VARNET MT in SW Ireland : Processing, Inversion and Modeling

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Abstract

Magnetotelluric fieldwork was carried out in the southwest of Ireland as part of an integrated study of the Variscan Front. Data from a network of stations in southwest Ireland were collected, processed and modeled using a variety of equipment and computational methods. Extensive 2D modeling and inversion yielded models which gave insights into Variscan processes. 3D modeling yielded a strong yet surprising result showing the interaction of Variscan and Caledonian processes. Profile and regional models are developed and described.

1 Introduction

1.1 VARNET Project

The Variscan orogenic frontal zone is a prominent feature on the tectonic map of Europe, postualted to have an extent of about 1500 km from Ireland to northern Germany [Ziegler, 1982] with a continuation off the west coast of Ireland (Fig. 1). It contains a series of fold and thrust structures suggesting a general south to north compression direction. The Front is only locally well exposed in southern Ireland and in western Germany. The exposure in Germany has been extensively studied (e.g [DEKORP, 1991]). There are, however, large variations in the seismic signatures associated with various sections of the Front, so it is important to quantify and qualify the structures and processes associated with the Variscan orogenesis. Along much of it's hypothesized extent it seems to lack pronounced subsurface expression, while it's geophysical signature is also poorly defined. Deep seismic reflection profiles in the vicinity of the Variscan Front of the British Isles image dipping events which have been interpreted as Variscan thrust structures. In these areas the location and structuring of a number of Mesozoic sedimentary basins appear to be controlled, at least in part, by transtensional reactivation of these features (e.g. [Shannon, 1991], [McCann and Shannon, 1994]). This is particularly the case in parts of the North Celtic Sea, central Irish Sea and English Channel-Wessex basins. Tertiary transpressive structures located on Variscan features further complicate the structuring within these petroliferous basins.

The region of Varsican Front in southwest Ireland is a unique location for observing and modeling several aspects of European geology. The onshore Variscan tectonics are exposed, as well as features of the onshore-offshore transition which show Mesozoic and Cenozoic reactivation. It is also significant because it is in southwest Ireland that the distinct Variscan and Caledonian geologies meet. An analysis of the southwest of Ireland allows the interaction of these two distinct processes to be understood.

The VARNET group is an interdisciplinary association of geoscientists throughout Europe whose aim is to document, interpret and explain data associated with Variscan structures using their expression in the southwest of Ireland as a basis. A diversity of geophysical methods has been implimented to facilitate such work, such as magnetotellurics, seismics and potential field methods.

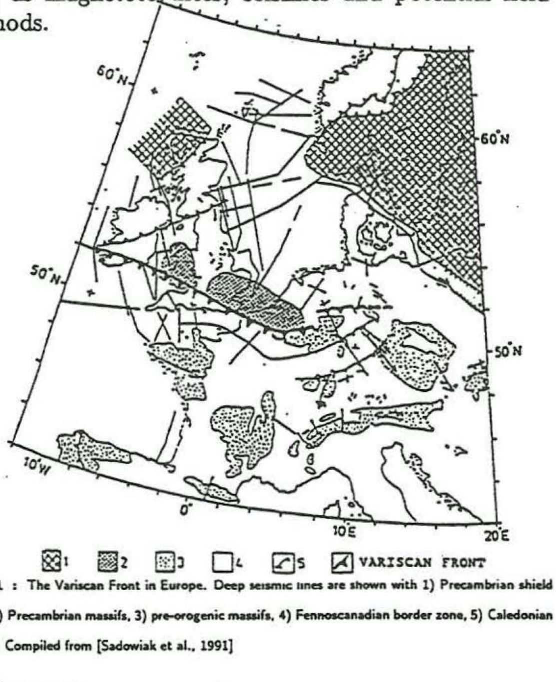

Fig.1 : The Variscan Front in Europe. Deep seismic lines are shown with 1) Precambrian shield crust, 2) Precambrian massifs, 3) pre-orogenic massifs, 4) Fennoscanadian border zone, 5) Caledonian thrusts. Compiled from [Sadowiak et al., 1991]

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1.2 Local geology

The local geology description given here is based on [Ford et al., 91]. In the Variscan province of southwest Ireland, Caledonian deformation is observed only in Lower Devonian, Ordovician and Silurian metasedimentary inliers. South of a line between Dingle Bay and the Galtee Mountains the Late Middle to Upper Devonian Old Red Sandstone (ORS) succesion was deposited in the ENE-WSW trending Munster Basin ([Graham, 1983],[Williams et al., 1989]). This succesion thins from the west, eastward along the axis of the basin. To the north, approximately 1km of ORS is observed to lie unconformably on Lower Palaeozoic strata. South of a map line from Cork to Kenmare, an uppermost Devnoian to Lower Carboniferous transgressive marine-clastic succession was deposited in a small asymmetrical basin, the South Munster Basin ([Naylor et al., 1989]).

