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IRETHERM: Multidimensional Geophysical Modelling of the Southern Margin of the Dublin Basin

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ABSTRACT

We present multi-dimensional modelling of the magnetotelluric (MT) data collected in the Newcastle area, west of Dublin, Ireland, in the frame of the IRETHERM project (www.iretherm.ie). IRETHERM's overarching objective is to develop a strategic and holistic understanding of Ireland's geothermal energy potential through integrated modelling of new and existing geophysical, geochemical and geological data. The Newcastle area is situated on the southern margin of the Dublin Basin, close to the largest conurbation on the island of Ireland. A description of data processing methods, 2-D and 3-D geoelectrical models of the area and integrated modelling with other geophysical data are presented here.

The MT soundings were carried out in the highly urbanized Dublin suburb in 2011 and 2012. The MT time series data were heavily noise-contaminated and distorted due to electromagnetic noise from nearby industry and DC tram/railway systems. Time series processing using several modern robust codes was able to obtain reasonably reliable and interpretable MT impedance and geomagnetic transfer function estimates at most of the locations. The most "quiet" 4-hour subsets of data during the night time, when the DC tram system was not operating, were used in multi-site and multi-variate processing, with the most reliable sounding curves spanning the frequency range 10 kHz to 0.001 Hz. A novel technique using inter-station transfer functions has been implemented as a processing tool to obtain broader primary data for final multi-dimensional modelling. In order to reduce distortion in the MT data, the dimensionality, and if two-dimensional (2-D) then the regional 2-D strike direction, must be determined. Tensor distortion decomposition was applied at each site to determine if the data are suitable for 2-D modelling, with most data at most sites accepting a 2-D description as valid. The final 2-D models underwent examination using a new stability technique, and the final two 2-D profiles with reliability estimations, expressed through conductance and resistivity, were prepared. As a conclusion to the modelling, 3-D models of all MT data in the Newcastle area have been performed and further on-going 3-D modelling along with the inter-station magnetic transfer functions have been performed.

The integrated modelling with existing seismic reflection profiles and gravity data in the area reveals that the Blackrock to Newcastle Fault (BNF) is visible in the models as a conductive area to depths of 4 km and is highly fractured. Generally, the southern area is more resistive and compact with a horizontal conductive layer at approximately 1 km depth, with a very thin sedimentary layer on top. The structures north of the BNF are more heterogeneous, with deeper conductive layers (2-3 km) and thicker (several hundred meters) sedimentary layers above.

1. INTRODUCTION

We would like to present geophysical and geological studies carried out within the framework of the IRETHERM project (www.iretherm.ie) to develop an understanding of Ireland's geothermal energy potential through joint-inversion/integrated modelling of new and existing data. The holistic geoscientific approach contributes significantly to a knowledge-based understanding of geological settings and identifying localities with the greatest potential to provide significant volumes of hot geothermal waters or hot, dry rock with geothermal energy potential in Ireland.

The DIAS geophysical group in the IRETHERM project is focused primarily on using the natural-source electromagnetic imaging method called magnetotellurics (MT) as the tool for subsurface studies. It utilizes natural variations in electromagnetic energy to deduce the conductivity properties of rocks within the Earth (Chave and Jones, 2012). The electrical conductivity variation in sediments, both laterally and with depth, represents information about ionic transport properties within the basin. In contrast, seismic velocity is a vibrational mechanical property of the medium and density is a bulk property. Electrical conductivity is sensitive to fluid content and interconnectivity and to the movement of ions. Therefore, saline-filled lithological units with greater porosity and permeability exhibit higher conductivity (lower resistivity). Electrical conductivity is thus the most suitable proxy for porosity/permeability determinations of the available physical parameters observable from the surface.

In this paper we present multi-dimensional MT modelling of the IRETHERM MT data collected in the Newcastle area, situated on the southern margin of the Dublin basin in the Greater Dublin Area. The southern margin of Dublin Basin succession includes Carboniferous permeable successions overlain by sedimentary sequences of sandstones, mudstones and shales bounded by rocks of Lower Palaeozoic era. This area has significantly elevated geothermal gradient (over 30°C/km) with significant potential for district space heating of nearby Dublin city (Figure 1), and possibly even electricity generation. The potential for geothermal energy development lies in permeable faults deep within the Dublin Basin below Newcastle that bring warm fluids from depth to closer to the surface. The regional structural conditions provide large scale fractures extending over a significant distance along the BNF.

