Joint Inverse Modelling of Geophysical Data from Lough Neagh Basin

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and the IRETHERM team

1.4.2016 – IRETHERM Workshop

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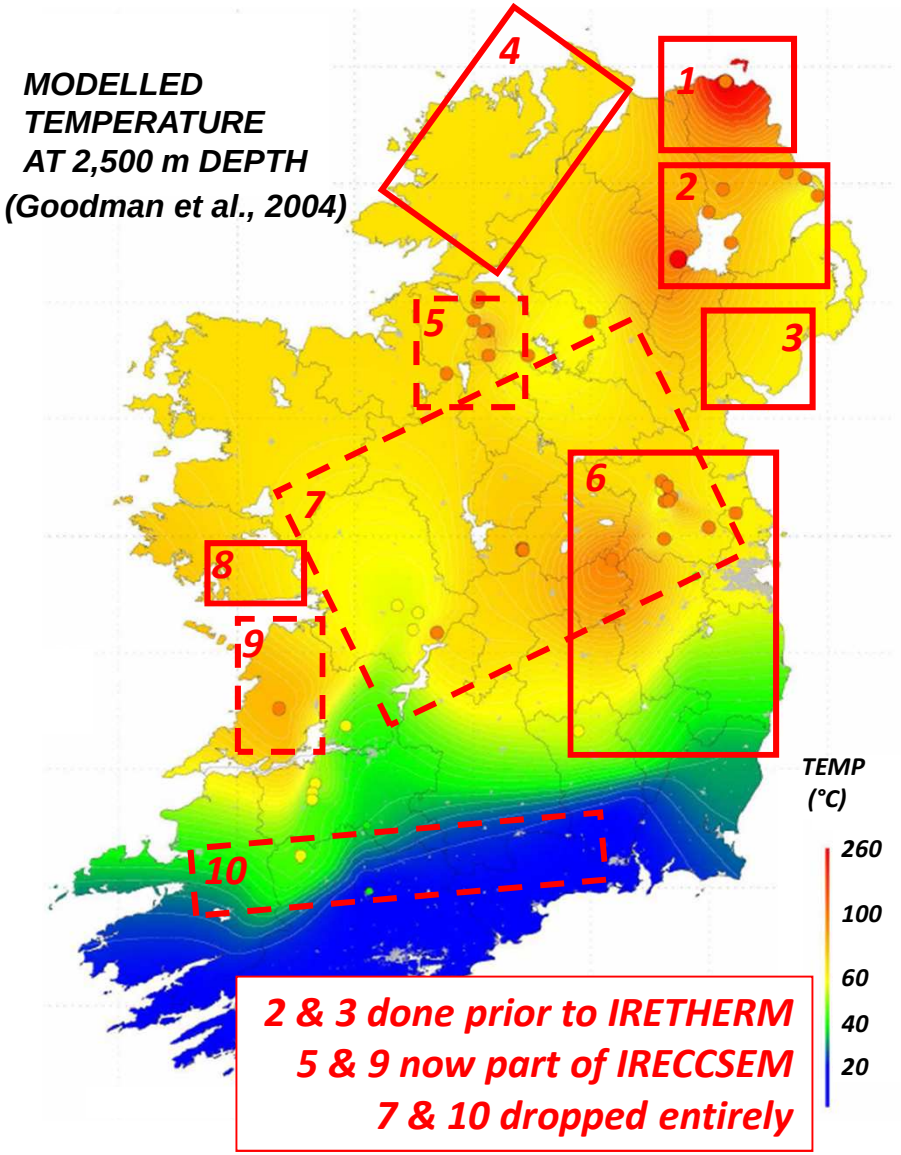
ORIGINALLY 10 TARGET AREAS



8 TARGET 'TYPES' OR SETTINGS

i Triassic Sherwood Sandstones (1, 2)
ii Radiogenic granites (3, 6, 8)
iii Warm-spring lineaments (6)
iv High heat-flow/temperature anomalies (1)
v Deeply penetrating, significant fault zones (secondary porosity) (6)
vi Gravity anomalies of unknown origin (6)
vii Areas of current seismicity (secondary porosity?) (4)
viii Basal sediments of the Carboniferous and Devonian successions (9)

- *Over 400 MT sites across Ireland: focussing in the depth range 1,000 – 6,000 m.*
- *Supplemented by existing gravity, seismic refraction & reflection, borehole core and wireline log data.*
- *High resolution CSEM methods to be used over shallow warm-spring targets – complemented by systematic hydrochemical measurements.*

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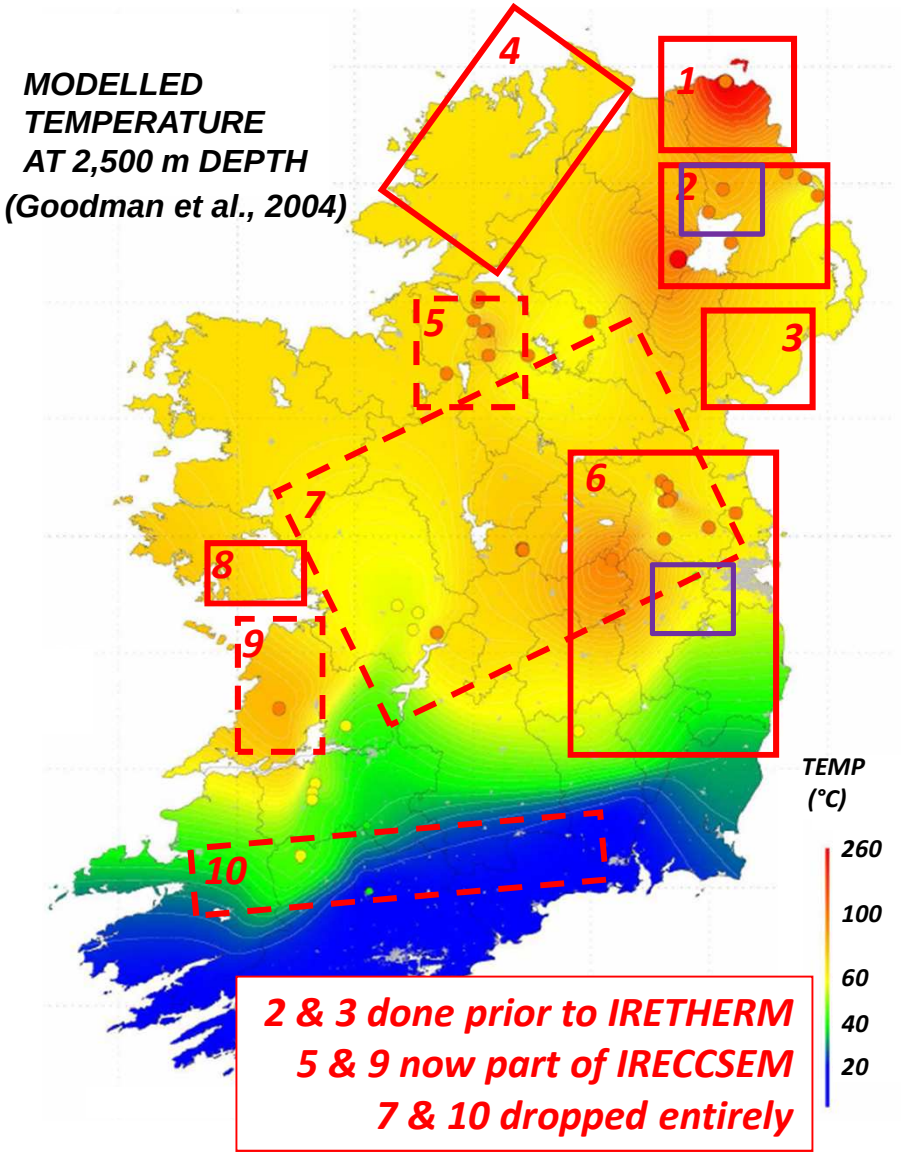

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Outline

Multi-dimensional geophysical modelling

- *3D modelling of MT data collected in Lough Neagh Basin (Northern Ireland)*
- *3D density models of Bouguer anomaly data from this region*
- *9 reflection profiles in western part of survey area*
- *Joint inversion 3D modelling – MT, gravity and seismic data*