In the Late Carboniferous, the area south of a map line from Dingle to Dungarvan accommodated approximately 50 % NNW Variscan shortening mainly by ductile folding and cleavage formation with late thrusting ([Cooper et al., 1986]), while the region to the north suffered approximately 30 % shortening. The Dingle-Dungarvan line has tectonic significance only between Mallow and Killarney where it is a major thrust, the Killarney Mallow Fault (KMF), with 6 km stratigraphical displacement. Within the fold belt, the Variscan structural trend swings from E-W to ENE-WSW towards the west. Further north, Variscan folds swing to a more Caledonian trend.

The Clare Shale Formation (CSF) overlies the Carboniferous Limestone in an abrupt facies change from shelf facies limestones to black mudstones ([Gill, 1979]).

2 Data Acquistion

2.1 Fieldwork

The initial fieldwork was carried out during August 1995 ([Denny et al., 1995],[Denny, 1996]). The original plan was to set up two north-south profiles which would cross the KMF in order to investigate the hypothesis that it was the surface expression of a "ramp and flat" structure. Fortunately, however, it was possible to impliment a whole network of 11 stations (Fig. 2) which covered the southwest of Ireland. The sparse distribution of the sites allowed low noise locations to be used, yielding good electric and magnetic data. However, large site separation results in low resolution, so it was decided to have a second campaign which would compensate for this sparseness by making denser profiles in areas of interest. Thus, in 1996 a second field campaign was initiated in a region on the east of the network, with the intention of making a N–S profile which would cross the Dingle – Dungarvan Lineament (DDL), which coincides with the KMF. The electrical data along this profile was unfortunately of poor quality, due to very strong noise electrical noise effects associated with the dense network of electrical fences used by farmers. The requirement that the profile should be dense meant that there was very little flexibility in attaining consistently high quality data in any profile in the easterly region. It was then decided to relocate the profile to a region that would provide an optimal combination of the geology which would provide data representative of regional Variscan processes, low electromagnetic noise and ease of access. The best compromise led to choosing a profile running between the 1995 sites BAW and CEC. The two field campaigns provided a total of 30 sites.

Several types of device were implimented. These included the recently developed SPAM 3 (e.g. [Ritter, 1995]), KMT devices from GFZ-Potsdam and LMT devices from Freie Universität Berlin. SPAM 3 measured data in the region 200 Hz – 1000 seconds and provided a realtime analysis of data quality, which assisted in evaluating potential site locations. KMT devices were especially designed to cover the "deadband", a region of low natural electromagnetic activity between approx. 10 Hz and 10 seconds, but was used to record from about 1 – 3000 seconds. LMT devices were used at 3 locations to measure the region from about 30s to several thousands of seconds. All of these devices were set up using a configuration of Ag–AgCl electrodes containing a KCl – Water solution to measure the electric fields as well as a triplet of Metronix coils aligned to measure the three spatial components of the magnetic fields. At all sites, landowners were encouraged to minimize electrical noise by turning off electrical fences on their land.

3 Data Processing

Corrections for anomalies associated with the magnetometer coils ([Ritter, 1996]) and thorough windowing of time series data were carried out. The data were predominantly noisy, so this step was very time consuming. Additional software was written to facilitate windowing. The windows of SPAM data were then processed using a robust selection procedure, while the KMT and LMT data were subjected to a robust remote reference method ([Gamble et al., 1985] and [Egbert and Booker, 1986]) where possible. Remote reference processing of the data yielded a con-

