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IRETHERM: Developing a Strategic and Holistic Understanding of Ireland's Geothermal Energy Potential through Integrated Modelling of New and Existing Geophysical, Geochemical and Geological Data

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ABSTRACT

The academia-government-industry collaborative IRETHERM project (www.iretherm.ie), initiated in 2011 and funded by Science Foundation Ireland, is developing a strategic understanding of Ireland's (all-island, south and north) deep geothermal energy potential through integrated modelling of new and existing geophysical, geochemical and geological data. Potential applications include both low enthalpy district space heating of large urban centres and electricity generation from intermediate-temperature waters. IRETHERM is unique in the breadth of the targets studied and the manner in which disparate data are being acquired, collated and combined in a unified, holistic manner.

High-resolution geophysical modelling tools are being constructed for imaging aquifers, fault zones and granitic bodies in the depth range 0–5 km. The new tools are being tested on seven "type" geothermal targets with a comprehensive program of electromagnetic field-surveys to identify those geological settings and localities that present the greatest potential for significant geothermal energy provision. New borehole temperature and heat-flow measurements and analyses of radiogenic element compositions of an island-wide suite of multi-depth crustal samples are being used to derive the first 3-D model of Irish crustal heat-production. Thermal variations are being modelled using new crustal thermal conductivity measurements and heat-production constraints and existing controls on lithospheric structure to determine the origin of the regional variation in heat-flow and identify high-temperature anomalies at upper-crustal levels for immediate and future targeting.

IRETHERM comprises three broad geothermal target types,
1) Assessment of the geothermal energy potential of Ireland's radiogenic granites (EGS),
2) Assessment of the geothermal energy potential of Ireland's deep sedimentary basins (HSA), and
3) Assessment of the geothermal energy potential of warm springs.

Linking these three together is subsurface imaging using both controlled-source electromagnetic methods (CSEM) and natural-source electromagnetic methods (magnetotellurics, MT). Electrical conductivity, being a transport property, is a proxy for permeability, and appropriate porosity-permeability relations are being developed. Modelling of the data will include constraints from other geoscientific data, both in a formal (e.g., joint inversion) manner and a less formal (i.e. co-operative) manner. These results will be complemented by (hydro) geothermal modelling of the processes relevant to the target-specific geothermal energy potential.

To date, MT measurements have been made at 466 sites over sedimentary basins (190 sites), granites (156 sites) and warm springs (120 sites), with CSEM across one warm spring. An ongoing continuous geochemical (temperature and electrical conductivity every 15 mins) and time-lapse seasonal hydrochemical sampling programmes are in progress at six warm spring sites. A database on heat production in Irish rocks has been compiled, of more than 3,300 geochemical sample measurements, with 3,000 retrieved from various archives and over 300 new analyses. Geochemistry, geochronology and isotopic analyses have been conducted on subsurface granites and exposed analogues astride the Iapetus Suture Zone in order to understand the underlying reasons for their radiogenic heat production. Finally, thermal conductivity measurements have been made on borehole samples from representative lithologies.

This paper will review all of the IRETHERM work within Ireland's low enthalpy setting.

1. INTRODUCTION

In this report we present a summary of geophysical, geologic and geochemical studies and selected preliminary results carried out under the auspices of the IRETHERM project (www.iretherm.ie) to May, 2014. IRETHERM's overarching objective is to develop an understanding of Ireland's geothermal energy potential through joint-inversion and integrated modelling of new and existing

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data. Such a 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 Science Foundation of Ireland (SFI) grant for this project (Award 10/IN.1/I3022) was awarded to Professor Alan G. Jones at the Dublin Institute for Advanced Studies (DIAS), together with Professor Stephen Daly at University College Dublin (UCD) as a co-principal investigator, in 2012. Funding is for 54 months with a total budget of approximately €850K, plus Overhead (total approx. €1.15M). The broad high interest for the project in geoscience community brings together expertise in academia, government and industry and many new collaborators, listed in co-authors list, have joined the IRETHERM consortium since its initiation.

The funding awarded was less than the request, resulting in some target areas being dropped or becoming part of another project entirely (see Fig. 1). Two of the sedimentary basins, the Clare Basin (area 9 in Fig. 1) and the Northwest Carboniferous Basin (area 5), will be studied as part of the IRECCSEM project to assess Ireland's potential for onshore carbon sequestration. Measurements in central Ireland (area 7) and in southernmost Ireland (area 10) will not take place.

