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The IRETHERM Project: Magnetotelluric Assessment of Sedimentary Basins in Northern Ireland as Possible Geothermal Aquifers

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ABSTRACT

In this study we present results from geophysical investigation of the sedimentary Rathlin Basin in Northern Ireland in order to assess the potential for a low enthalpy geothermal aquifer within the porous Permian and Triassic sandstone groups. The area and groups were identified as a potential geothermal resource due to the presence of both an elevated geothermal gradient (observed in two deep boreholes) and favourable hydraulic properties (measured from core samples). Prior seismic experiments were not able to fully image the sediments beneath the overlying flood basalt. A new experiment applying the magnetotelluric method has had more success, as the magnetotelluric signal is not dissipated by the crystalline overburden. Magnetotelluric data were acquired at 69 sites across the north-eastern portion of the onshore Rathlin Basin and on the nearby Rathlin Island in order to image the thickness, depth, and lateral continuity of the target sediments. Analysis and modelling of the data have been performed to determine a resistivity model that maps the variation in thickness of the sediment fill and the truncation of the basin sediments against the structurally-controlling Tow Valley Fault. Further synthetic testing of the model sensitivity to variations of the thickness of the Sherwood Sandstone Group within the sediment fill has also been performed, as the overlying sediments have lower porosities and permeabilities from core sampling.

1. INTRODUCTION

The IRETHERM Project (www.iretherm.ie) is a multi-disciplinary collaborative research programme to identify and evaluate potential geothermal resources within Ireland, with particular emphasis on low-to-medium enthalpy resources. Significant sedimentary basins in the north-east of Ireland have been identified as having elevated geothermal gradients measured in deep boreholes, with the highest of these (approximately 40 ^{o}C/km, significantly higher than the regional average across Ireland of approximately 25 ^{o}C/km) observed in the Rathlin Basin in the Port More borehole (deepest temperature measurement of 63.3 ^{o}C at 1481.9 m) on the northern coast (Wilson 1978).

Permian and Triassic sandstones form large parts of the fill in the Rathlin Basin, with the same formations well known offshore as hydrocarbon reservoirs. Upper Permian and lower Triassic sandstone core samples (cylindrical plugs of length 25 mm) from the onshore Port More borehole have had their hydraulic properties assessed, with ranges of 9 – 24% and 1 – 727 mD observed for effective porosity and converted permeability, respectively (Wilson et al., 1978). The samples with lower hydraulic properties are noted as tending to be from the bottom part of the sequence. With measurements obtained from core plugs, permeabilities are probably underestimated. The combination of elevated geothermal gradient and hydraulic properties suggests the potential for an exploitable geothermal resource within the sedimentary basin, with the relatively porous sandstones acting as an aquifer.

Previous geophysical exploration over the Rathlin Basin includes 2-D seismic reflection surveys and regional gravity measurements, with mixed success. Seismic work is been hampered by the presence of the surficial overlying Antrim Basalt Group, a flood basalt group that covers the region in up to 100 m of crystalline rock, wholly concealing the basin and scattering returning seismic waves at the negative impedance contrast between the overlying basalts and the sediments. Gravity models presented in Mitchell et al (2004) show a modelled basement depth of approximately 4 km, however the model is stated as using a possibly lower than acceptable density for some sediments (enlarging the basin). Furthermore, there is currently little published information on the presence of Carboniferous sediments within the Rathlin Basin, which, if present, could further complicate interpretation of the models.

The magnetotelluric method (MT) was selected for further investigation and imaging of the Rathlin Basin area as the quantity sensed, bulk electrical conductivity, is more strongly affected by the presence and organisation of fluids within the rocks than the lithology of the area. In particular, strong conductivity contrasts are expected between the porous sedimentary material (electrically conductive), surrounding Precambrian to Cambrian metasedimentary basement rocks (electrically resistive), and overlying igneous rocks (also resistive). The goal of magnetotelluric modelling of the survey area is to evaluate both the lateral and vertical extent of the sediments to establish the volume of potential aquifer, and to assess if there are any indications of heterogeneous structures within the sediments themselves that may affect aquifer potential.

In this paper we present results from magnetotelluric data acquired in two phases. The first phase in June, 2012 focused on acquiring data in seven profiles across the onshore basin, whilst the second phase in April, 2013 acquired data along two perpendicular profiles on the nearby Rathlin Island. The locations of the magnetotelluric recording sites acquired are shown in Figure 1, overlain on a simplified bedrock geology map of the region.