The objective of geothermal energy potential estimation in this sedimentary basin area is to identify formations and localities where higher primary porosities are preserved (e.g., basal formations of sedimentary successions, porous sandstones and limestones) or where secondary porosity is high (e.g., along major and secondary crustal fault and shear zones associated with main BNF structure) within the sedimentary strata and to map the geometry of the basins. This information can answer the overarching question about whether the presented lithologies and their depositional environment in this area are suitable to deliver geothermal heat for industrial and/or residential utilization.

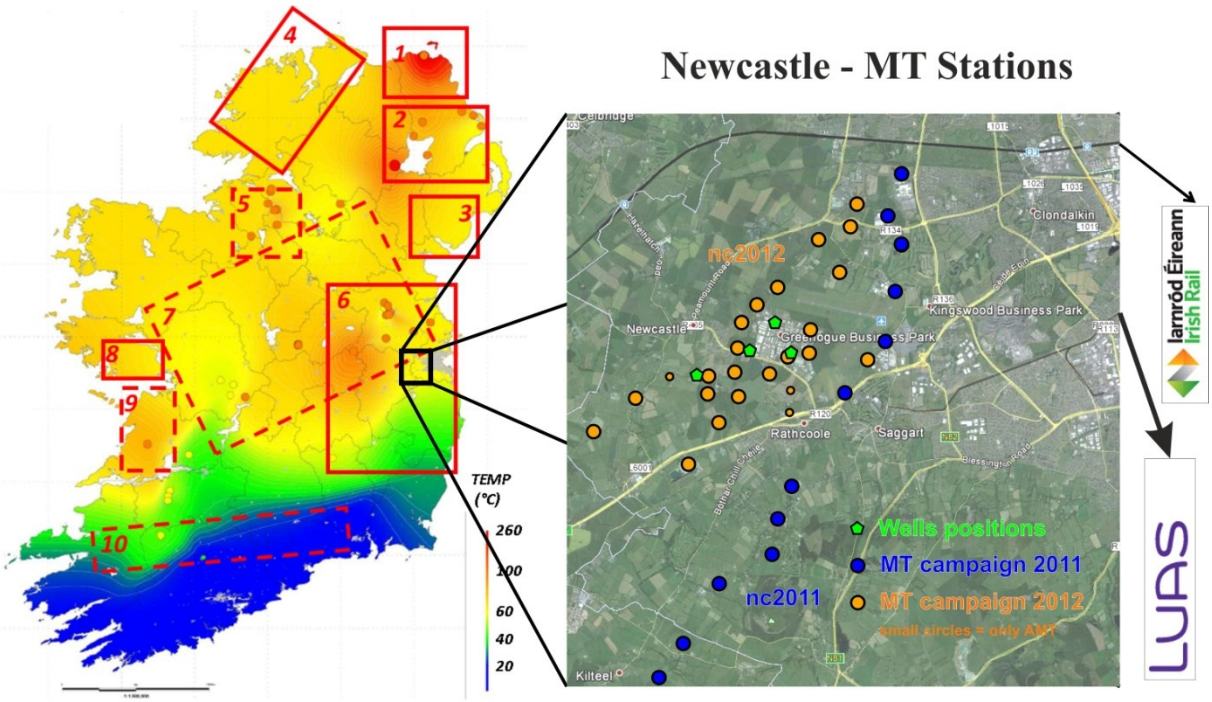

Figure 1: (left) Survey areas in Ireland to investigate geothermal targets overlain on modelled temperatures at 2,500 m depth (Goodman et al., 2004); (right) Location of the MT stations, at which measurements were made during2011 and 2012, and wells in Newcastle area. Black lines represent railways tracks with DC traction, which are one of the sources of electromagnetic noise in the area.