2. SURFACE HEAT FLOW IN IRELAND

One of the key roles for assessment of Ireland's geothermal potential is the origin of the regional and local heat flow variation in Ireland. The temperature and heat-flow modelling and understanding across Ireland allows for a better estimation of temperature at depth and better selection of the most perspective geothermal regions. The contribution to surface heat flow (SHF) is based on the 3-D distribution of radiogenic heat producing rocks and their thermal conductivity within the crust, and the heat flow from the mantle; where the latter critically depends on lithospheric thickness. Daly's (UCD Geology) group is focused on the geochemical technique of mapping the 3D heat production in the Irish lithosphere and studying the petrogenesis of Caledonian granites in order to understand the underlying sources of radioactively-generated heat within individual granitic plutons. These studies are supported by geochemical analyses and also thermal conductivity measurements on samples obtained from boreholes being conducted by Long's (UCD Engineering) group.

The available data coverage of SHF measurements in Ireland is insufficient and also the existing estimates have very large uncertainties connected with attributed thermal conductivities to the lithologies in the old industry boreholes with their bottom-hole temperatures. Recent reconsideration of the primary data, mostly acquired in the late-1970s and early-1980s by Andrew Brock at NUIG, by [*Jones et al.*, 2014] led to production of an updated robust heat flow map of Ireland, where the SHF has only moderate south-to-north increase in comparison with original SHF map from [*Goodman et al.*, 2004] (Figure 1).

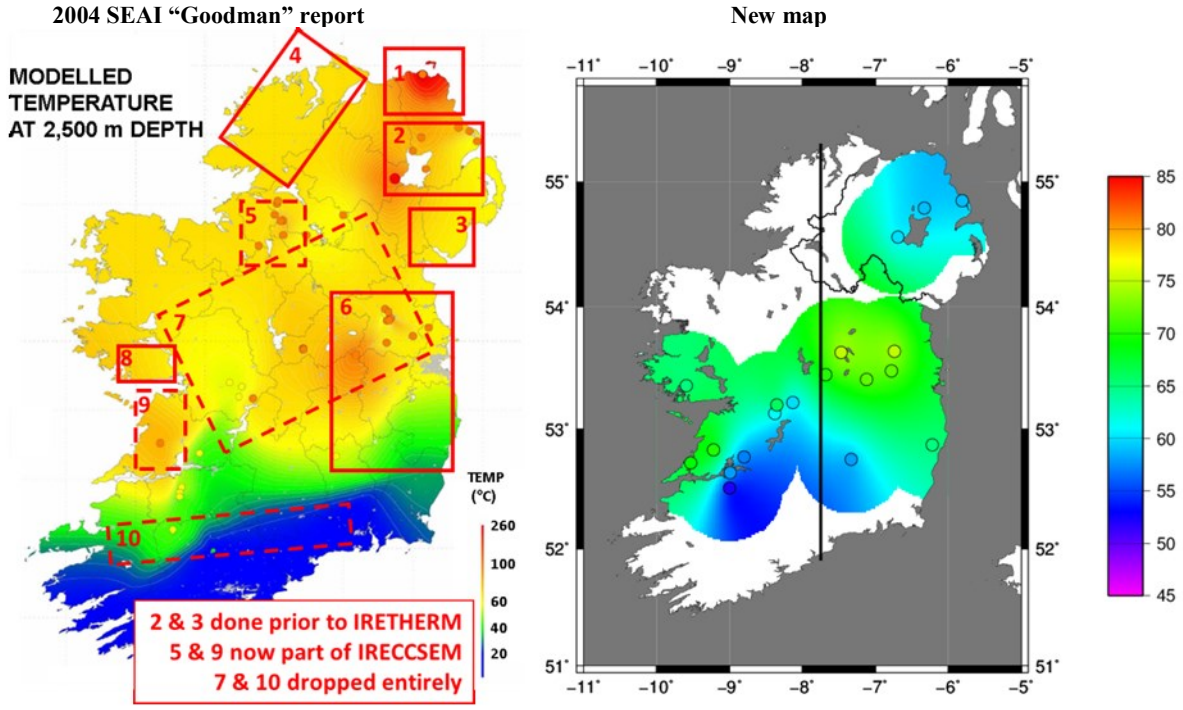

Figure 1: Re-assessed all available heat flow measurements, mostly made in the late-1970s and early-1980s through interrogating original reports and communicating with Professor Andrew Brock (now in South Africa). Left: SHF map in [*Goodman et al.*, 2004] report, with original 10 IRETHERM target areas identified. Right: Revised SHF map in [*Jones et al.*, 2014].