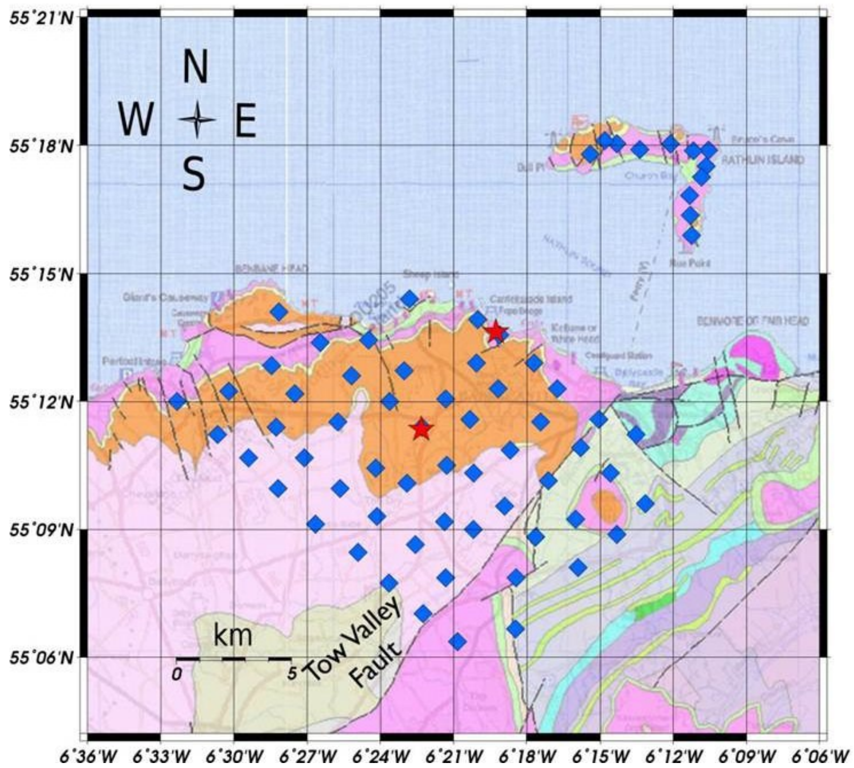

Figure 1: Geological map of the study area showing magnetotelluric site locations across the Rathlin Basin (blue diamonds). The two deep exploration boreholes in the basin are shown by red stars. The Antrim Basalt Group is shown by pink, purple and orange shadings, whilst the Precambrian and Cambrian metasediments are shown by pale green shading. The structurally-controlling Tow Valley Fault is indicated.

2. MAGNETOTELLURICS

2.1 Experimental Design

The magnetotelluric (MT) method measures the attenuation of electromagnetic waves propagating downwards into the Earth, with attenuation being primarily controlled by the frequency of the wave (lower frequency waves penetrate further) and the conductivity of the Earth (conductive materials are more attenuating). As the Antrim basalt overburden is electrically resistive, the magnetotelluric method is far less affected than prior seismic reflection experiments by their presence, allowing clearer observation of the sediment fill. As the magnetotelluric method is a passive measurement of natural time varying electromagnetic signals, it is susceptible to cultural noise, including industrial machinery and electric livestock fencing.

The first phase of MT measurements, comprising 56 sites along Profiles RBA to RBG, was carried out from late May to late June, 2012. The instrumentation consisted of Phoenix MTU-5A audiomagnetotelluric (AMT) and broadband (BBMT) systems, resulting in responses estimated over the period range of 0.0001 s (10,000 Hz) to 1000 s, with some data sets having good quality response estimates extending to 10,000 s. Data quality is mostly good, with a small number of sites suffering from cultural noise disturbances. The onshore sites were assigned to seven parallel profiles that run in a SE-NW direction perpendicular to the bounding Tow Valley Fault, with between six and eleven sites on each profile. A site spacing of 2 km both along and between profiles was achieved where possible, with accessibility and land usage limiting this in some areas.

The second phase of magnetotelluric measurements, twelve sites that comprise Profiles RIE and RIN on Rathlin Island, was carried out in April 2013. The instrumentation used was the same as the previous phase, however the data are of slightly lower quality due to stronger cultural noise sources, with good quality data extending from 0.0001 s to approximately 100 s at most sites. The two profiles on Rathlin Island run along the spine of the L-shaped island in order to minimise the effect of the electric currents that concentrate at land-ocean boundaries, with a nominal spacing of 800 m.

The data were processed using the remote reference scheme present in the Phoenix processing software (based on that presented in Jones and Jödicke, 1984). Audiomagnetotelluric and broadband magnetotelluric data were merged, resulting in responses ranging from 0.0001 s to 1000 s in period for most sites. Current work is focusing on analysis of distortion parameters present in the data using the program STRIKE (McNeice and Jones, 2001), based upon the Groom-Bailey decomposition outlined in Groom and Bailey (1989). The validity of assuming the data are one or two dimensional for modelling purposes is also being tested by comparing the consistency of the apparent resistivity and phase of each data record (Parker & Booker, 1996).