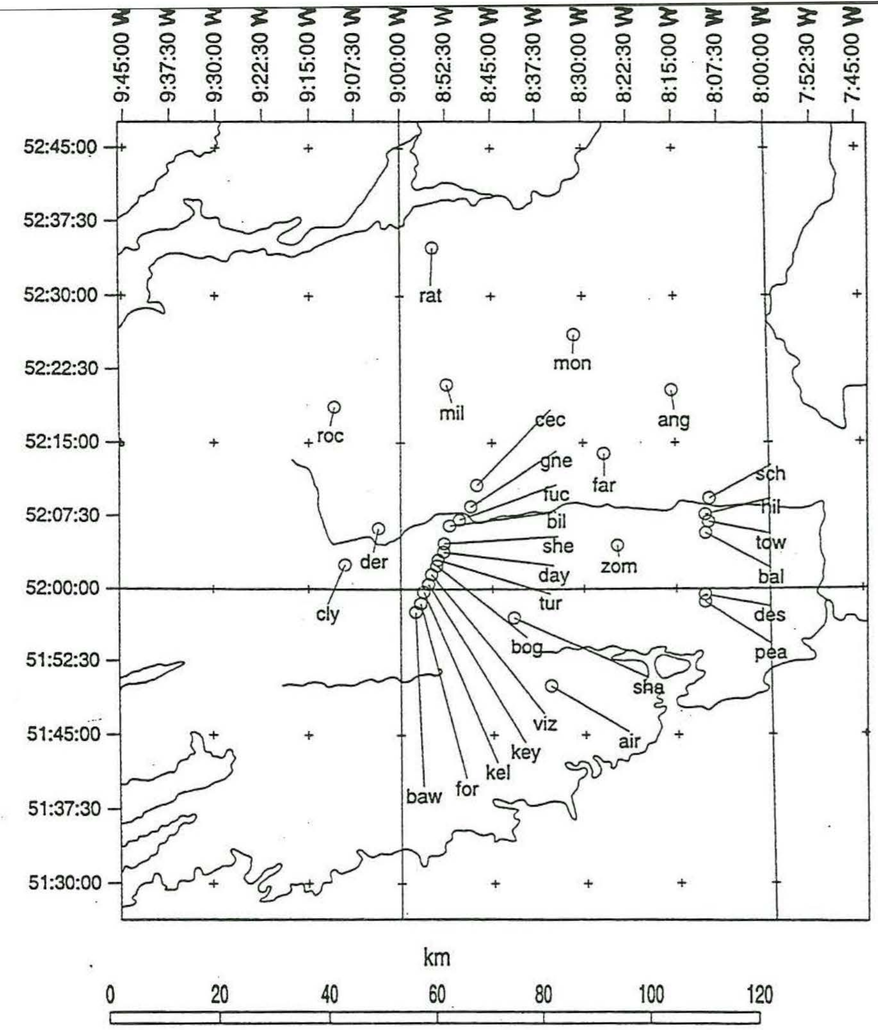


Fig. 2 : 1995 Varnet sites

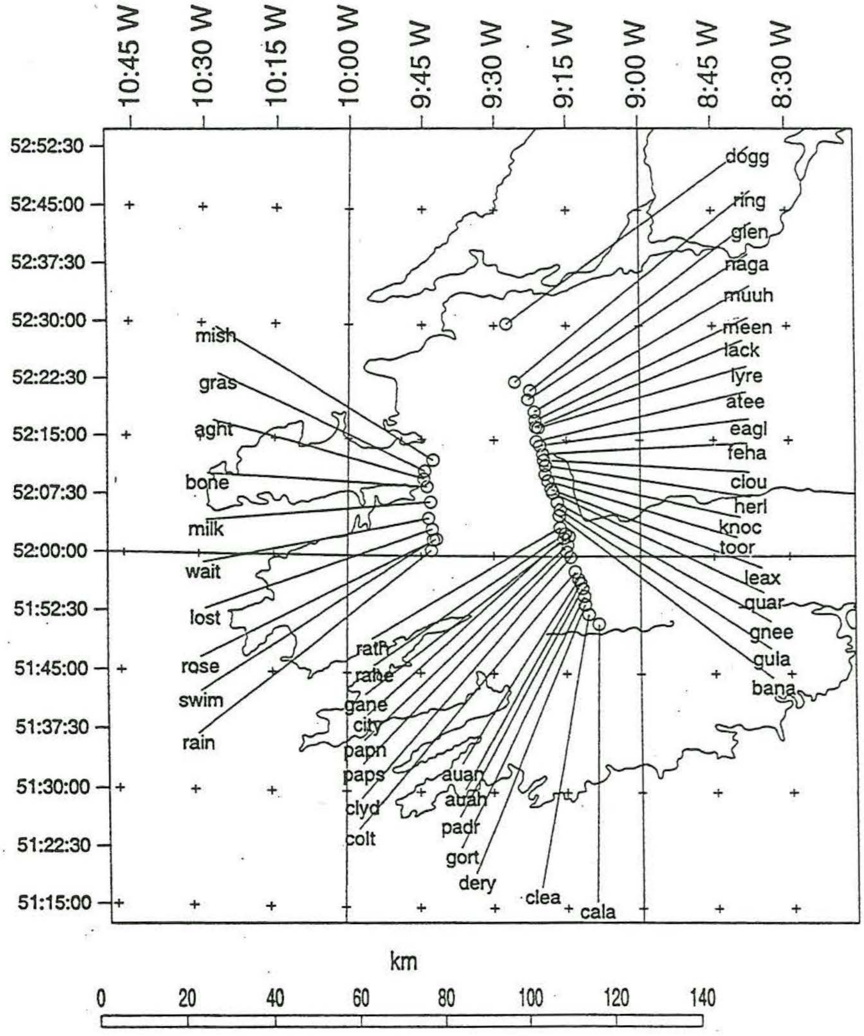


Fig. 3 : Profiles of [Bruton:94]

siderable improvement to the downweighted appparent resistivity curves in the deadband region. A coherence criterion was applied to the LMT and KMT data, until compromises were reached between data quality and subsequent dataset size by examining the degree of scatter and error bar magnitude of the resultant apparent resistivity and phase curves. Software was then written to merge the outputs of the different processing methods together into a single workable format.

4 2D Modeling of profile crossing the KMF

Data from the 11 sites on the BAW - CEC profile were examined. A strike angle of 90 degrees was found, which is consistent with the general Variscan trend. The TE and TM apparent resistivity and phase curves was generally of very low quality however, but the magnetic transfer functions at most sites, as well as apparent resistivity and phase curves from BAW and CEC, were of higher quality. After rotating the impedance tensor to strike, inversion and forward modeling of the data was undertaken.

4.1 Occam and PW2D

Occam code ([De Groot-Hedlin and Constable, 1990]) was used to invert the data. This code inverts data based on a starting model and selections of TE/TM apparent resistivity/phase curves and/or magnetic transfer functions. It attempts to create the smoothest possible model, based on a weighted misfit metric of data and model values. It is possible to introduce biases into a model, or even to fix certain structures. PW2D code ([Wannamaker, 1990]) is a finite element forward modeling code for 2D magnetotelluric data, producing both MT curves and magnetic transfer functions.