2. MT METHOD

Magnetotellurics uses plane polarized, natural electromagnetic waves, that are vertically incident on the surface of inhomogeneous Earth, to obtain information about subsurface distribution of electric conductivity/resistivity within the Earth. Measured time-varying magnetic and induced electric (telluric) fields on the surface of the Earth are used to estimate the frequency domain MT impedance and vertical magnetic (tipper) response functions (GTF: geomagnetic transfer functions). The response transfer functions varying with periods can be modelled/inverted to derive multidimensional models of subsurface resistivity structure. The resistivity models provide complementary information to other geophysical methods about geological units with conductivity contrast between structures from scales of 100 m to 100 km, e.g. in groundwater exploration, geothermal energy, mineral and hydrocarbon exploration, volcano and earthquake hazards, and crustal and upper mantle studies.

2.1 Measurements and processing

The MT soundings at 40 audio MT (AMT, short periods, sampling frequency 24 kHz) and MT (long period) sites were carried out in the highly urbanized Dublin suburb in 2011 and 2012. The spacing between stations was about 1 km, with a remote reference station situated far from the known target area to reduce the local noise in data through cross-correlation type methods extracting coherent signal from incoherent noise. The MT data are highly disturbed by electromagnetic noise from Dublin's industry and nearby DC tram system (LUAS line is 800 m from closest MT site) and Irish Railway (600 m from site). The noise is caused by non-harmonic impulse-like artificial sources, such as engines during acceleration in the DC traction system.

We are overcoming this noise problem in two steps. First, we estimate the quietest periods of each day directly from the pre-processed transfer functions, which are during night from 0:30 - 3:30. During this time most industry and train systems are shut down in the surrounding region. In the second step we are using three different processing tools to compare stability of MT impedance transfer function estimations (Figure 2). The first tool is the robust processing package EMTF from Egbert (2003), which is based on multivariate statistical methods. The second is the code of Smirnov based on one-step reduced M-estimator with Huber weights. Last is the processing code from Phoenix Geophysics provided with their MT systems, and based on Jones's tscascade code (Jones, 1984).

Also a new methodology based on estimation of local transfer-functions by combining interstation transfer-functions (ELICIT) was applied. This method improves results when the acquired magnetic fields have been truncated or are highly affected by sporadic noise (Campanya et al., 2014). The method is also useful to enhance processing in noisy areas, by improving the statistics used to obtain the final transfer function.

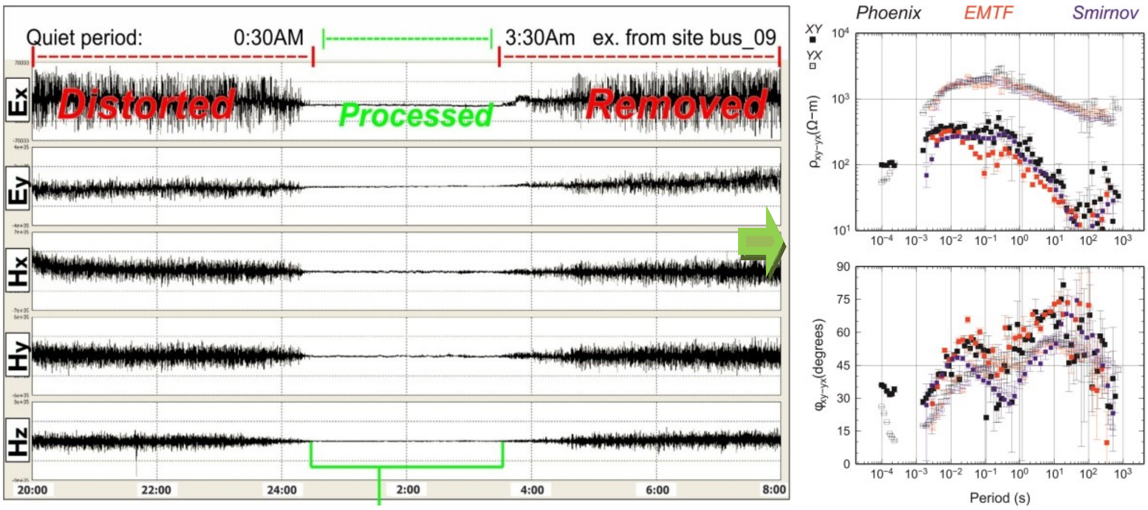

Figure 2: (left) Time-series dataset example of the electromagnetic field components (Ex, Ey, Hx, Hy, Hz) from site bus09. The green line marks data used for processing with less EM cultural noise; (right) Example of good sounding curves for site ncw_12 from 3 different processing tools. Top graph showing apparent resistivity within the periods and bottom phase shift between electric and magnetic field (higher values means higher apparent resistivity). Shorter periods indicate shallower information about resistivity and longer periods refer to deeper information (approximately from 50 m to 70 km).

