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IRETHERM: The Geothermal Energy Potential of Radiothermal Granites in a Low-Enthalpy Setting in Ireland from Magnetotelluric Data

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ABSTRACT

The academia-government-industry collaborative IRETHERM project (www.iretherm.ie), funded by Science Foundation Ireland, is developing a strategic understanding of All-Ireland's (north and south) deep geothermal energy potential through integrated modelling of new and existing geophysical and geological data. One aspect of IRETHERM's research focuses on Ireland's radiothermal granites, where increased concentrations of radioelements provide elevated heat-production (HP), surface heat-flow (SHF) and subsurface temperatures. An understanding of the contribution of granites to the thermal field of Ireland is important for assessing the geothermal energy potential of this low-enthalpy setting.

This study focuses on the Galway granite in western Ireland, and the Leinster and the buried Kentstown granites in eastern Ireland. Shallow (less than 250 m) boreholes were drilled into the exposed Caledonian Leinster and Galway granites as part of a 1980's geothermal project. These studies yielded HP = 2-3 μWm^{-3} and HF = 80 mWm^{-2} at the Sally Gap borehole in the Northern Units of the Leinster granite, located to the SW of Dublin. In the Galway granite batholith, on the west coast of Ireland, the Costelloe-Murvey granite returned HP = 7 μWm^{-3} and HF = 77 mWm^{-2}, measured at the Rossaveal borehole. The buried Kentstown granite, 35 km NW of Dublin, has an associated negative Bouguer anomaly and was intersected by two mineral exploration boreholes at depths of 660 m and 490 m. Heat production is measured at 2.4 μWm^{-3} in core samples taken from the weathered top 30 m of the granite.

The core of this study consists of analysis, modeling and interpretation from a program of magnetotelluric (MT) and audio-magnetotelluric (AMT) data acquired across the three granite bodies. MT and AMT data were collected at 59 locations along two profiles over the Leinster granite. Over the Galway granite, MT and AMT data were collected at a total of 75 sites (33 consist of only AMT data acquisition, with both MT and AMT recorded at the remaining 42). MT and AMT data have been acquired along a profile at 22 locations over the Kentstown granite.

The MT and AMT data will be integrated with gravity and seismic refraction data (in the case of the Leinster granite) to identify deeply-penetrating faults, which may provide conduits for hydrothermal fluids, and to produce a robust estimation of the volumetric extent of the granites, which is crucial for defining their thermal contribution and therefore geothermal energy potential. Thermal conductivity and geochemical data will be incorporated to constrain the heat contribution of granites to the Irish crust.

1. INTRODUCTION

As Ireland is located on stable lithosphere and far from plate boundaries (Figure 1), it lacks the high-enthalpy setting of geothermal systems associated with recent tectonism and volcanism. All current geothermal energy use in Ireland is derived from shallow low-enthalpy Ground Source Heat Pump technology that exploits water temperatures in the range of 8-15 °C for the provision of space heating. No electricity is currently generated in Ireland from geothermal sources. As of 2010, the total heat pump capacity estimated by Sustainable Energy Authority of Ireland (SEAI) to be installed in Ireland was 164 MW with non-domestic installations in public and commercial buildings accounting for only 16 MW (Allen and Burgess 2010). There therefore exists a significant opportunity for the expansion of both shallow and, if suitable resource rocks can be located at depth, deep geothermal energy in Ireland.

The objective of the IRETHERM project is to develop a strategic understanding of All-Ireland's (north and south) poorly understood deep geothermal energy potential. IRETHERM seeks to achieve this by integrated modelling of new and existing geophysical, geochemical and geological data. Within this framework, this study focusses on radiothermal granites in Ireland where elevated concentrations of potassium, thorium and uranium may result in elevated heat-production (HP) and can lead to elevated surface heat flow (SHF) and subsurface temperatures. The granites studied as part of this research are (Figure 2): the exposed Galway granite, located on the west coast of Ireland, the exposed Leinster granite, located in south-eastern Ireland to the south and southwest of Dublin, and the buried Kentstown granite, located in eastern Ireland to the north-north-west of Dublin. The aim of this study is to constrain the subsurface volumetric extent of the granites and to identify structures and features, such as deeply penetrating fluid-filled fracture zones and/or geothermal waters associated with the granite margins, key to assessing the prospectivity of the granites for geothermal energy provision. This assessment is being achieved through the collection of new geophysical data (MT and AMT data) and incorporating these data with existing geophysical, geochemical, thermal conductivity and geological data to constrain the heat contribution of these granites and to place them into an overall context within the thermal regime of the Irish crust. The MT method is particularly suited to imaging electrically resistive granites hosted in more electrically conductive country rocks and to identifying electrically conductive fluid-filled geothermal reservoirs.

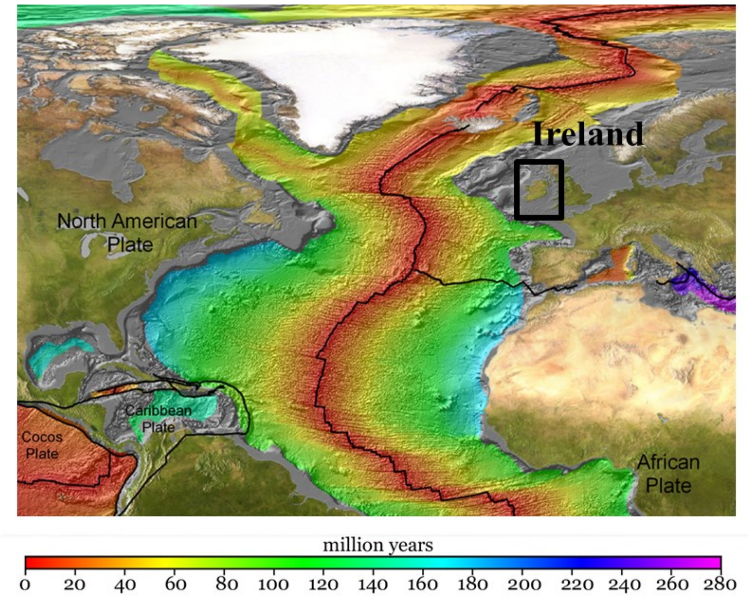

Figure 1: Map of sea-floor age in the North Atlantic, with Ireland's position shown in black box. Plate boundaries marked by narrow black lines (after Muller et al. 2008)