Decomposition of the impedance tensor was undertaken in order to remove effects of local anomalous conductive bodies. The standard decomposition hypothesis test ([Groom and Bailey, 1989]) was not satisfied, since the assumption of retrievable, frequency independent rotation parameters fails and the residuals between the idealised, two-dimensional model data and the measured data are significant. The rotation parameters of the impedance tensor vary not only with frequency but also considerably along the profile. Skew values depart significantly from zero, primarily due to noise in the time series data. Subsets of the curve values for the various sites were selected for the inversion process. Several hundred models were made on this basis in order to identify consistencies in the data. An examination of induction arrows, combined with the hypotheses of a "ramp and flat" structure to the south of the KMF led to the inclusion of a conductive "flat" structure at a depth of 6 km, becoming progressively more resistive in a southerly direction to generate a lateral conductivity gradients in order to affect the magnetic transfer functions. This structure was given a wide range of thicknesses (100-1300 metres) and conductivity gradients, but it was found that a magnetic effect due to such a structure would be too subtle to have a noticeable effect, that even a small nearer surface lateral conductivity boundary would have a much more striking effect, and that the magnetotelluric effect of such a conductor would not be traceable using the collected dataset. Inversion based purely on magnetotelluric parameters showed some consistencies, but was deemed inadequate. Another method was needed.

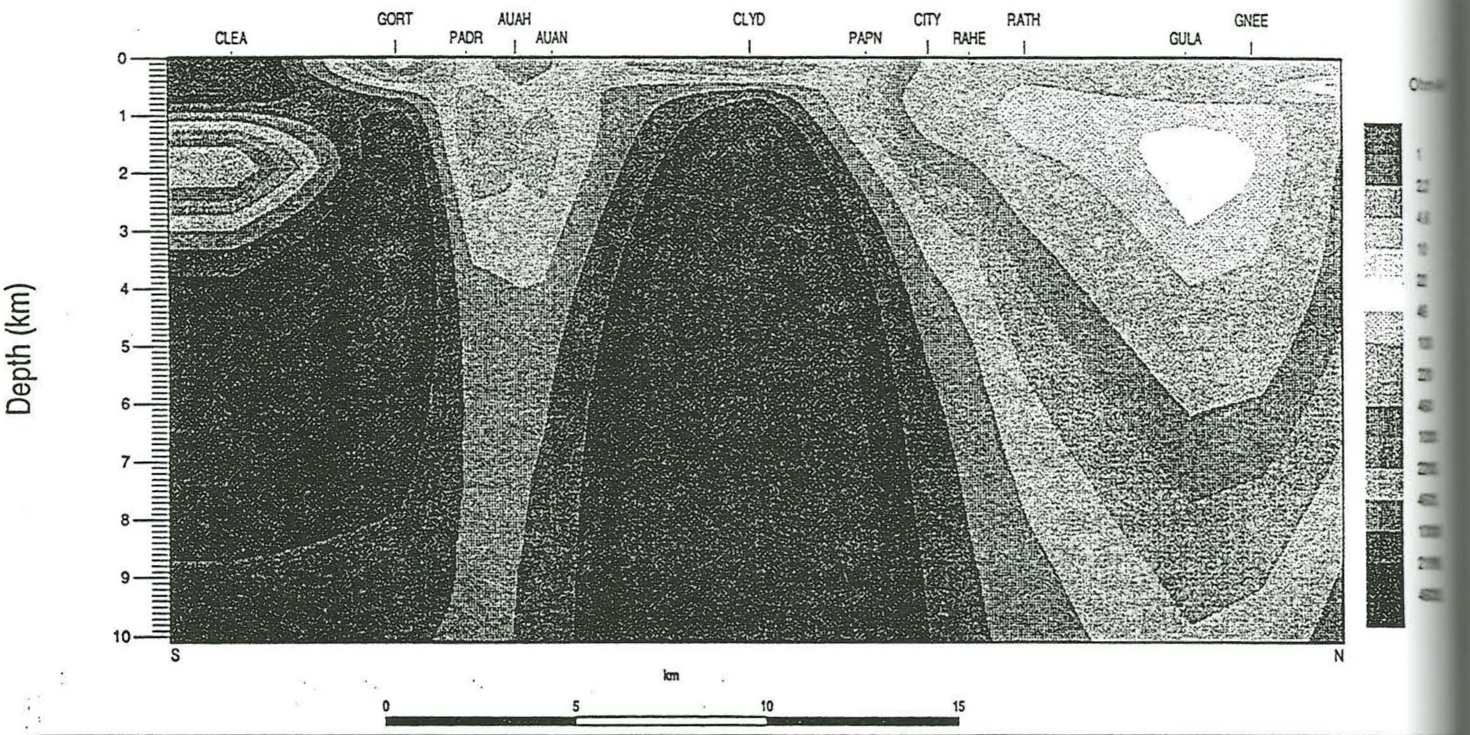
4.2 Modeling with magnetic transfer functions