2.2 Preliminary Modelling results

Modelling has been carried out with 1-D (Constable, S.C., Parker, R.L. & Constable, C.G., 1987), 2-D (Rodi & Mackie, 2001) and 3-D (Egbert & Kelbert, 2012; Kelbert et al., 2014) inversion schemes, with further modelling to be done after distortion analysis has been completed. Preliminary models from 1-D and 3-D inversions are shown in Figures 2 and 3.

One dimensional modelling of magnetotelluric data is based upon the assumption that the resistivity structure varies solely in one dimension (depth), resulting in a layered model (e.g. Constable et al., 1987). The model presented here (Figure 2) uses the lithological interface depths observed in the Port More borehole (Wilson 1978) to define boundaries for the resistivity model, using magnetotelluric data from site RBA006, located 170 m east of the borehole. The sedimentary fill in general has a strong resistivity contrast to the overlying basalts and limestones, and the underlying metasediments. Within the sediments the resistivity contrasts between the porous target sandstones and the overlying less favourable sediments are more subtle, varying within the same order of magnitude. Whilst differentiating the sediments at this site is possible due to the nearby borehole, the majority of magnetotelluric recording sites do not have such strong borehole constraint and other geophysics may be required to assist.

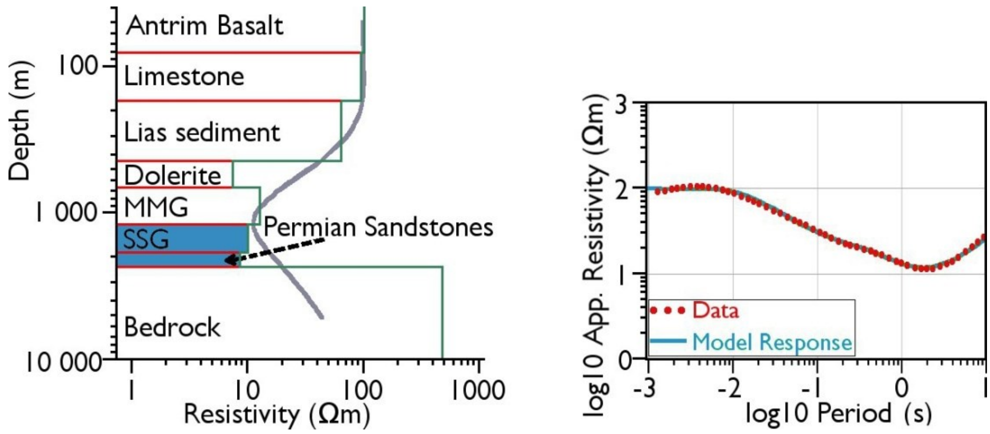

Figure 2. Layered earth resistivity model (left) and comparison of magnetotelluric data and model response (right) for site RBA006, adjacent to the Port More borehole. The left plot shows a schematic of the layered resistivity in green (with lithological unit boundaries in red), and the Bostick transform of the data (Chave & Jones, 2012) in grey. The target porous sediment units are shaded in blue. The right plot shows the magnetotelluric response of the model (blue) in good agreement with the data (red), reflecting the low RMS misfit of 1.49. The depths to lithological group interfaces from the borehole records were used as *a priori* information to constrain the layer thicknesses, allowing only the resistivities of each defined layer to vary. The resulting resistivity structure in the deeper basin shows the expected resistivity contrasts between the less permeable Mercia Mudstone Group (MMG) and the target Sherwood Sandstone Group (SSG) and Permian sandstones, making quantitative interpretation with respect to geothermal potential more challenging at distance from borehole constraint. The Port More borehole at this site reached its total depth of 1897 m in the Permian sands rather than the basement, which, according to this model, occurs at approximately 2150 m depth.

In contrast, three-dimensional (3-D) modelling allows for variation of the resistivity structure in both horizontal dimensions in addition to vertically, allowing more complicated structures to be determined (Egbert & Kelbert, 2012). However, 3-D inversion is in its infancy, and much needs to be done to progress it to the mature levels of 1-D and 2-D inversion. Figure 3 shows four horizontal slices through the current best-fitting 3-D resistivity model, two at mid-basin depths, and two at depths approaching the expected depth of the basin. The basin itself is clearly visible as a large conductive body at depths 500 m and 1000 m, with the resistive metasedimentary material to the south-east and the Tow Valley Fault coincident with the steep resistivity gradient running north-east to south-west. The slices from depths of 2000 m and 3000 m show reduced conductivity across the basin, suggesting a reduction in the amount of porous sediments present; i.e, either the lithology of the sediments is markedly different from the overlying successions or the porosity/permeability is significantly reduced. One major consideration with 3-D modelling in a coastal environment such as the Rathlin Basin is the presence of the ocean as a large, extremely conductive nearby body, typically on the edge of a model. If not accounted for in the starting model for inversion large anomalies, its effects may be introduced into the model as the algorithms try to account for the large, relatively thin conductor (but of high conductance) outside the region of data coverage. The model presented here, as a preliminary model, does not have bathymetry introduced, resulting in a large anomaly that has been suppressed for interpretation.

