Proceedings World Geothermal Congress 2015
Melbourne, Australia, 19-25 April 2015

Porosity and Permeability Constraints from Electrical Resistivity Models: Examples Using Magnetotelluric Data

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Keywords: geothermal resource, Ireland, magnetotelluric, porosity, permeability, cementation exponent.

ABSTRACT

The efficiency of geothermal energy extraction from reservoirs depends not only on temperature, but also on the porosity and permeability of the target rocks. Data from boreholes can constrain these parameters well at specific points but not across the entire geothermal targets. In this paper, the electrical resistivity information of the subsurface obtained from magnetotelluric data is calibrated by laws relating electrical conductivity to porosity and permeability, with the aim of extrapolating the porosity-permeability values measured in the boreholes to the whole area of study. A new approach, based upon the Generalized Archie's law, was created to determine the cementation exponent of different types of Irish rocks from porosity and electrical conductivity data. Using sandstone as the target rock, the permeability values were calculated from porosity, electrical conductivity and cementation exponent data using different approaches. The influences of the parametric variables were tested, showing which variables create more instability in the final results. Synthetic electrical resistivity models of the subsurface were also created to analyze the sensitivity of MT data to differences in the porosity - permeability of the target rock. These results of this work will be used within the geothermal IRETHERM geothermal project to assist with the project aims of identifying those areas of Ireland with the most potential for geothermal energy provision.

1. INTRODUCTION

IRETHERM (www.iretherm.ie) is an academic-government-industry collaborative project with the aim to evaluate Ireland´s geothermal energy potential through integrated modeling of new and existing geophysical and geological data. In this project, the magnetotelluric (MT) geophysical technique has a major role, characterizing the electrical resistivity distribution of the subsurface below several geothermal target areas.

Relating electrical resistivity values to rock properties will help to upscale porosity-permeability data estimated from borehole samples or geophysical logs to a wider region of study. With this aim, the relationship between electrical resistivity values and porosity, permeability and cementation exponent values has been analyzed using data from Morris (1973). Significant occurrences of Permo-Triassic sandstones exist in the north of Ireland and have been the subject of MT surveys during the IRETHERM project. Focusing on sandstones as a geothermal target rock, different approaches have been tested to constrain rock properties from electrical resistivity values, whilst also quantifying the resolution constraining these parameters. Finally, synthetic electrical resistivity models have been created to determine the sensitivity of MT data to differences in the porosity-permeability values of the target reservoir.

2. RELATIONSHIP BETWEEN ROCK PROPERTIES AND ELECTRICAL RESISTIVITY

Three empirical equations associated with sedimentary rocks have been analyzed: (1) Archie's law for multiple phases (Glover et al., 2010) relating porosity to electrical conductivity; (2) The Katz and Thompson (1986) (KT) equation, based on Mercury injection capillary pressure (MICP) and used to determine the permeability from electrical resistivity values; and (3) the Revil, Glover, Pezard and Zamora (RGPZ) model (as coined by Glover et al. 2006), which is used to calculate permeability values from porosity and cementation exponent data.

2.1 Porosity-electrical conductivity

The Generalized Archie's law for multiple phases (Glover, 2010) (Equation 1) has been used to determine the relationship between porosity and electrical conductivity.

$$\sigma = \sum_i^n \sigma_i \emptyset_i^{m_i} \tag{1}$$

where the exact solution is

$$m_j = \frac{log\left(1-\sum_{i\neq j}\emptyset_i^{m_i}\right)}{log(1-\sum_{i\neq j}\emptyset_i\ )} \tag{2}$$

where σ is the conductivity of the sample, σ_i is the conductivity of the i phase, $\emptyset_i$ is the volume fraction of i phase and m_i is the cementation exponent of i phase.