  - coupling strategy: a) direct parameter relationship

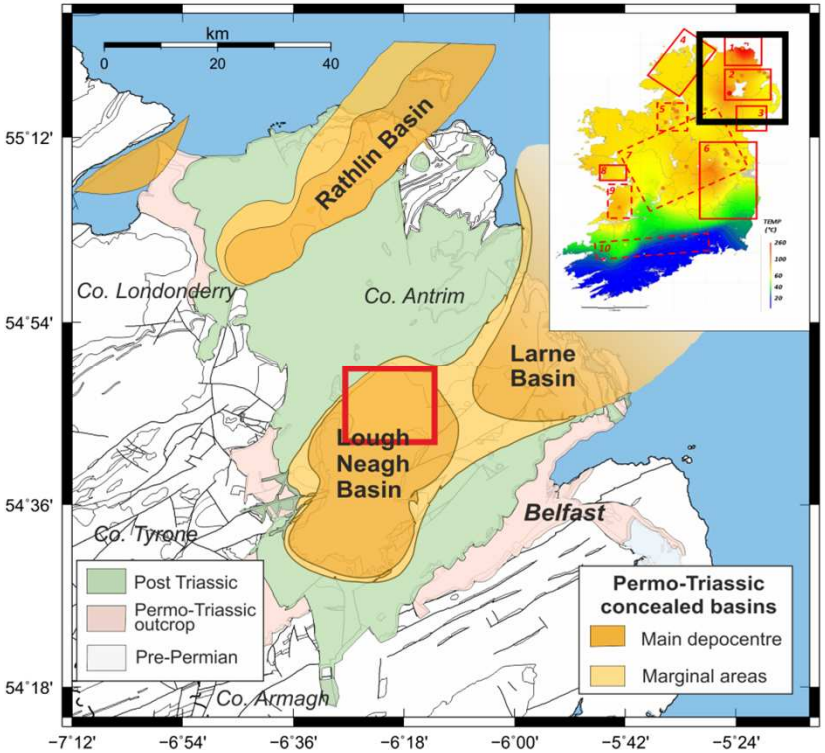
  b) a structural constraint (matching the directions of the changes in the different parameters)

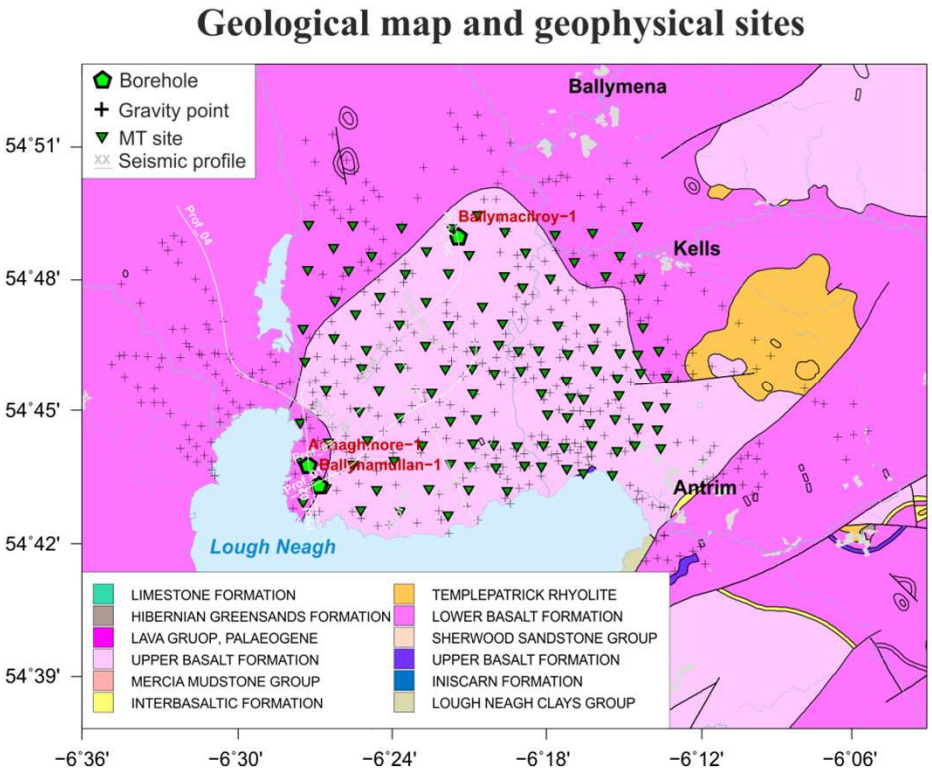
Geothermal reservoir modelling

- *The objective of geothermal energy potential estimation for geothermal resources in this sedimentary basin area is to identify the deep aquifers formations and localities where higher primary porosities are preserved*

Lough Neagh Basin

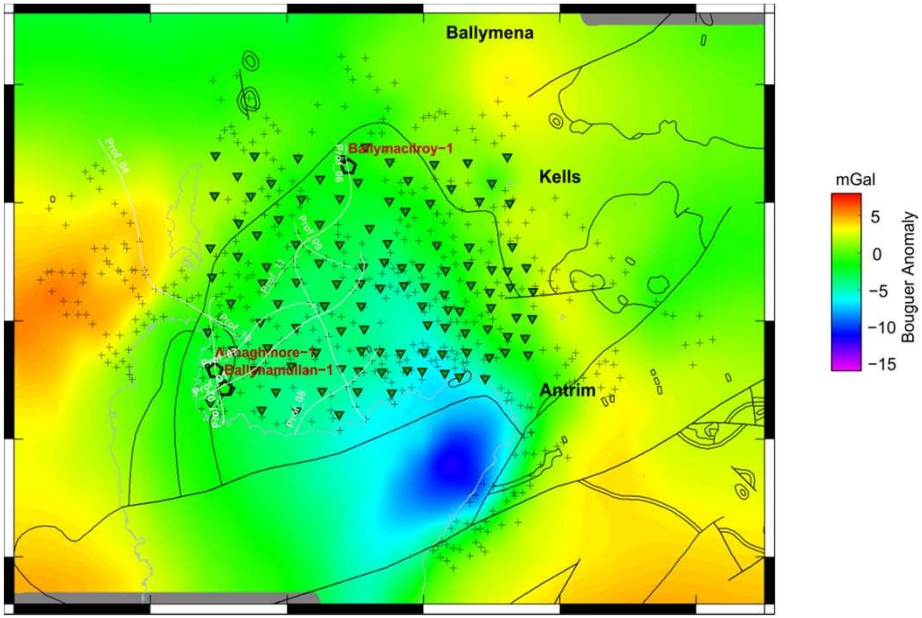
- *Permo-Triassic basin, exhibits elevated geothermal gradient (~30 ℃/km) are found in the depth range of 500m to 2250m in the exploratory drilled boreholes*
- *Water bearing layer correlated with Sherwood sandstones*