2.2 2-D Modelling

The main goal of the Newcastle MT measurement was to obtain electrical resistivity models of the regional 2-D structure of the BNF and surrounding area. The principal advantage of 2-D inversion is that it allows for controlling dimensional distortion that creates artefacts in the MT data models, and it produces simpler models closer to our expected structures. The distribution of stations in the area defines north-south oriented models crossing the BNF with less lateral coverage of the area necessary for precise 3-D modelling. Comparing to 3-D inversion, 2-D inversion can run effectively on a single line and is much faster than 3-D MT inversion; it can be quickly rerun to test reliability and resolution hypotheses.

To prepare the input data for 2-D inversion, assumptions must be made about the orientation of geoelectrical 2-D strike to orient the two MT modes for each station. Several decomposition approaches are used in regional surveys to reduce dimensional complications and distortion in the data. Carefully selected and edited processing results were analysed by the McNiece and Jones, (2001) multi-site and multi-frequency extension to the Groom-Bailey MT tensor decomposition technique (Groom & Bailey, 2001). In this technique, a global minimum is sought to determine the most appropriate regional 2-D strike direction and telluric distortion parameters for a range of frequencies (or approximate depths) and a set of sites. The regional strike azimuth of N125°E for line NC11 (9 sites) and strike of N110°E for profile NC12 (14 sites) were determined. These orientations are very close to our expected regional structures represented by the surface trace of the BNF. Tensor distortion decomposition to strike direction allows removing some level of static shift distortion and obtains clean data that are then appropriate for 2-D modelling. Both profiles were inverted by a 2-D inversion code (Baba et al., 2006) with root-mean-square (RMS) misfits between observed and modelled data equal to 2.6 and 2.7 (should be 1 for a fit by 68% of the data to within errors, or 2 for 95% to within double the errors) for phase error floors set to 5%, apparent resistivity error floors set to 20% and geomagnetic transfer function absolute error floor set to 0.05. Due to the slightly distorted input data for 2-D inversion, we decided to perform a stability technique examination of the models based on a statistical Jackknife method.

The averaged 2-D models of the same structures from 9 independent inversions and 14 for profile NC12 are presented in Figure 3. We also show 2-D reliability plots based on simple formulae for model conductance and resistivity variance. The presented version is the logarithmic standard deviation of 2-D model resistivity in each cell. The standard deviation can be used as the resistivity error input for future estimations of porosity or integrated modelling with other geophysical data. The reliability models indicate which conductive bodies tends to influence or modify total conductance. Both 2-D models are reliable in areas with significant conductive structures, which is important for identification of water bearing layers.

Both resistivity models exhibit quite resistive structures in the survey area and reveal conductive structures reaching about some hundreds of Ωm (except for conductive bodies on profile NC12 at a depth of about 1 km). This indicates that the structures do not contain high amount of interconnected saline water. From the models we can see that the geometries of the units close and below the BNF are complex and complicated, probably because the area has more faulted and fractured horizons. For structures further into the Dublin basin (more to the north from BNF) we can observe a simplified layered character with a small dipping angle. Also, structures south of the BNF are more compact and resistive with a lack of deeper conductive layers.

2.3 3-D Modelling

From the difference between the two parallel 2-D models in the previous section, we can see significant change of structures in the east-west direction. It is clear that 2-D modelling alone is not recovering the higher complexity of geological structural geometries in the area, and 3-D modelling is needed to correctly reveal all structures and their geometries. The 3-D MT inversions have many more degrees of freedom than 2-D inversions (more parameters in input data and higher dimension of model). Due to this higher degrees of freedom, it is likely that 3-D MT inversions, in general, are less tolerant of noisy data and data gaps than 2-D MT inversions, and so the input data require more careful editing to avoid unrealistic results in the final inversion model. Unfortunately, even the latest forward and inverse 3-D codes are not able to reproduce the full real electromagnetic field components collected in the field with all distortion effects (Jones, 2011), with the exception of that of serial Avdeeva x3di code (Avdeev and Avdeeva, 2009). The original MT data transfer functions, with distortion effects, were input into the 3-D inversion. Just small modifications, like manual removal of spurious data and smoothing over period with their decimation to certain evenly spaced periods number (usually 3 or 4) of periods per decade, were performed.