A new computer code has been developed which is used to determine the cementation exponent in Equation 1 of several Irish rocks from porosity - electrical conductivity data by a stabilized, nonlinear, least-squares regression procedure (Marquardt, 1963). The algorithm randomly calculates the parameters of the Generalized Archie's law using possible values between ranges defined by the inputs to the program. Then it checks if the obtained curve fits the data. If it does, the used parameters are saved; otherwise, they are discarded. The inputs of the program are: porosity error; conductivity error; range of possible cementation exponent values; range of possible conductivity values of the matrix; range of possible conductivity values of the fluid; number of data points. In addition, the program allows the user to indicate a number of data points (without specifying the data points) that do not need to be fitted, thus avoiding bias error from data points that cannot be fitted. The outputs of the program provide the ranges of parameters that fit the data: range of cementation exponents (*m*) values; range of conductivity values of the matrix; range of conductivity values of the fluid; total number of created Archie´s curves; number of how many points that fit the data.

Using saturated samples and a fluid with conductivity of 1 S/m (Morris, 1973), the results obtained are shown in Table 1. Adopted errors used are between 0.24 and 0.40 (log10 conductivity (S/m)) for electrical conductivity and 0.01 for porosity. Figure 1 shows the data points for three different types of sandstone and the obtained Archie's law curves that fit the data.

Table 1: Cementation exponent (m) of different Irish rocks. Av: is the Average between *m_min* and *m_max*.

Rock type	m_min	m_max	Av.	Error
Amphibolite	1.88	1.97	1.93	0.05
Gneiss	1.66	1.72	1.69	0.03
Granite-Gneiss	1.21	1.40	1.31	0.10
Granite diorite	1.44	1.53	1.49	0.05
Quartzite	1.49	1.60	1.55	0.06
Coarse Sandstone	1.63	1.67	1.65	0.02
Medium Sandstone	1.66	1.69	1.68	0.02
Fine Sandstone	1.66	1.7	1.68	0.02
Shale Argillite	1.35	1.45	1.4	0.05
Siltstone	1.67	1.73	1.7	0.03
Carbonate Calcareous	1.73	1.77	1.75	0.02

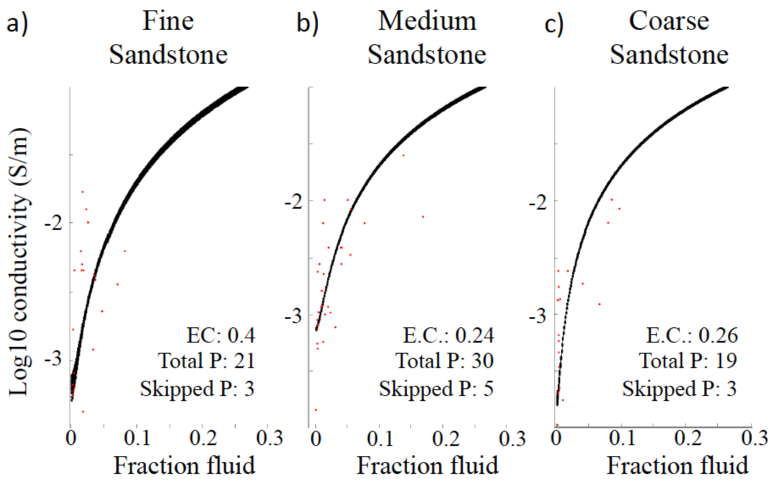

Figure 1: Results obtained for different types of sandstone: a) Fine sandstone b) Medium sandstone c) Coarse sandstone. EC: assumed log10 error on conductivity. Total P: Total points. Skipped P: Points that do not need to be fitted. In all cases an error of 0.01 is assumed for fraction fluid values (which is equivalent to porosity).

<u>2.1.1 Resolution in determining porosity values from electrical conductivity data</u>

Assuming an error of 0.24 (log10 conductivity (S/m)) for electrical resistivity values and a cementation exponent of between 1.66 and 1.69 (in the case of medium sandstone in the examples above), the resolution of the porosity as determined using the Generalized Archie's law has been assessed for three different porosities: 0.05; 0.1 and 0.25 (Figure 2).

Each color represent the assumed error bar on the electrical conductivity values and it propagation when determining the porosity values. The results show that resolution in determining the porosity values from electrical resistivity data decreases when the porosity increases. Resolution is between 0.035 and 0.070 for a porosity of 0.050, between 0.075 and 0.135 for a porosity of 0.100, and between 0.145 and 0.270 for a porosity of 0.200. So the derivation of porosity values from electrical resistivity data is more accurate when porosity is small.

