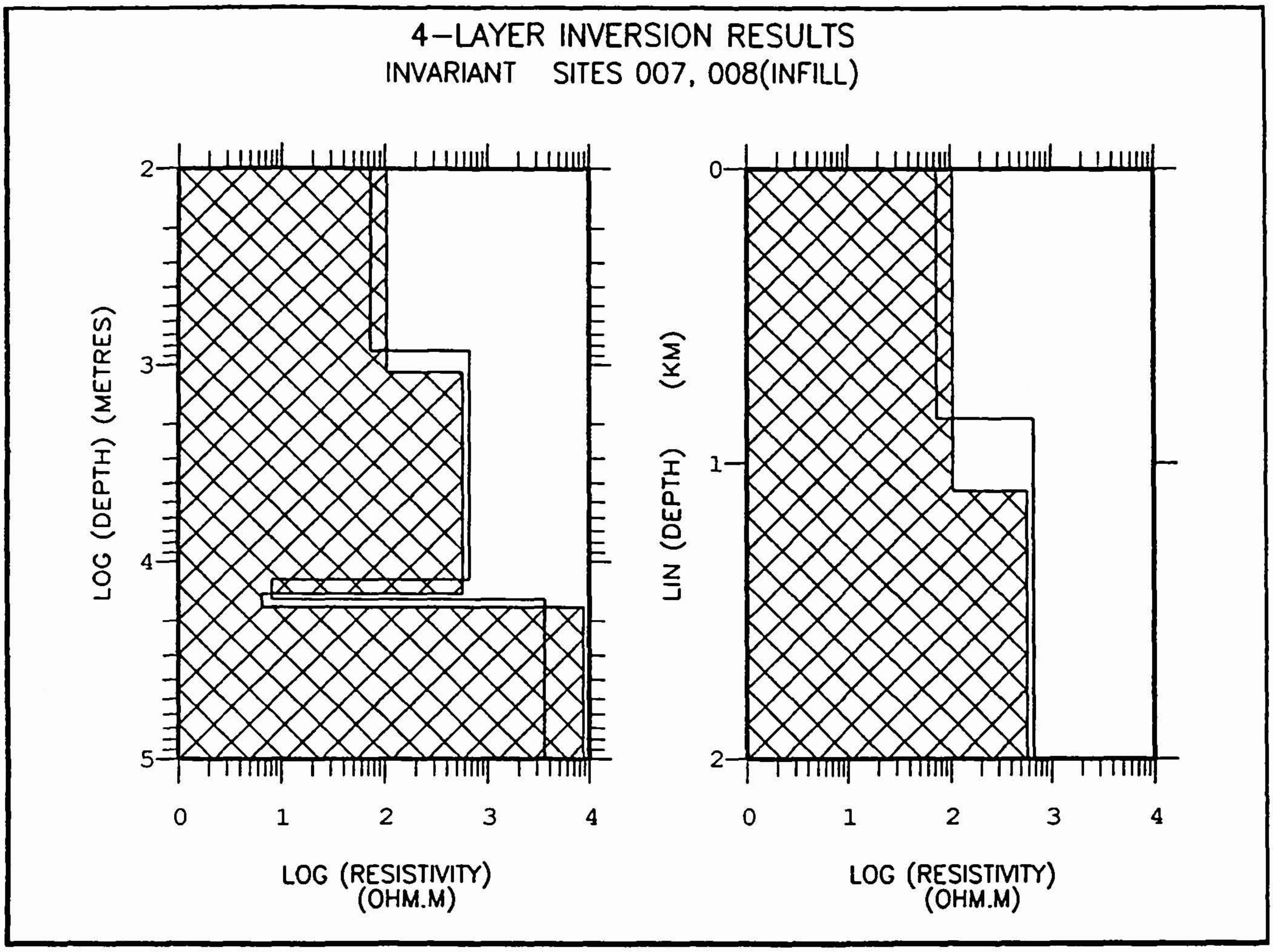
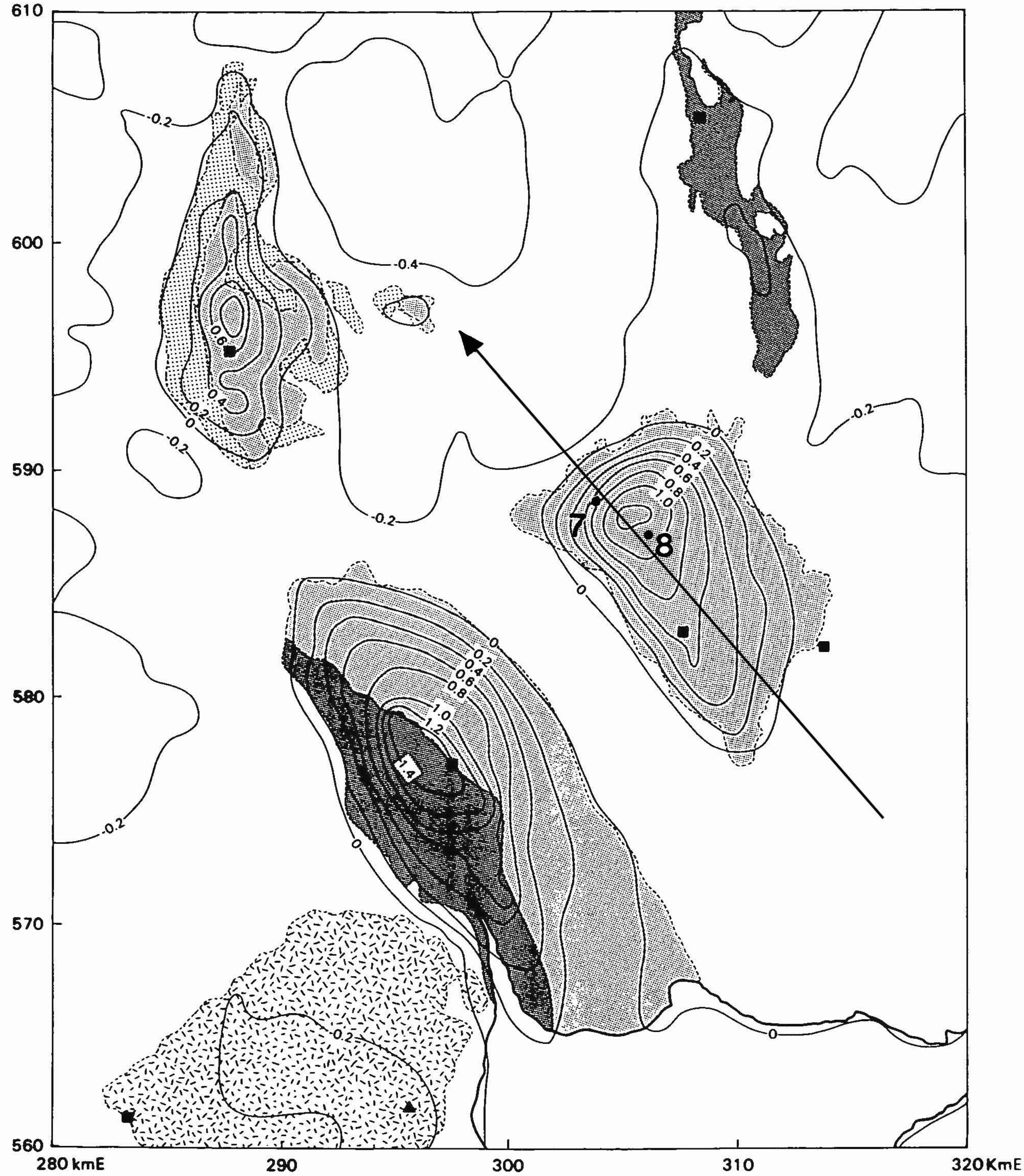