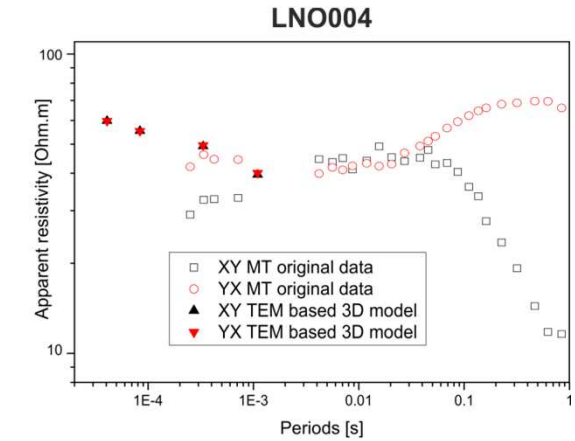


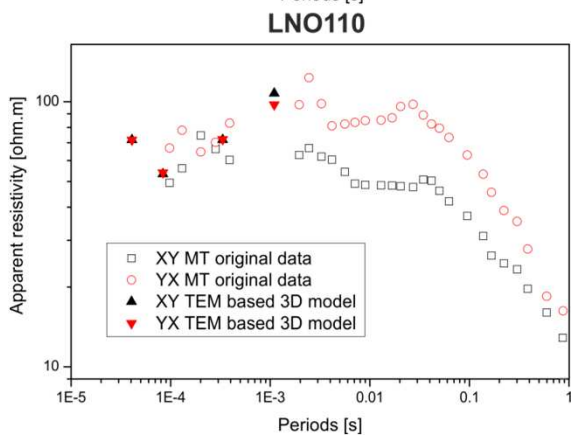


Lough Neagh Basin – geophysical data

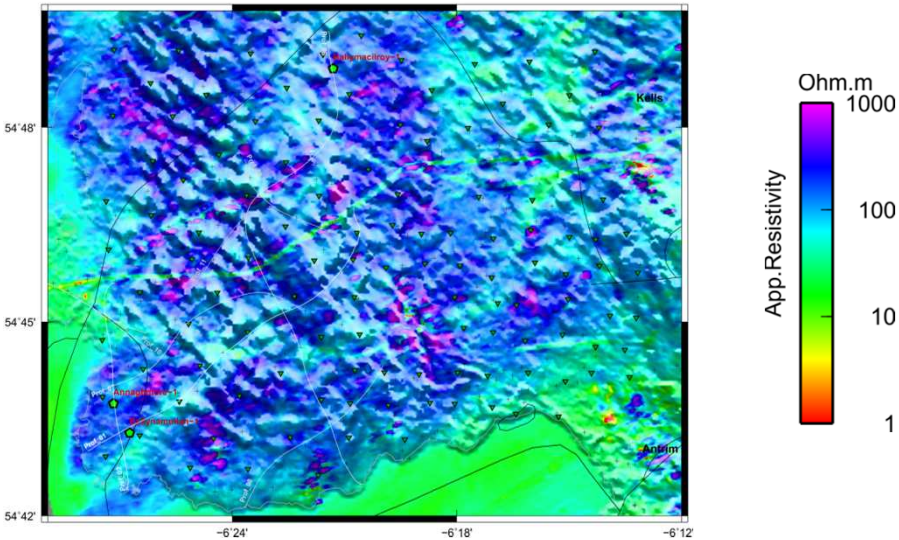
Bouguer anomaly map







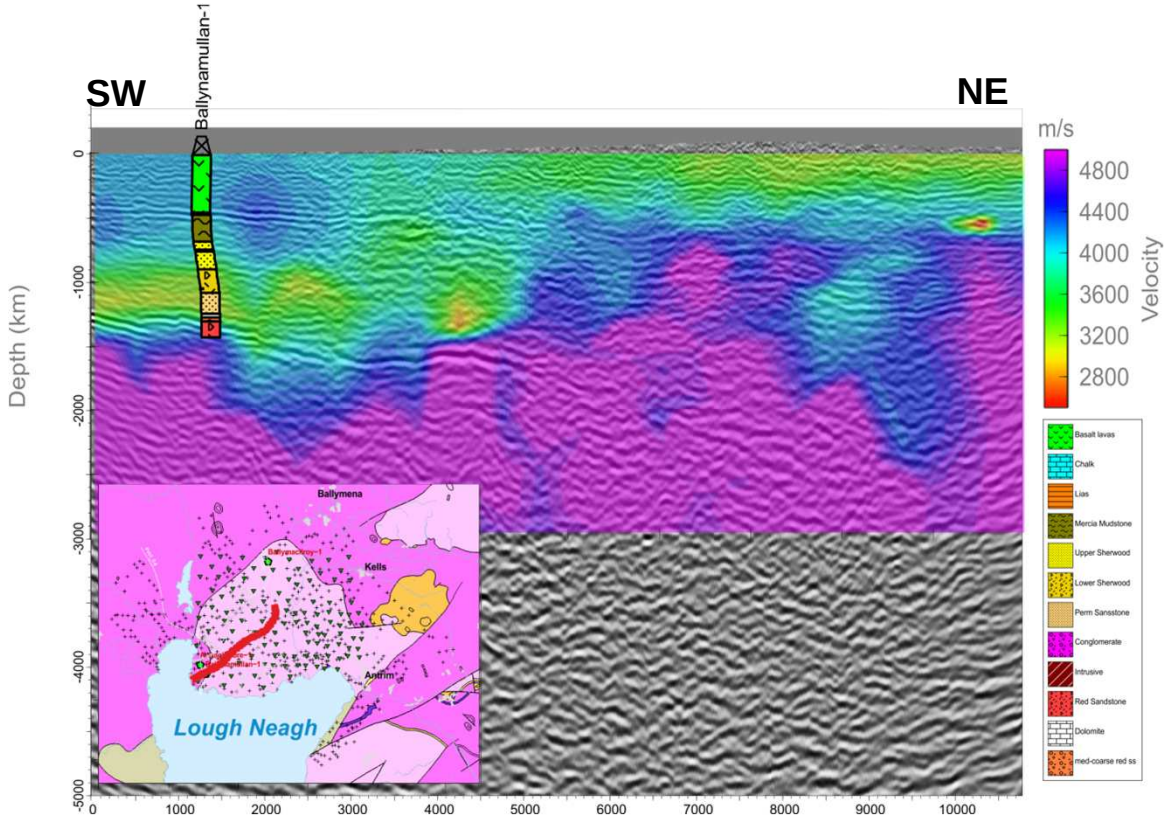
Tellus airborne data (3kHz)

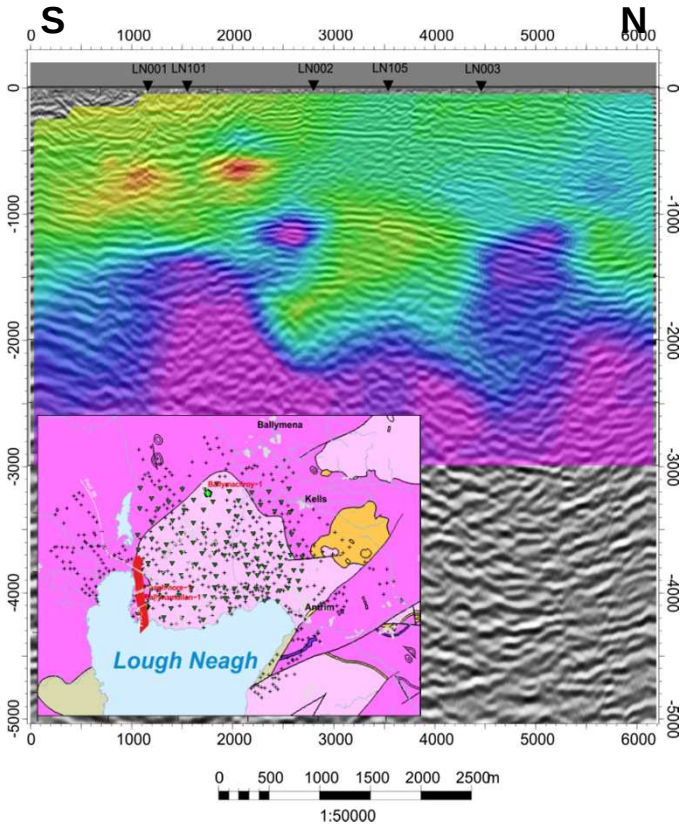


The Tellus data information can be used for correction shortest periods (see site LNO004 in figure), particularly Lough Neagh MT data suffers from missing shortest periods due to noise

Lough Neagh Basin - reflection seismic data

- *The Pre-Stack Time Migration (PSTM) depth and RMS velocities were converted to velocity model along measured profiles, example for profile 01 and 09*
- *The reliability of velocity models are low, play just informative role*

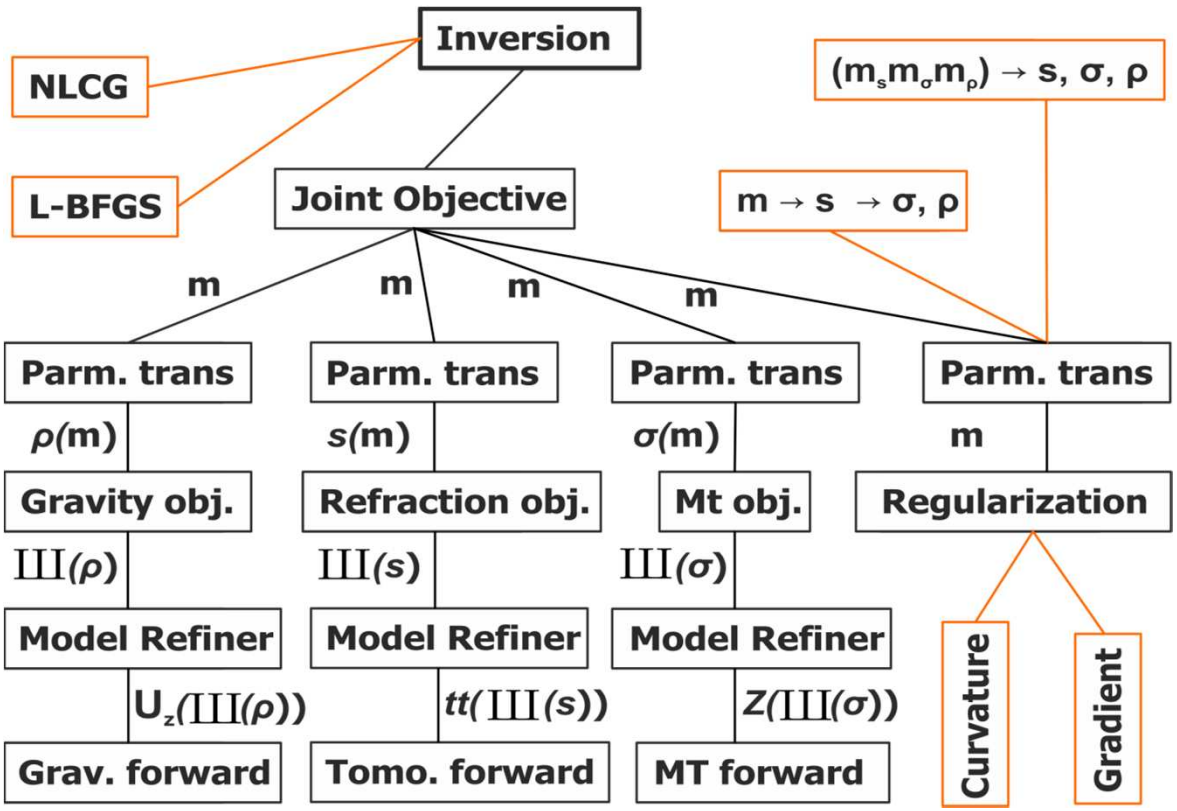




JIF3D package

JIF3D – 3D joint inversion framework (Moorkamp et al., 2011)

- *joint inversion for electromagnetic, seismic and gravity data*



Coupling : *a) parameter relationship*

b) cross-gradient

Coupling strategy for parameters

LitMod3D integrated modelling (upper-mantle):

