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The Contribution of Radiogenic Heat Production Studies to Hot Dry Rock Geothermal Resource Exploration in Ireland

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ABSTRACT

Ireland is located within stable lithosphere, unaffected by recent tectonism and volcanism. The upper crust under Ireland includes several thick Carboniferous sedimentary sequences where measured geothermal gradients are, for the most part, moderate (<25°C/km), though viable sources of geothermal energy may exist beneath them.

Exploration for deep-drilled, low enthalpy geothermal energy can benefit from knowing the variation in heat production rates (HPR) in 3D. Generally extrapolation in depth is challenging. However, Ireland is fortunate in this regard since the surface geology provides a series of quasi-3D sections as a result of several episodes of deformation and exhumation during the early and late Palaeozoic Caledonian and Variscan orogenies. Effectively, measurements of HPR at outcrop are a valid proxy for rocks at depth. By extrapolating the HPR of the major stratigraphic units combined with a consideration of structural geology, borehole data and geophysical data, including new magnetotelluric surveys undertaken as part of the IRETHERM project, a 3D model of the Irish upper crust is in progress.

The first step towards achieving this has been to calculate heat production rates of rocks exposed at the surface and obtained from drilling. Published whole-rock geochemical data have been combined with new analyses, using XRF and field-based gamma-ray spectrometry of a wide range of crustal rocks from across Ireland. Concentrations of ^{238}U, ^{232}Th and ^{40}K of over 3300 samples have been used to produce a map of bedrock radiogenic heat production.

The data show that heat production generally corresponds to rock type. Of the large volume lithologies, basalts yield the lowest HPR with a mean of 0.6 μW/m^3 and, as might be expected, granitoid rocks are generally hotter than other major lithologies. For example, the Cenozoic Mourne Granite records the highest mean HPR of granitoids of 6.83 μW/m^3. Other high heat production rates are found in the mid-Caledonian Carnsore Granite (6.42 μW/m^3) and the late Caledonian Costello Murvey Granite (6.33 μW/m^3). Granite petrogenesis likely controls heat production but universal relationships between HPR and bulk composition and tectonic setting are not seen, although a weak correlation with crystallisation age is apparent.

The highest mean HPR for any formation is recorded in the Clare Basin where high-uranium, phosphatic shales of Upper Carboniferous age have a mean HPR of 27.7 μW/m^3. Such high heat production suggests that these shales and others elsewhere in Ireland should be investigated as potential geothermal prospects.

Extrapolation into the crust reveals that basement rocks that represent Laurentia in the north of Ireland have a higher HPR (1.64 μW/m3) than Avalonian continental basement in the far south (0.94 μW/m^3). Lower Palaeozoic rocks that form the basement of much of the south and the midlands, also show a similar divergence in heat production values to their age equivalents north of the ISZ. On a regional scale HPR at shallow crustal levels beneath Ireland is in line with global averages, though compilation of the 3D map is ongoing.

1. INTRODUCTION

Exploitation of geothermal resources for energy is common practice in areas where geothermal gradients are high, such as tectonically active regions and in volcanic areas e.g., Iceland and Italy. As demand for sustainable energy increases, however, and the technology to harness it improves, geothermal resources in relatively quiet regions prove increasingly viable. Ireland's location within old, cold continental crust and its low to moderate geothermal gradients (Goodman et al., 2004) have, until now, warranted little investigation into its geothermal properties. The IRETHERM project (www.iretherm.ie) has been established to gain insight into the geothermal prospectivity of the whole island of Ireland through multidisciplinary methods, and the research presented here contributes to the project's aim of identifying likely targets.

By far the biggest source of crustal heat is radioactive isotopic decay which, depending upon geographic location, is estimated to generate up to 98% (Slagstad, 2008). Friction from plate motions, oxidation of sulphides and exothermic metamorphic and diagenetic processes make up the difference (Jessop, 1990). Other contributions, such as cosmic neutrino interaction with the Earth's mass (Hamza and Beck, 1972) and gravitational distortion (Beardsmore and Cull, 2001), are likely to be very small indeed. The decay of the unstable isotopes of uranium (^{238}U and, to a far lesser extent, ^{235}U), thorium (^{232}Th) and potassium (^{40}K) provide the largest internal source of crustal heat that is geologically significant today (Brown and Mussett, 1993). Using the heat production constant values, assumed or measured density (ρ, kg/m^3) and measured ppm concentrations of uranium (C_U) and thorium (C_{Th}), and wt.% concentration of potassium (C_K), the heat production rate (HPR) in has been determined thus:

$$HPR\ (\mu W/m^3) = 10^{-5}\rho\ (9.52C_U + 2.56C_{Th} + 3.48C_K)\quad \text{(Rybach, 1988)}$$

