

GEOELECTROMAGNETICS IN THE SOLUTION OF SOME TECTONIC,
STRATIGRAPHIC AND ENVIRONMENTAL PROBLEMS

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A B S T R A C T

Important and in many respects unique information about the subsurface can be derived from electromagnetic (EM) models. Deep EM surveys have been conducted in a variety of geological environments in order to resolve some outstanding problematical observations. In the case of the Caledonides of Scotland, it is shown that a wealth of structural information is contained in the EM models thus allowing the resolution of problems encountered in previous geological and geophysical studies. From basin evaluation applications, it is shown that EM methods are useful stratigraphic mapping tools. Also, EM methods are used to confirm the geologically suggested presence of a NW-SE axial block-faulted structure (the Larnaca Graben) in the NNE Troodos Ophiolite, Cyprus. A new method for transforming surface resistivity data into pseudo-borehole logs is discussed and applied in the location of a deep contaminated aquifer in a landfill site.

ΓΕΩΗΛΕΚΤΡΟΜΑΓΝΗΤΙΚΕΣ ΜΕΘΟΔΟΙ ΣΤΗ ΛΥΣΗ ΜΕΡΙΚΩΝ ΤΕΚΤΟΝΙΚΩΝ
ΣΤΡΩΜΑΤΟΓΡΑΦΙΚΩΝ ΚΑΙ ΠΕΡΙΒΑΛΛΟΝΤΟΛΟΓΙΚΩΝ ΠΡΟΒΛΗΜΑΤΩΝ

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Π Ε Ρ Ι Λ Η Ψ Η

Τα ηλεκτρομαγνητικά μοντέλα μπορούν να δώσουν σημαντικές και σε ορισμένες περιπτώσεις μοναδικές πληροφορίες για το υπέδαφος. Βαθείες ηλεκτρομαγνητικές διασκοπήσεις (EM) έχουν διεξαχθεί σε διάφορα γεωλογικά περιβάλλοντα με σκοπό να διαφωτίσουν προβληματικές παρατηρήσεις. Στην περίπτωση των Καληδονιδών της Σκωτίας, φαίνεται ο πλούτος των τεκτονικών πληροφοριών που περιέχεται στα τεκτονικά μοντέλα και ο οποίος μας επιτρέπει την επίλυση προβλημάτων που είχαν εντοπιστεί σε προηγούμενες γεωλογικές και γεωφυσικές μελέτες. Όσον αφορά την μελέτη λεκανών, αποδεικνύεται ότι τα EM μοντέλα είναι χρήσιμα στρωματογραφικά εργαλεία. Επίσης, EM μέθοδοι χρησιμοποιήθηκαν για να επιβεβαιώσουν την παρουσία δομής διάρρηξης με άξονα ΒΔ-ΝΑ (βύθισμα της Λάρνακας) η οποία είχε υποδειχθεί με γεωλογικές μεθόδους στον οφιόλιθο του Τροόδου στην Κύπρο. Μιά νέα μέθοδος μετασχηματισμού των ειδικών αντιστάσεων που μετριοούνται στην επιφάνεια του εδάφους σε ψευδοδιαγραφίες γεωτρήσεων συζητάται και εφαρμόζεται σε μια περιοχή όπου παρουσιάζεται ένας βαθύς μολυσμένος υδροφόρος ορίζοντας.

INTRODUCTION

Important and in some respects unique information about the physical property distribution in the subsurface can be deduced from resistivity measurements. Electrical and electromagnetic (EM) methods are routinely used in determining the resistivity structure of the earth. The EM methods have the advantage of being able to image great depths without requiring large spread lengths and find applications in deep crustal studies, natural resources exploration, and shallow engineering and environmental investigations. Of the currently available deep probing EM methods, the magnetotelluric (MT) and transient electromagnetic (TEM) techniques are the most popular and sophisticated modelling techniques have been developed for interpreting the field data. Unlike the TEM method which requires artificial sources of EM energy, the MT method uses naturally occurring interminable magnetic and electric field variations at the surface (and within the earth). Along separate paths, both methods have now developed from their initial reconnaissance applications into powerful subsurface mapping tools second only to seismics in the depth and quality of information they provide. In fact, coincident MT and/or TEM surveys are increasingly being undertaken during seismic reflection surveys and Jones (1987) argues that the interpretation of seismic reflection images should be constrained by electrical resistivity information. There are some geological environments or geopolitical situations where seismics will not be the favoured choice. For example, areas of thick sedimentary or volcanic sequences may be unfavourable to the seismic method but favourable to the MT method. In some other cases an integrated approach in exploration may be desirable. Jones (1987) gave an interesting account of cases in which MT results aided the geologic/tectonic interpretation of seismic sections. Berkman et al., (1984) have successfully used the combined MT-seismic techniques to delineate the structure of the South Clay Basin in Utah. An integrated interpretation of MT, gravity and aeromagnetic data sets has also been recommended by Prieto et al., (1985) who showed that in basalt-covered areas, reasonable rock compositions and regional structural information can be derived from the combined data sets.

Besides natural resources exploration, electrical resistivity is recognized as an important diagnostic subsurface parameter in environmental and engineering applications of geophysics. In particular, the increasing public awareness of the impact of our past industrial and domestic activities on the environment now make electrical and EM surveys mandatory in some environmental assessment programs. It is a well known fact that the decline in heavy industrial activities have left us with a legacy of derelict excavation sites some of which are polluted. Many of these sites have been backfilled and redeveloped for domestic infrastructure and some are characterised by high levels of hazardous gas (methane and carbon dioxide) generation and polluted groundwater. To minimize any health risk to the unsuspecting inhabitants of such redeveloped property, there is a need to understand the structure and composition of contaminated land. Saline (polluted) groundwater appears as a good conductive target for the EM methods and depending on the

resistivity contrast with the surrounding fill material, may be easily detected using TEM and/or dc resistivity methods.

This paper will discuss a few case histories where the use of MT and/or TEM methods have helped in resolving or illuminating important practical problems. The issues addressed range from regional geotectonic problems through local basin exploration for natural resources to shallow subsurface imaging of polluted land. Although these cases are chosen to reflect trends in geophysical exploration (i.e., integrated interpretation of various data sets, novel applications to environmental problems and better data processing techniques), they are drawn from the author's own work and may not be the best gauge of the general trend.