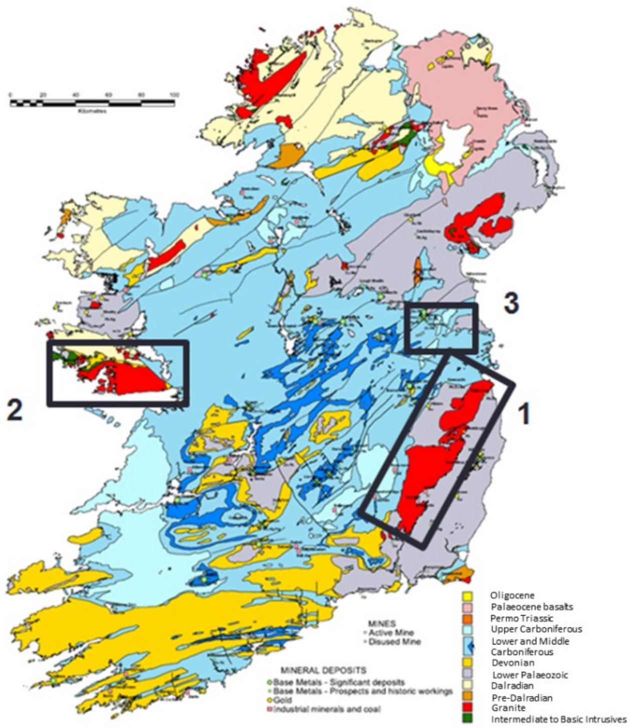

Figure 2: Geological map of Ireland with survey areas marked: 1. Leinster Granite, 2. Galway Granite, 3. buried Kentstown Granite (geological map modified from that of the Geological Survey of Ireland)

2. GEOLOGY AND GEOLOGICAL SETTING OF IRISH RADIOTHERMAL GRANITES

2.1 Geological and Tectonic Setting of Ireland

The emplacement of the majority of exposed intrusive bodies in Ireland is dominantly controlled by tectonic events that occurred in the Ordovician, Silurian and Devonian. In the Early Ordovician, the northern (Laurentian) and southern (Avalonian) parts of Ireland were separated by the Iapetus Ocean. The collisional events associated with the closure of Iapetus formed the Iapetus suture zone, now buried in Ireland beneath Carboniferous rocks, and also formed the rocks into which Irish radiothermal granites intruded. The granites on which this research is focused were emplaced during transcurrent and trans-tensional plate motions that took place during the late Silurian and early Devonian, subsequent to the closure of Iapetus.

2.2 Surface Heat Flow in Ireland

Ireland is not densely covered with surface heat flow (SHF) data, the distribution being largely controlled by access to mineral and petroleum exploration boreholes and core. Consequently, the available SHF derivations are concentrated in central Ireland where such exploration has been focused (Figure 3). In total, there are 22 calculated SHF values, mostly carried out in the late 1970's and early 1980's (reported in Brock, 1989), and 6 further estimates using bottom-hole temperatures (BHT) and assumed thermal conductivities (Brock and Barton, 1984). Leaving aside the SHF estimates derived from BHTs and the elevated SHF values on granites, Ireland shows an elevated SHF (about 70 – 75 mW m^{-2}) in the Midlands, but there are large gaps in data in the north-west and in the south.

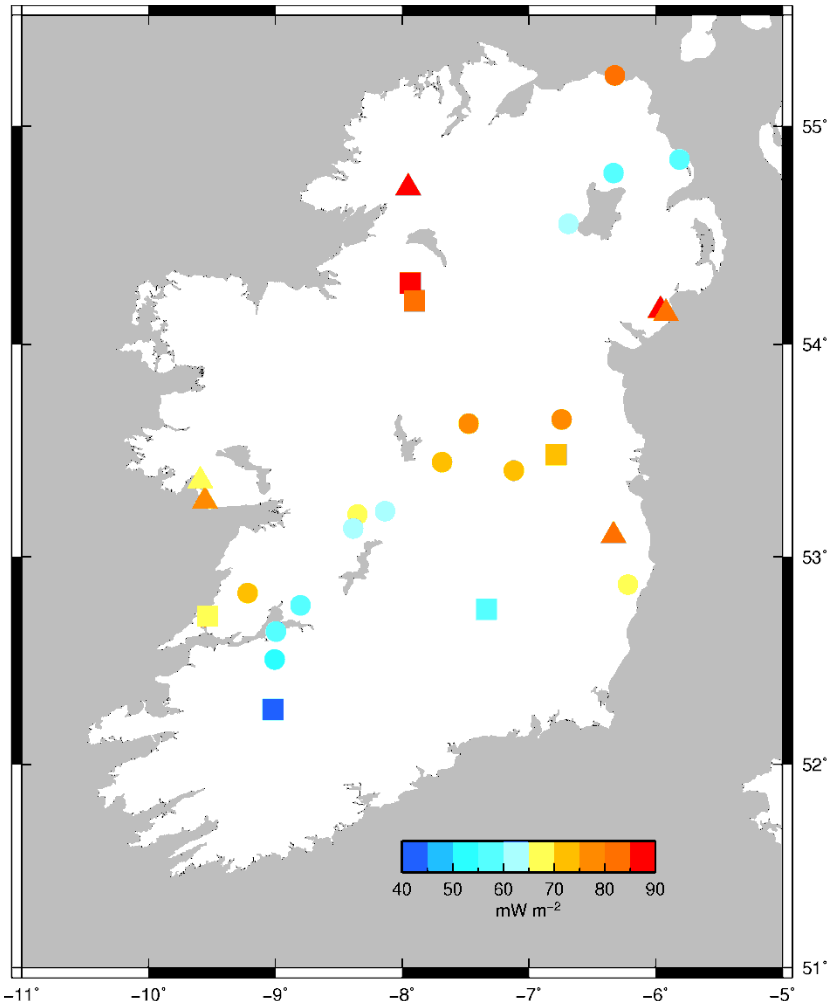

Figure 3: Surface Heat Flow across Ireland. Circles are SHF calculations in sedimentary boreholes, triangles are SHF calculations in granites, squares are SHF estimates based on bottom-hole temperatures and using assumed thermal conductivities (SHF data from Brock 1989 and Barton et al 1989)