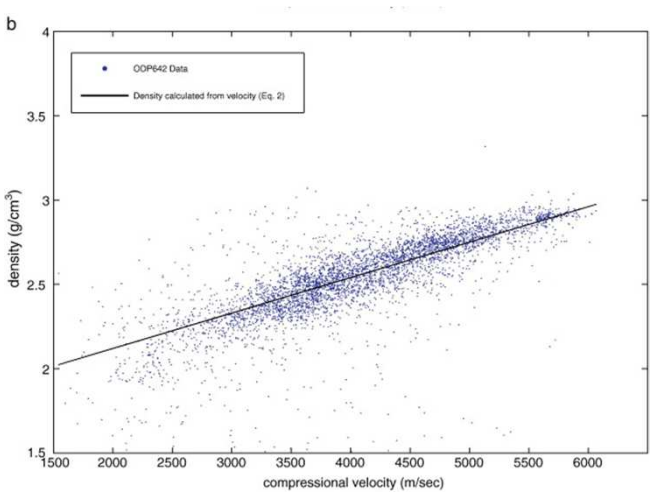
- *All geophysical models of upper-mantle are coupled based on mantle composition, temperature and pressure distribution*

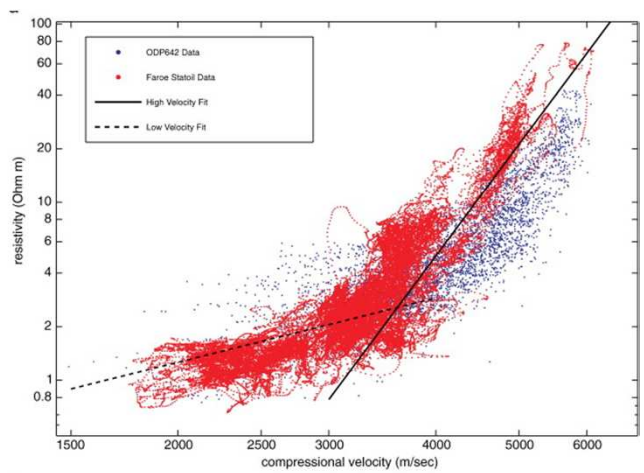
JIF3D coupling (crust):

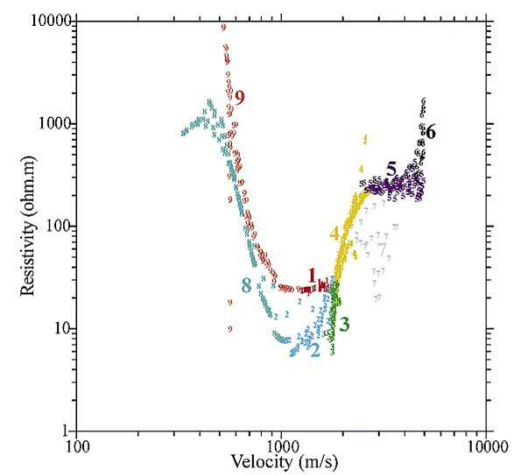
- *Direct relationship (Christensen and Mooney, 1995; Jegen et al., 2009) – borehole info*

  - between densities and seismic velocities (app. linear)

  - between resistivity and velocity (structural dependence)





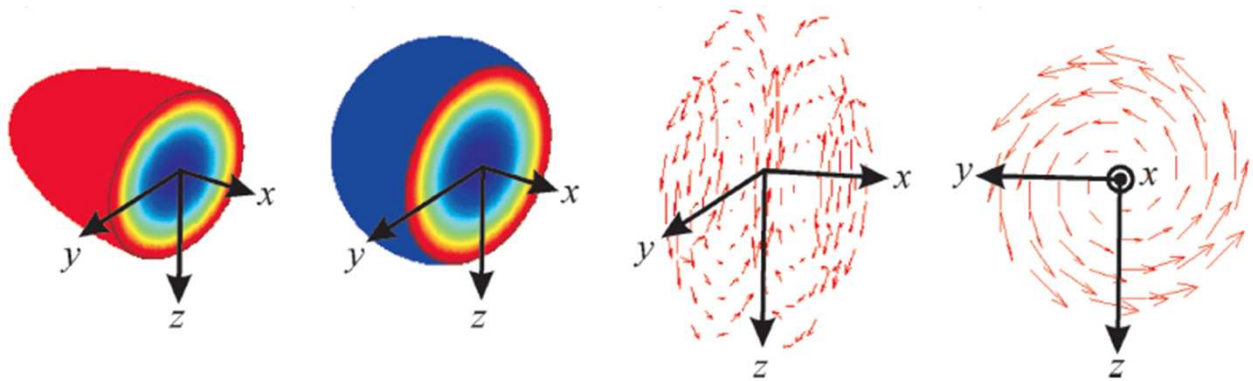


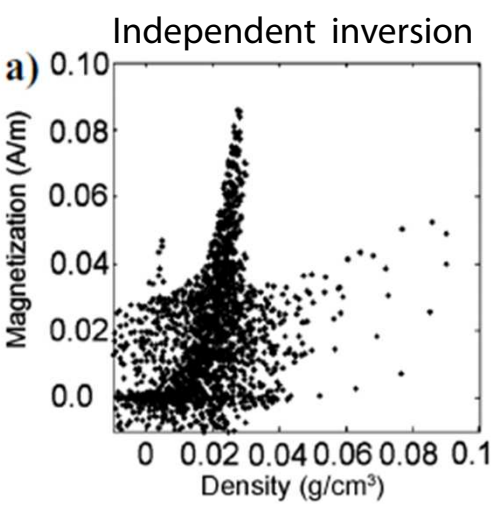
Coupling strategy – Cross-Gradient

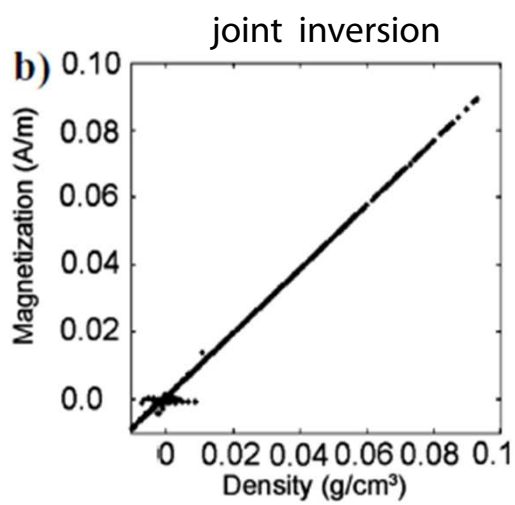
Jif3D coupling (crust):

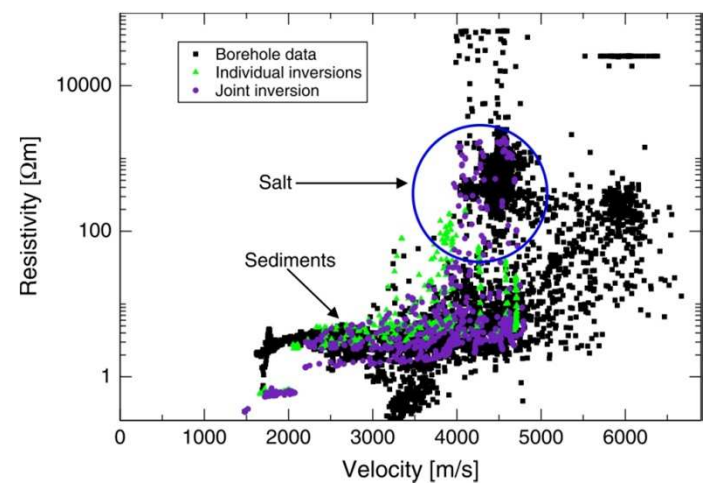
- *Cross-gradient (Gallardo & Meju, 2003; Fregoso & Gallardo, 2009; Moorkamp et al., 2013)*

$$\vec{t}(x,y,z) = \nabla m_1(x,y,z) \times \nabla m_2(x,y,z) \quad \Rightarrow \quad \vec{t}(x,y,z) = \vec{0}$$