DEEP CRUSTAL EXPLORATION

Although a great deal of the surface geology of northern Britain has been uncovered, the deep geology of the region is still not well understood. The surface geology is complex and the distribution of the main tectonic units (see Watson, 1984 and references therein) is shown in Fig.1. Major NE-SW trending faults separate the region into tectonic units and the tectonic framework is related to the Caledonian crustal deformation of about 500 my ago. The Metamorphic Caledonides (a complex sequence of metamorphosed sediments) are separated from the Lewisian Foreland (consisting of highly deformed basement gneisses and granulites) to the northwest by the Moine Thrust Zone (MTZ) and from the Midland Valley to the south by the Highland Boundary Fault (HBF). The Metamorphic Caledonides are subdivided into two parts (the Northern and Grampian Highlands of Scotland to the north and south respectively) by the Great Glen Fault (GGF) zone (Fig. 1). The northwestern part of the Metamorphic Caledonides is believed to be underlain by Lewisian continental crust and there appears to be some geological evidence for appreciable motion associated with the main faults in the region (Watson and Dunning, 1979).

Previous geophysical work on the mainland have attempted with varying degrees of success to unravel the deep structure of the region (e.g., Hall and Dagley, 1970; Bamford et al., 1978; Hutton et al., 1980, 1981; Dimitropoulos, 1981) but there are still several outstanding problematical observations one of which is the deep structure of the GGF (see Meju, 1988). Additionally, recent offshore deep seismic reflection surveys across the suggested submarine extensions of the features seen on the mainland (e.g., Brewer et al., 1983; McGeary, 1987) reveal the presence of interesting structures at depth but there is no compelling evidence that the same features would be observed on the mainland. This latter issue was the main thrust of a very recent tectonic study by Meju (1992a) that integrates gravity models and the previous geoelectromagnetic models of the deep structure across the region (e.g., Hutton et al., 1980, 1981; Meju 1988; Meju and Hutton, 1992; Hill 1987). The locations of the relevant surveys are shown in Fig. 1. A two-dimensional geoelectric model for the GGF (Meju and Hutton, 1992) (profile M1 in Fig. 1) is shown in Fig. 2a. This model shows the fault zone as a narrow vertical zone of low resistivity that runs from the

surface down to the lower crust and bordered by anomalously thickened highly resistive upper crust. The lower crust is of comparable resistivity to the GGF zone. Note that this deep geoelectric model of the GGF confirms the previously held geological view based on the surface expression of the fault and agrees with McGeary's (1987) seismic reflection model (Fig. 2b) for the Walls Boundary Fault (WBF, Fig. 1) - a suggested northeastern submarine extension of the GGF (Flinn, 1961). A re-interpretation of part of the WINCH seismic profile (see Fig. 4) across the suggested southwestern submarine extension of the GGF (Hall, 1986) is also presented in Fig. 2c for comparison.

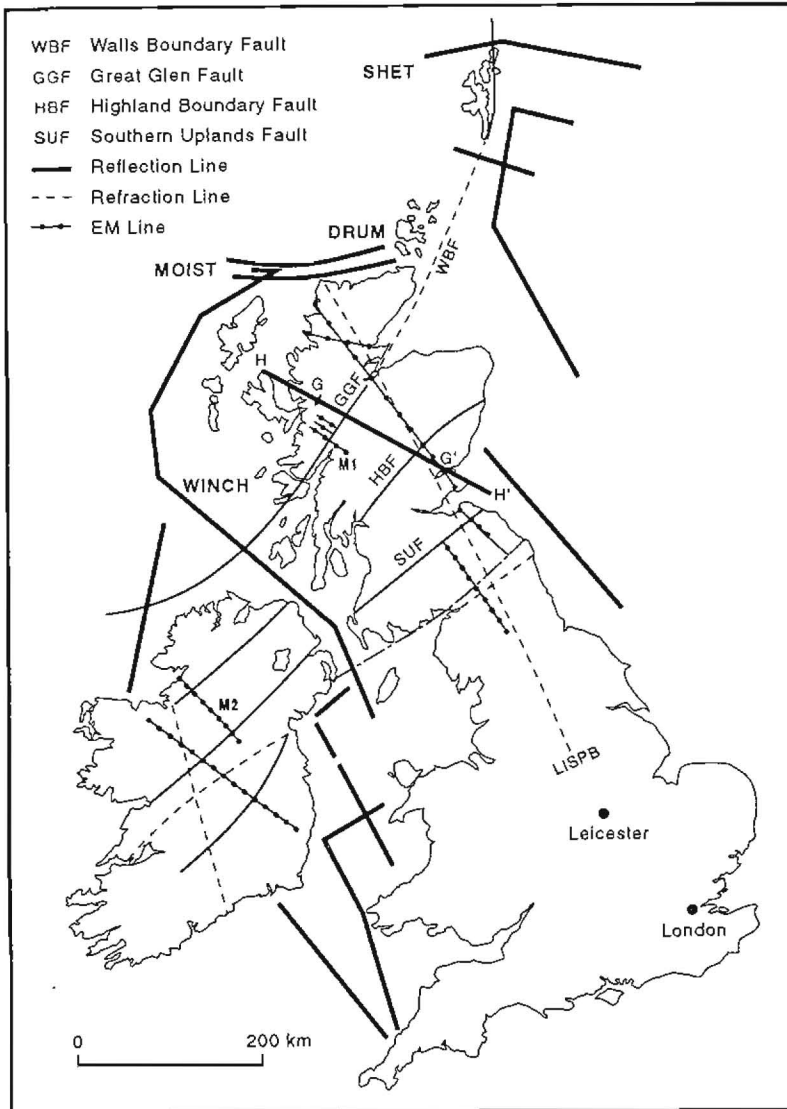


Fig.1. Seismic and electromagnetic map of Britain and Ireland.