2.2 Permeability-electrical conductivity

Permeability is associated with how well a fluid flows through the rock, and it can be related to how well an electrically conductive phase is connected inside the rock, giving a chance for electromagnetic (EM) methods to determine the permeability of the rock.

The RGPZ (Glover et al. 2006) and KT (Katz and Thompson, 1986) approaches have been used to evaluate the resolution we should expect when determining the permeability from electrical resistivity data. The first case depends upon porosity and cementation exponent values, here obtained from porosity-electrical conductivity data using the Generalized Archie's law. In the second case, permeability is directly constrained by electrical conductivity data.

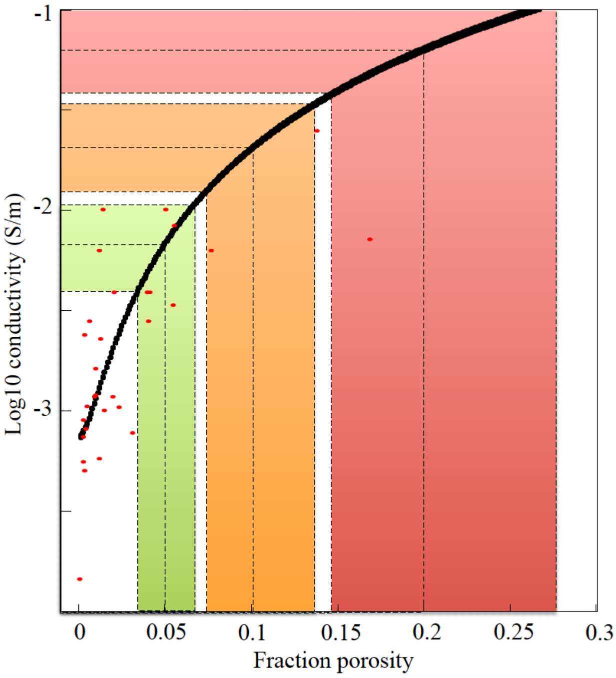

Figure 2: Resolution determining porosity values from electrical resistivity data assuming an error of 0.24 on the log10 electrical conductivity.

2.2.1 RGPZ

The RGPZ model (Glover et al. 2006) is used to obtain permeability values from porosity and cementation exponent data (Equation 3).

$$k = \frac{d^2 \phi^{3m}}{4pm^2} \tag{3}$$

where k is permeability, d is effective grain diameter, phi is porosity, m is cementation exponent, and p is the packing parameter (p=8/3 is assumed for quasi spherical grains).

This approach is valid when the range of grain sizes in the rock is large compared to the difference between the mean, maximum, and minimum effective grain radius; the values for the formation factor and the cementation exponent are derived from saline water bearing rock; the rock is non-fractured such that the formation factor is much larger than 1; the model is not used at the porosity limit (i.e. 100 % porosity).

2.2.1.1 Dependence of permeability upon porosity and the cementation exponent

The RGPZ dependence on cementation exponent and porosity is shown in figure 3. The results show that dependence on cementation exponent increases for high cementation exponents and for lower porosity values.

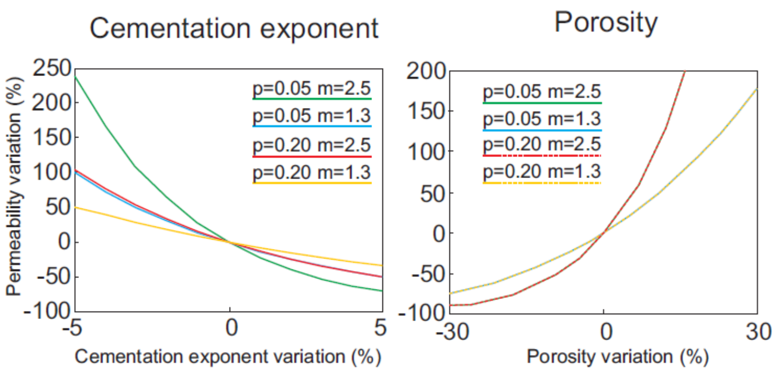

Figure 3: Dependence of the permeability values to cementation exponent (m) and porosity (p).