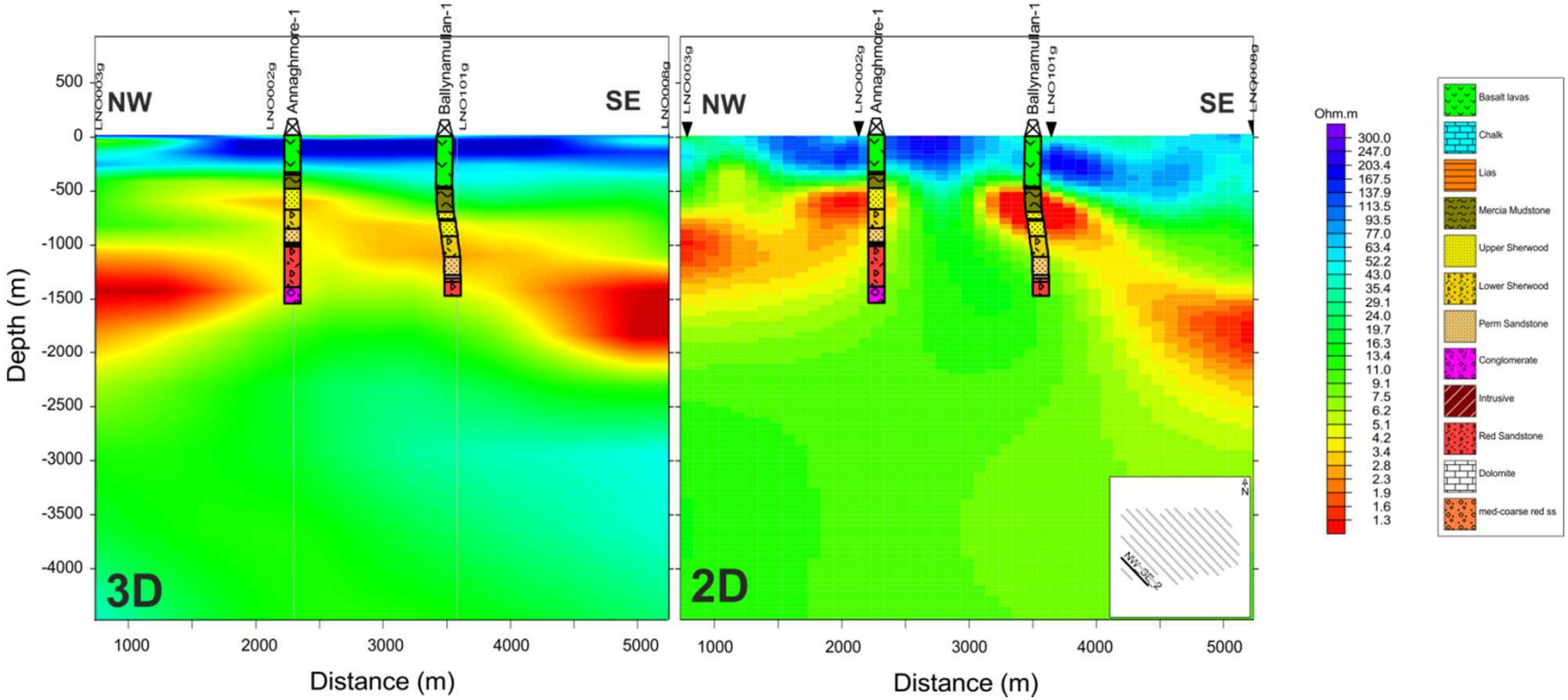




Lough Neagh Basin - 2D vs joint 3D

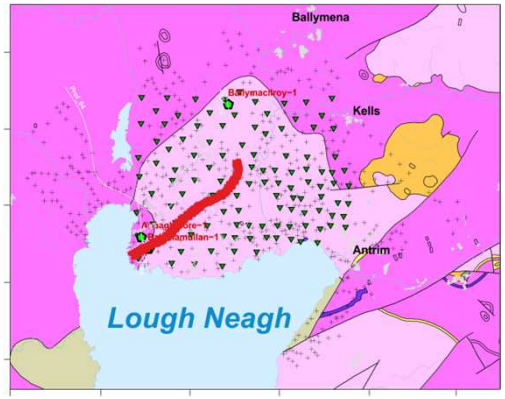
We are presenting side by side joint inversion 3D and MT only 2D model (Loewer, 2011) in form of slice of 3D model and 2D profile through two available boreholes Annaghmore1 and Ballynamullan1. The 3D model exhibits better consistency with borehole information and SE deepening of layer.

3D MT slice versus old 2D MT model



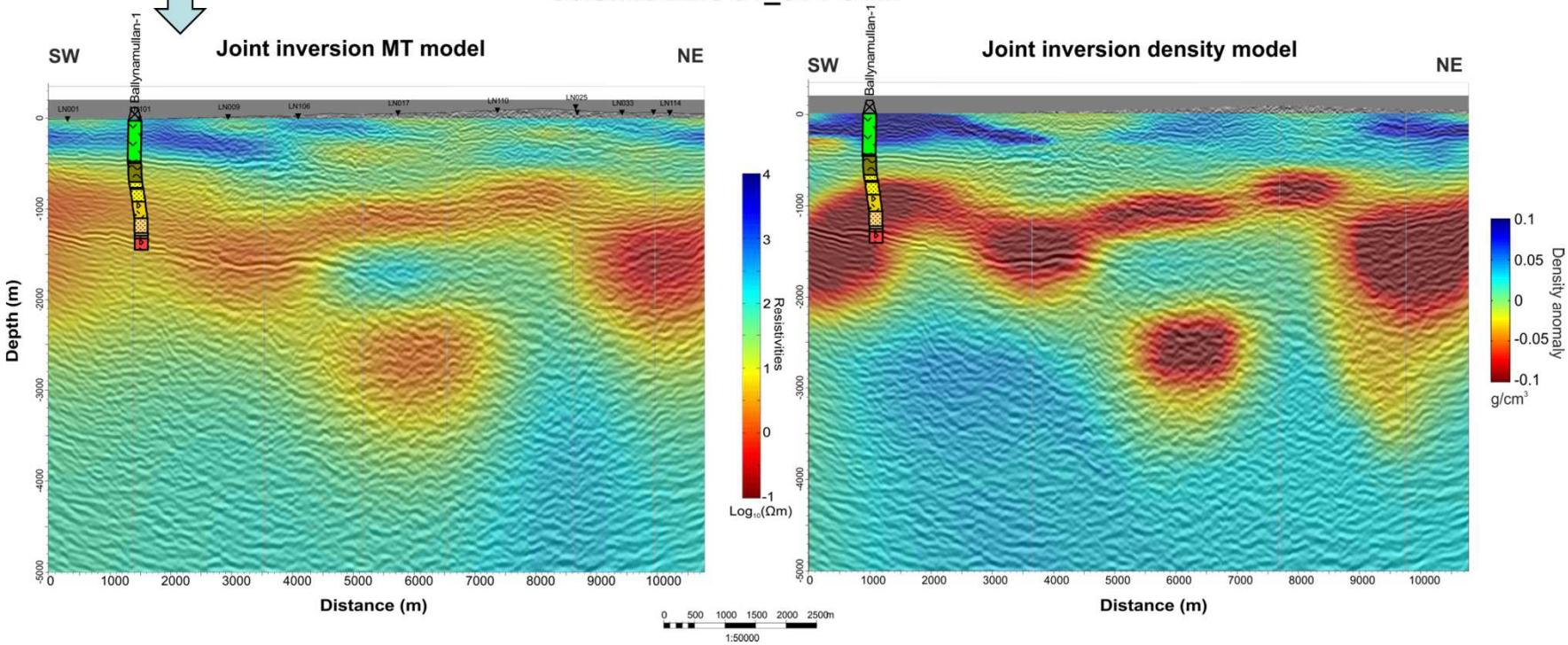
Joint 3D model vs reflection seismic line 01

Seis. Profile 01



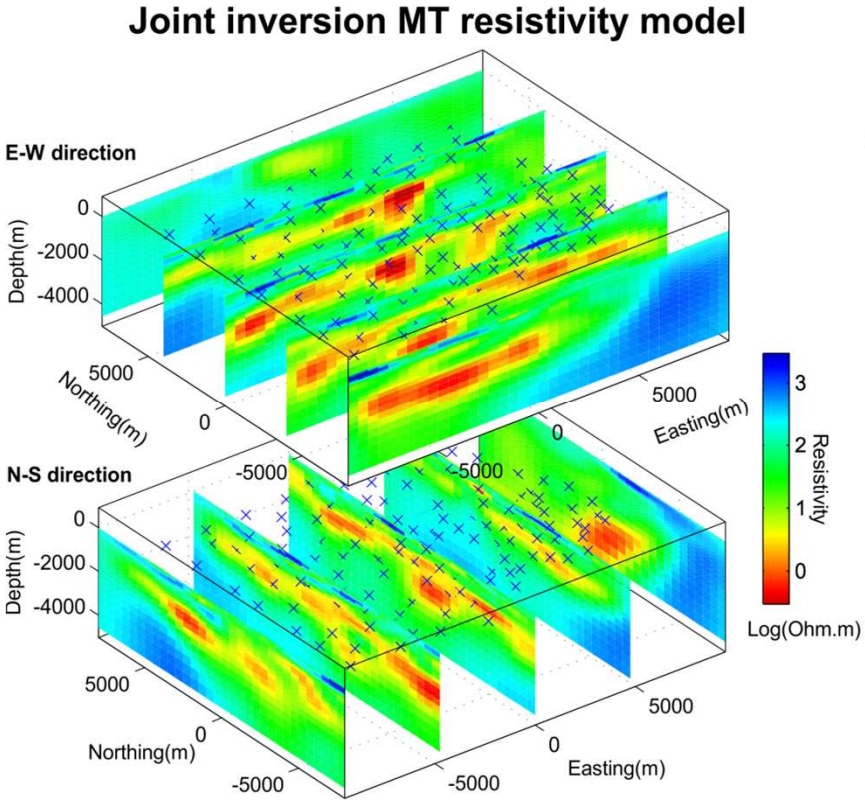
The seismic data have not been used because of poor coverage of area, quality of converted seismic velocities from reflection modeling, and 2D distribution of source-receiver data. However the Pre-Stack Time Migration (PSTM) depth converted results are used for evaluation of the geophysical inversion models.