Radiogenic heat production values in the crust, in conjunction with heat flow density data, contribute to our knowledge of the structure of Earth's lithosphere (e.g., Taylor and McLennan, 1985; Beardsmore and Cull, 2001; Jaupart and Mareschal, 2003) and heat variation plays an important role in crustal processes (e.g., Bea et al., 2003; Sandiford and McLaren, 2005). More practically, areas of high heat production are increasingly being identified as possible targets for hot, dry rock geothermal resources (Hasterok and Chapman, 2011). This paper describes the methods involved and the progress made in producing the first 3D heat production map of Ireland. To this end, radiogenic heat production values have been calculated from a dataset of more than 3300 new and previously published chemical analyses and over 2300 rock density measurements.

2. THE GEOLOGY OF IRELAND

A simplified map of Ireland's bedrock geology (Figure 1) displays predominantly Carboniferous sedimentary formations across central and western central Ireland. Precambrian rocks make up only about 10 per cent of Ireland's surface geology and are found exclusively in the NW (Laurentian crystalline basement and thick Dalradian metasedimentary sequences) and SE (Avalonian basement). Silurian sedimentary rocks form inliers within the Carboniferous mainly at a few locations centrally and to the east; Ordovician volcanic and sedimentary sequences are found in the south-east and northern central areas; Devonian red bed facies dominate the south of Ireland. The most recent bedrock geology is formed by Cenozoic basalts. Igneous intrusions, especially granites, of varying size and age, are widespread. These date chiefly from the Caledonian Orogeny, c. 450-380 Ma, which marks collision between Laurentia and Avalonia as the Iapetus Ocean closed (Soper and Hutton, 1984; Soper et al., 1992).

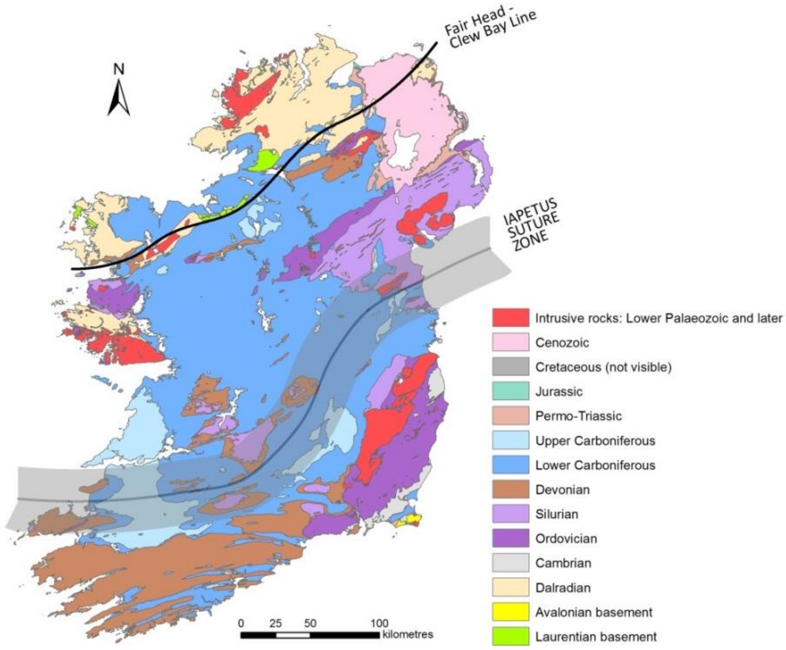

Figure 1: Simplified map of Ireland's bedrock geology showing the approximate location of the unexposed Iapetus Suture Zone and Fair Head-Clew Bay Line.