3. CONCLUSION

Magnetotelluric data have been acquired over the concealed Rathlin Basin in Northern Ireland in order to evaluate the potential of porous Permian and Triassic sandstones to host a low-enthalpy geothermal reservoir. Analysis and modelling of magnetotelluric data is ongoing, with preliminary models clearly imaging the contrast between the conductive sediments and the resistive basement. Once complete, the information from magnetotellurics over both the onshore Rathlin Basin and Rathlin Island will be combined with information from the existing gravity and seismic data in the area to evaluate the dimensions of the possible geothermal aquifer of the Rathlin Basin. Estimates of porosity and permeability distributions will also be obtained from comparison of our results to borehole logging from the very few existing wells, and the aforementioned laboratory measurements of porosity and permeability. This will hopefully provide us with a more quantitative assessment of the resource potential and the corresponding uncertainties.

4. ACKNOWLEDGEMENTS

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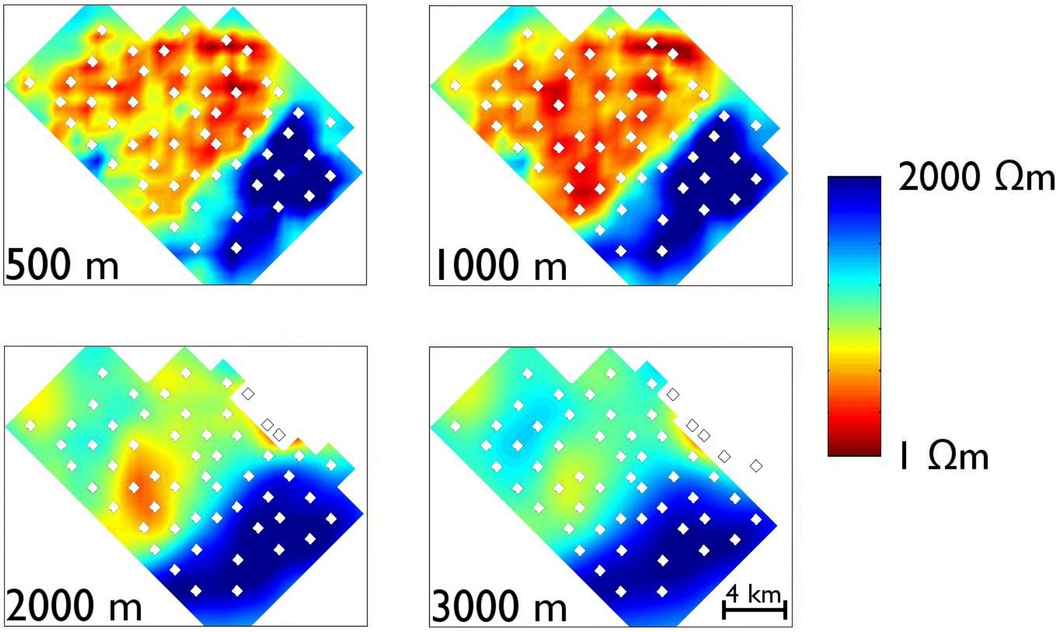

Figure 3. Preliminary resistivity model of onshore data in the Rathlin Basin, from 3-D inversion of data. Four horizontal slices through the model are presented from depths of 500 m, 1000 m, 2000 m and 3000 m. The two shallow slices show the sediment fill as bright red to yellow, indicating low resistivities of 1 – 10 Ωm, with a sharp boundary running NE-SW that corresponds to the Tow Valley Fault. The Cambrian to Precambrian metasedimentary basement is present to the south-east as the large, dark blue resistive body (high resistivities exceeding 2,000 Ωm). The 2000 m depth slice shows elevated resistivities in comparison to the shallower slices for the sediment fill area, suggesting the absence of the more conductive sediments in some areas, with low resistivities still present in a large area south-west of the central survey area. The 3,000 m slice shows less conductivity across the basin, indicating the absence of the highly conductive porous units sought, however the smooth nature of the model prevents a discrete estimate of the depth at this stage. Note that the model has been cropped to remove anomalous edge effects present outside the area of data coverage (cropped to approximately 1 km beyond outermost site locations), and a large anomaly introduced by the presence of the ocean.

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