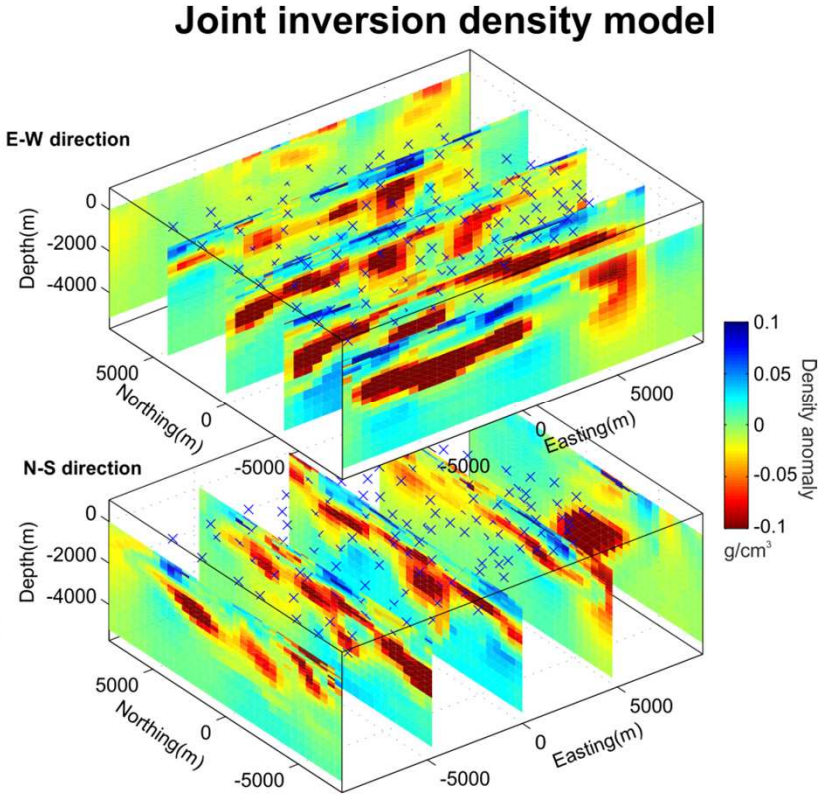
Seismic Line 91_01 PSTM



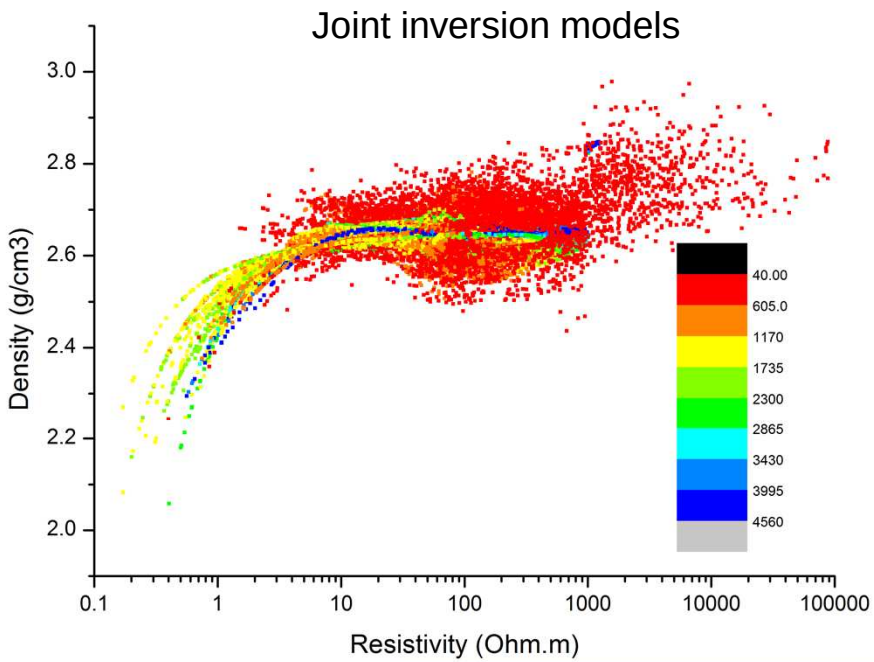
Lough Neagh Basin – 3D results

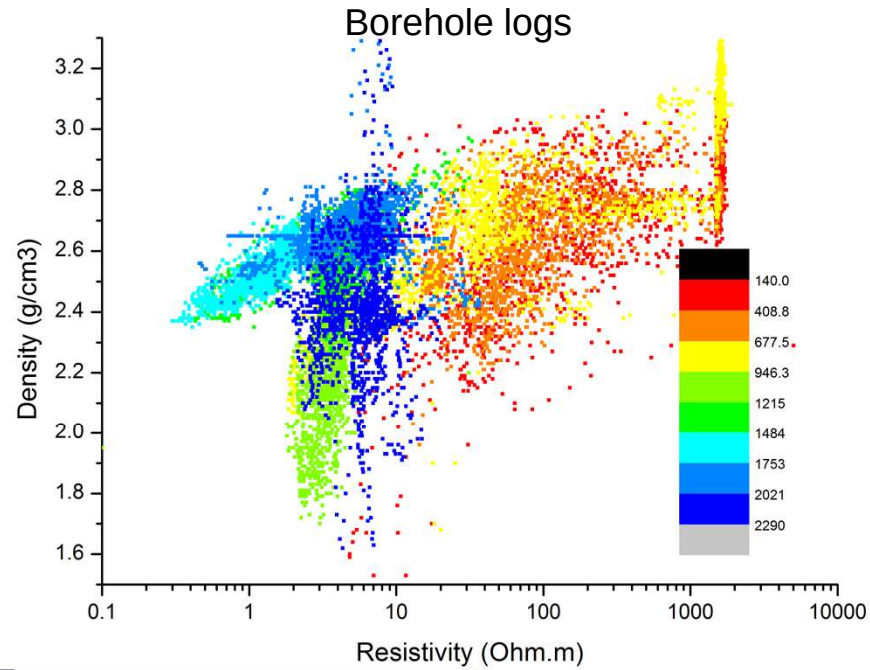
Possible issues with joint inversion models are coming from different coverage of survey area by MT and gravity measurement points and simple physical dissimilarities of resistivity and density parameters.