Regional structures are dominated by NE-SW-directed features, evidence for the Caledonian and Acadian orogenies of the Early to Middle Ordovician and Early Devonian. The closure of the Iapetus Ocean marked the docking of the continent of Laurentia (which included NW Ireland) with the microcontinent of Eastern Avalonia (which encompassed SE Ireland). The likely region of the Iapetus Suture Zone (ISZ) is shown in Figure 1, although the trace of the suture is obscured by Carboniferous cover. Following closure of the Iapetus, the Variscan Orogeny of the late Palaeozoic and Carboniferous generated intense deformation in the south, where thrusts, tight folds and extensive shortening occur; its less severe influence northwards resulted in fault reactivation and gentle folding (Cooper et al., 1986).

Down to lower crustal depths Laurentian crystalline basement is thought to extend across the northern part of Ireland to the Fair Head-Clew Bay Line (Figure 1). This interpretation is based on geophysical evidence from deep seismic experiments (Lowe and Jacob, 1989; Landes et al., 2005). South of this fault, the character of the basement of the Midland Valley Terrane, an oceanic arc which collided with the Laurentian margin, is unclear, but may be sediment derived from Laurentia (Flowerdew et al., 2009). The geochemistry of lower crustal metapelitic xenoliths from the ISZ (Van den Berg et al., 2005) supports seismic data interpretation that Lower Palaeoezic lower crust, derived from accreted sedimentary material during Caledonian collision, extends under much of southern Ireland (Hauser et al., 2008; O'Reilly et al., 2010). Avalonian continental basement would appear to be confined to the far south east.

3. RADIOGENIC HEAT PRODUCTION RATES IN IRELAND

3.1 Methods

In excess of 2300 bulk density values from across Ireland have been collated from published data (Jackson, 1951; Morris, 1973; O'Brien, 1999). A mean density was calculated for each lithology (Table 1) and was used in the HPR calculation for each geochemically analysed sample.

Table 1: Measured density for some major rock types in Ireland and comparison with global values.

Rock type	*n*	Irish rocks: mean bulk density (kg/m^3)[1]	1 σ	Global rock bulk density[2]	Global rock density[3]
amphibolite	8	3049	124	2790-3140	2992
basic	93	2846	148	2789	2878
conglomerate	16	2564	184		
dolomite	7	2761	61		
gneiss (undifferentiated)	103	2720	143	2590-2840	
granite - diorite	101	2635	102	2694	2654-2810
granite gneiss	29	2637	52		2662
greywacke	27	2689	102	2670-2700	2615
limestone	610	2682	64	1550-2750	
marble	2	2636	20	2670-2750	2721
shale - mudstone - argillite	68	2670	74	2060-2670	
psammite	42	2675	115		
pyroclastic rocks	74	2685	132		
quartzite	70	2631	83	2647	2646
rhyolite - andesite	78	2792	74	2510-2650	2600
sandstone	224	2633	111	2200	2400
schist	20	2826	170	2730-3190	2830
shale - argillite	62	2667	74	2006-2670	
siltstone	18	2645	54		
slate	50	2684	97	2720-2840	2801
[1] Sources: Jackson, 1951; Morris, 1973; O'Brien, 1999					
[2] Johnson & Olhoeft, 1994					
[3] Christensen & Mooney, 1995					

More than 3300 geochemical analyses (dataset available from the author) have been compiled from peer-reviewed publication, PhD theses and new measurements for exposed bedrock across Ireland (Figure 2). The precision of the measurements for all legacy analyses included in this study has been verified by comparing the data for a given geological unit with measurements of the same by other workers or by comparison with new analyses. Analytical methods used are (in descending order or frequency): gamma-ray spectrometry (both laboratory- and field-based), x-ray fluorescence (XRF), inductively-coupled plasma mass spectrometry (ICP-MS), epithermal neutron activation (ENA), slow gamma counting (SGC) and flame photometry. The precision of measurements varies up to a maximum of ±10% 1σ, which is always less than natural heterogeneity of rock type. 459 new measurements have been made using portable gamma-ray spectrometry and XRF.