ROTATED DATA, SITES 1-8
140 DEGREES (TM-MODE)
LOG (FREQUENCY) (Hz)
LOG (APPARENT RESISTIVITY) (OHM.M)
PHASE (DEGREES)
2
1
0
-1
-2
0
1
2
3
4
0
30
60
90

Fig. 5



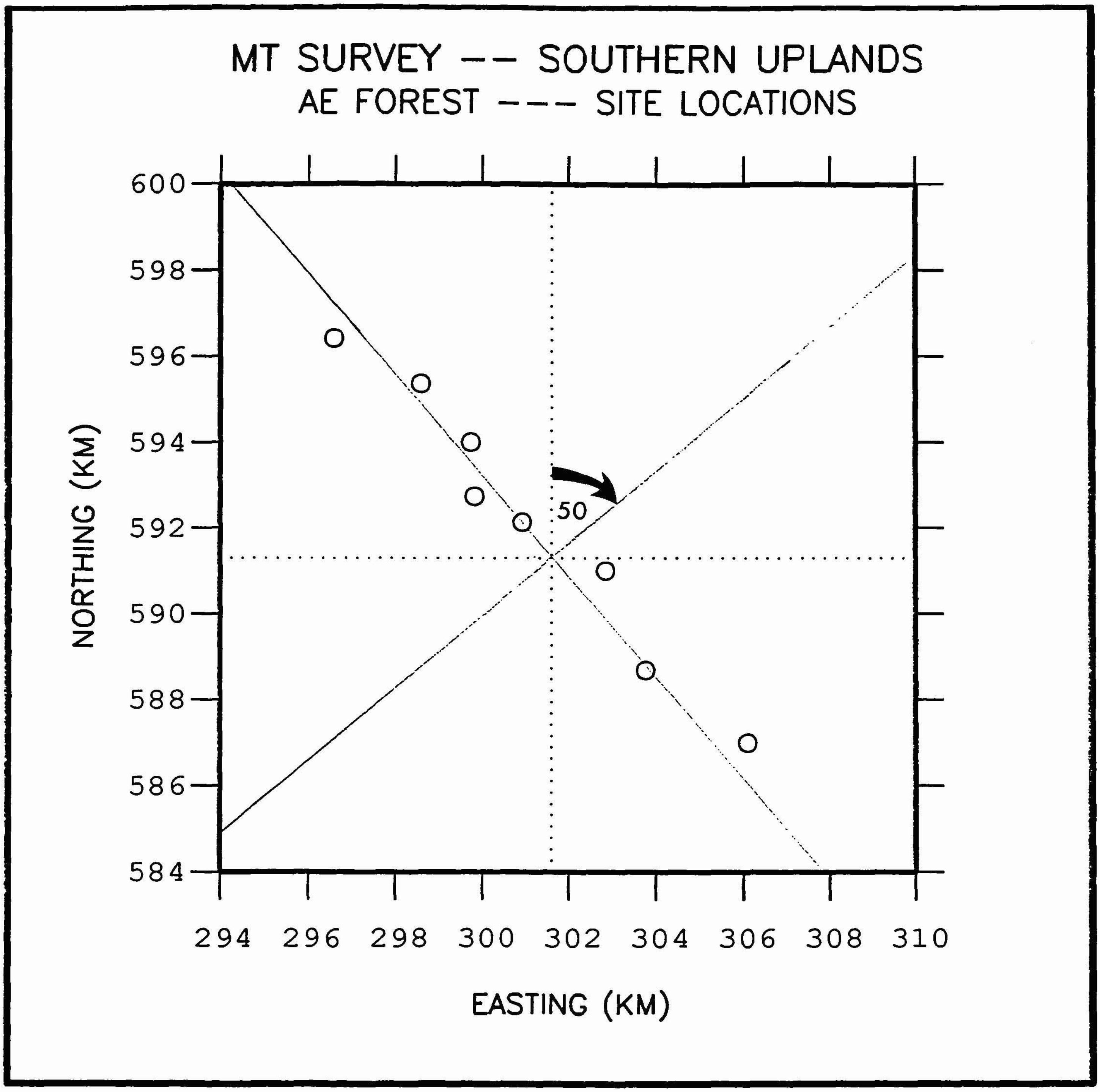
4-LAYER INVERSION RESULTS
INVARIANT SITES 007, 008(INFILL)
LOG (DEPTH) (METRES)
2
3
4
5
0
1
2
3
4
LOG (RESISTIVITY)
(OHM.M)
LIN (DEPTH) (KM)
0
1
2
0
1
2
3
4
LOG (RESISTIVITY)
(OHM.M)

Fig.6



610
600
590
580
570
560
280 kmE
290
300
310
320 KmE
-0.2
-0.4
-0.2
0.6
0.4
0.2
0
0.2
0.4
0.6
0.8
1.0
7
8
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
0
0
-0.2