2.2 The Galway Granite

The calc-alkaline Galway granite consists of the main Galway granite batholith, which is divided into the Carna dome and the Kilkieran dome and four earlier smaller plutons (Leake 2011). The granitoid bodies that comprise the main batholith were emplaced between 425 Ma and 380 Ma (Feely et al. 2010). This study focusses on the Kilkieran dome of the main Galway granite batholith (Figure 4) which intruded into the Connemara metamorphic complex to the north (Leake and Tanner 1994) and the South Connemara group to the south (Ryan and Dewey 2004). The Kilkieran dome is cut by two major fault zones, the Shannawona and Barna fault zones, which divide it into three distinct blocks, the West, Central and East blocks (Figure 4). SHF has been calculated to be 77 mW m^{-2} at the Ros a Mhil borehole in the Costelloe Murvey granite (Central Block) and 65 mW m^{-2} at the Camus borehole (West Block) in the ETG 1 granite (Figure 5). Heat production calculations across the Galway granite are shown in Figure 5.

2.3 The Leinster Granite

The five plutons of the Leinster granite (Figure 6) were emplaced simultaneously (Brindley 1973) at 405 +/- 2 Ma (O'Connor et al. 1989) into the Lower Ordovician shales and siltstones of the Ribband group. These pelitic host rocks, away from the granite aureole, are sub-greenschist facies (Holland and Sanders 2009). The aureole of the granite is characterised by the development of muscovite, biotite, garnet and andalusite and staurolite in the inner aureole. The presence of coticule, tourmalinite and lead/zinc mineralisation in the aureole suggests that the Lower Ordovician host rocks were deposited as metalliferous sediments on the ocean floor near a hydrothermal vent system (Williams and Kennan 1983). The source of the magmas that crystallised to form the Leinster granite appears to be an anatectic melt of upper crust metasediments. The granite intruded during the development of shear zones, (McArdle and Kennedy 1985).

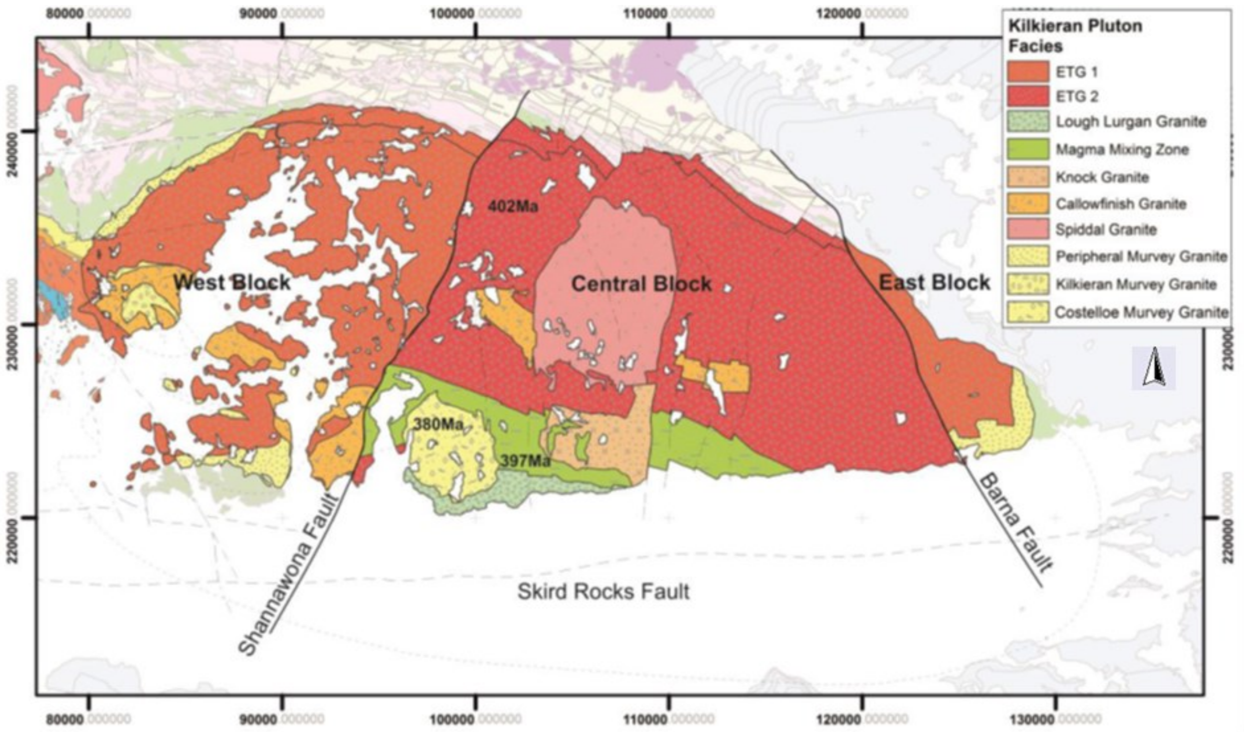

Figure 4: The geology of the Kilkieran dome of the main Galway granite batholith (after McCarthy 2013)

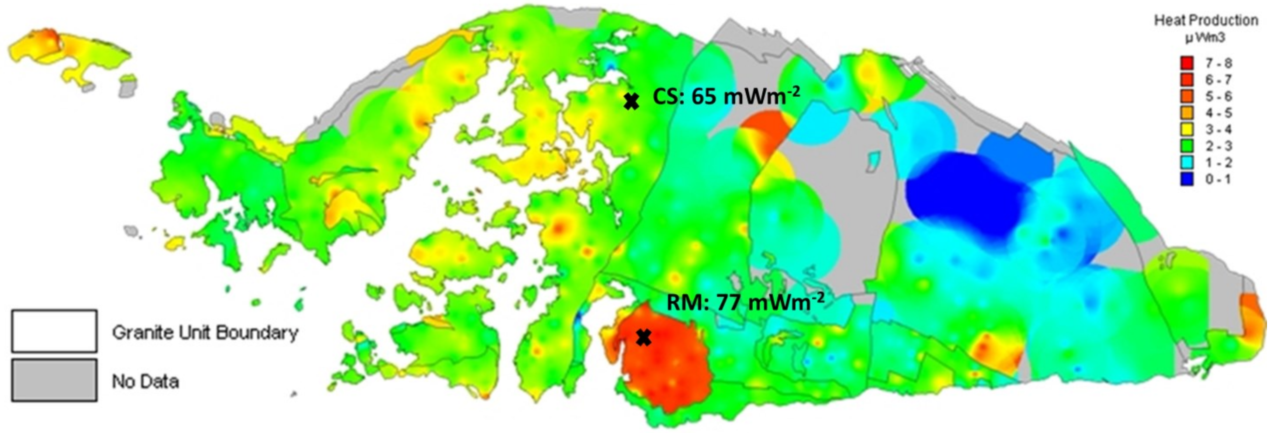

Figure 5: Heat Production across the Galway granite. CS – Camus borehole, RM – Ros a Mhil borehole (HP data from Feely and Madden (1987) and SHF calculations from Brock and Barton (1984), map adapted from Hennessy and Feely (2008))