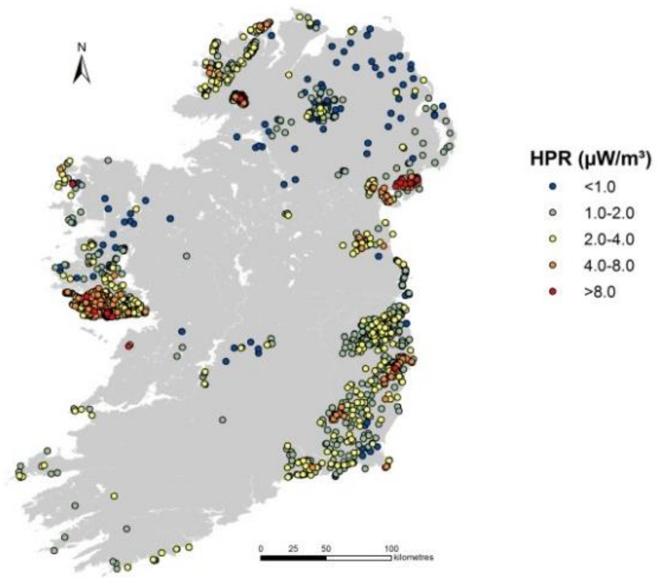

Figure 2: Heat production data.

Data collection has focused on lithologies that potentially yield a wide range of HPRs, as well as those geological formations likely to be present in volume at depth. For this reason, the geographical spread of surface geochemical data is uneven (Figure 2). Much of the midland area in particular shows relatively limited sampling, but here the Lower Carboniferous limestone that dominates has a uniformly low HPR and, owing to erosion, is rarely more than 1000 m thick.

A mean HPR was calculated for each geological formation or unit (as designated on the Geological Survey of Ireland's 1:100,000 bedrock geological map of Republic of Ireland and the Geological Survey of Northern Ireland's 1:250,000 bedrock geological map of Northern Ireland) for which geochemical data are available.

The geochemical dataset was then used to characterize broadly similar heat-producing regions. Helpfully, many of the major stratigraphic geological units (shown in Figure 1) are dominated by limited lithologies that exhibit such modest variation that extrapolation of HPR is likely to produce a representative value. Nevertheless, for those in which significant volumes of acid igneous rocks and shales are present there is benefit in further discrimination. Moreover, Ireland's geological history features not only the collision of two palaeocontinents, but the coalescence of island and microcontinental terranes at various periods. Some of these vary in composition, making separate consideration of their geochemistry worthwhile.

Employing broad stratigraphic age, 13 provinces were delineated. Six of these – Proterozoic Basement (unit no. 1), Precambrian Dalradian (2), Ordovician (4), Devonian (7), Upper Carboniferous (9) and Tertiary (13) – were further subdivided into units on the basis of lithology and/or tectonic setting. Caledonian intrusive rocks (6) were also subdivided owing to their heterogeneity. Using ArcGIS 10.0 software, an area-weighted mean HPR for each unit was calculated by multiplying the mean HPR value of each formation polygon by its area, and dividing the sum by the total area of the unit.

3.2 Results

3.2.1 Density

There are some notable differences between Irish rock density and global values, as summarised by Johnson and Olhoeft (1994) and Christensen and Mooney (1995) (Table 1). For limestone, sandstone, shale-mudstone-argillite and rhyolite-andesite categories, mean densities in the Irish dataset are at the top end of global averages or notably higher. The high density of these Irish volcano-sedimentary and sedimentary rocks is perhaps unsurprising given that many of them are pre-Devonian and have been subjected to burial, tectonic deformation and metamorphism. Porosity is therefore decreased, and density correspondingly increased. Upper Palaeozoic sedimentary rocks in Ireland also have low porosity presumably owing to the effect of the Variscan orogeny, e.g., the cemented sandstones of the Upper Carboniferous Clare Basin. For sandstone, a mean porosity of 2.3% is calculated in the whole dataset, with only five from 224 measurements of Upper Palaeozoic and older sandstones recording higher than 10%, four of those from a single small Carboniferous unit in the north (Jackson, 1951; Morris, 1973; O'Brien, 1999). The presence of heavy minerals may also have an effect. For example, the more recent Triassic Sherwood Sandstone records a mean density of 2663 kg/m^3 (n=3, Jackson, 1951) despite porosity of up to 25% (Cowan, 1993).