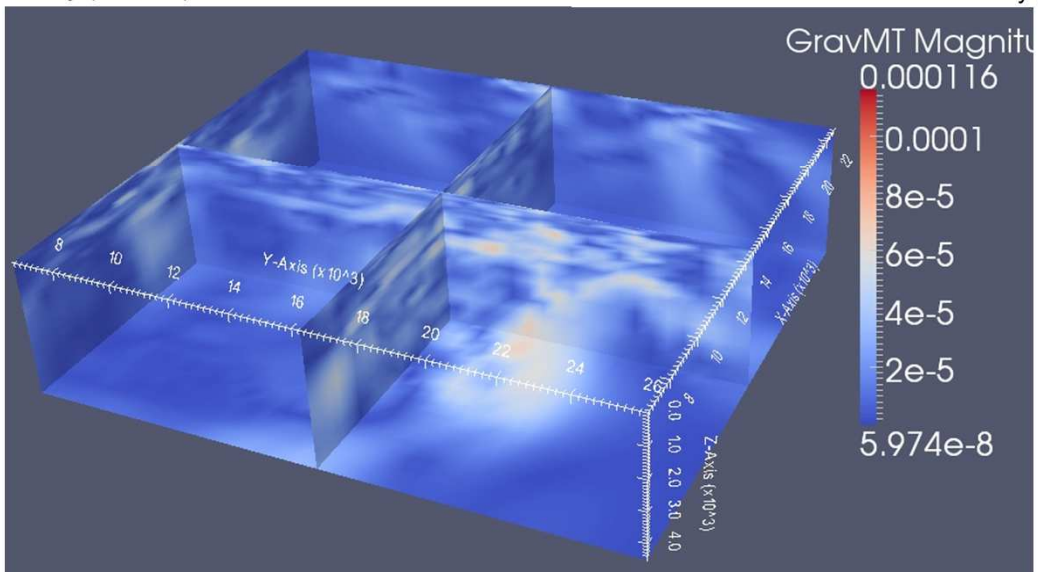




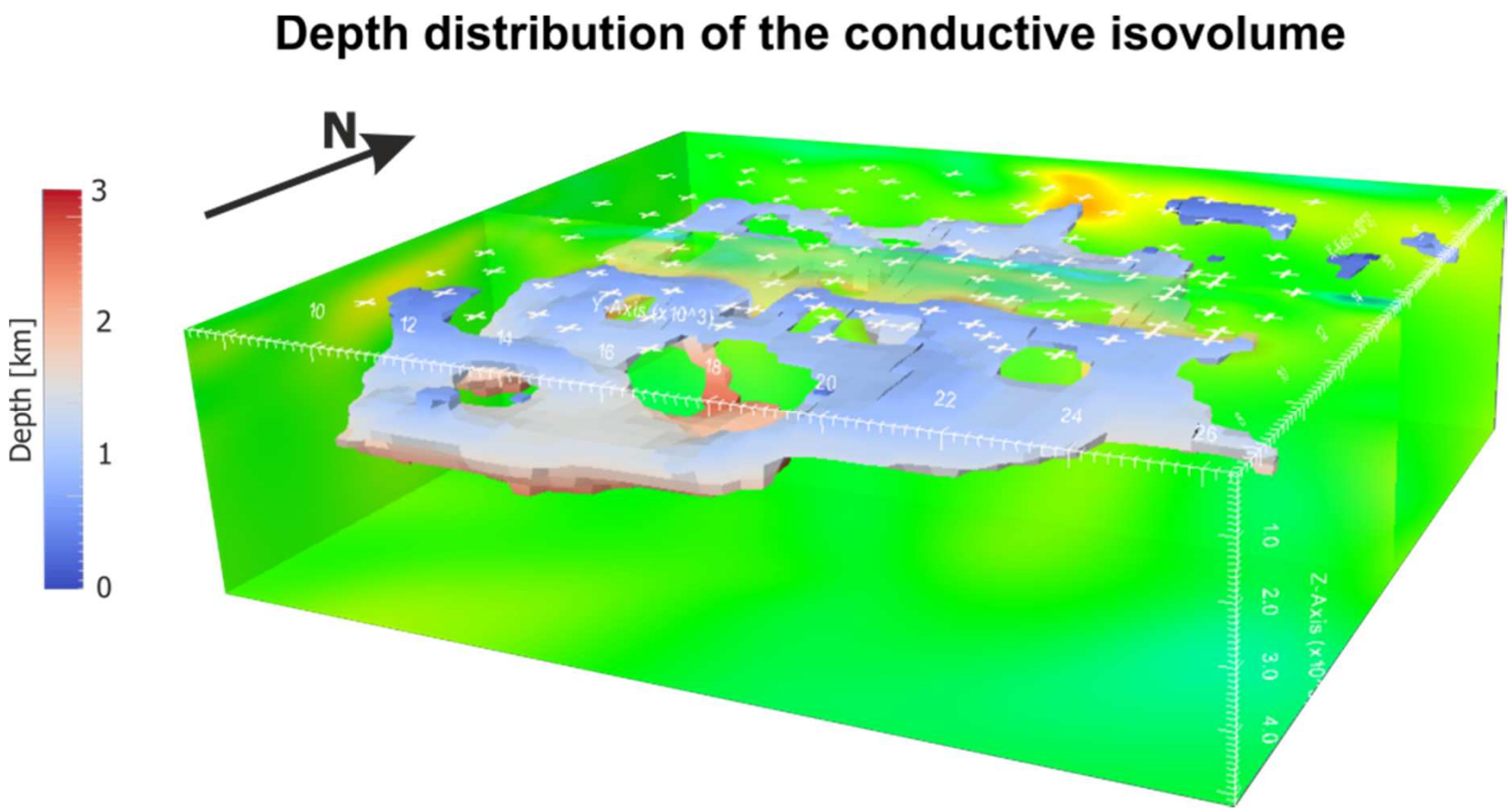
Cross plots


Joint inversion models
Density (g/cm3)
Resistivity (Ohm.m)
3.0
2.8
2.6
2.4
2.2
2.0
0.1
1
10
100
1000
10000
100000
40.00
605.0
1170
1735
2300
2865
3430
3995
4560


Borehole logs
Density (g/cm3)
Resistivity (Ohm.m)
3.2
3.0
2.8
2.6
2.4
2.2
2.0
1.8
1.6
0.1
1
10
100
1000
10000
140.0
408.8
677.5
946.3
1215
1484
1753
2021
2290


GravMT Magnitu
0.000116
0.0001
8e-5
6e-5
4e-5
2e-5
5.974e-8
Y-Axis (x 10^3)
Z-Axis (x 10^3)

Lough Neagh Basin – 3D visualization



Determination of aquifer porosity and permeability

In terms of geothermal energy potential, we are most interested in hydraulic permeability. Therefore wish to determine porosity and permeability independently

Porosity
$F = \alpha \ \phi^{m} \ S^{n}$

Permeability
$F = a^{-1} \ k^{-1} \ S_0^{-2}$

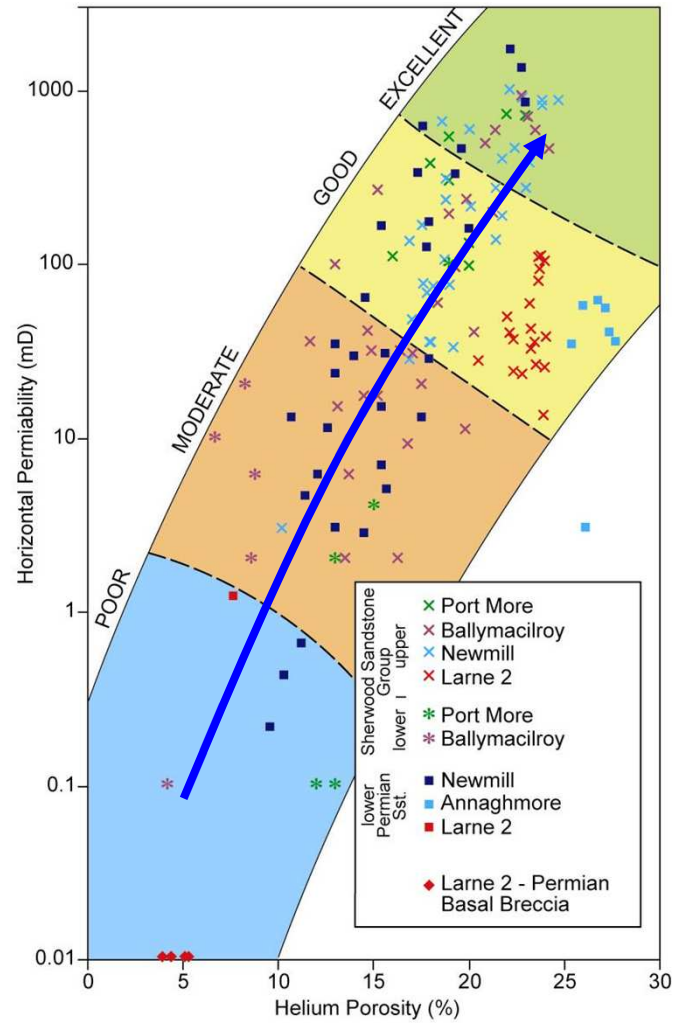
*One measured parameter –> **resistivity***
Two unknowns –
- porosity and permeability
- plus unknown empirical constants

The relation between porosity and electrical conductivity can be estimated by the Generalized Archie's law for multiple phases (Glover, 2010, Campanya et al., 2015):

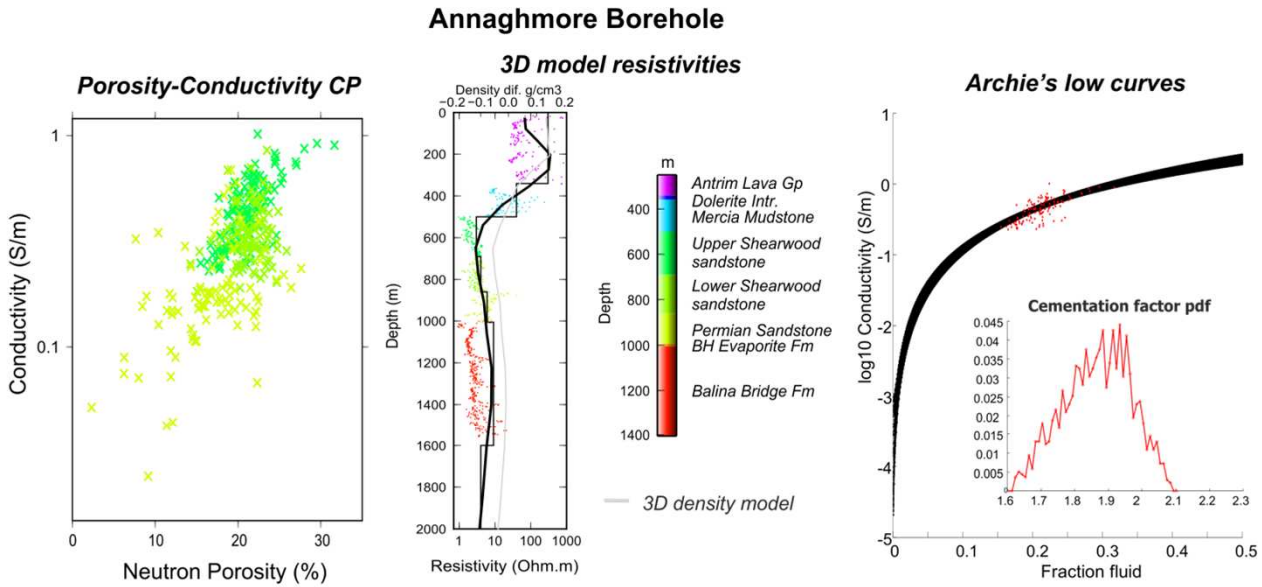
$$\sigma = \sum_{i}^{n} \sigma_i \phi_i^{m_i} ,$$