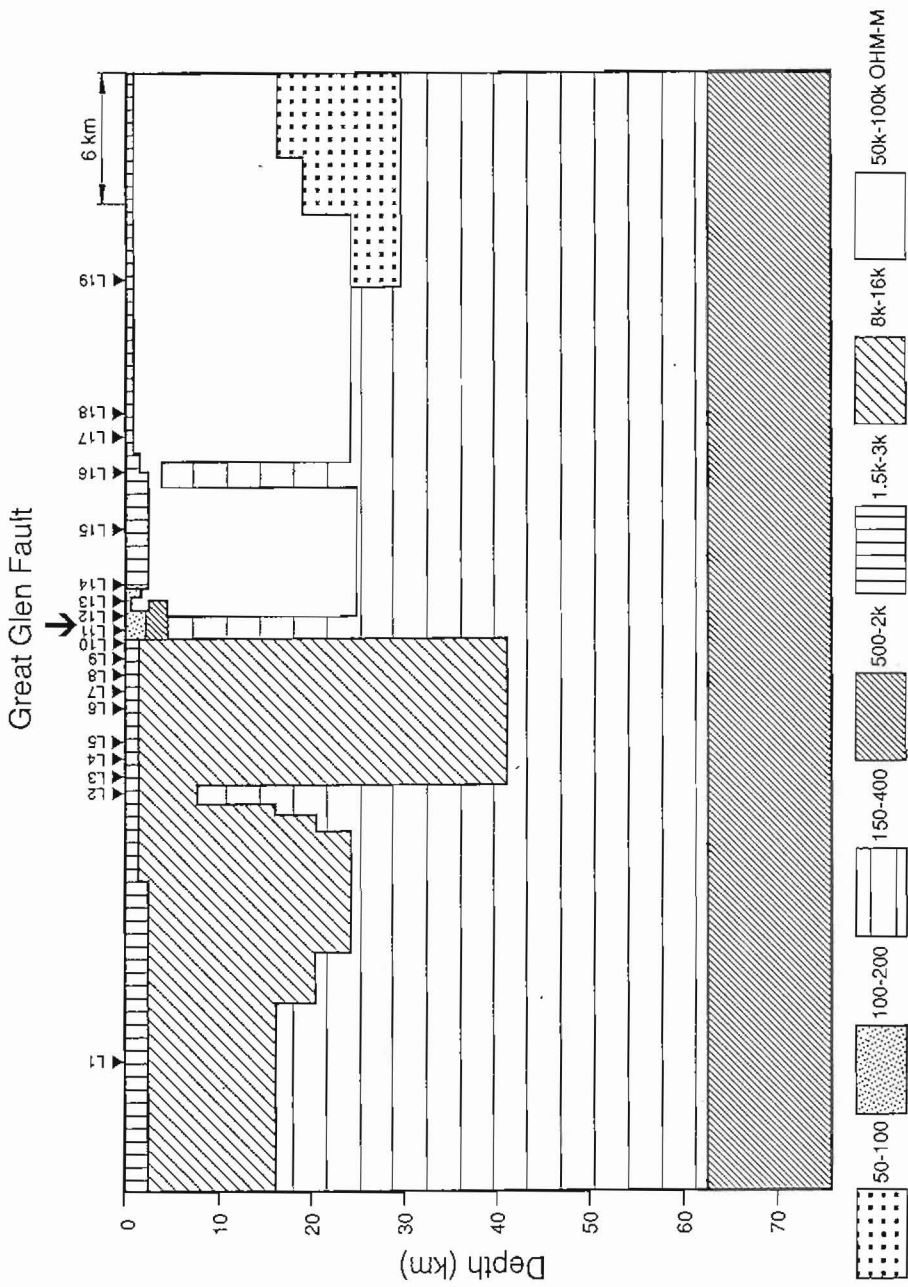


Fig.2a. A 2-D MT model for the Great Glen fault (from Meju and Hutton, 1992).

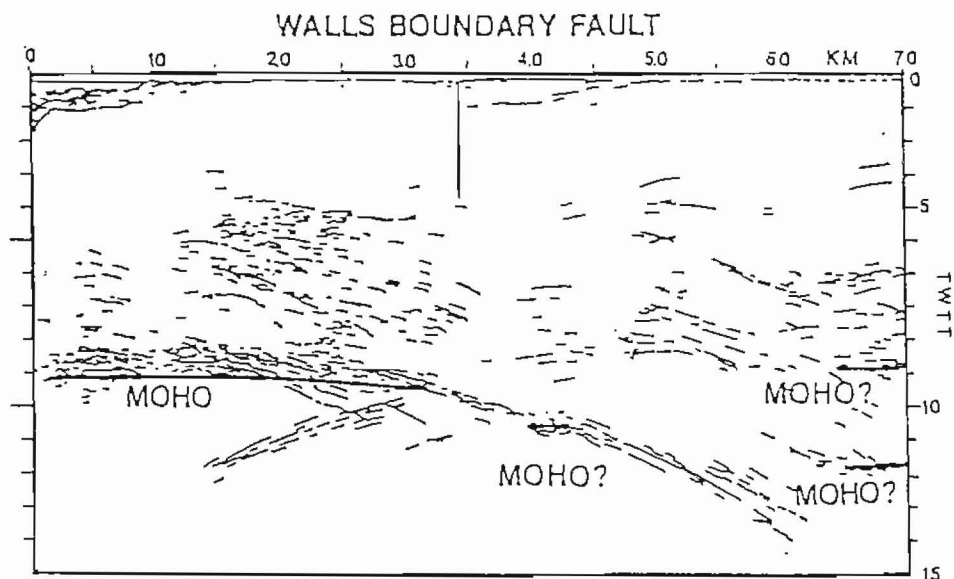


Fig.2b. The SHET deep seismic section across the Walls Boundary Fault (from McGeary, 1987).

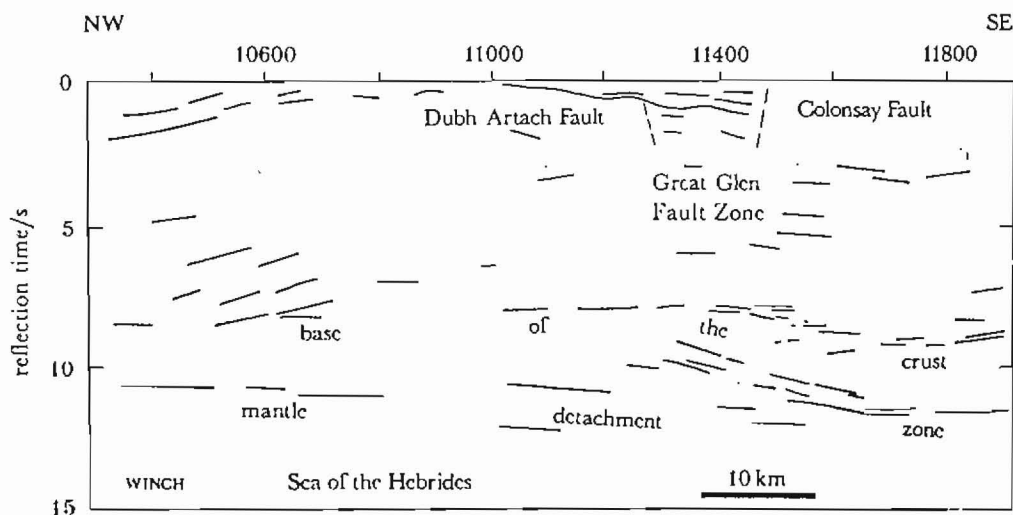


Fig.2c. Part of the WINCH profile across the South-western submarine extension of the Great Glen fault (after Hall, 1986).