3.2.2 Heat Production Rate

Estimating HPR in rocks is problematic because it is dependent on concentrations of two trace elements and one major element in rock chemistry which not only are controlled by petrogenesis, but also are affected by secondary processes (e.g., Wollenberg & Smith, 1968; Zielinski et al., 1982). Nevertheless some general correlation between HPR and rock type is observed (Figure 3). For the most part, HPRs of Irish rock types are within error of global mean and demonstrate a positively asymmetric distribution. Heat production is, on average, highest in acid igneous rocks – particularly granitoids - and lowest in mafic rocks and carbonates. In common with global values, Irish granites exhibit a substantial range – 0.21-16.73 µW/m^3 from 1984 measurements – but have slightly elevated average HPR. The mudrock/shale rock type yields median and mean values which are significantly higher than global averages. Examination of the Irish dataset shows that values are skewed by the presence of a uraniferous black shale formation in the Clare Basin which has a mean HPR of 27.70 µW/m^3. Excluding these from the dataset produces a median HPR of 1.90 ± 1.70 µW/m^3. Sandstone also records anomalously high rates by comparison with global values. A possible explanation might be that most sandstone measurements derive from samples of Upper Devonian Old Red Sandstone and Lower Carboniferous marine sandstone in the south, much of which has an association with volcanism. In the South Munster Basin, for example, interbedded tuffs record values in excess of 9 µW/m^3.

Summaries of the designated main units are presented in Table 2, along with average HPR where available. Figure 4 depicts this information graphically. The chief purpose of this main unit characterisation is to enable downward extrapolation of the distribution of radiogenic heat production at a regional scale. However, Caledonian intrusive rocks (6) have an area-weighted mean HPR of 2.12 µW/m^3 but, as seen in Figure 5, the variation in heat production values within plutonic complexes can be almost as great as the variation between them. Given the scale of disparity and possibility of high HPR, consideration of a granite's potential as a geothermal resource requires examination of its HPR distribution at a higher resolution than that afforded by the main unit designation. Similarly, the Clare Shale Fm in the Upper Carboniferous Clare Basin (Figure 6) shows a narrow, ribbon-like outcrop at the surface and has a mean HPR of 27.7 µW/m^3, a feature which is largely lost when the whole basin, as a single unit (9c), is ascribed an area-weighted mean.

4. HEAT PRODUCTION RATES IN THE IRISH CRUST

Whilst large swathes of 'cold' carbonate and basaltic rocks are evident in Ireland's surface geology, these are but a thin layer, for the most part less than 1000 m, upon older and mostly higher heat-producing rock. Ireland has at its surface an abundant range of rocks extending back to the Precambrian; these Proterozoic continental basement rocks are likely to be present in large volumes at depth aside from the ISZ. Calculated values of heat production where they outcrop at the surface are valid proxies for HPR certainly at shallow crustal levels. The vertical distribution of heat production can be mapped by downward extrapolation (Figure 4), taking into consideration the surface evidence of structural geology – such as faults and plunging structures – borehole data and geophysical data, and will include interpretation from magnetotelluric surveys undertaken within the IRETHERM project.