The induction arrows associated with the profile generally indicated reasonable two dimensional behaviour at higher frequencies. It was thus decided to impliment the magnetic transfer functions as part of the inversion. Magnetic transfer functions are not good indicators of conductivity values, but of lateral conductivity gradients. Fortunately, the MT data for the sites at the extremes of the profile, CEC and BAW, were of very high quality. Thus, inversions were made based on this combination, with various biases towards the CEC and BAW data, which will be described in detail in a subsequent paper. Using this method, models with magnetic behaviour consistent with the data were attained. Both methods clearly show a conductive anomaly in the top 2 km beneath site GNE. One notable property of both modeling methods is the very large crustal resistance (typically 5000 - 10000 Ωm).

5 2D Modeling of Bruton's data

The raw impedance and magnetic data which were collected and processed by Paul Bruton for his Ph.D. thesis ([Bruton, 1994]) were generously made available for reprocessing and modeling. The set consisted of two approximately N-S running profiles (Fig. 3). An analysis of the data from the easternmost profile showed that a strike direction of 85 degrees was reasonable for frequencies in the range 8 - 120 Hz. The data was reprocessed to attain as much data in this frequency range with low skew (≤ 0.2) for as many sites as possible. After rotating this data through 85 degrees, a fitting curve was made to the data, and 4 frequencies

Fig. 4 : Profile from CLEA to GNEE



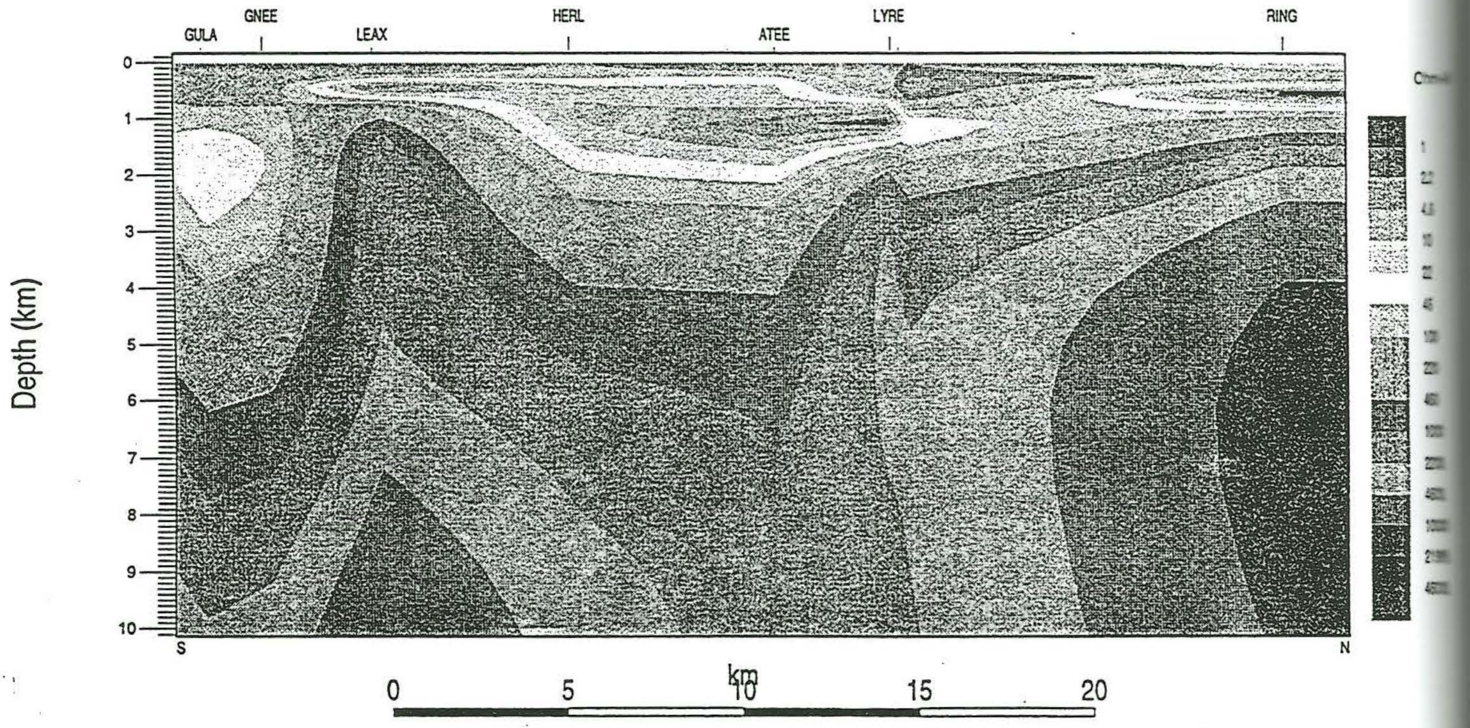


Fig. 5 : Profile from GULA to RING

per decade were used for the inversion. Initially, Occam inversions based on TM mode data and homogeneous halfspaces were attempted, but the Occam models were never than those previously attained for sections of the profile ([Bruton, 1994]). Extensive forward modeling using PW2D was attempted, but the quality did not improve. As a means of investigating the possibility of an improved fit, the data was investigated using the more recent method of Rapid Relaxation Inversion (RRI) ([Smith and Booker, 1991]).