Fig.7



MT SURVEY -- SOUTHERN UPLANDS
AE FOREST --- SITE LOCATIONS
600
598
596
594
592
590
588
586
584
NORTHING (KM)
50
294
296
298
300
302
304
306
308
310
EASTING (KM)

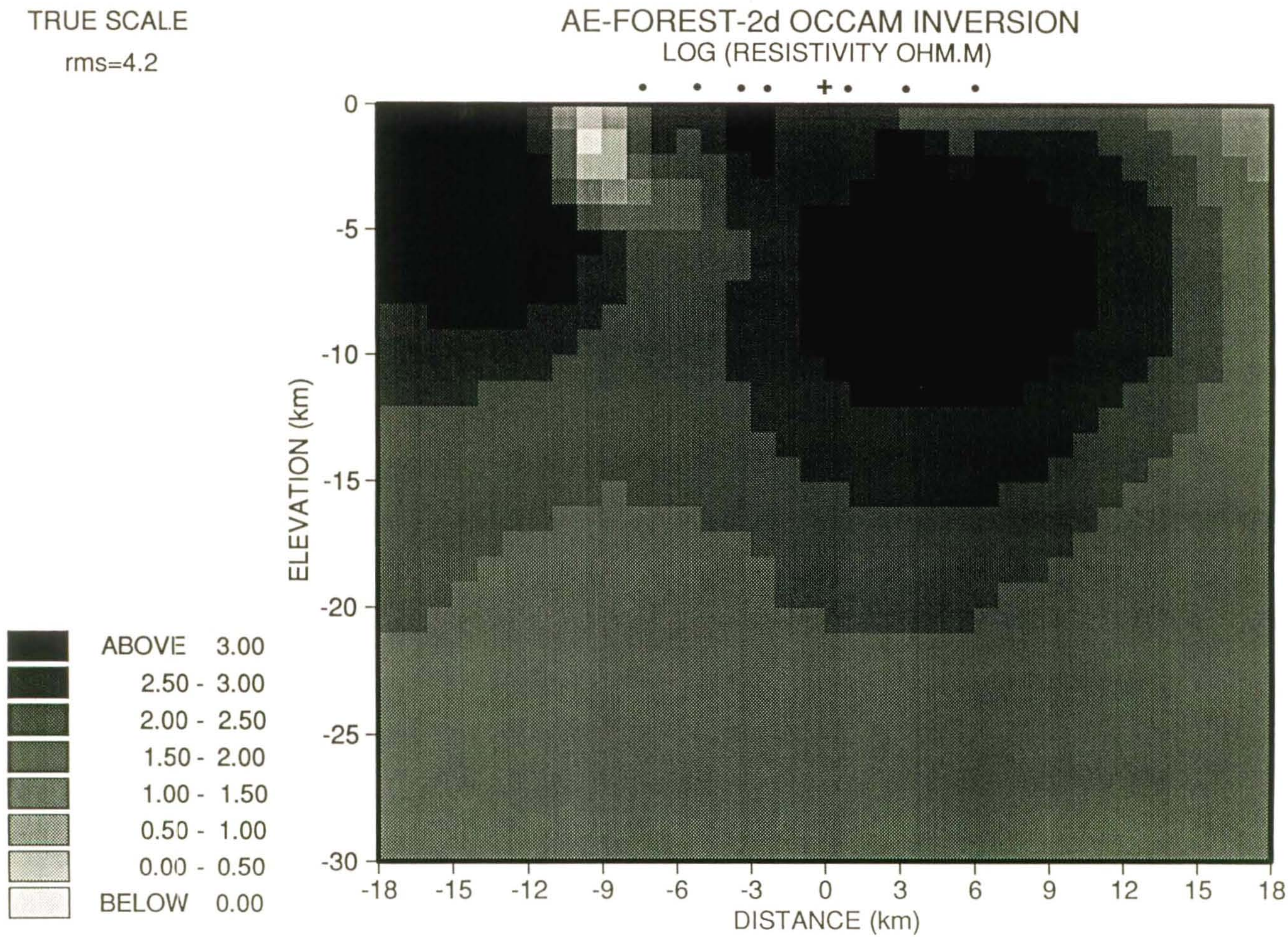

TRUE SCALE
rms=4.2
AE-FOREST-2d OCCAM INVERSION
LOG (RESISTIVITY OHM.M)
ELEVATION (km)
DISTANCE (km)
0
-5
-10
-15
-20
-25
-30
-18
-15
-12
-9
-6
-3
0
3
6
9
12
15
18
ABOVE 3.00
2.50 - 3.00
2.00 - 2.50
1.50 - 2.00
1.00 - 1.50
0.50 - 1.00
0.00 - 0.50
BELOW 0.00