3. IRETHERM ACTIVITIES TO MAY 2014

3.1 DIAS group (PI Jones)

3.1.1 Overview

The DIAS group in the IRETHERM project is focused on using electromagnetic methods for deducing the geometries of subsurface structure, as represented by their electrical conductivity (resistivity) variations both laterally and vertically. The principle technique used is the natural-source electromagnetic method called magnetotellurics (MT) which utilizes natural variations in electromagnetic energy to deduce the conductivity properties of rocks within the Earth. The MT method is frequently used in application for surveys

of geological units with conductivity contrast between structures from scales of 100 m to 100s km, e.g. in groundwater exploration, geothermal energy, mineral and hydrocarbon exploration, volcano and earthquake hazards, and crustal and upper mantle studies. In addition, controlled source EM (CSEM) measurements are being made for shallow structures at depths less than 500 m and also where cultural noise contamination is severe. In the IRETHERM project MT is focused on eight strategic geothermal targets represented mainly by sedimentary basins with high heat flow/temperature anomalies, radiogenic granites and warm-spring lineaments (Fig. 1).

3.1.2 Petrological-geophysical modelling of Ireland (Jones, Fullea, DIAS)

The primary SHF, thermal parameters, topography, gravity and seismic data have been used in integrated modelling of Ireland's lithosphere in two recent papers; [*Jones et al.*, 2014] discusses the data and undertakes first-order 1D and 2D modelling, and [*Fullea et al.*, 2014] undertakes detailed 3D modelling. The modelling was accomplished with thermodynamically-consistent petrological 2D/3D modelling/inversion framework called LitMod of Juan Carlos Afonso and Javier Fullea [*Afonso et al.*, 2008; *Fullea et al.*, 2009]. The LitMod software combines petrological and geophysical modelling of the lithosphere and sub-lithospheric upper mantle within an internally consistent thermodynamic-geophysical framework, where all relevant properties are functions of temperature, pressure and composition (including water content).

Through first-order considerations the [*Jones et al.*, 2014] paper showed that the thermal lithosphere-asthenosphere boundary (LAB) beneath Ireland lies in the range of 90–115 km for a crust thickness of 29–31 km. The greatest effect on the LAB depth estimation is the assumption made of the crustal density, followed by crustal thickness. The errors introduced from potential incorrect crustal parameterization will lead to a maximum variation in the LAB depth of the order of ±15 km at the most extreme and assuming all biases are in the same direction.

The modelling shows that the LAB depth in the north beneath Ireland is far deeper than previously published 55-85 km of [*Landes et al.*, 2007], and that the maximum "step" of the LAB between northern and southern Ireland must be less than 20 km. The "LAB" of [*Landes et al.*, 2007], based on S receiver functions (SRFs), would yield a very large topographic change between southern and northern Ireland of almost 1 km (Fig. 2 left), a very large Bouguer anomaly and a large geoid variation, none of which are seen. The three zone lithosphere model on Fig. 2 right fits the all of the data, and has an LAB at 110-90 km with a mid-lithospheric discontinuity (MLD) to explain the observed SRFs.