2.3 The Kentstown Granite

Little is known of the buried Kentstown granite. In the mid-1990s, mineral exploration boreholes drilled by Tara Exploration intersected the Kentstown granite, overlain by Dinantian limestones, at depths of 662 m and 492 m (O'Reilly et al. 1997). These boreholes were drilled near the centre of a gravity low that, along with the presence of microgranite and felsite dykes and hornfels metamorphism in the nearby Balbriggan Inlier, was taken as evidence of the presence of a granite at depth. Geochemical studies of the Kentstown granite samples show that they plot in the Leinster granite compositional field of Sweetman (1987) and lie on the boundary between syn-collisional and volcanic arc granites on the Rb vs Y + Nb tectonic setting discrimination diagram of Pearce et al. (1984) (McConnell and Kennan 2001). Radioelement concentrations have been determined on Kentstown granite samples to yield a heat production of 2.44 μWm^{-3} (Tobias Fritschle, pers. comm.)

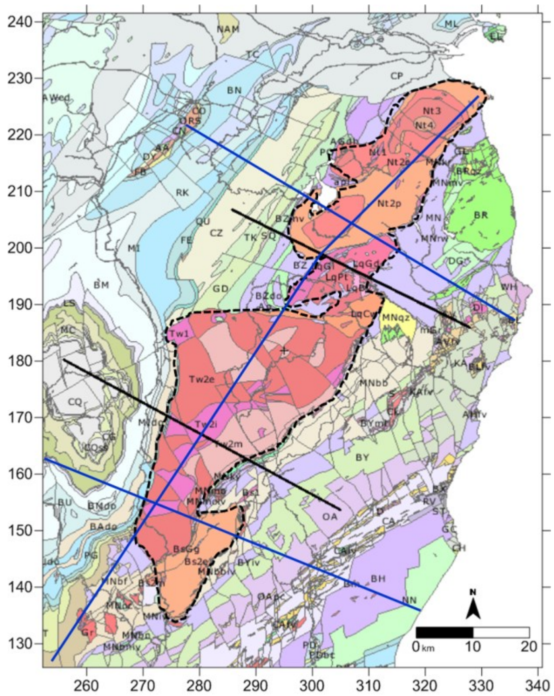

Figure 6: Geological map of Leinster Granite (Granite marked out by dashed black line. Solid black lines are IRETHERM MT/AMT survey lines, LGN profile to the north and LGS profile to the south. Blue lines are LEGS seismic refraction survey lines (Hodgson 2001)).

3. NEWLY ACQUIRED DATA AND PREVIOUSLY AVAILABLE DATA

3.1 Newly Acquired MT and AMT data

Over the Galway granite and surrounding rocks, MT and AMT data were acquired at 75 locations in a grid of approximately 1,600 km^2 (Figure 7). At the Galway granite, data was acquired over two field seasons, with apparent resistivity and phase showing good consistency typically to periods of 1,000 s and greater, with the exception of the AMT and MT deadbands in most cases. Figure 8 shows apparent resistivity and phase of the XY and YX modes (rotated to true north) of merged AMT and MT data acquired at sites ggr012 and gga019 (shown on map in Figure 7). This is typical of the data used to produce the 3D model from which Figure 13 is derived. In Leinster, MT and AMT data were acquired at 59 locations along two profiles, LGN (Figures 6 and 9) and LGS, of length 44 and 55 km respectively (Figure 6). At Kentstown, MT and AMT data were collected at 22 locations along a 29 km long profile. At both Kentstown and Leinster, data quality was affected at some sites by noise from agricultural electric fences operating at a period of approximately 1s.

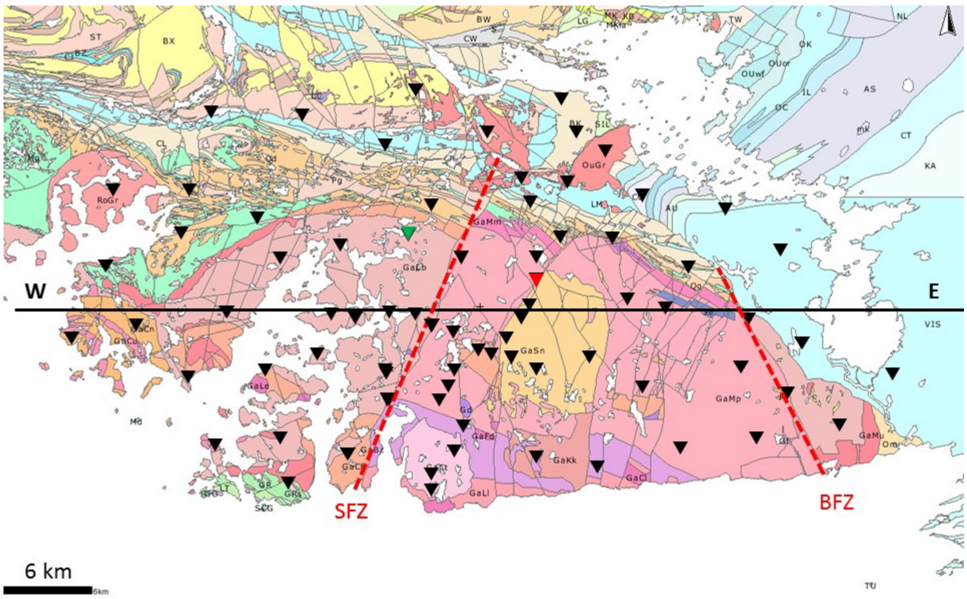

Figure 7: Locations of MT/AMT sites across the Galway granite marked by black triangles. Sites ggr012 and gga019 marked by red and green triangles respectively. Resistivity structure beneath line W-E shown in cross-section in Figure 12. SFZ – Shannawona Fault Zone BFZ – Barna Fault Zone