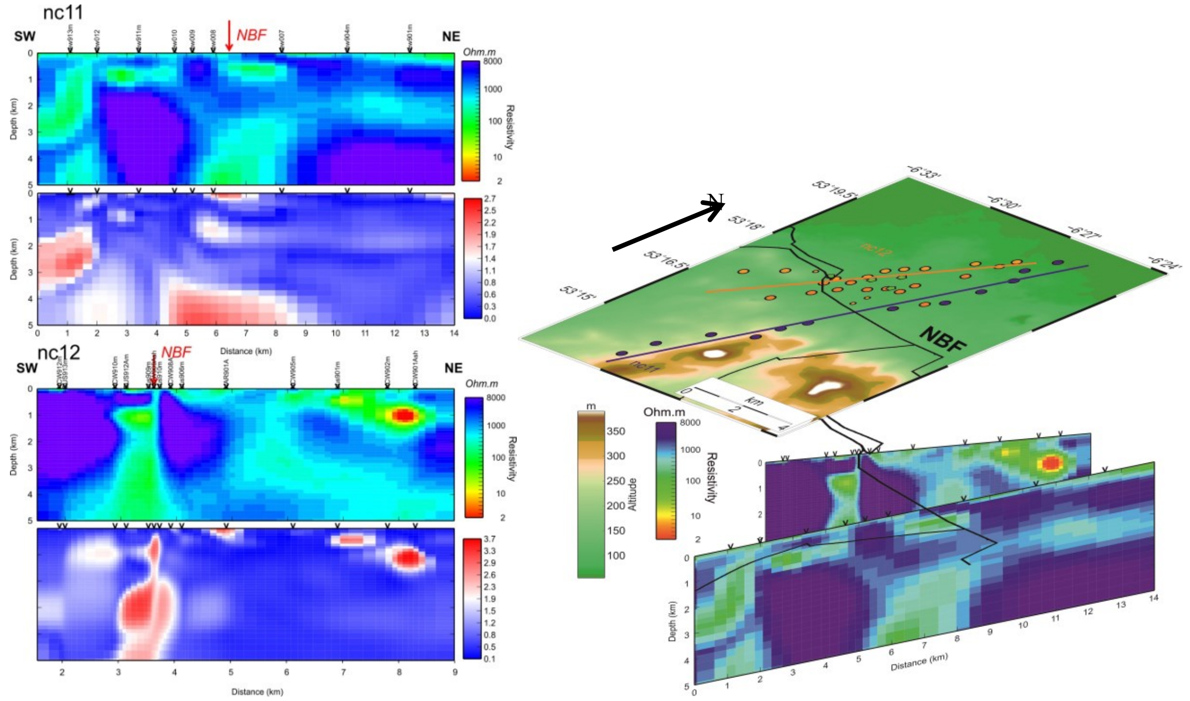

Figure 3: (right) 2-D models with reliability standard deviation estimation, where red means less reliable part of the model; (left) 3-D visualization of the two 2-D models of profiles nc11 and nc12.

The 3-D models of all MT sites in the Newcastle area have been prepared and 3-D modelling with two different codes based on data (Siripunvaraporn et al., 2005) and model space inversion algorithms (Egbert and Kelbert, 2012; Kelbert et al., 2014) have been performed. The 3-D inversion model we present and discuss has been obtained by the newest version of the 3-D MT inversion program WSINV3DMT, based on the data-space variant of OCCAM scheme (DeGroot-Hedlin and Constable, 1990), which includes modifications to allow inversion of the geomagnetic transfer functions (GTF). The inversion models from ModEM code are insensitive to deeper structures and final RMS misfits are higher, that's why we selected inversion model from WSINV3DMT code as a final one. The parallelized code version is used to facilitate its implementation on computer clusters and improve the time of computation.