Fig.8

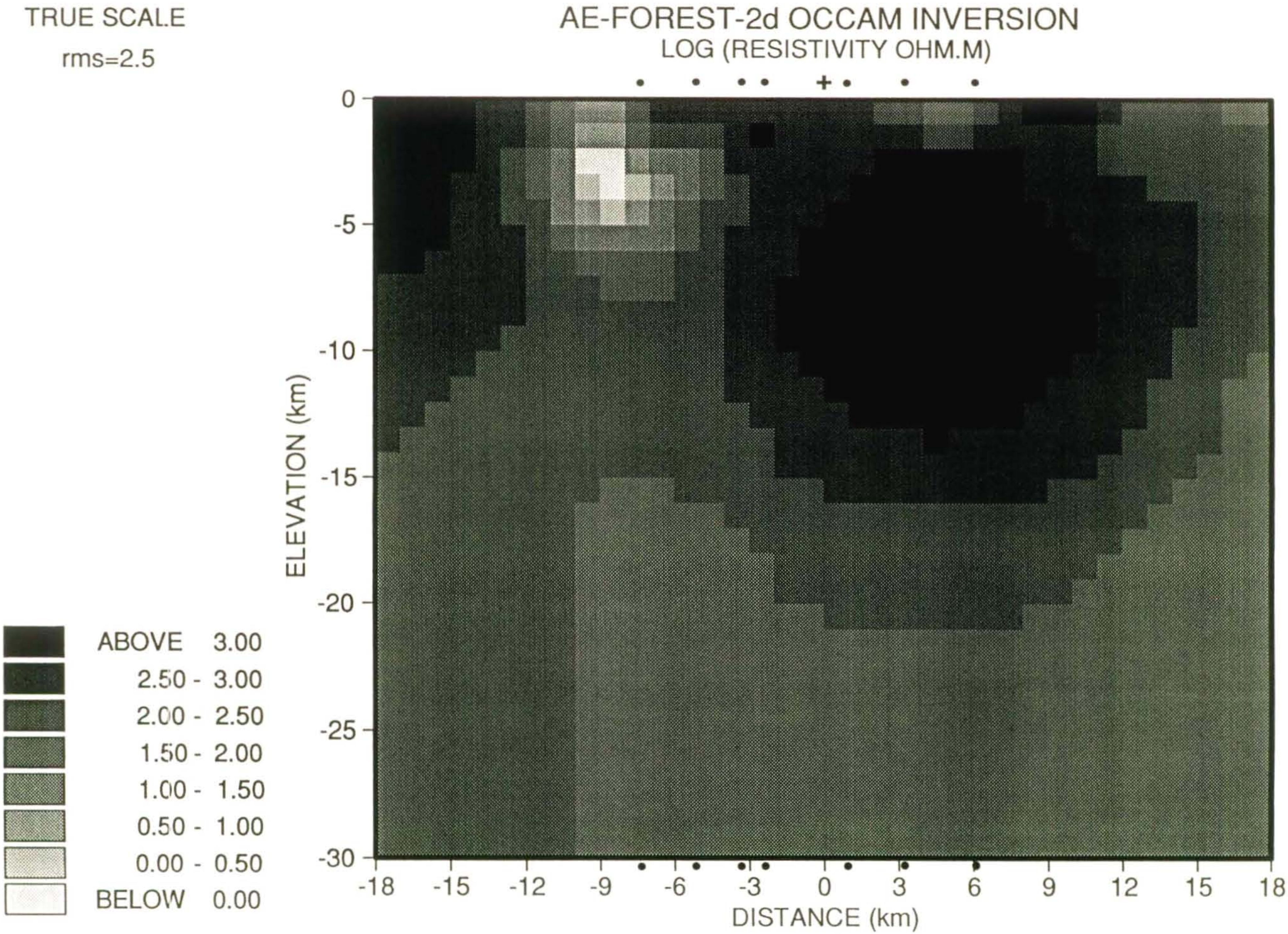

TRUE SCALE
rms=2.5
AE-FOREST-2d OCCAM INVERSION
LOG (RESISTIVITY OHM.M)
ELEVATION (km)
0
-5
-10
-15
-20
-25
-30
-18
-15
-12
-9
-6
-3
0
3
6
9
12
15
18
DISTANCE (km)
ABOVE 3.00
2.50 - 3.00
2.00 - 2.50
1.50 - 2.00
1.00 - 1.50
0.50 - 1.00
0.00 - 0.50
BELOW 0.00