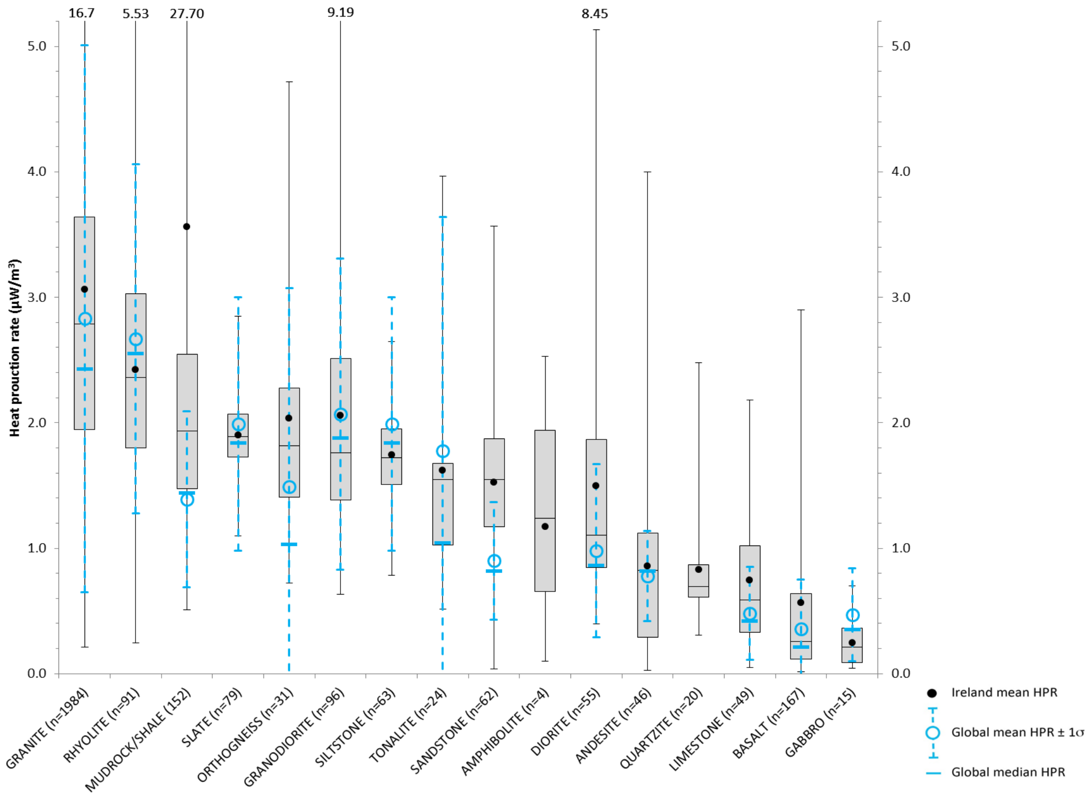

Figure 3: Heat production statistics for some major rock types in Ireland. The horizontal line of median HPR divides the box; lower box = 2nd quartile; upper box = 3rd quartile; whiskers extend to maximum and minimum HPR values. Global data (in blue) are from Vilà et al., 2010 (no data for amphibolite or quartzite).

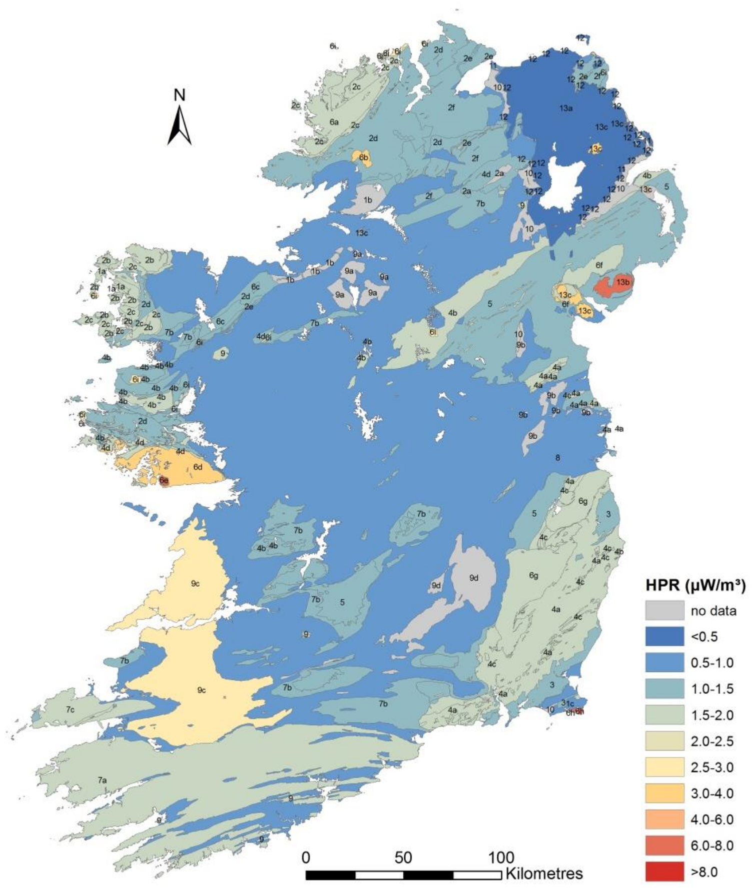

Figure 4: Heat production for each main unit, identified by number as listed in Table 2.