5.1 RRI Inversion

RRI inversion is a fast and effective method for inverting magnetotelluric inversion. One major distinction between it and Occam is that the horizontal field gradients are neglected, thus reducing the computation to and upward integration of an exact differential at each site and at each frequency. The misfit between the measured and predicted data is used to modify the model and the process is repeated iteratively until convergence is reached. The method has the tendency to produce strongly downward continued anomalies ([Schnegg, 1996]) but this problem was circumvented in the case of the Varnet data by experimenting with a parameter which affected the general vertical extension of structure in the inversion as well as raising and lowering conductive structures in subsequent start models, until strong consistencies in output were found.

5.2 2D model along eastern profile

The MT and magnetic transfer functions for the easternmost profile of [Bruton, 1994] were reexamined, and a strike direction of 85 degrees was found to be valid. A compromise between large frequency range, representative distribution of data across sites and data quality was sought when selecting data. Thus, a selection of data with skews ≤ 0.1 in the frequency range 100 Hz – 5 Hz for 18 sites was made. A starting model consisting of a homogeneous halfspace of 500 Ωm and intially TM and TE phase based inversion were initially used, as these data contained a large amount of information but were not subject to static shift. The inversion output model was then used as an input model for apparent resistivity based inversion. In an attempt to ensure that the inversion was not merely converging to a local minimum in model space, the modeling was repeated using several different homogeneous halfspaces as starting models, as well as starting models with structures from previous inversions placed at different depths or with different apparent resistivity values.

RRI inversion was very successful for this profile and several robust structures are visible (Fig. 4 and 5). Starting on the southern end of the profile derived from the eastern sites, a 100 Ωm structure can be seen 2 km beneath CLEA. The next prominent structure is the enormously resistive 150 $k\Omega$ body beneath CLYD. The very conductive ($2 - 200\ \Omega m$) structure in the top 4 km between sites GULA and RING is believed to be the Clare Shale Formation (CSF). The profile is the most well resolved geoelectric model in Ireland and more detailed results of analysis will appear in subsequent papers.

5.3 2D model along western profile

The western profile was successfully processed with a GB decomposition to give a strike of 90 degrees, consistent with the trend of the Variscan orogenesis. Several inversions and forward models were made using both Occam and RRI. These models suggest a strong near surface conductive boundary between sites MILK and BONE, but this is not yet conclusive

6 3D Modeling

The geometry of the 1995 stations was essentially a sparse network, thus it was deemed practical to attempt 3D modeling based on the behaviour of the magnetic transfer functions. This modeling was done using RM3D

6.1 RM3D

RM3D[3] ([Mackie and Madden, 1993]) is a three dimensional finite element forward modeling program based on conjugate gradients. Given a model and a model grid, it calculates the relevant Green's functions at each node, and subsequently derives the various magnetotelluric and magnetic transfer functions at chosen locations.

6.2 Creating a model of SW Ireland

An initial model of SW Ireland was constructed using a combination of a-priori structure and values derived directly from the measured MT data. Bathymetric data from the USGS was used to construct the geometry of a 0.4 Ωm conductor representing the Atlantic Ocean and the Celtic Sea. A layered starting model of the rock material was assigned values based on a 1-D inversion of the Berdichevsky apparent resistivities[4] for the 11 sites

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[3] The RM3D code is used with *Geotools* , an interactive MT tool from WSE Associates

[4] square root of the determinant of the apparent resistivity matrix

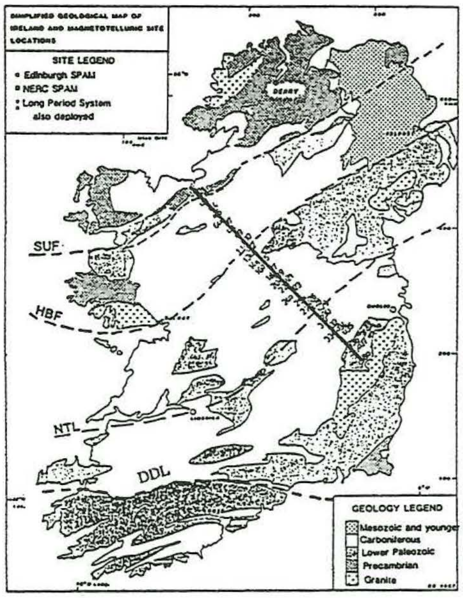

Fig. 6 : Irish Magnetotelluric Profile [Brown et. al.:95]