Fig. 9

Fig.10

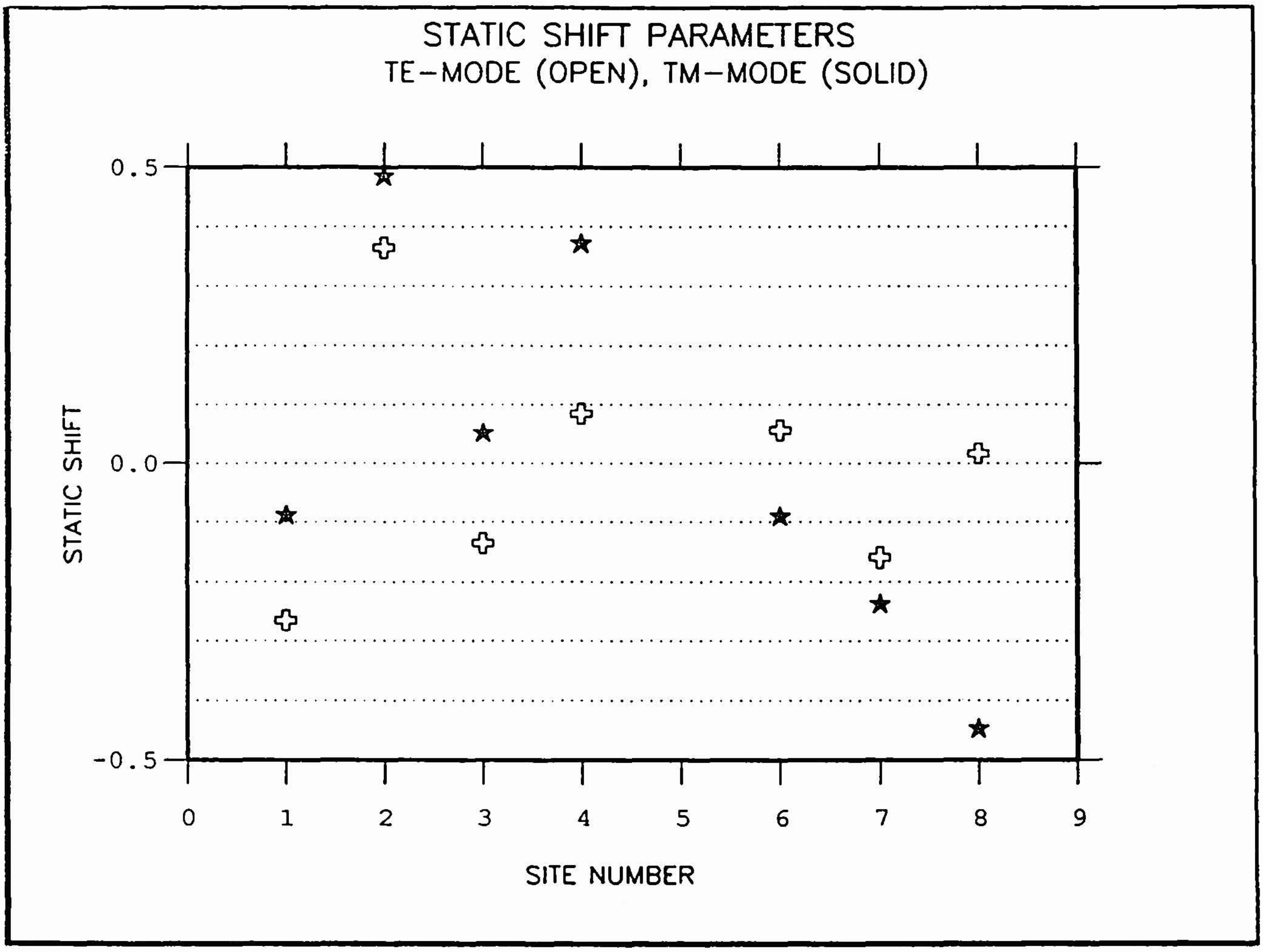
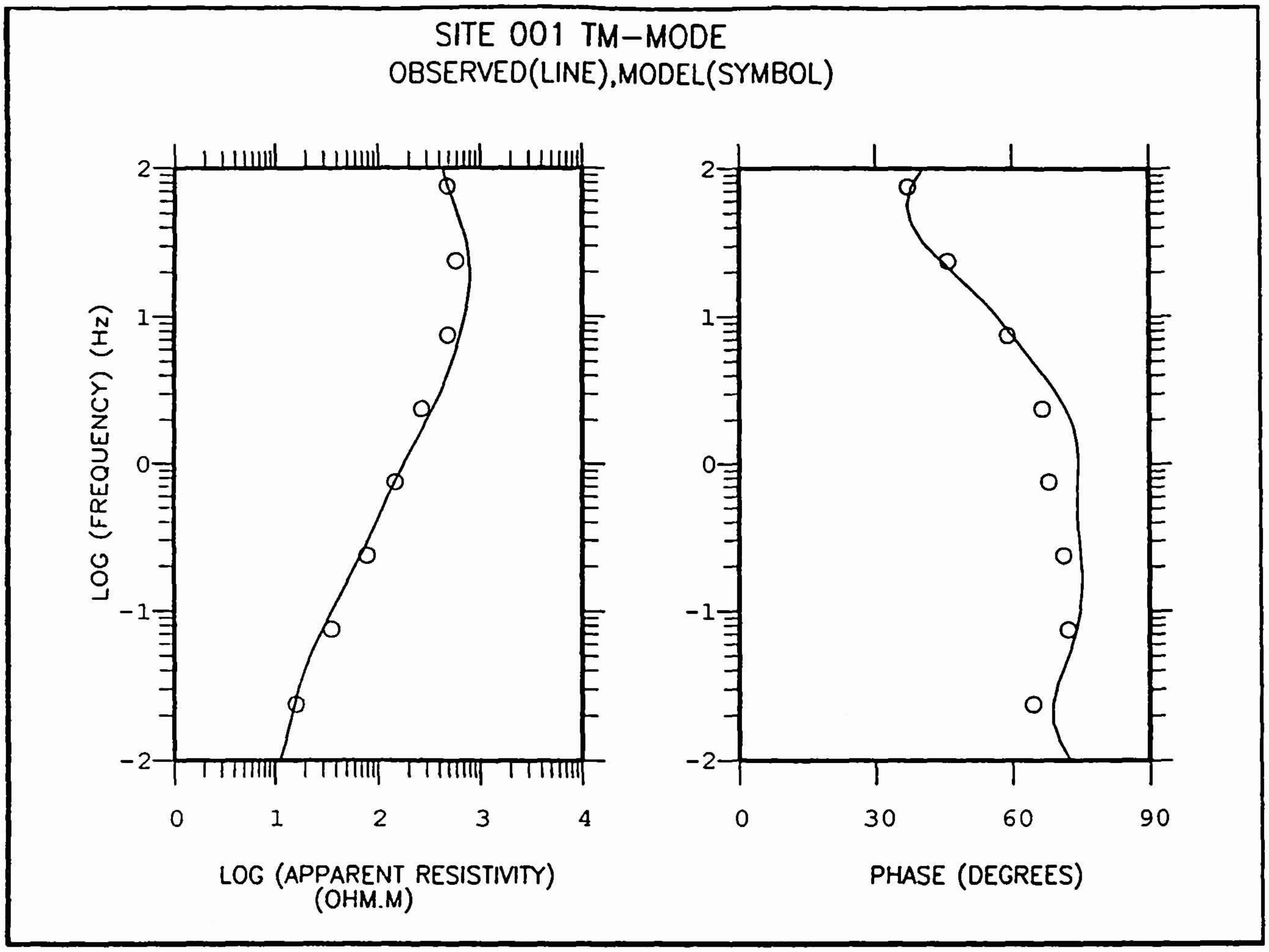

STATIC SHIFT PARAMETERS
TE–MODE (OPEN), TM–MODE (SOLID)
STATIC SHIFT
0.5
0.0
-0.5
0
1
2
3
4
5
6
7
8
9
SITE NUMBER

Fig.11


SITE 001 TM-MODE
OBSERVED(LINE),MODEL(SYMBOL)
LOG (FREQUENCY) (Hz)
2
1
0
-1
-2
0
1
2
3
4
LOG (APPARENT RESISTIVITY) (OHM.M)
0
30
60
90
PHASE (DEGREES)