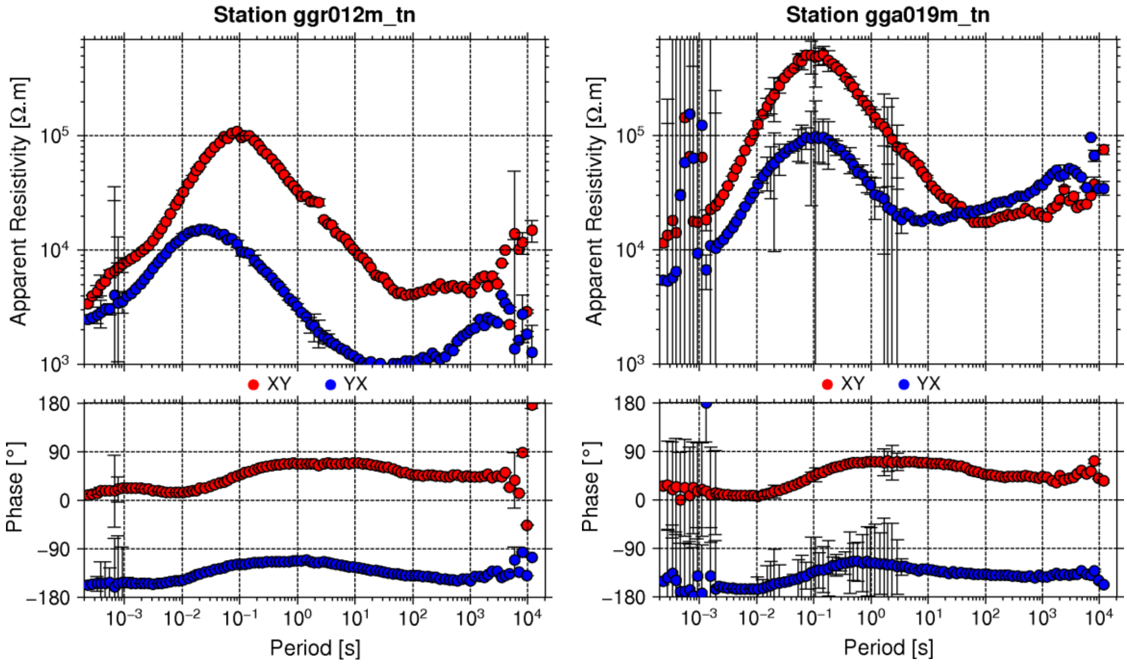

Figure 8: Apparent resistivity and phase from data acquired at sites ggr012 and gga019. Locations of sites marked on Figure 7

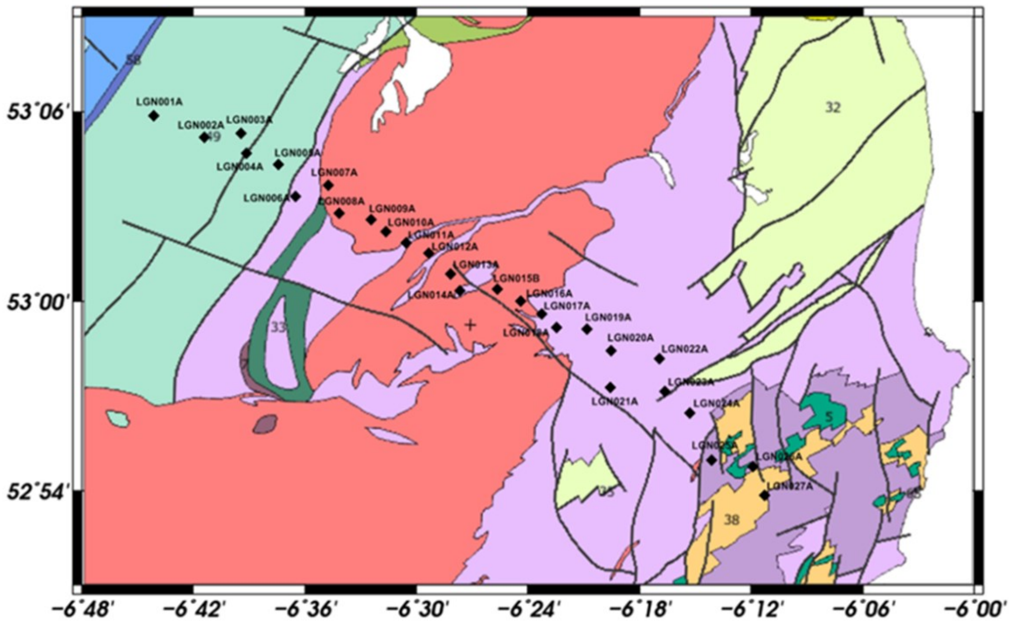

Figure 9: Locations of MT/AMT sites along profile LGN marked by black diamonds. Resistivity structure beneath this profile is shown in Figure 12

3.2 Previously available data

3.2.1 Gravity Data

The Irish national gravity dataset is available but coverage is quite variable across Ireland. As an example, Figure 10 shows the gravity data coverage across the west of Ireland around the Galway granite. The data coverage is quite poor over the MT survey area. Gravity data coverage is much better over the Leinster and Kentstown granites. Inversion of gravity data will be constrained by resistivity models produced by the inversion of MT and AMT data, which are particularly suited to detecting the base of an electrically resistive granite hosted in electrically conductive country rocks.

3.2.2 Other Data

Seismic refraction data, collected as part of the LEGS project (Hodgson 2001) (Figure 6), are available over the Leinster granite. Estimates of the depth to the base of the granite from these seismic data will help to constrain the geometry of the Leinster granite.