The mesh size depended on the selected sites included in the inversion, and was 110x90x54 (110 in the N-direction, 90 in the E-direction, and 54 vertically). Initialization parameters input into WSINV3-DMT included the error floor for the impedances, defined as a percentage of square root of module of multiplied off-diagonal xy and yx impedance components, and an impedance error floor 5% was used for the current models. However, two other sets of error floors were used to test different data weighting in the inversion between diagonal and off-diagonal components (percentage of square root of xx and yy impedances for diagonal components) or all four components alone. The inversion of the impedance is also sensitive to the global resistivity of the starting model (usually a homogeneous half space), and a poor choice of starting model can result in being trapped in local minima of the misfit penalty functional. Topography was not included into models; it is not a significant issue as we are concerned with structures on scales of kilometres and change in topography is tens of metres.

Here we are presenting the current 3-D inversion model based on inversion of all impedance components after several rounds of inversions with improving starting model. We did not include inversion of the GTF data, because the model lost resolution in its deeper parts. The final RMS misfit for present model is 2.7. The 3-D RMS misfit is similar to 2-D modelling misfits. However the error bars applied for 3-D RMS misfit calculation are smaller than in 2-D case. For 3-D inversion models where the GTF data were included (not presented here), the final RMS misfit is similar. The inversions with higher smoothing applied to the model were also calculated, but without significant simplification of the structures in the resulting final model and also with higher RMSs.

The current model presented in Figure 4 exhibits much higher conductive structures in comparison to the 2-D models, with similarly resistive background rocks. The shallow conductive structures up to the depth of 1 km have north-south elongation correlated with the surface traces of faults, which are perpendicular to the NBF. Deeper structures become more oriented to regional geoelectric strike similar to 2-D regional strike estimated in the previous section, and also less conductive as it is observed in the 2-D modelling. The only exception is a strong conductor in the southern edge of the investigated area, but this conductor is based just on responses from one or two sites.