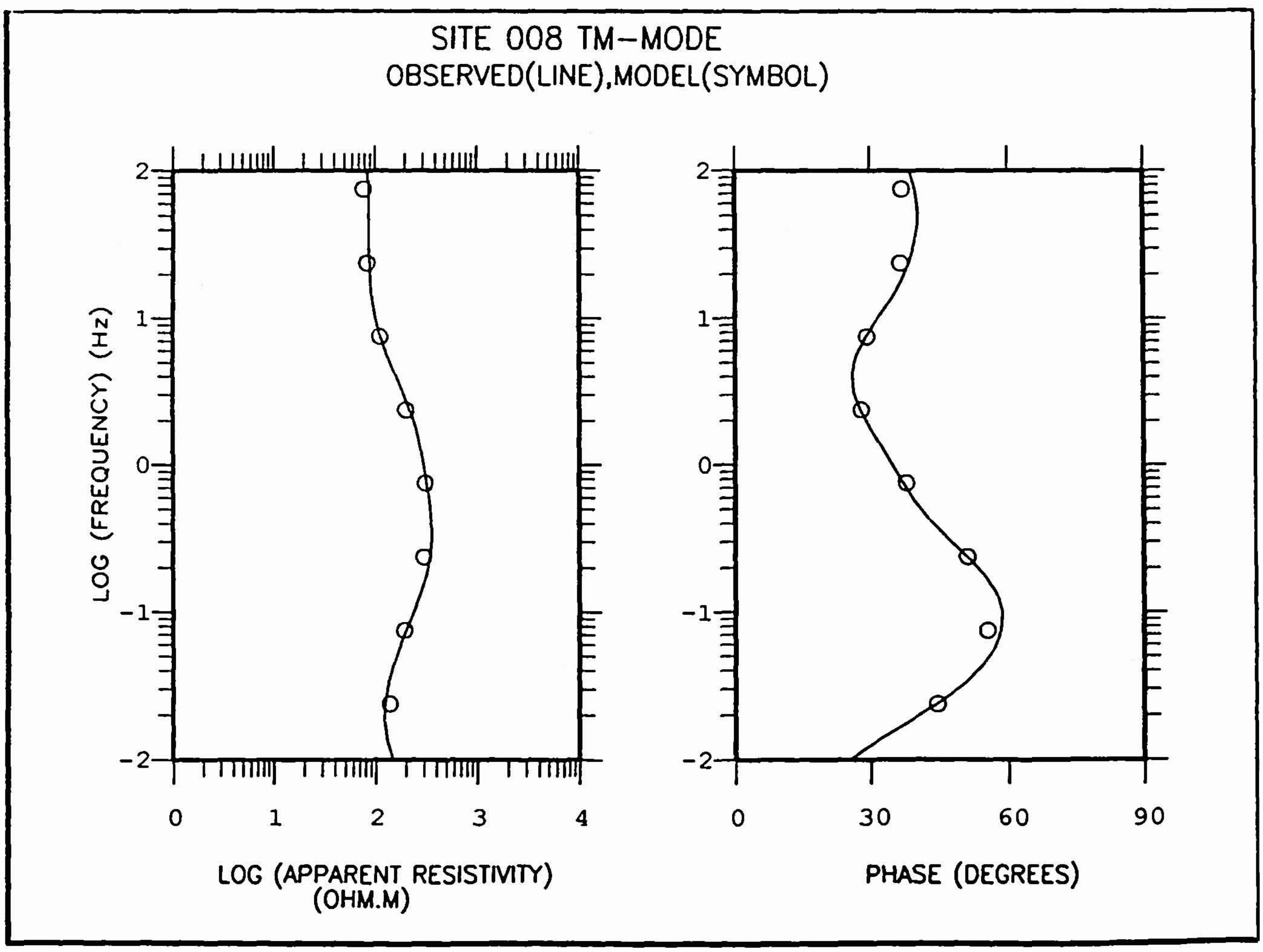
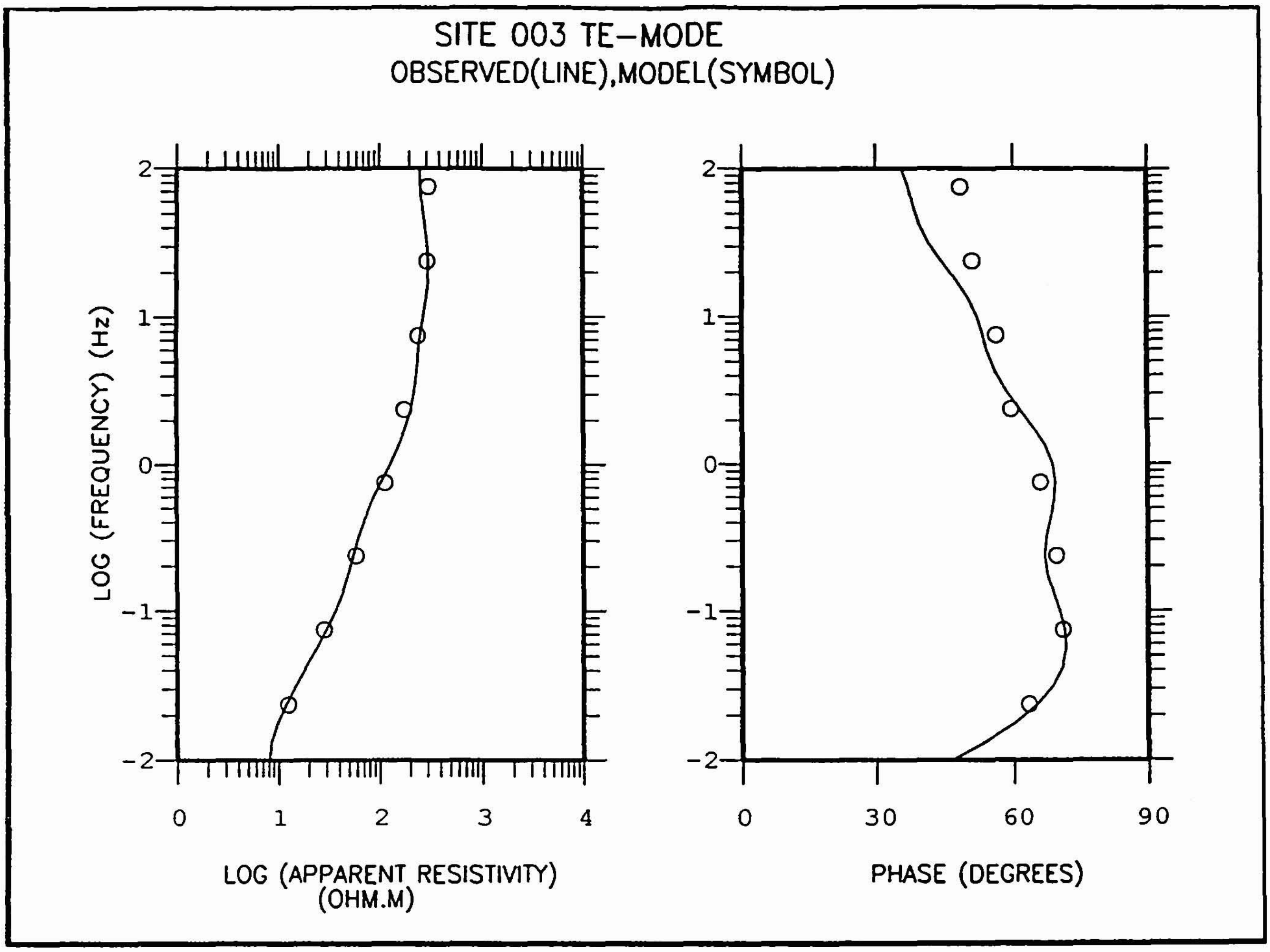