Satellite magnetic data are also available and may be used to investigate the depth to the base of the magnetic crust to infer the Curie depth (and isotherm) beneath Ireland. Radioelement concentration and heat production data are also available (Figures 5 and 11). IRETHERM is expanding the heat production database across Ireland through the work of another PhD researcher (Figure 11). Geochronology and isotopic data, both pre-existing and measured by another PhD researcher as part of the IRETHERM project, is also available to investigate the petrogenesis and emplacement mechanisms of the granites. Thermal conductivity data are also available to explore how heat propagates through the Irish crust.

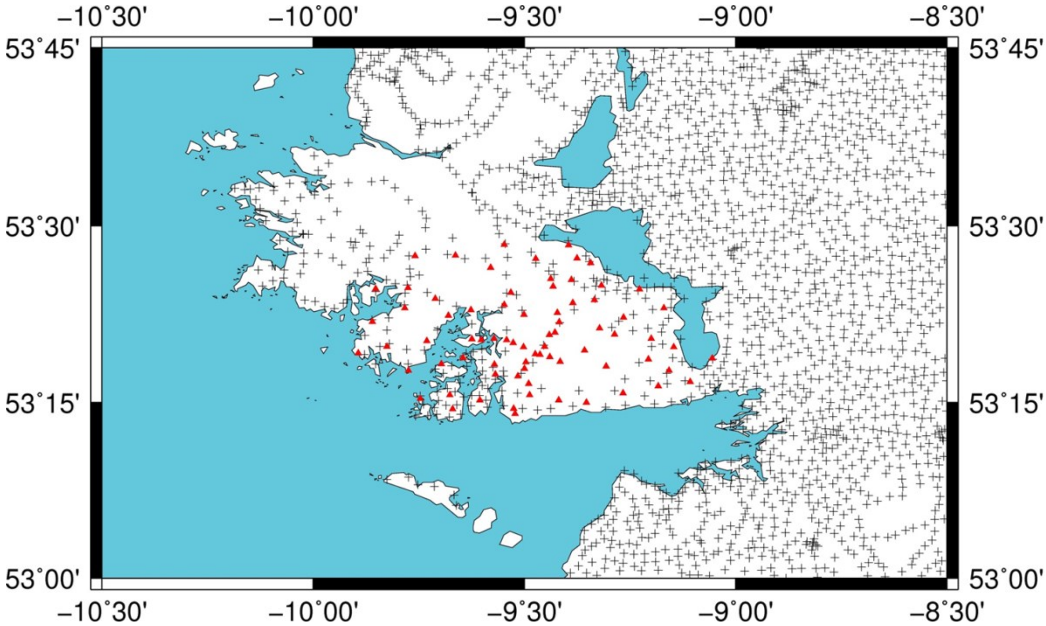

Figure 10: Gravity data coverage across western Ireland. Location of gravity stations marked by black crosses. Location of MT/AMT sites marked by red triangles

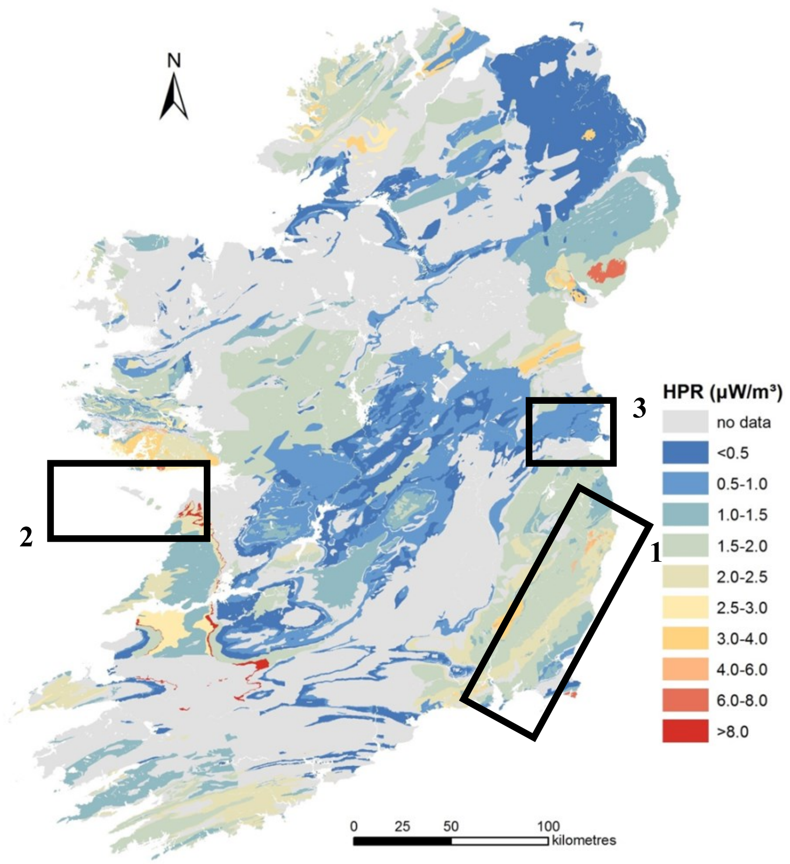

Figure 11: Heat Production Rate of lithological units across Ireland 1. Leinster granite 2. Galway granite 3. Kentstown granite (after Willmot-Noller 2013)

4. PRELIMINARY RESULTS AND INTERPRETATIONS

The inversion of MT and AMT data, acquired over three field seasons is currently underway. The results of preliminary 1-D inversions of AMT data from the LGN profile in Leinster (Figures 6 and 9) are shown in Figure 12. The granites are electrically resistive and are represented by the blue/purple colours. Beneath the LGN profile, the granite is shown to extend to depths of 4.5 – 5 km beneath the more north-westerly Northern Units, whereas the Lugnaquilla Pluton extends to depths of approximately 2.5 km.