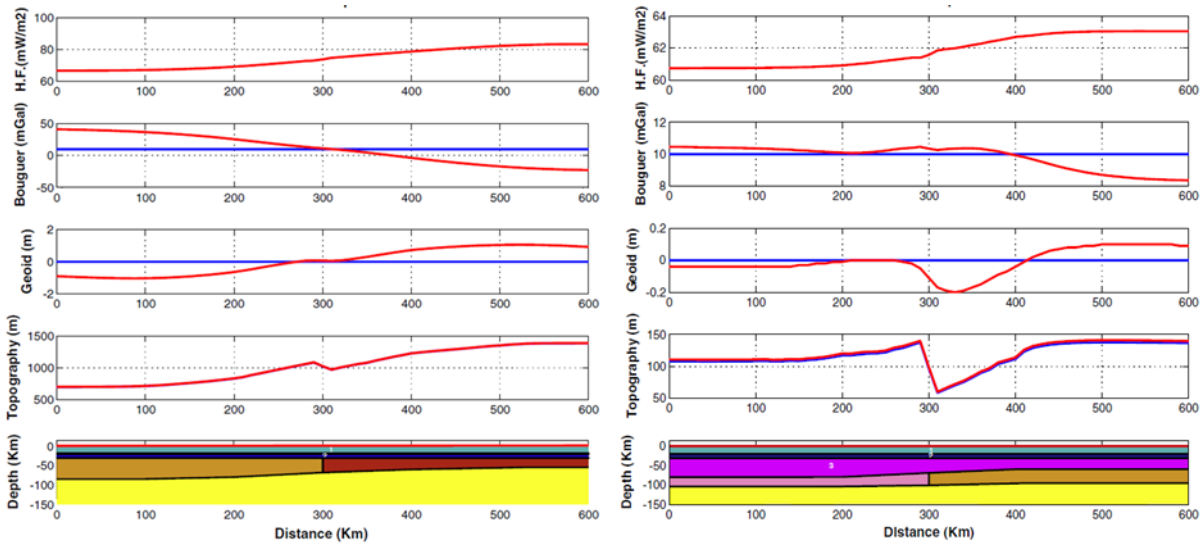

Figure 2: Petrological-geophysical modelling of Ireland along a N-S profile (trace shown in Fig. 1 right). Left: Proposed lithospheric geometry of [*Landes et al.*, 2007] with an "LAB" change from 85 km in the south to 55 km in the north. Right: Three-zone lithospheric model of [*Jones et al.*, 2014] that fits the surface observations of SHF, geoid, Bouguer gravity and topography.

3.1.3 Geothermal potential in Irish Sedimentary Basins (Delhaye, Vozar, Jones, DIAS; Reay, Desissa, GSNI; Pasquali, Geoserv; Hanly, GT Energy; Smyth, Providence)

The lateral and depth electrical conductivity variation in sediments represent information about transport property within the basin. In contrast, seismic velocity is a vibrational property of the medium and the density is a bulk property. The electrical conductivity is sensitive to the fluid content and the movement of ions. So for the greater values of the porosity and permeability properties of units they are represented by the greater movement of ions measured by the higher conductivity (lower the resistivity). The electrical conductivity is thus the best proxy for porosity/permeability of the available physical parameters observable from the surface. On the other hand, the granites are resistive bodies usually surrounded by more conductive lithologies. The depth to the base of a resistive body is the same as the depth to the top of the conductive region below. Defining the top of a conductor is a well resolved parameter and a first-order result from MT studies. Fractures/fissures within the body of granite are easily imaged from the surface using EM/MT methods due to the strong conductivity contrast between the body and fluid-filled cracks.

The objective of geothermal energy potential estimation in Ireland's sedimentary basins is to try to identify formations and localities where higher primary porosities are preserved (e.g., the basal formations of sedimentary successions) or where secondary porosity is high (e.g., along major crustal fault and shear zones) within the sedimentary strata and to map the geometry of the basins.

- Rathlin Basin (Delhaye, Jones, DIAS; Reay, Desissa, GSNI; Smyth, Providence)

We acquired magnetotelluric data sets over the onshore Rathlin Basin (target area 1 in Fig. 1), composed from Dalradian metasedimentary formations, Carboniferous sediments and basalts on the surface, and on the nearby Rathlin Island as a part of Providence Resources joining the IRETHERM project. First preliminary multi-dimensional MT modelling results from Rathlin basin and Rathlin Island indicate thickness of sedimentary basins to 3 km and 2 km on Rathlin Island.

- Dublin Basin (Vozar, Jones, DIAS; Pasquali, Geoserv; Hanly, GT Energy)

Magnetotelluric data were acquired across the Dublin Basin southern margin with GT Energy as an industry IRETHERM collaborator The MT data in Dublin basin margin area are highly distorted by electromagnetic noise from Dublin's industry and nearby DC tram/railway system, and careful and exacting processing had to be applied with four different tools, including a novel technique of interstation magnetic transfer functions (SPIT). This method improves the results when the acquired magnetic fields have been truncated or are highly affected by sporadic noise. The method is also useful to improve the processing in noisy areas, as increase the statistics used to obtain the final results. The 2D models underwent a stability technique examination based on statistical Jackknife method, and 3D models of all MT sites in the Newcastle area have been prepared and further on-going 3D modelling with different inversion algorithms based on data and model space inversion algorithms is being calculated. The 3D modelling work has been focused on improving the used modular 3D inversion programme implementing the Horizontal Magnetic Tensor (HMT).