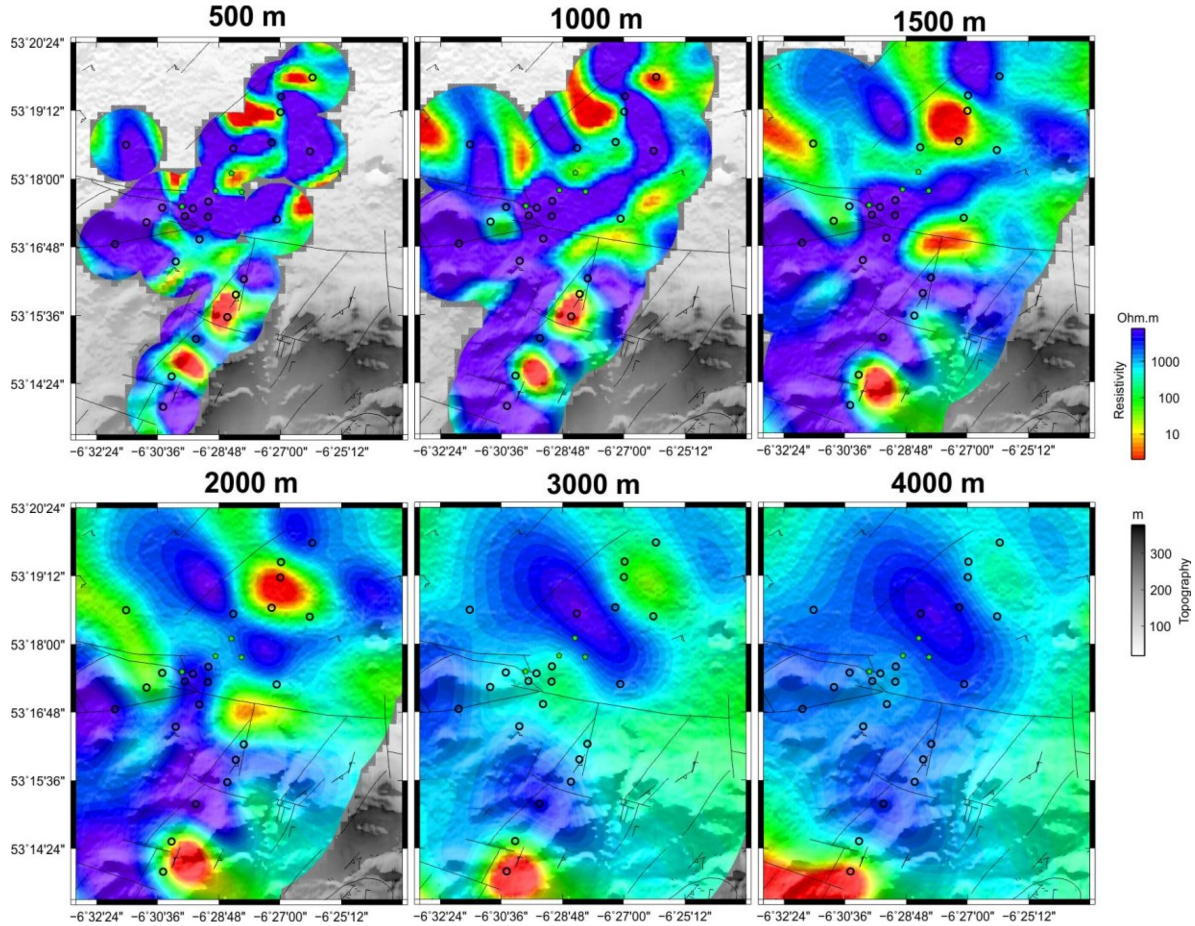

Figure 4: Horizontal slices of final 3-D model with shown surfaces traces of major faults and dip symbols in the modelled area (GSI online maps).

3. DISCUSSION

One of the goals of the survey with GT Energy as an industry IRETHERM collaborator was to provide the geoelectrical information to the base of the Carboniferous sequence at a depth of 4,000 m. The reliability of the presented 2-D and 3-D modelling suffers from distortion and urban noise from nearby industry and railway systems. We have completely removed one quarter of all stations in the area and almost half of all periods (all longer periods) in the stations used to be sure that we are not influenced by spurious MT data in the inversion modelling. The area exhibits high resistive background structures (hundreds of Ωm) and AMT and MT data from the highest frequencies up to 1 s period are enough to obtain sufficient information to depths of more than 5 km.

The aim of presenting both the 2-D and 3-D models is to identify possible 3-D effects in the previous 2-D modelling, and to estimate how unrealistic the final 2-D model may be for geological interpretation. There are well known problems of galvanic and induction effects of 3-D structures that cannot be removed by classic decomposition techniques (Ledo, 2005) and the distribution of these has an effect on the two modes of 2-D MT data and the GTF data. The 3-D inversion models show a relatively good match with the 2-D modelling for deeper crustal depths, down to 5 km. For shallower structures up to 1 km there are dominant 3-D effects from north-south oriented conductors.

The investigated area below Newcastle can be divided to two different layer zones. The first zone up to 1 km is dominated by NNE-oriented conductors connected with shallow faults probably filled with saline waters. The conductors are also crossing the surface trace of the BNF. The second zone can be identified from depths of 2 km to 3 km, where structures are along the BNF and have lower conductivity. We have quite good correlation between the 2-D and 3-D models for this depth range. The part of model where these 2-D conductive structures below the BNF are smeared to deeper depth are not taken into consideration, because these areas have also high standard deviation and they are less reliable. The structures in the centre of our investigated area at about 4 km depth and deeper are more resistive, and we cannot identify any significant conductor associated with the BNF; either a water bearing layer or other conductive faults. The strong conductor in the south of area probably originates from distortion at one of the most south site.

The higher conductivities in the 3-D model are probably closer to real values. The conductivities in the 2-D models are the result of averaged local 3-D body conductivity with very resistive surrounding rocks over 2-D space. Also, less conductive deeper structures can be the result of the averaging influence of several thin more conductive layers that cannot be resolved by inversion due to the small vertical resolution of inversion algorithms in these depths.

4. CONCLUSION

The recorded MT data are strongly affected by artificial noise due to nearby industry and railway systems. Nevertheless, because of resistive structures, the penetration depth of the good quality data extends to 10 km. Multidimensional MT modelling yields preliminary reliable geological interpretations to 5 km depth.

The NBF is visible in the models as a conductive area to depths of 4 km and is interpreted to be a highly fractured fault system infilled by saline waters. Generally, the south-western part of the area is more resistive and compact with a horizontal conductive layer at approximately 1 km depth, with a very thin sedimentary layer on the top. The structures north of the NBF are more heterogeneous, with deeper conductive layers (2-3 km) and thicker (several hundred metres) sedimentary layers above. The conductive layers are interpreted as saline water bearing rather than as conductive meta-sediments (black shales, sulphides, iron oxides etc.).

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