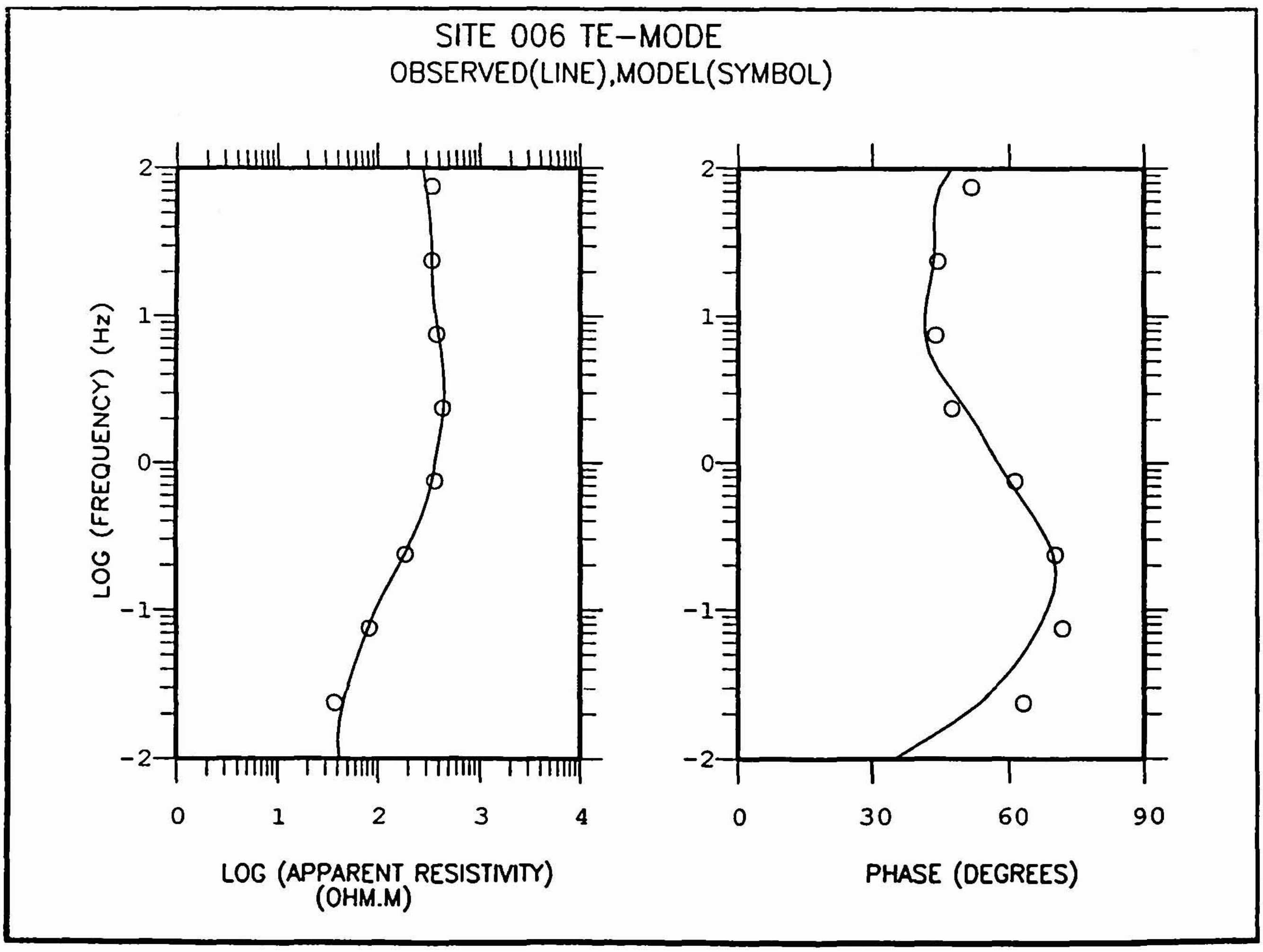