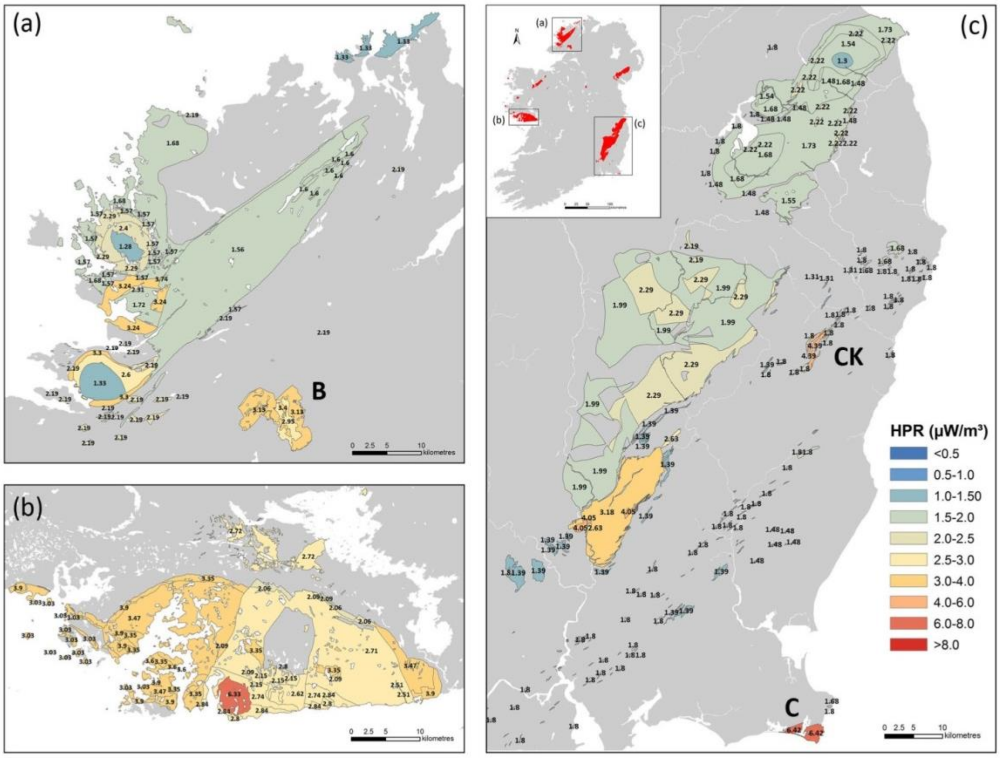

Figure 5: Varying heat production within and between major Caledonian granitoid intrusions; numbers give mean HPR for each granitic unit: (a) The Donegal Granites have an HPR range of 1.33-3.30 µW/m3 (mean: 1.59 µW/m3) compared with a mean of 3.11 µW/m3 for the contemporaneous Barnesmore pluton (B); (b) With a mean HPR of 6.33 µW/m3 the late Caledonian Costelloe Murvey intrusion (380.1 ± 5.5 Ma [Feely et al. 2003]) has a considerably elevated HPR by comparison with the older (c. 410-384 Ma [Feely et al., 2003; Selby et al., 2004]) Galway Granites into which it was intruded; (c) The late Caledonian Leinster batholith and the older, and hotter, Carnsore Granite (C). The Leinster batholith HPR range is 1.19 to 4.69 µW/m3. The Lower Palaeozoic Croghan Kinshelagh intrusion (CK) has moderately high HPR values (mean: 4.32 µW/m3); also shown are small Ordovician intrusions.

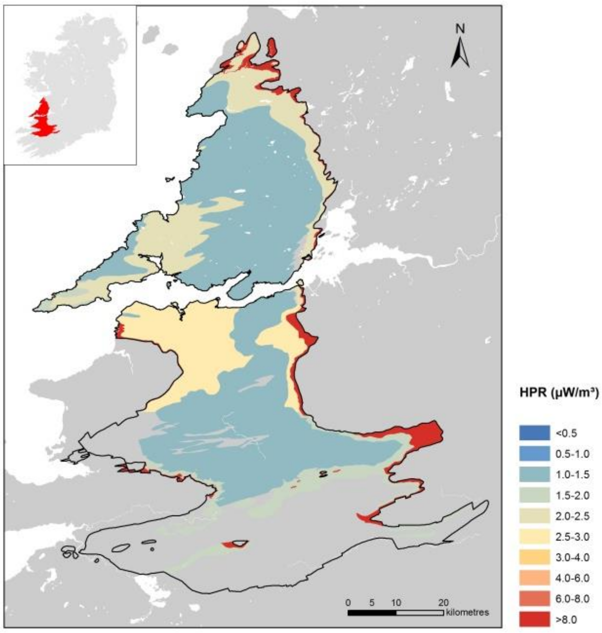

Figure 6: Mean surface heat production for formations in the Upper Carboniferous Clare Basin. The narrow surface expression of the Clare Shale Formation records the highest mean HPR of 27.70 µW/m^3.

Table 2: Summary geological history and HPRs of main units in Ireland.