An integrated MT and gravity model across the region (profile HH in Fig. 1) (Meju, 1988,1992a) is shown in Fig. 3. Note the good fit between the computed model response and the observed gravity data (Fig. 3a). Note also the locations of plausible vertical zones of major crustal disruption and thickening in this model (Fig. 3b). The wedge-like high density feature to the northwest of the MTZ is also obvious and the agreement with Watson and Dunning's (1979) geological model for this area can be demonstrated. To facilitate easy structural correlation with the offshore seismic images of the western coast of the region, the MT-Gravity model of Fig. 3a is redrawn in Fig. 4 on the same horizontal scale as the relevant part of the WINCH seismic profile (Brewer et al., 1983) (see Fig. 1 for location). The remarkable correspondence between the vertical borders of the zones of inferred thickened crust in the MT-Gravity model and the zones of truncated seismic reflections that run from the near-surface to sub-Moho depths suggests that there is a strong correlation in deep structure across mainland and offshore northern Britain (Meju 1988,1992a). The MT-Gravity model thus provides a crucial geophysical evidence of NE-SW continuity and strong lateral (NW-SE) differences in the deep structure across northern Britain; and Meju (1992a) showed how this model may be used to resolve previous problematical seismic refraction observations on the mainland (e.g., Moho offsets north of the region, the deep structure of the GGF, and rapid deepening north of HBF) by various workers (e.g., Bamford et al., 1978).

SEDIMENTARY BASIN EXPLORATION

MT and TEM are commonly used in sedimentary basins for groundwater investigations (e.g. Vozoff et al., 1982), geological mapping (e.g. de Beer et al., 1991) and basin evaluation for petroleum exploration (e.g., Strack et al., 1991; Meju and Swift, 1993). In a recent exploration campaign (Meju and Swift, 1993), the basement cover relations across the Northern Irish Caledonides (and in particular the structure of some of the basins) were the geophysical targets. Several MT and TEM soundings were made along a 37Km profile (Fig. 5; Line M2 in Fig. 1). The tectonic framework of the area is related to the Caledonian orogeny and the dominant strike is NE-SW. The surface geology is summarised in Fig. 5. The TEM and MT data were jointly analysed with attention being paid to the problem of static shifts in such sedimentary environments. The resulting interpretive model is shown in Fig. 6. In general this regional model evokes a picture of a deeply sheared resistive basement forming block and trough structures into which were deposited thick piles of conductive sedimentary materials. The resistivity variations reproduce the rock and fault distribution known from surface geology and reveal additional features concealed at depth like the shallowing of the basement in the vicinity of Tempo-Sixmilecross fault (TSF) and its rapid deepening immediately south of the Clogher Valley fault (CVF). The structure of the fault-bounded basins is apparent in Fig. 6. A suggested geological cross-section. (IGS, 1982) for a shorter parallel profile (AB in Fig. 5) is shown in Fig. 7 for

comparison. Note the structural similarities between the geophysical model and that inferred from geology (with control data provided by the Glenoo borehole in the south; see Fig. 5).

Similar techniques were also used by Meju (1993b) to test the hypothesis put forward by Varga and Moores (1985) about the spreading structure in NNE Troodos, Cyprus. Varga and Moores interpreted the structural expressions in the area as representing fossilised eastwards propagating ridge structure (in present day coordinates) and identified several NNW trending axial (Solea, Mitsero and Larnaca) grabens. TEM and MT surveys were conducted across the proposed axis of the Larnaca graben (Fig. 8) and the interpretive model is shown in Fig. 9. Note the block-faulted eastward propagating geoelectric structure which would seem to confirm the geological interpretation of Varga and Moores. This model also provides useful structural constraints for this sulphide mineralised region.

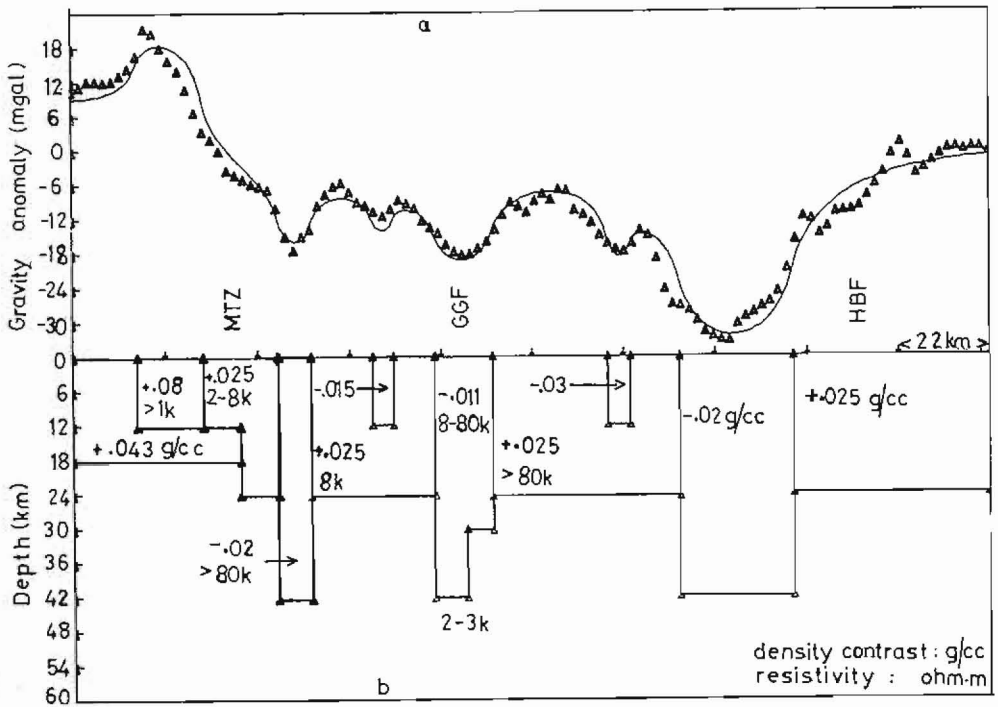


Fig.3. An integrated geophysical model for northern Scotland (a) Bouguer gravity anomaly along profile HH' (b) MT/gravity model for profile HH'.