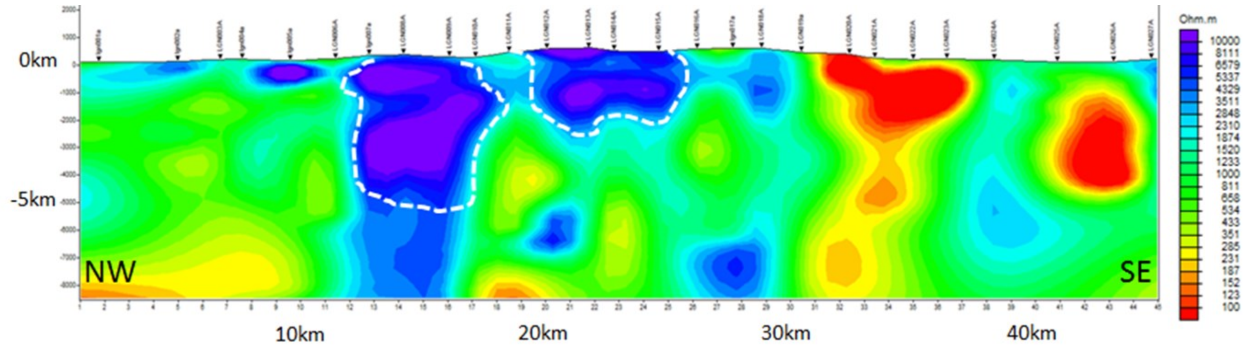

Figure 12: Resistivity structure beneath profile LGN interpolated from 1-D Occam models of AMT data at each site. Interpreted granite bodies outlined in white dashed lines. The more south-easterly resistive body in the section corresponds with the Lugnaquilla Pluton

Preliminary 3-D inversions of Galway granite MT and AMT data have been carried out. Figure 13 shows a 2-D slice beneath an east-west line (shown in Figure 7) through the resulting 3-D model. In Figure 13, white areas are resistivities greater than 10,000 Ωm, typical for granites. The granite is revealed to be a highly resistive body with no indications, within the resolution constraints of the survey, of electrically conductive zones associated with significant fluid-filled connected fractures. The resistive body extends to 6 km depth in the western block, west of the Shannawona Fault Zone, and deepens to 11 km depth beneath the central block, between the Shannawona Fault Zone and the Barna Fault Zone. This geometry is in contrast to previous thinking that proposed the central block to have shallower depth extent than the western block (Madden 1987). This previously held idea was based on Bouguer anomaly maps of the area in which the western block exhibited a more pronounced negative Bouguer anomaly than the central block. SHF calculated on the Galway granite is not particularly elevated (77 and 65 mW m^{-2}), which also suggests that it is unlikely that there exists radiogenic, lower density granite to a depth of 11 km. That the central block therefore has a higher average density than the western block, is an inference that corresponds well with the observed lithologies at outcrop that exhibit a higher abundance of more mafic granitoids. The potential distribution of these higher density mafic granitoids will be examined by inversion of gravity data constrained by the geometry revealed by the MT/AMT inversions.

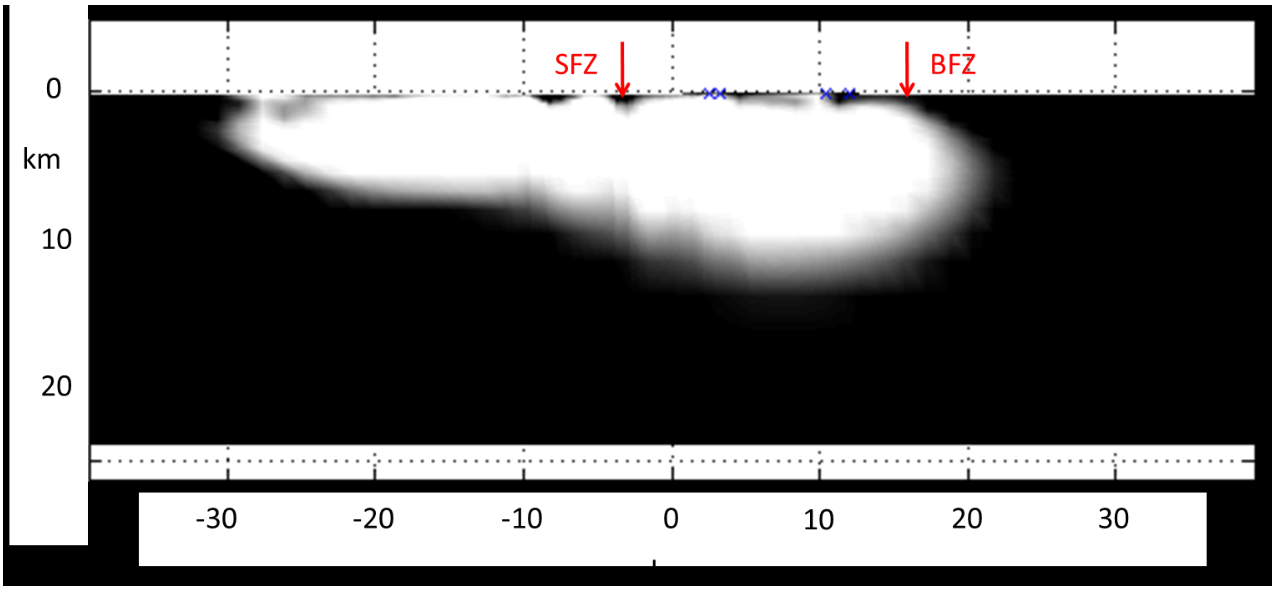

Figure 13: East-west 2-D cross-section through 3-D model produced by inversion of MT and AMT data across the Galway granite (along profile W-E (see Figure 7)). SFZ – Shannawona Fault Zone, BFZ – Barna Fault Zone. White areas in the section correspond with resistivities greater than 10,000 Ωm.

5. FUTURE WORK

Inversions of MT and AMT data are ongoing. These inversions, integrated with seismic and gravity data will be used to constrain the volume and geometry of the granite bodies. Satellite magnetic data will be used to determine estimates of the Curie depth and isotherm beneath Ireland in order to constrain the thermal conditions found in the lower crust. This information, together with heat-production calculations derived from geochemical studies, will be incorporated with thermal conductivity data to undertake modelling of crustal heat-flow and to examine the contribution of granites to the thermal regime of the Irish crust. This modelling will be performed using LitMod3D, an interactive 3-D computer program developed to perform combined geophysical-petrological modelling of the lithosphere and sublithospheric upper mantle within an internally consistent thermodynamic geophysical framework, where all relevant properties are functions of temperature, pressure, and composition (Fullea et al. 2009).

6. CONCLUSIONS

Preliminary 1-D inversions of AMT data along the LGN profile over the Leinster granite show the Northern Units to extend to depths of 4.5 – 5 km, with the Lugnaquilla pluton extending to depths of 2.5 km. At the Galway granite, preliminary 3-D inversions show the western block of the Galway granite to extend to a depth of 6 km, with the central block extending to a depth of 11 km. The Galway granite batholith appears to be quite homogenously resistive, with no evidence of large-scale electrically conductive fluid-filled fractures, within the resolution constraints of the MT survey.