2.2.1.2 Resolution of the permeability estimation

The resolution constraining the permeability values of a synthetic case were calculated using errors for porosity and cementation exponent similar to those observed above (Table 1) and undertaking stochastic modeling (Figure 4). Most of the obtained values are around 169 mD (red column in figure 4, 2.23 at log10 scale). A range of values is between 100 mD (2.0 at log10 scale) and 281 mD (2.45 at log10 scale) were obtained for a permeability of 169 mD.

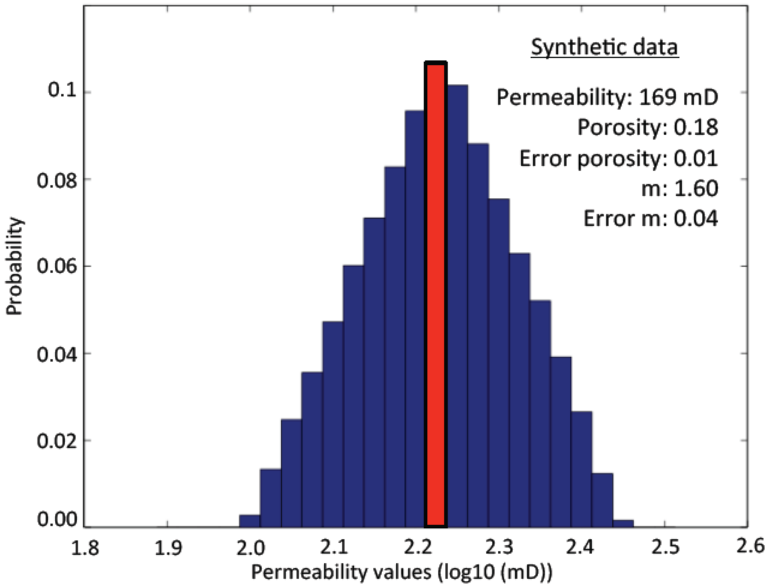

Figure 4: Resolution of permeability estimates following the RGPZ equation on a synthetic case with standard errors obtained from the examples above. m: cementation exponent.

2.2.2 KT

Following Katz and Thompson (1986), the permeability can also be constrained by electrical conductivity values of the sample and the electrical conductivity values of the fluid in the pores (Equation 4).

$$k = cl_c^2\left(\frac{\sigma}{\sigma_f}\right) \tag{4}$$

where σ is the conductivity of the sample, σ_f the conductivity of the fluid, c is 1/266 and l_c is the length of pore space. This approach is valid when data from mercury injection capillary pressure (MICP) analysis (used to determine pore size distribution, permeability and porosity) is available.

2.2.2.1 Dependence of Permeability upon electrical conductivity

The KT dependence on electrical conductivity is shown in Figure 5. A linear dependence is observed between electrical conductivity differences and permeability differences.

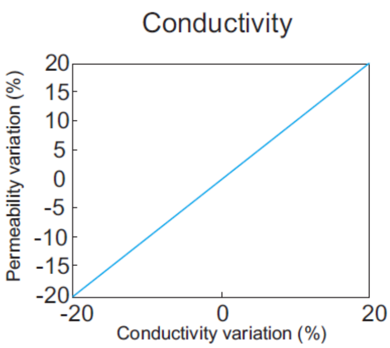

Figure 5: Dependence of the permeability values upon electrical conductivity data for KT analysis.

2.2.2.2 Resolution of the permeability estimation

The resolution in determining the permeability using the KT approach (Figure 6) has been constrained using an equivalent situation than in the RGPZ analysis. Assumed electrical conductivity errors are similar to the ones shown in Table 1. Results show that following the KT equation we should expect values between 100 mD (2.00 at log10 scale) and 298 mD (2.48 at log10 scale) for a permeability of 169 mD. The ranges of permeability values obtained from both approximations are similar, but there is a difference between the distributions of the results. Following the KT approach results are equivalent distributed between the ranges of possible values while following the RGPZ most of the results are close to the expected value, 169 mD (Figures 4 and 6).