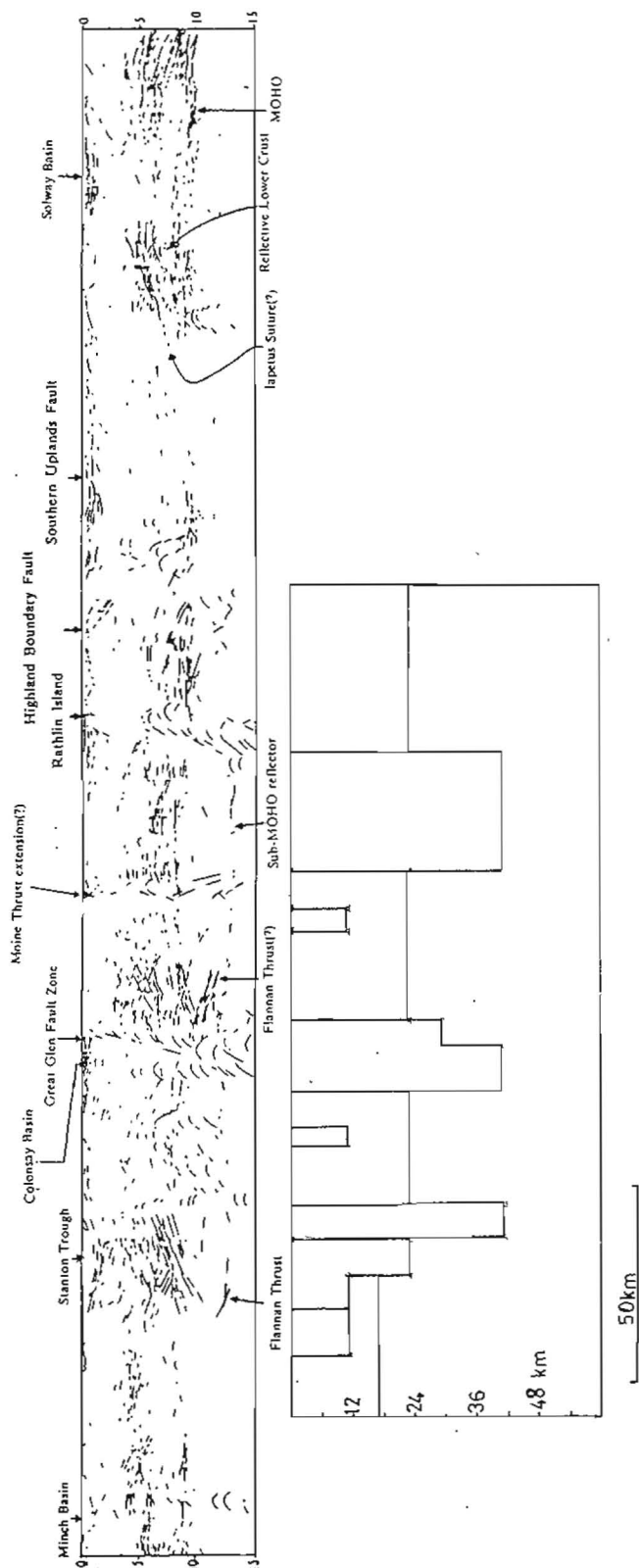


Fig.4. A comparison of MT/Gravity and seismic (after Brewer et al., 1983) structure across the Scottish Caledonides.

KEY



Sedimentary and contemporaneous igneous rocks

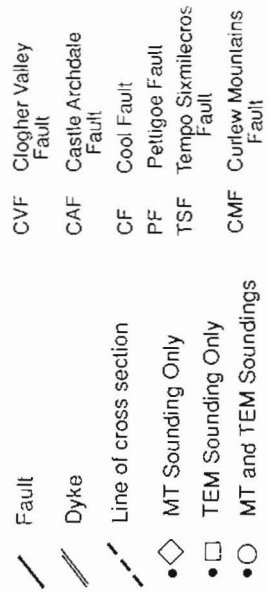
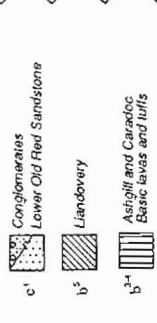
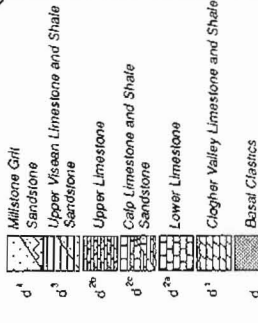


Fig.5. Geology and site location map for Northern Irish surveys (from Meju and Swift, 1993).

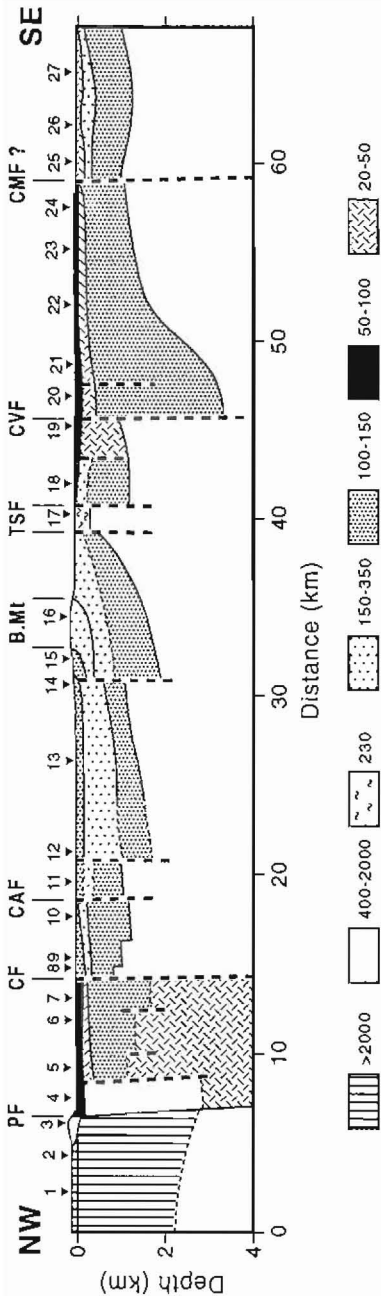


Fig.6. Geoelectric basement-cover relations in Northern Irish Caledonides.