7. ACKNOWLEDGEMENTS

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REFERENCES

Allen, A. and Burgess, J.: Developments in Geothermal Utilization in the Irish Republic, *Proceedings World Geothermal Congress*, April 25-29, Bali, Indonesia (2010).

Brindley, J.C.: The Structural Setting of the Leinster Granite, Ireland: a Review. *Scientific Proceedings of the Royal Dublin Society*, **5A**, (1973) 27-34.

Brock, A.: Heat Flow Measurements in Ireland. *Tectonophysics*, **164**, (1989) 231-236.

Brock, A. and Barton, K.J.: Equilibrium Temperature and Heat Flow Density Measurements in Ireland, *Final Report on Contract No. EG-A-1-022EIR(H)*, Report EUR 9517, NUIG AGR Internal Report AGR 84/1 (1984).

Barton, K.J., Brock, A. and Sides A.D., 1989. Preliminary results from temperature, heat-flow and heat production studies in Ireland. In: Louwrier, K., Staroste, E., Garnish, J.D., Karkoulias, V. (Eds.), *European Geothermal Update, Proceedings of the Fourth International Seminar on the Results of EC Geothermal Energy Research, Held in Florence*, 27–30 April, 1989, pp. 551–559.

Feely, M. and Madden, J.S.: The Spatial Distribution of K, U, Th and Surface Heat Production in the Galway Granite, Connemara, Western Ireland. *Irish Journal of Earth Sciences*, **8**, (1987), 155-164.

Feely M., Selby, D., Hunt, J. and Conliffe, J: Long-lived Granite-Related Molybdenite Mineralization at Connemara, Western Irish Caledonides, *Geological Magazine,* **147** (6), (2010) 886-94.

Fullea, J., J. C. Afonso, J. A. D. Connolly, M. Fernàndez, D. García-Castellanos, and H. Zeyen.: LitMod3D: An Interactive 3-D Software to Model the Thermal, Compositional, Density, Seismological, and Rheological Structure of the Lithosphere and Sublithospheric Upper Mantle. *Geochem. Geophys. Geosyst*. **10**, Q08019. (2009).

Hennessy, R. and Feely, M.: Visualization of Magmatic Emplacement Sequences and Radioelement Distribution Patterns in a Granite Batholith: An Innovative approach using Google Earth. In: (Ed.) Declan De Paor, *Google Earth Science*, *Journal of the Virtual Explorer, Electronic Edition*, ISSN 1441-8142, **volume 29**, paper 3, doi:10.3809/jvirtex.2008.00196 (2008).

Hodgson, J. A.: A seismic and Gravity Study of the Leinster Granite: SE Ireland. *Unpublished PhD thesis*, University College Dublin (2001).

Holland, C. H. and Sanders, I.S.: The Geology of Ireland, second edition. *Dunedin Academic Press* (2009).

Leake, B. E.: 'Stoping and the Mechanisms of Emplacement of the Granites in the Western Ring Complex of the Galway Granite Batholith, Western Ireland', *Earth and Environmental Science Transactions of the Royal Society of Edinburgh,* **102** (01), (2011) 1-16.

Leake, B.E. and Tanner, P.W.G.: The Geology of the Dalradian and Associated Rocks of Connemara, Western Ireland: A Report to Accompany the 1:63,630 Geological map and Cross Sections: *Dublin, Royal Irish Academy*, 96 p. (1994).

Madden, J. S.: Gamma-ray Spectrometric Studies of the Main Galway Granite, Connemara, West of Ireland. Unpublished PhD thesis, National University of Ireland Galway. (1987).

McArdle, P. & Kennedy, M.J.: The East Carlow Deformation zone and its Regional Implications. *Geological Survey of Ireland Bulletin*, **3**, (1985) 237-255.

McCarthy, W.J.: An Evaluation of Orogenic Kinematic Evolution Utilizing Crystalline and Magnetic Anisotropy in Granitoids. *Unpublished PhD thesis*, National University of Ireland Galway (2013).

McConnell, B. & Kennan, P.: Petrology and Geochemistry of the Drogheda Granite. *Irish Journal of Earth Science* **20** p. (2001) 53-60.

Muller, R.D., Sdrolias, M., Gaina, C. and Roest, W.R.: Age, Spreading Rates and Spreading Symmetry of the World's Ocean Crust. *Geochem. Geophys. Geosyst*., **9** Q04006, doi:10.1029/2007GC001743 (2008).

O’Connor, P.J., Aftalion, M. and Kennan, P.S.: Isotopic U-Pb ages of Zircon and Monazite from the Leinster Granite, SE Ireland. *Geological Magazine*, **126**, (1989) 725-728.

O'Reilly, C., Feely, M., Holdstock, M.P. and O'Keefe, W.G.: Fluid Inclusion Study of the Unexposed Kentstown Granite, Co. Meath, Ireland. *Transactions of the Institution of Mining and Metallurgy* **B107**, (1997) 31-7.

Pearce, J.A., Harris, N.B.W. and Tindle, A.G.: Trace Element Discrimination Diagrams for the Tectonic Interpretation of Granitic Rocks. *Journal of Petrology* **25**, (1984) 956-83.

Ryan, P. D. and Dewey, J. F.: The South Connemara Group Reinterpreted: a Subduction-Accretion Complex in the Caledonides of Galway Bay, western Ireland, *Journal of Geodynamics*, **37** (3–5), (2004) 513-529.

Sweetman, T.M.: The Geochemistry of the Blackstairs Unit of the Leinster Granite, Ireland. *Journal of the Geological Society, London* **144**, (1987) 971-84.

Williams, F.M. & Kennan, P.S.: Stable Isotope Studies of Sulphide Mineralization on the Leinster Granite Margin and some Observations on its Relationship to Coticule and Tourmalinite rocks in the Aureole. *Mineralium Deposita*, **18** (2), (1983) 399-410.

Willmot-Noller, N.: Heat Production Rates in Irish Rocks. *Presentation to IRETHERM SFI External Review Panel*, Dublin, (2013).