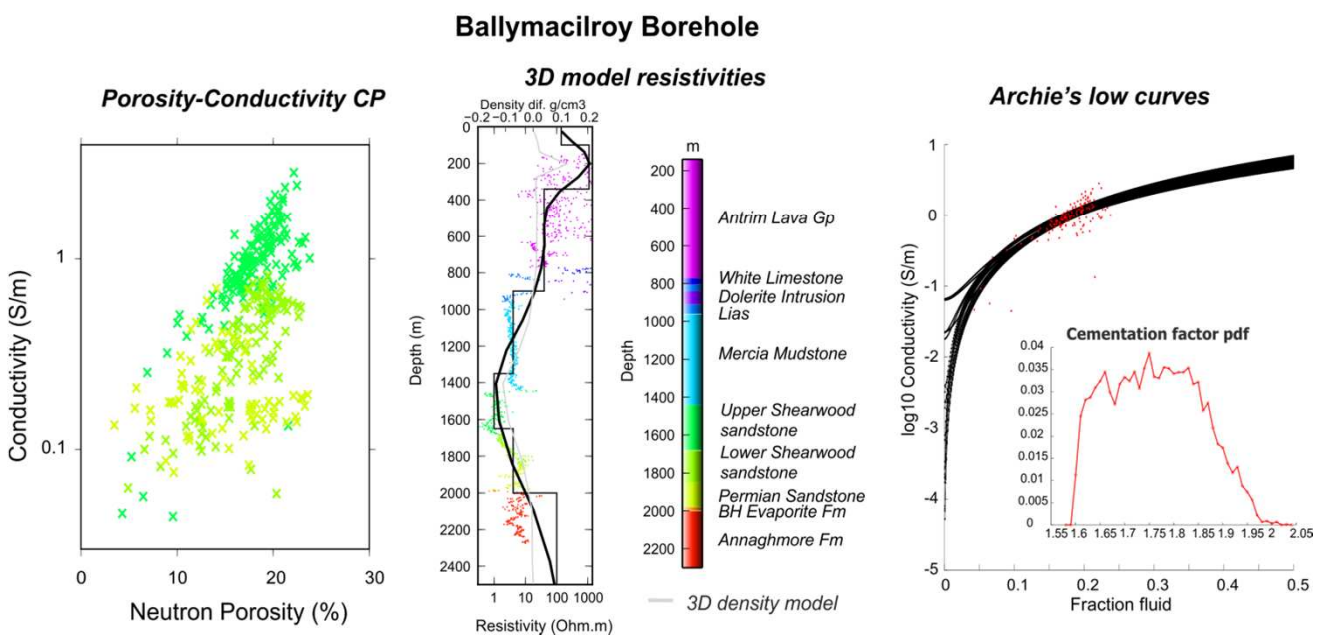
where $$m_j = \log\left(1 - \sum_{i \neq j} \phi_i^{m_i}\right) / \log\left(1 - \sum_{i \neq j} \phi_i\right)$$

BOREHOLE CORE POROSITY VERSUS PERMEABILITY FOR N. IRELAND PERMO-TRIASSIC



Lough Neagh Basin - porosity studies





De Block, 2013

Conclusions

- The joint inversion improved a lot density model and resolution of geoelectrical model
- The seismic part was not used in the final inversion modeling, because of unreliable 3D input data
- The 3-D joint inversion modelling reveals that the Sherwood Sandstone Group and the Permian Sandstone Formation are imaged as a conductive or less dense zone at the depth range of 500 m to 2000 m
- Thickness, depth, and conductance of layer are varying laterally
- The conductive target sediments become shallower and thinner to the north and they are laterally continuous with some vertical offsets
- The layer is thickening and deepening in south-east direction.
- The conductivities varies from 0.1 to 1 S/m, which indicates high concentration of fluids
- The conductive layers are interpreted as water bearing or geothermal fluids and estimated porosity and permeability indicates potential to act as geothermal aquifer.

Thank you for attention!

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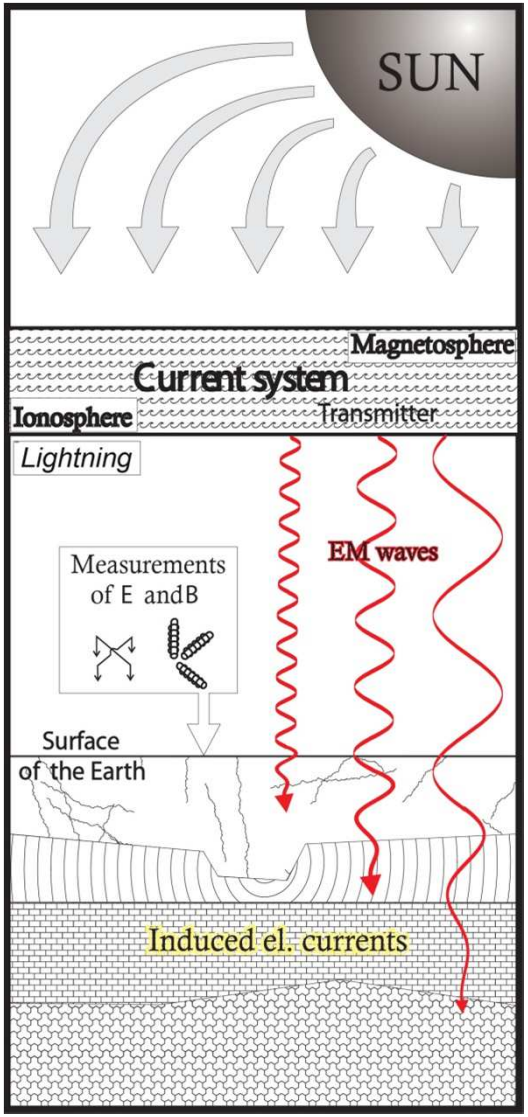
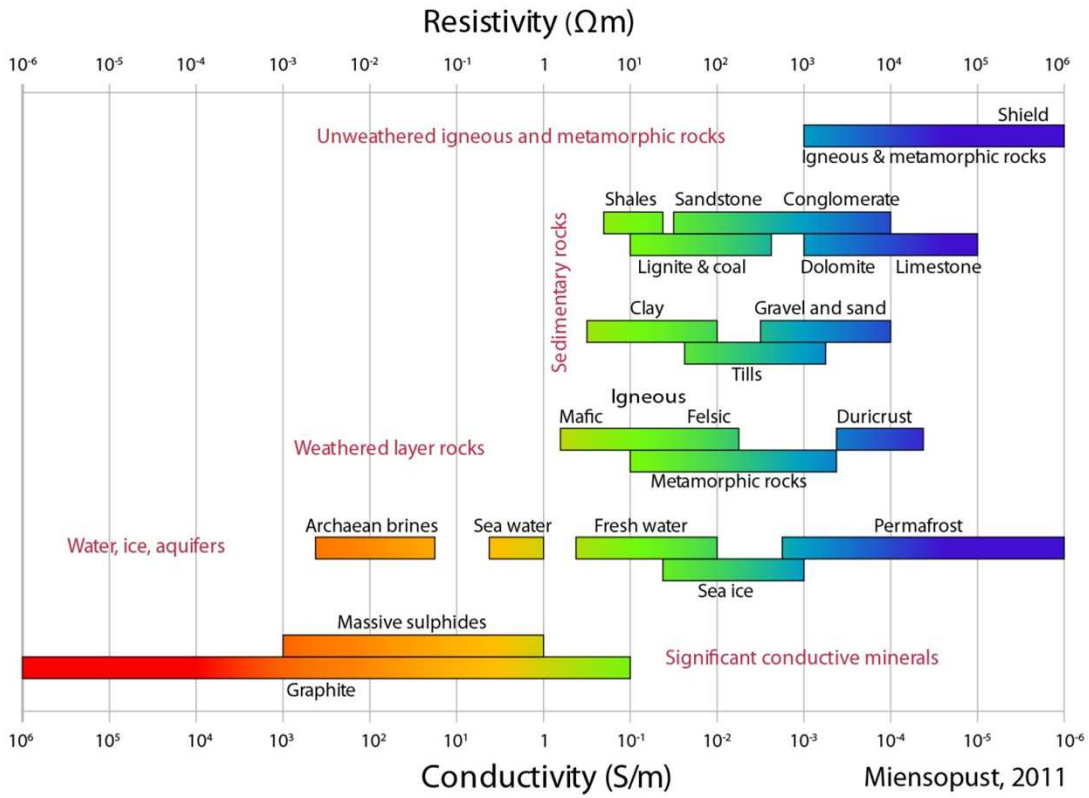
Department of Enterprise, Trade and Investment
www.detini.gov.uk
Geological Survey of Northern Ireland

SLR Geoserv

GT Energy
Energy for the future

How does MT works?





- Sun, ionosphere, magnetosphere -> source field
- 5 components of EM field Hx, Hy, Hz, Ex, Ey
- Dead band zones – weak source and responses

$$\begin{bmatrix} E_x \\ E_y \\ H_z \end{bmatrix} = \begin{bmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \\ T_{zx} & T_{zy} \end{bmatrix} \begin{bmatrix} H_x \\ H_y \end{bmatrix}$$

$$\left|\rho^*\right| = 0.2\,T\left|Z\right|^2$$

$$Arg\,\rho^* = 2\,ArgZ \pm 90^\circ$$

$$p(T) \approx 500\sqrt{T\rho_a}$$

Aim of integrated modelling

To understand *regional and local thermal and structural parameters in the crust and upper-mantle*

Consistent interpretation of:

→ *crustal & lithospheric structure, Moho & LAB discontinuities*

→ *temperature & composition & structure estimation at depth*

✓ *Joint petrological, geological and geophysical characterization of the lithosphere*