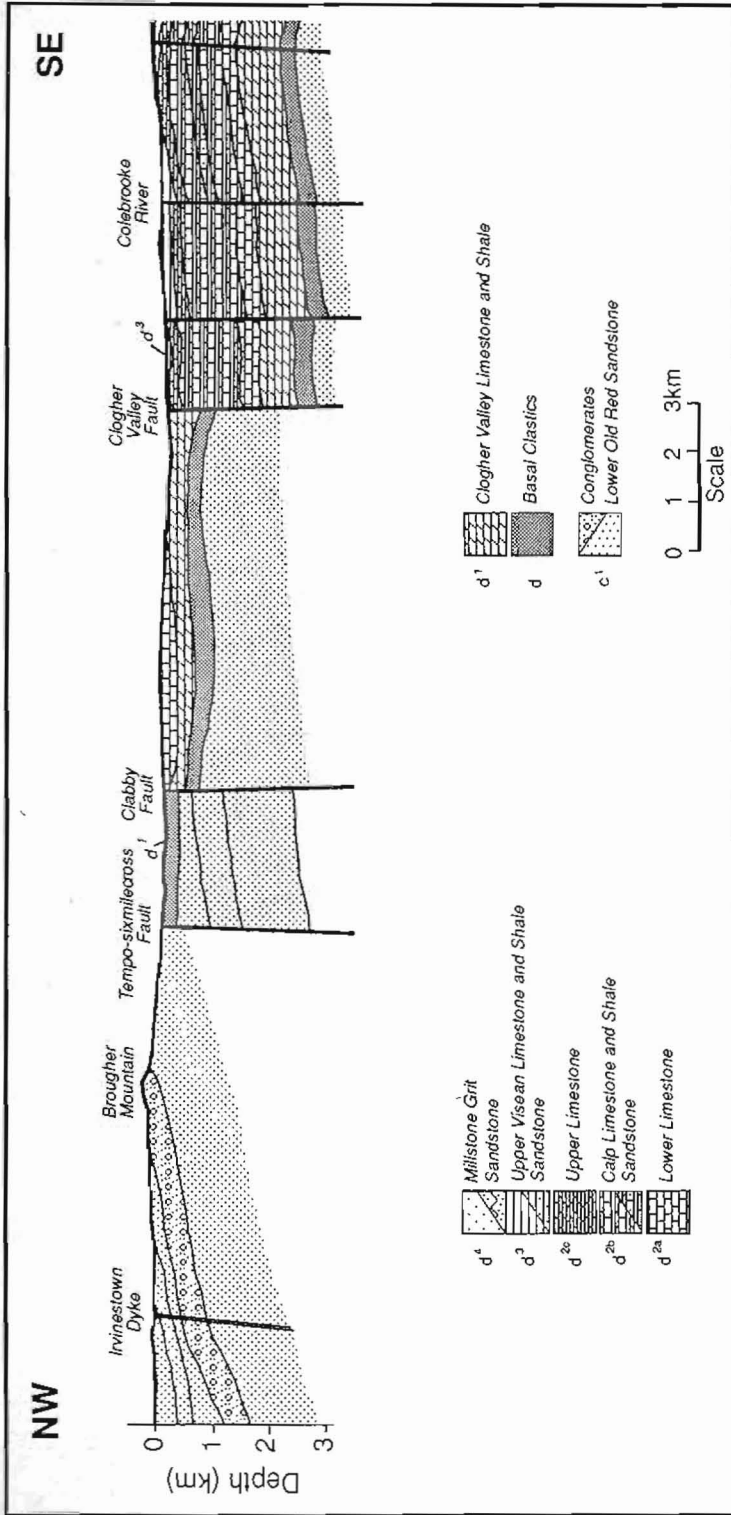


Fig.7. Geological cross section for line AB (after Institute of Geological Sciences, 1982).

Revised Aeromagnetic Grid

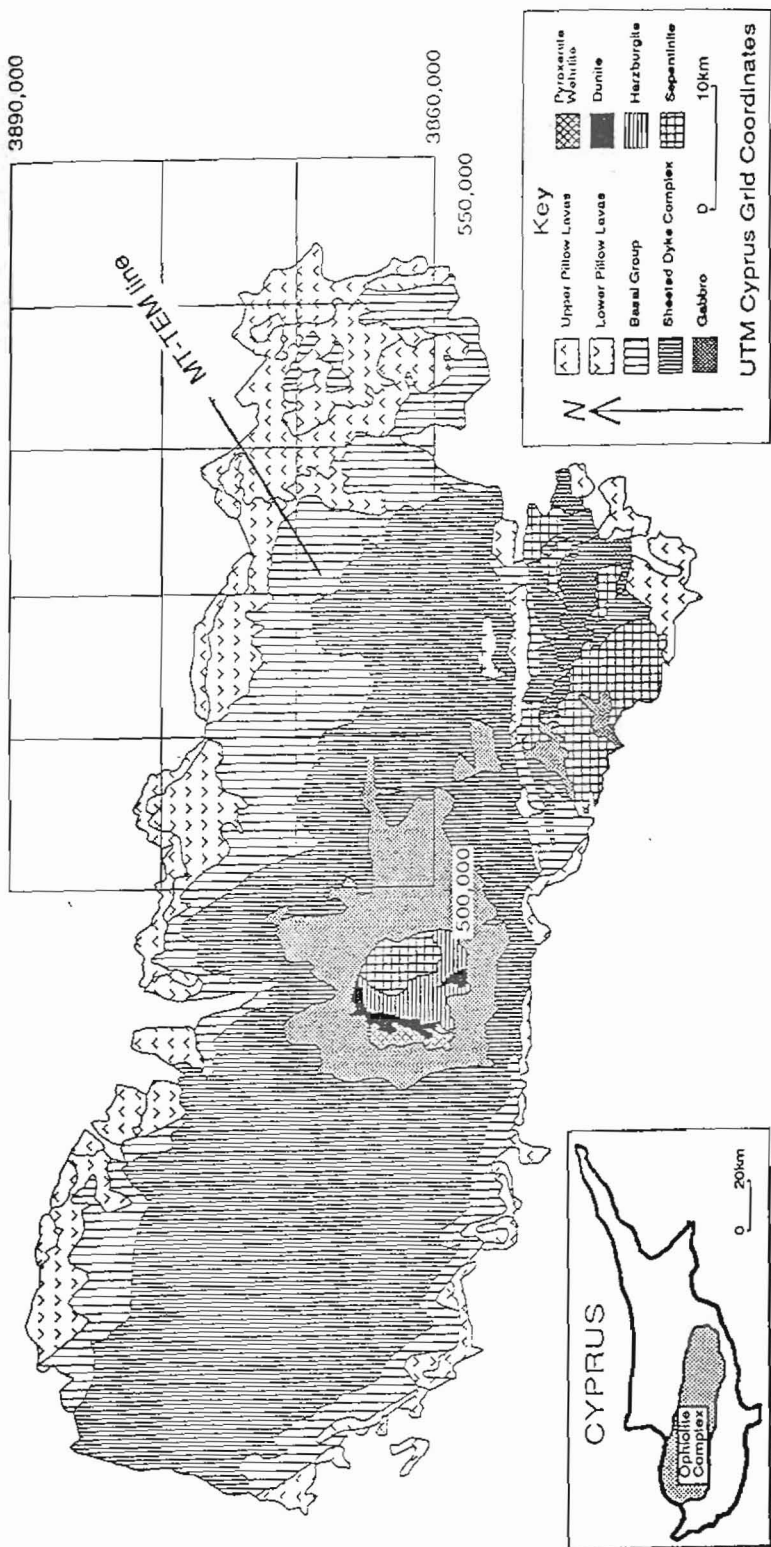


Fig.8. Geology and location map of the NNE Troodos survey.