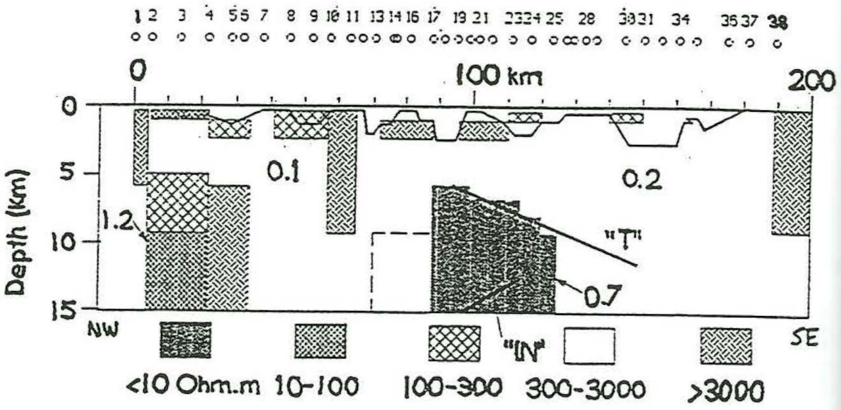

Fig. 7 : Structure from the Irish Magnetotelluric Profile. Note the large conductor beneath sites 16 to 24. Induced magnetisations given in Am^{-1}. Seismic reflectors "T" and "IN" from the NEC line shown. [Brown et. al.:95]

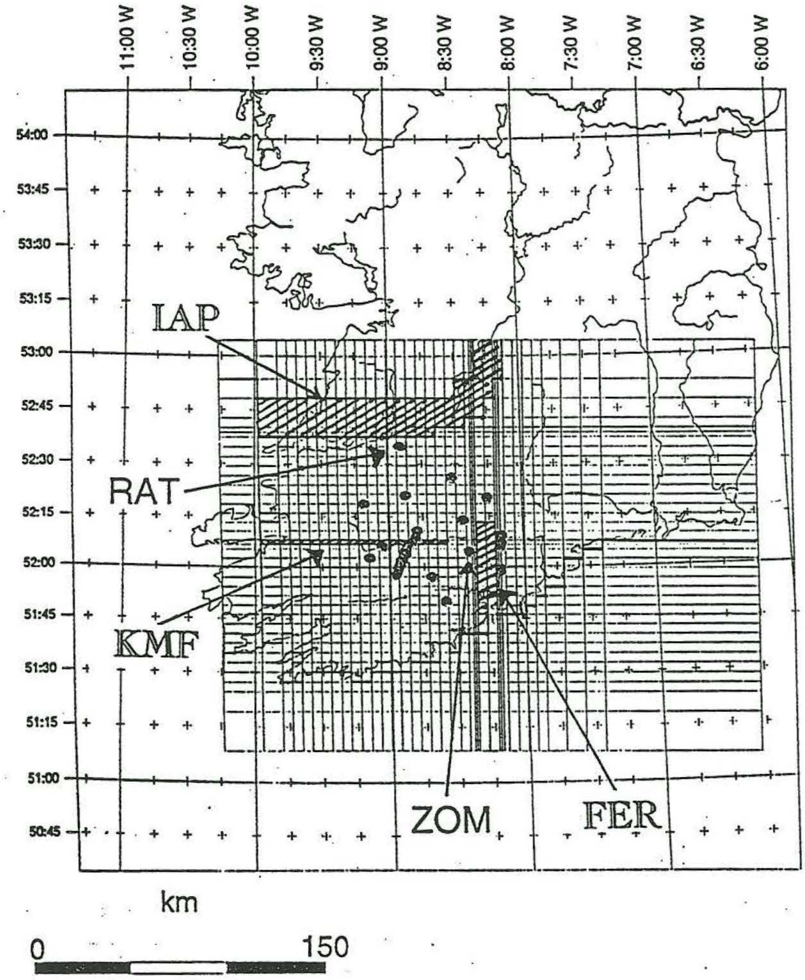

Fig. 8 : Basic 3D Model indicating required structures

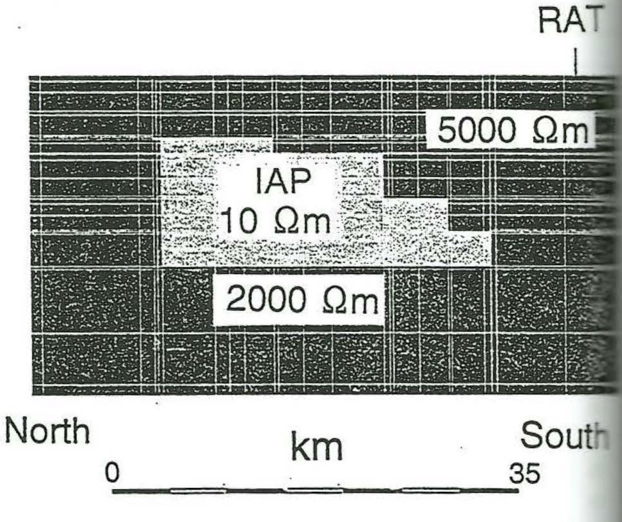

Fig. 9 : IAP conductor model section at 9° West The vertical and horizontal have the same scale

deployed in 1995. The values at the longest periods of a few thousand seconds were surprisingly large ($10^3 - 10^4 \Omega m$), in strong contrast with values suggested for oceanic mantle ([Heinson and Constable, 1992]). After these values had been inserted in a modeling grid, the grid itself was modified to ensure a dense set of computational nodes between any areas with strongly differing resistivities.