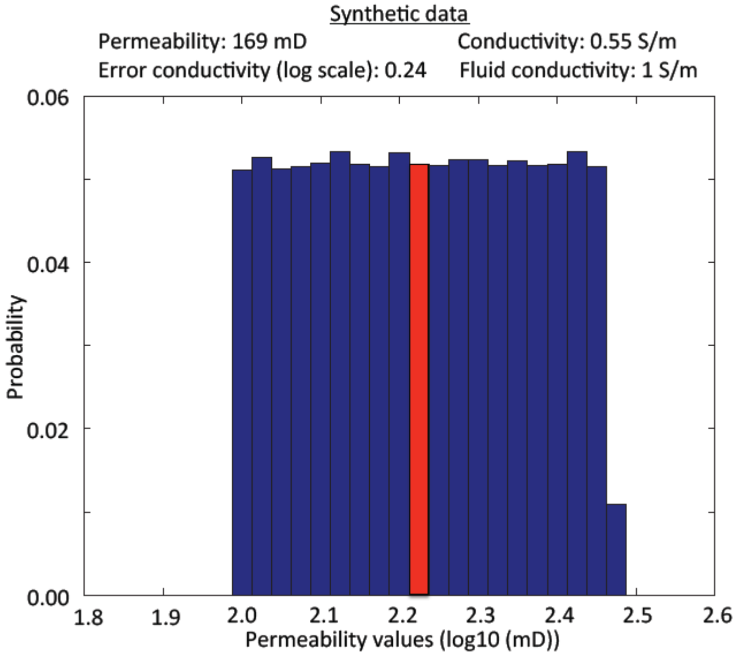

Figure 6: Resolution of permeability estimates values following the KT equation on a synthetic case with standard errors obtained from the examples above.

3. INTEGRATION WITH MT MODELS

The forward MT responses of synthetic models have been calculated in order to study the effect of rock property variations on MT responses. Figure 7 shows the electrical resistivity model of a horst-like geothermal scenario used in this work.

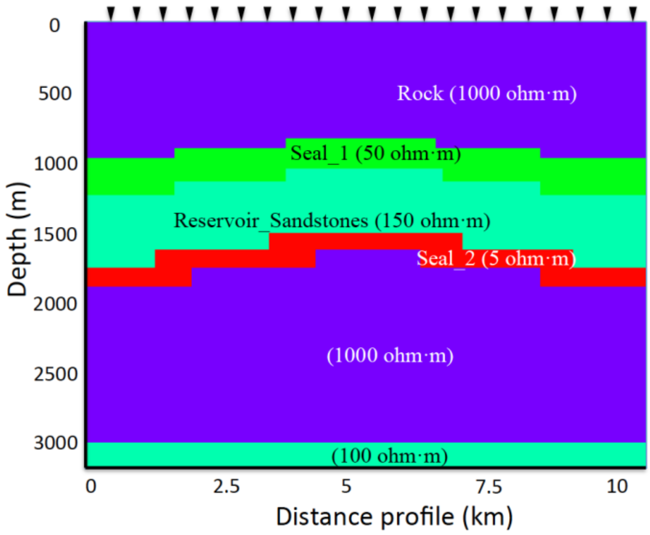

Figure 7: Synthetic 2D electrical resistivity model of a geothermal reservoir assuming a sandstone porosity of 5 %. Inverted triangles are sites where MT data is calculated.

3.1 Dependence upon the porosity of the reservoir

The forward response of the MT model (Figure 7) has been obtained for three different situations, assuming three different porosities for the sandstones (5, 10 and 20 %) that, using the Generalized Archie's law, are related to the three different corresponding electrical resistivity values (150, 50, 20 ohm·m, respectively). Differences on magnetotelluric data (for TM and TE modes) associated with different porosities of the sandstone are shown in figure 8. Differences bigger than 10% for the AP and 2.86º for the Ph can be detected in a real situation.