SHALLOW SUBSURFACE IMAGING: ENVIRONMENTAL ASSESSMENTS

The difficulties often encountered in environmental surveys include: restrictive field conditions that sometimes require novel experimental geometries, complex nature of fill materials in landfills, say that may defy our simplistic theoretical modelling assumptions, and the need for urgent effective solutions to the problem at hand. Such difficulties may require us to modify the existing theory and/or practice to suit the given problem. Recently, there have been major improvements in EM instrumentation in line with the changing field conditions but the development of supporting interpretation schemes is slower in pace. However, a useful development in shallow subsurface data processing is in the area of approximate data imaging that allows the success of a survey to be reliably assessed on-site rather than at the base laboratory (e.g., Smith and Buselli, 1991; Meju, 1992b); an operator simply transforms the field responses to the equivalent resistivity-versus-depth information on a hand-held calculator or portable field computer and, based on the results, may decide to change the experimental geometry as appropriate to achieve the desired goals in the minimum possible time. This increases the cost-effectiveness of field operations.

An illustration of the imaging technique is given below using data acquired from a backfilled excavation on the outskirts of Leicester City (Meju, 1993a) (see Fig. 1 for location). Several boreholes were drilled to a maximum depth of 11 at the site to monitor the level of hazardous gases in the subsurface. The excavation was found to have attained a maximum depth of 10 from the borehole data and the fill materials were found to vary over the site but are mostly topsoil, concrete and brick fragments, metal, plastic, sacking, paper, rotting vegetation and animal carcasses, tyres and soft to firm clayey materials. The regional geological stratification consists of glacial deposits (clays, sands and gravels) underlain by mudstone deposits. Dc resistivity and TEM surveys were conducted in the vicinity of the boreholes and it was found that the capping materials and the enclosed fill materials and local groundwater levels could be distinguished from the basal geological materials. The interpretive models were found to be in accord with the borehole data as in the example shown in Fig. 10 suggesting that drilling costs could be minimized by having pre-drilling geophysical surveys which would then serve as guides for only a few exploratory/confirmatory wells. Additionally, the TEM data revealed the presence of a possible highly polluted groundwater reservoir system not penetrated by the boreholes and a typical result is shown in Fig. 11. The forward responses of the conventional models derived from the imaging results are plotted together with the field data for comparison in Figures 10 and 11 so as to highlight the effectiveness of such direct data transformations.

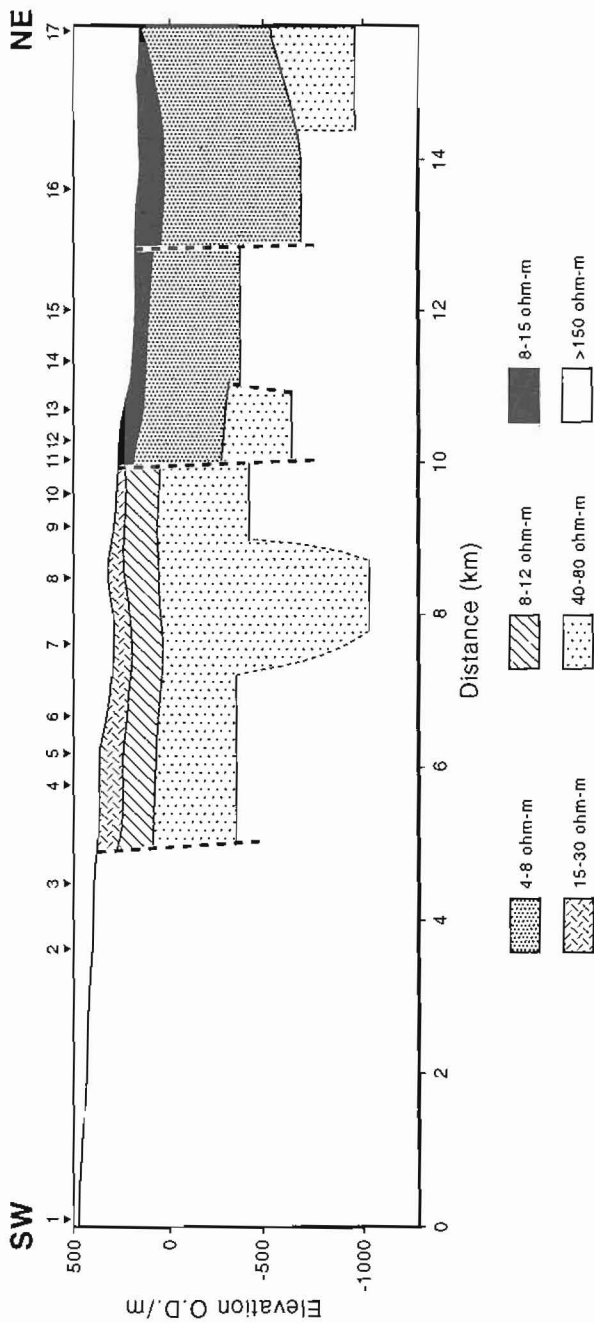


Fig.9. Interpretive (preliminary) MT-TEM Section for N.N.E. Troodos.