SITE 008 TM-MODE
OBSERVED(LINE),MODEL(SYMBOL)
LOG (FREQUENCY) (Hz)
2
1
0
-1
-2
0
1
2
3
4
LOG (APPARENT RESISTIVITY) (OHM.M)
0
30
60
90
PHASE (DEGREES)

Fig. 12


SITE 003 TE-MODE
OBSERVED(LINE),MODEL(SYMBOL)
LOG (FREQUENCY) (Hz)
2
1
0
-1
-2
0
1
2
3
4
LOG (APPARENT RESISTIVITY)
(OHM.M)
0
30
60
90
PHASE (DEGREES)


SITE 006 TE-MODE
OBSERVED(LINE),MODEL(SYMBOL)
LOG (FREQUENCY) (Hz)
2
1
0
-1
-2
0
1
2
3
4
LOG (APPARENT RESISTIVITY)
(OHM.M)
0
30
60
90
PHASE (DEGREES)

AE-FOREST TM MODE RESPONSE
OBSERVED/MODELLED PSEUDO-SECTIONS
LOG (APPARENT RESISTIVITY OHM.M)

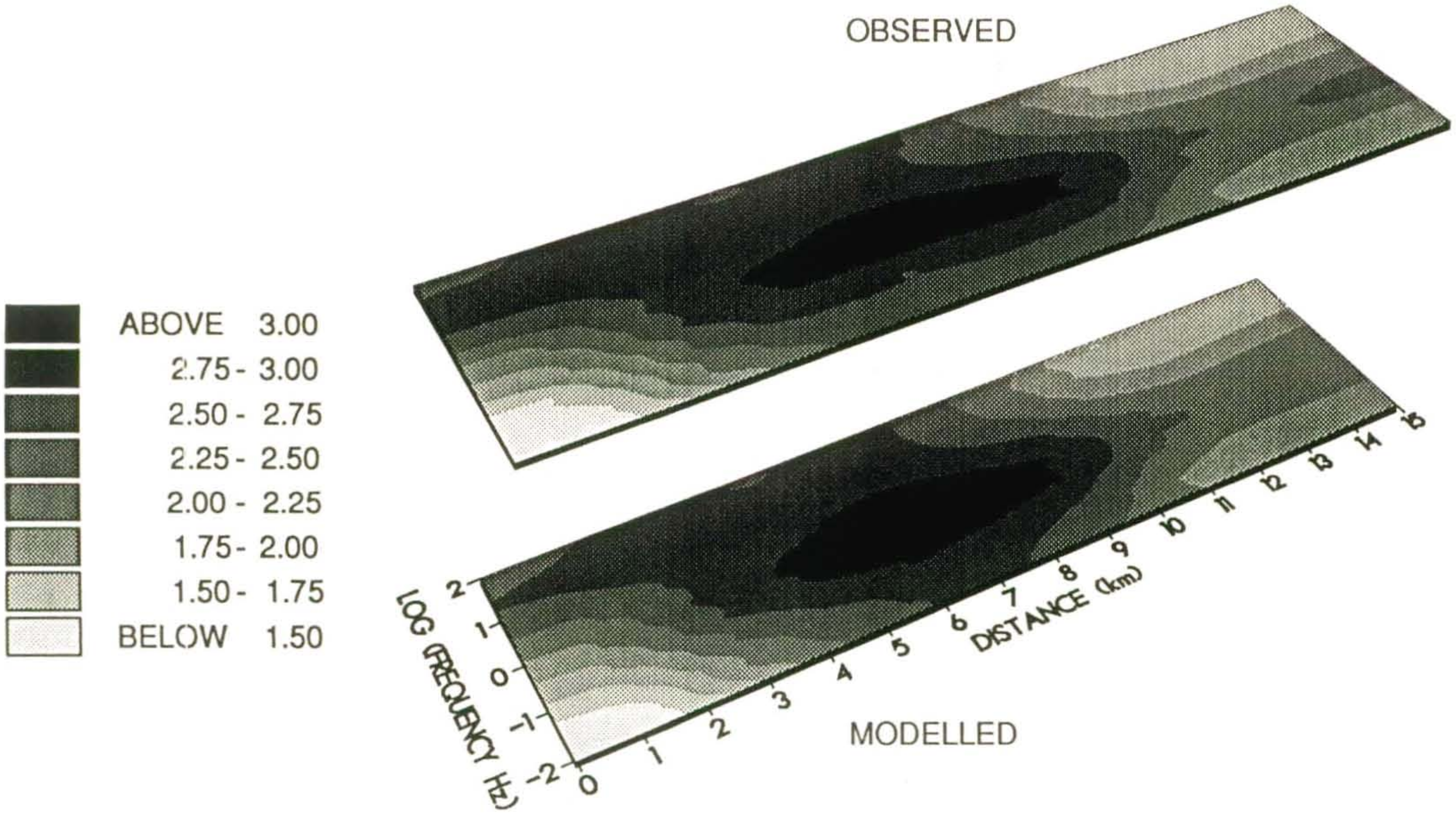


Fig.13

AE-FOREST TM MODE RESPONSE
OBSERVED/MODELLED PSEUDO-SECTIONS
PHASE (DEGREES)

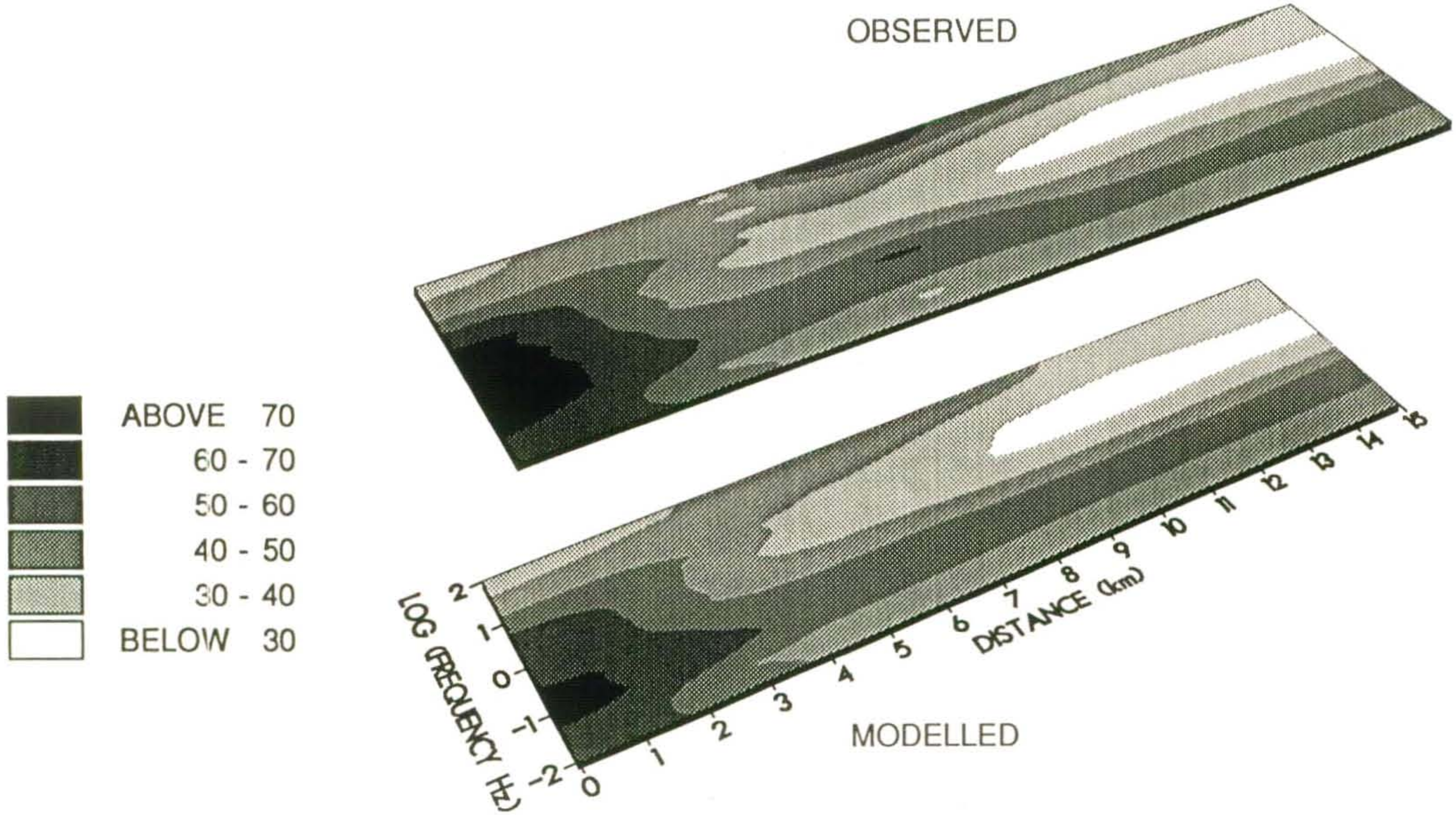


Fig.14