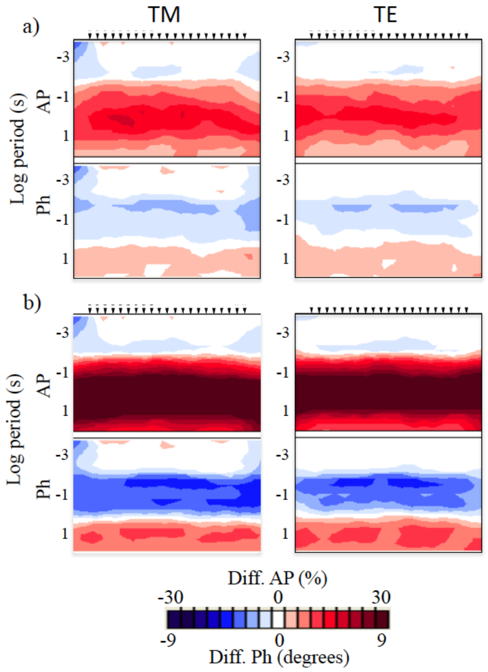

Figure 8: Differences observed in the MT responses associated with different porosities of the sandstone rock for each of the MT modes (TM and TE). a) Differences between 5% and 10 % porosity. b) Differences between 5% and 20 % porosity. AP: Apparent resistivity. Ph: Phases.

3.1.2 Influence of geoelectrical structures below the reservoir

The influence of Seal 2 (Figure 7) in determining the properties of the reservoir has also been analyzed. In this case, the thickness of this layer was increased by a factor of two. Following the same analysis as above, Figure 9 shows differences on magnetotelluric data associated with differences of the reservoir when the thickness of the Seal_2 is increase by a factor of 2. Comparison between Figures 8 and 9 shows that the effect of the target area on magnetotelluric data is also affected by the structures located below. In this case, a thicker conductive structure reduces the sensitivity constraining the properties of the Sandstone by electrical resistivity values.

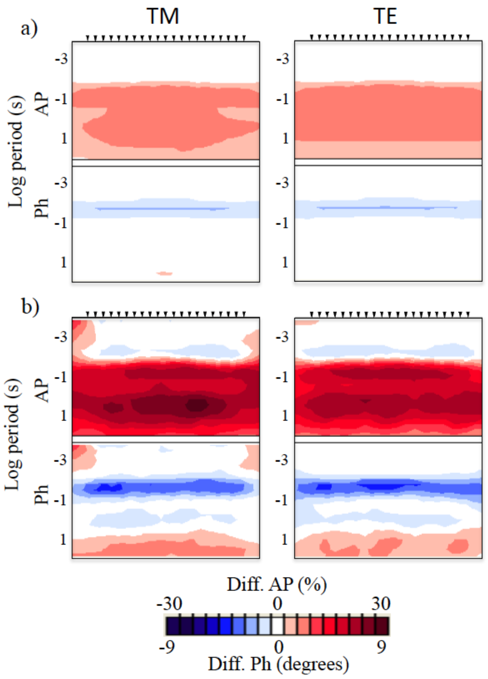

Figure 9: Differences observed in the MT responses associated with different porosities of the sandstone rock for each of the MT modes (TM and TE) when increasing the thickness of Seal_2 (x2). a) Differences between 5% and 10 % porosity. b) Differences between 5% and 20 % porosity. AP: Apparent resistivity. Ph: Phases.

3.1.3 Presence of an anomalous region with high porosity

The effect on magnetotelluric data associated with an anomalous region in the reservoir with higher porosity has been analyzed by modifying the model in Figure 7 adding an anomalous area in the reservoir with higher porosity, 10 - 20 % (Figure 10).