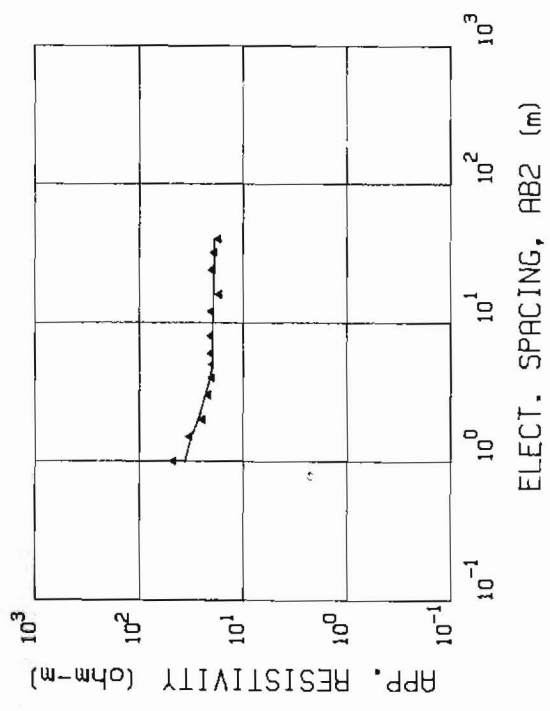
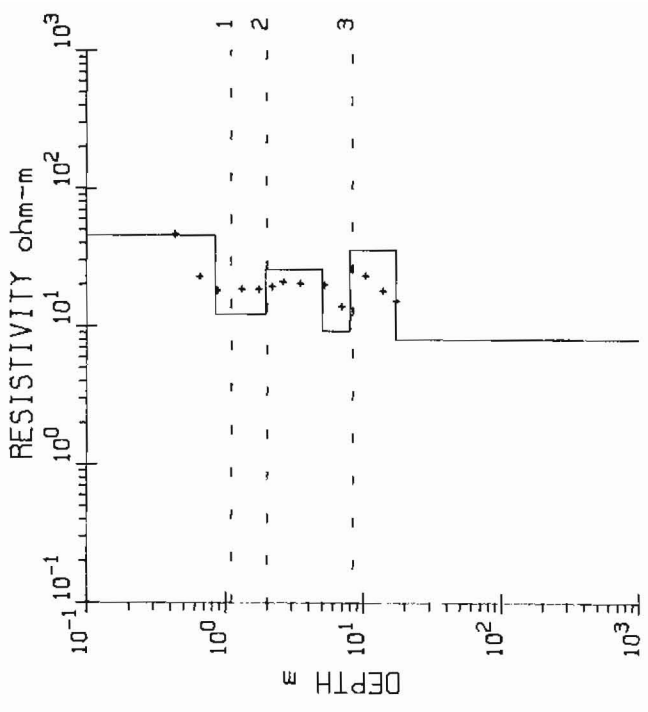


Fig.10. 1-D models for site SLBH3.

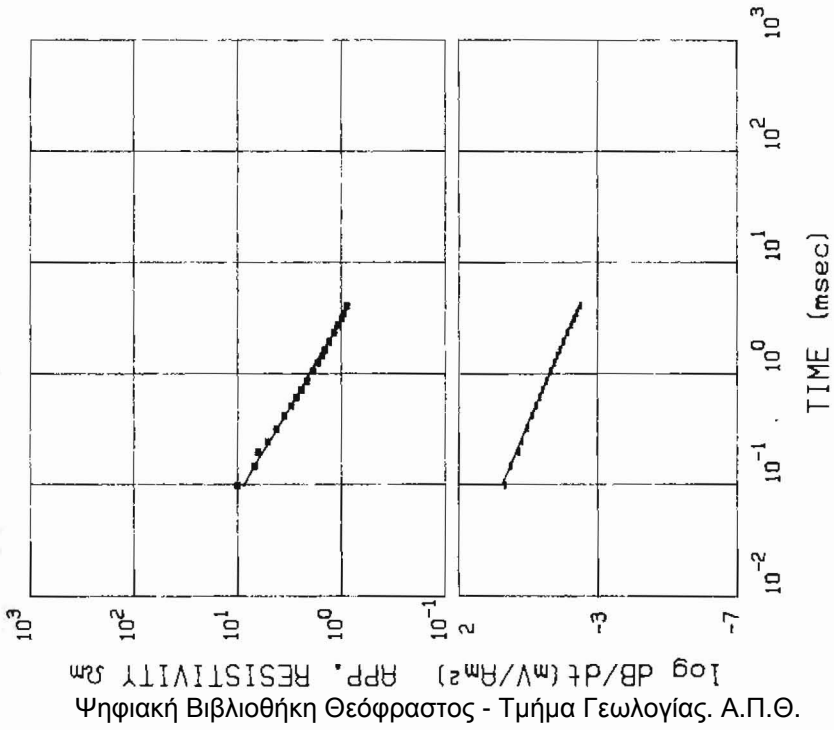
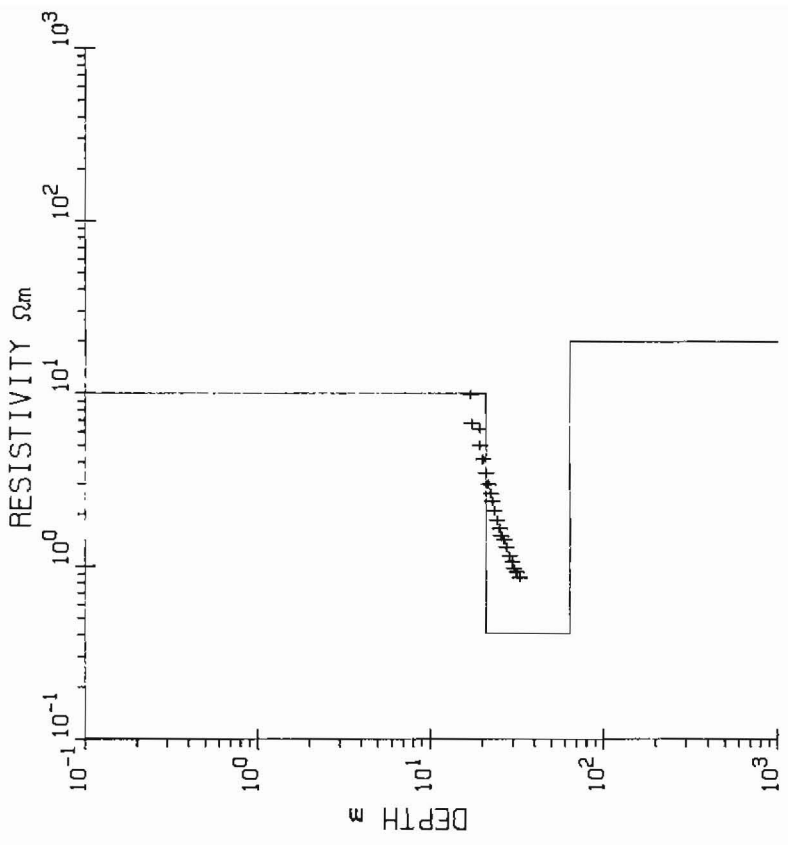


Fig.11. 1-D models for site TEMBH3.



CONCLUSIONS

It has been demonstrated that electrical and electromagnetic exploration can sometimes furnish important information about the subsurface. However, current effort is directed towards the integration of all available geophysical data to obtain a better picture of the subsurface. The development of cooperative interpretation schemes should be seen as a research problem of high priority. The recent simple data transformation schemes such as the one demonstrated in this paper may develop into effective tools for subsurface characterisation at the datum scale.

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