From multidimensional MT modelling we can conclude preliminary geological interpretations to 10 km depth. The Newcastle Blackrock Fault (NBF) is visible in the models as a more conductive area down to a depth of 4 km. Generally the southern part of the area is more resistive and compact with horizontal conductive layer at a depth of about 1 km and very thin sedimentary layer on the top. The structures north to the NBF are more heterogeneous with deeper conductive layers (2-3 km) and thicker (several hundreds of metres) sedimentary layer on the top (Figure 2). The integrated modelling with old available geophysical data and newly collected seismic data (new seismic data in frame of SIMCRUST project will be ready by the end of the year) will be prepared in next step.

3.1.4 Geothermal potential in Irish Granites (Enhanced Geothermal Systems) (Farrell, Jones, DIAS; Feely, Brock, NUIG)

The MT data acquired over the granite bodies will be used along with the Irish national gravity dataset to constrain the depth and lateral extent of Ireland's many promising (exposed and buried) radiogenic granites, which present favourable targets for Engineered Geothermal Systems energy provision and are poorly known. Their heat-generation potential requires further verification. These will be integrated with geochemical and thermal conductivity work, conducted in UCD as a part of IRETHERM, to provide a unique perspective on the geological settings of the granites and their geothermal energy potential.

During the winter programme, MT data were recorded along a 55 km survey line across the Tullow pluton of the Leinster granite, and further data were recorded along a 30 km survey line across the Kentstown granite. Summer fieldwork in 2013 involved an MT survey across the Galway granite.

In 2012, in collaboration with the Geological Survey of Ireland (GSI), an opportunity arose to drill into the buried Kentstown granite in County Meath. To focus the selection of an appropriate drilling site, a 2D gravity model across the Kentstown granite was produced and MT data were recorded just north of the village of Kentstown. This work identify a depth to the top of the granite at 370 m. Unfortunately, the drilling ran into difficulties and had to be stopped at a depth of 200 m.

3.1.5 Geothermal potential of Irish Warm Springs (Blake, Jones, DIAS; Kalscheuer, Uppsala; Hunter-Williams, Lee, GSI)

The last important information about geothermal sources is coming from the understanding nature of plumbing system of Ireland's warm springs. The intent is to know whether the warm waters are indicative of deeper buried heat sources. We are looking for deeper water circulation patterns which might offer higher temperature waters in the depth of 2-5 km. A 40 station AMT survey in Lucan, Co. Dublin over St. Edmundsbury warm spring were carried out to identify faults and deep bedrock aquifers. A hydrochemical sampling programme was launched at six warm spring locations in Leinster, and the second season of water sampling was completed in early October 2013.

3.1.6 Porosity/permeability of Irish rocks (Campanya, Jones, Rath, DIAS)

A new program has been developed to calculate (by Marquardt inversion) the connectivity of the rocks from porosity/conductivity samples. The program uses phases of Archie's law suggested by Glover. This program will be used to create a database of the connectivity of the Irish rocks using different available data of porosity and conductivity. Results will be used to interpret the IRETHERM geoelectrical models and analyse the possibilities of monitoring the fluids during the injection.

3.1.7 Mapping potential secondary porosity/permeability (Delhaye, Jones, DIAS; with Piana Agostinetti, DIAS)

Magnetotelluric data were acquired across the western side of Lough Swilly in Co. Donegal (target area 4 in Fig. 1), which centred above an areas of microseismicity investigated also by an independent SFI SIRG (Starting Investigator Research Grant) SIMCRUST project by Nicola Piana Agostinetti at DIAS. This overlap in areas and objectives of both projects gives an opportunity for research synergy and collaboration, particularly joint MT/seismic/gravity inversion.