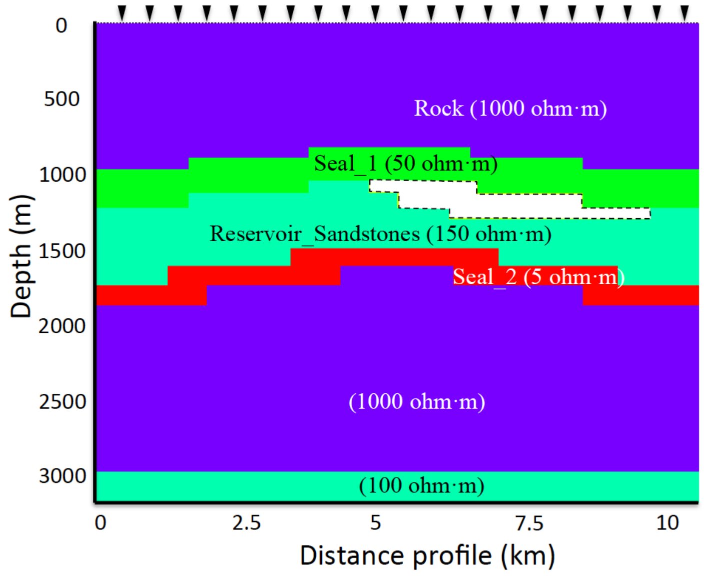

Figure 10: Electrical resistivity model of a geothermal reservoir with 5% porosity of the sandstone but with a region (white area surrounded by black dashed line) of high porosity: 10% (50 ohm·m) and 20% (20 ohm·m).

Figure 11 shows the differences of the MT responses between the model shown in Figure 7 (reservoir porosity of 5 %) and the model shown in Figure 10 (with an anomalous region with higher porosity, 10% - 20%). From the results obtained, the most sensitive magnetotelluric data to this anomaly is the TM component of the sites located above the anomalous area.

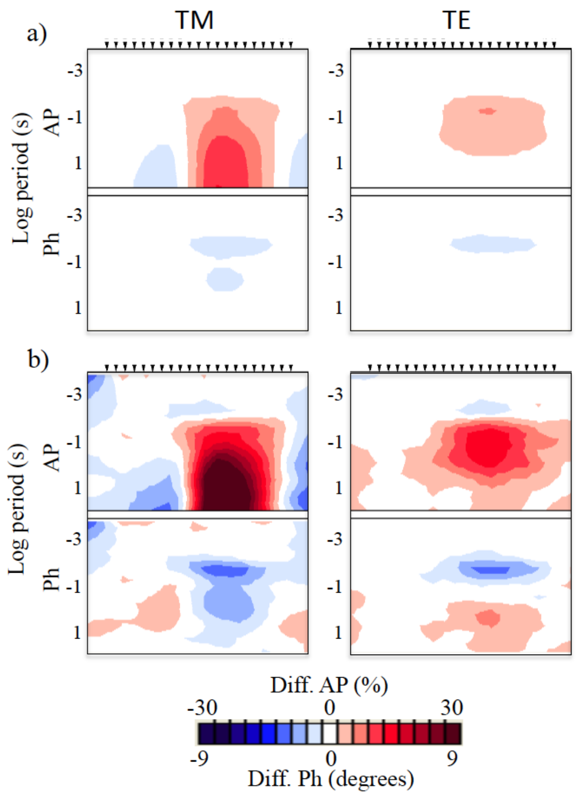

Figure 11: Differences on MT data (TM and TE modes) associated with an anomalous area in the Sandstone reservoir with higher porosity. a) Differences between model without anomaly and model with an anomaly with 10% porosity. b) Differences between model without anomaly and model with an anomaly with 20% porosity. AP: Apparent resistivity. Ph: Phases.

4. CONCLUSIONS

Using data from Morris (1973) and a new algorithm based on the Generalized Archie's law, the cementation exponent of different Irish rocks have been constrained with an average error of 0.04, and in most of the cases with an error lower than 0.06. These results, together with porosity and electrical resistivity values, have been used to determine permeability values following two different approaches, namely the KT and RGPZ models. Resolution of these approaches and influence of the variables determining permeability values have been determined suggesting similar resolution in both cases. In the case of RGPZ, the results are more precise when porosity increases and the cementation exponent decreases. Sensitivity tests with synthetic electrical resistivity models shows the effect of porosity anomalies on magnetotelluric data and corroborates MT as a geophysical tool to estimate porosity–permeability values of the reservoir at a big scale. The results also show that not only structures above but also structures below the reservoir has to be take into account as they could have influence on the sensitivity constraining the properties of the reservoir.

ACKNOWLEDGEMENTS

We would like to acknowledge the financial support for the IRETHERM Project from Science Foundation Ireland (SFI), the IRECCSEM project funded by a Science Fundation of Ireland (SFI) Investigator Project Award and from Providence Resources, and the data provided by GT Energy. We gratefully thank all members of the IRETHERM consortium for their efforts in this project.

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