The next step was to consider comparisons between tabulated rock material resistivity values ([Telford et al., 1984]) and the locations of large regions of these materials, in order to estimate what the directional behaviour of induction arrows at various sites should be. This was necessary in order to construct blocks that were not directly within the 1995 network of sites. These suggested that the limestone region north of the River Shannon should have a resistivity value of 5–10 $k\Omega m$, with lower values of between 2–5 $k\Omega m$ for the clastics and sandstone south of the Shannon. When these values were inserted into the model, it was found that the model induction arrows were almost negligible, in stark contrast to the induction arrows of the northernmost station RAT, which indicate a conductor north of it whose conductive effect could be seen over a range of almost 4 decades ! Attempts were made to lower the value of the limestone south of the Shannon, as well as examining the possibility of an effect due to Galway bay 100 km to the north of RAT, but initially no reasonable explanation was forthcoming.

The region immediately north of the site RAT, comprising the River Shannon, running through Co. Louth and into Scotland, is associated with the closure of the Iapetus Ocean during Ordovician times. The signature of the Iapetus Suture has been examined in Scotland ([Beamish and Smythe, 1986]) and in the Irish Midlands ([Brown and Whelan, 1995]) (Fig. 6), but there was no significant geophysical dataset in this southwest region before the Varnet project. One of the features suggested in the Irish midlands is a largescale conductor (Fig. 7) ([Brown and Whelan, 1995]), with a N–S extent of approx. 30 km and resistivity $< 10 \, \Omega m$. On the basis of the simplistic assumption that similar processes create similar structures, a conductor (IAP) of these dimensions (Fig. 8 and 9) was inserted in the region coincident with the Iapetus Suture Zone in the River Shannon in order to somehow explain the induction arrows of the site RAT. The fit between data and model was good for both the real and imaginary parts (Fig. 10). The conductor also provided an explanation for the induction arrows encountered in [Bruton, 1994].

A conductive region associated with the KMF is also evidenced by the induction arrows at several sites. The east–west continuation of this structure is suggested by induction arrows. Coincidentally, the suggestion of a conductor from the induction arrows for the westernmost profile ([Bruton, 1994]) is seen in both the 2D and 3D model for the westerly profile of Paul Bruton.

Induction arrows at the sites ZOM and AIR indicated the existence of a near surficial conductive body (FER) 5km deep, 10 km wide and with a resistivity of $200\Omega m$, trending southwards from the town of Fermoy to Cork city although there is insufficient data to constrain the geometry of this conductor. An explanantion of this conductor is not yet forthcoming, although it has been remarked that this is the eastern boundary of microquakes in southern Ireland.

The bathymetry of the ocean introduces a very large "coast effect" to any dataset recorded in the SW Ireland. Several heuristic descriptions of the "coast effect" or "ocean effect" exist (e.g [Singer and Fainberg, 1995], [Agarwal and Dosso, 1993]), but there is an absence of empirical metrics associated with the coast effect. Since the southwest of Ireland is one of the most significantly affected regions in the world, anomaly software was developed, which would display the difference between magnetic transfer functions for geological models in with/without the inclusion of the ocean. Due to the complicated nature of the distortion that takes place, it was found that the best way to define "coast effect" in an empirical manner, is by deciding on a lowest cutoff frequency for a particular site, at which the induction arrow evidence of a hypothetical geological structure in a model becomes masked by the inductive effect of the ocean. It is important to note this effect before making interpretations in the case of SW Ireland, because, for example, it was found that at the far inland site CEC, the ocean has a significant effect on induction arrows at periods beginning at only 10 seconds ! An appreciation of the absence or presence of a coast effect at particular frequencies reduced modeling runtimes because it allowed the extent of the grid to be optimally minimized.

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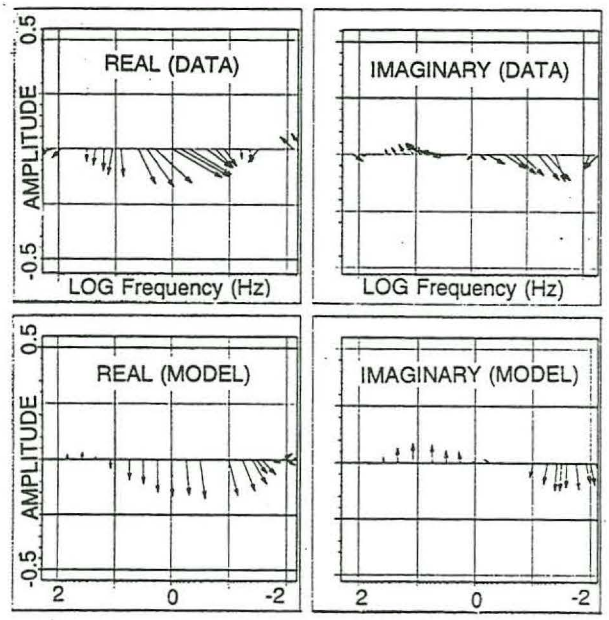

Fig.10 : Site RAT Schmucker Real and Imaginary arrows from (top) data and (bottom) model in Fig.8

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