3.2 UCD Geochemistry group (PI Daly)

3.2.1 Chronology and geochemistry of Irish granites (Fritsche, Daly, UCD)

The petrogenesis of Caledonian granites is being studied in order to understand the underlying reasons for radioactively-generated heat within individual granitic plutons. In the course of the last year U-Pb geochronology, oxygen and Lu-Hf isotopic analyses have been undertaken on zircon crystals from eight Irish and two Isle of Man granites. U-Pb and oxygen isotopic analyses were carried out using the ion microprobe (SIMS) at the Swedish Museum of Natural History in Stockholm. The hafnium isotopic analyses were conducted by LA-MC-ICPMS at the National Centre for Isotopic Geochemistry at University College Dublin. The objectives were

to determine reliable intrusion ages for the granites as well as the characterization of their sources. Linking the granites' intrusion ages and petrogeneses with the particular heat production rates of the plutons introduces the opportunity to investigate possible causes for elevated heat production, and hence the likelihood of a granite to be exploited for geothermal purposes. Results of the geochronological investigations place the genesis of the Irish granites into the late Caledonian Orogeny in four discrete episodes at c. 435, 417, 410 and 393 Ma. Contrasting this, the Isle of Man granites appear to have been formed earlier at c. 455 Ma, although further investigations are required to confirm their ages and their tectonic significance. Zircon isotopic analyses elucidated the likely contribution of juvenile protoliths to the genesis of several of the granites, which have mantle-like δ18O ratios below 6‰ and slightly radiogenic εHfi values. Furthermore, isotopically distinct materials have contributed to the sources of several of the granites.

U-Pb geochronology, oxygen and Lu-Hf isotopic analyses have been undertaken on zircon crystals from eight Irish and two Isle of Man granites. U-Pb and oxygen isotopic analyses were carried out using the ion microprobe (SIMS) at the Swedish Museum of Natural History in Stockholm. The hafnium isotopic analyses were conducted by LA-MC-ICPMS at the National Centre for Isotopic Geochemistry at University College Dublin.

Element maps imaging the distribution of heat-producing elements in granite and veins occurring therein were conducted using the electron micro probe analyzer (EMPA) in Mainz, Germany.

- U-Pb zircon geochronology
- Lu-Hf isotopic analyses
- Oxygen isotopic analyses
- EMPA element maps

Element maps were produced to elucidate the differences in heat producing element concentrations between veins and host-rock. Hence, the role of a granite's elevated uranium content due to hydrothermal distribution in a vein-network is tested.

3.2.2 Concentrations of U, Th and K in Irish rocks (Willmot Noller, Daly, UCD)

The 3D heat production in the Irish lithosphere is being studied under this thread. Calculating the heat production rate requires determining concentrations of the radioelements uranium, thorium and potassium in rock, as well as its density. During the past year, work has focused on geochemical data gathering. This has included searching for data from existing analyses, which has resulted in obtaining more than 3000 data points. In addition, over 300 new analyses to establish radioelement concentrations have been made on rocks across Ireland, using laboratory techniques and portable gamma-ray spectrometry. Data points have been extrapolated to generate a surface map of the heat production rate by geological formation/rock unit to give about 50% surface coverage of the island of Ireland. Preliminary results have established that heat production mainly correlates with rock type, with granites, shales and felsic volcanics producing the highest heat production rates - respectively, up to about 40 μW/m3 in the Clare Shale Formation, 17 μW/m3 in Mourne Granite and 9 μW/m3 in tuff horizons of the South Munster Basin. A correlation between heat production and age is observed in high heat-producing intrusive igneous rocks. Tectonic setting is shown to be an influence upon distribution of uranium and thorium in volcanic rocks, with substantial differences in heat production rate is between the oceanic arc volcanics of Ordovician age north of the Iapetus Suture Zone and those of back-arc volcanics south of it. A sampling method for the portable gamma-ray spectrometer has also been established. Density measurements have also been made and are ongoing.

3.3 UCD Engineering group (PI Long)

Thermal conductivity (TC) measurements (Long, Waters, UCD)

The thermal conductivity on representative samples of rocks from Ireland are being measured. A new divided bar apparatus has been built especially for the task at UCD. The results from this apparatus are being calibrated through comparison with results obtained from two other laboratories that use different techniques to determine thermal conductivity. The lab at Trondheim in Norway uses a laser pulse system to determine the conductivity value, whereas the lab at Uppsala in Sweden uses a heat decay method.

4. CONCLUSIONS

The understanding of the potential for low-enthalpy geothermal resources and the data mining that is being undertaken are adding significantly to the improved baseline knowledge of the geology, geophysics, geochemistry and hydrology of Ireland in specific localities. New and existing geophysical, geochemical and petrological data will be interpreted in a holistic manner seeking models of the subsurface that satisfy all of them simultaneously.

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