Unit no.	Stratigraphic unit	Age (Ma)	Lithology	Tectonic setting	Metamorphic and structural history	*n*	Area-weighted mean HPR (μW/m³)
1	Proterozoic basement						
1a	Laurentian basement: Rhinns Complex, Annagh Gneiss Complex	1800-1000	Dominantly tonalitic, granitic and psammitic gneisses	Active continental margin, magmatism associated with compressional and extensional regimes	Grenvillian deformation (c. 1.2-1.0 Ga) and amphibolite-facies metamorphism. Regional crustal extension c. 590 Ma	54	1.64
1b	Laurentian basement: Slishwood Division, Lough Derg, Rosses Point inliers	c. 940	Migmatitic psammitic gneiss with minor tonalite, serpentinite, metabasite	Microcontinental indenter likely of Laurentian origin	Pre-Grampian (580-540 Ma) eclogite-facies metamorphism. Grampian (475-465 Ma) shearing and extension.		nd
1c	Avalonian basement: Rosslare Complex	c.1000-620	Amphibolites and paragneisses	Passive margin deposition of grains from mainly igneous source	Neoproterozoic deformation. Avalonian (c. 620 Ma) orogenic deformation and amphibolite-facies metamorphism. Monian (c. 485) deformation and retrograde metamorphism. Caledonian shearing.	20	0.96
2	Precambrian Dalradian Supergroup						
2a	Tyrone Central Inlier	c. 920-550	Psammitic and pelitic paragneiss	Microcontinental indenter likely of Laurentian origin	Grampian (475-465 Ma) deformation and amphibolite-facies metamorphism.		nd
2b	Grampian, Appin, Argyll and Southern Highland Groups	c. 920-550	Fine- and coarse-grained siliciclastics with minor carbonate, tillite and volcanics	Ensialic rift basin on Laurentian continental margin	Grampian (475-465 Ma) multiple deformation episodes and greenschist- to amphibolite-facies, and blueschist facies metamorphism.	94	1.43
3	Cambrian sedimentary rocks	542-488	Dominantly slates, interbedded greywacke sandstones and siltstones, quartzite	Turbidite sequences in a subsiding basin	Low-grade metamorphism and deformation during the Acadian orogeny (c. 405 Ma)	70	1.38
4	Ordovician extrusive and sedimentary sequences, and intrusive rocks						
4a	South of the Iapetus Suture Zone (ISZ): Leinster basin, East Central inliers and Rosslare block	480-440	Interbedded siltstones, sandstones and mudrocks, basalt-rhyolite volcanics, limestone	Oceanic basin with marginal arcs, extensional volcanism and accreting exotic terranes as Iapetus Ocean closed	Low-grade metamorphism and deformation during the Acadian orogeny (c. 405 Ma)	304	1.90
4b	North of the ISZ: South Connemara, Clew Bay Complex, South Mayo, Charlestown, Tyrone,	475-460	Basaltic to rhyolitic tuffs interbedded with siliciclastics and marine sediments	Oceanic arc, marginal basin complex	Low-grade metamorphism and extensive folding and deformation during the Acadian orogeny (c. 405 Ma)	228	1.16
4c	South of the ISZ: intrusive rocks	480-440	Diorite, andesite, granite	Oceanic basin with marginal arcs, extensional volcanism and accreting exotic terranes as Iapetus Ocean closed		58	1.94
4d	North of the ISZ: intrusive rocks	475-460	Diorite, andesite, granite	Oceanic arc, marginal basin complex		77	1.60
5	Silurian sedimentary rocks	440-420	Sandstones, siltstones, mudrocks, conglomerate, minor tuffs and breccias, silty and black shales	Marine basin	Low-grade metamorphism and extensive folding and deformation during the Acadian orogeny (c. 405 Ma)	113	1.47
6	Caledonian intrusive rocks	435-380	Dominantly granitoid	Active continental margin	Acadian (c. 405 Ma) deformation		
6a	Donegal batholith	c. 420-386				272	1.59
6b	Barnesmore Pluton	c. 397				257	3.11
6c	Ox Mountains	c. 412				11	1.50
6d	Galway Granites	c. 410-384				768	3.30
6e	Costelloe Murvey Granite	c. 381				52	6.33
6f	Newry Granite	403-387				11	1.81
6g	Leinster batholith	c.405				255	1.82
6h	Carnsore Granite	c.434				17	6.42
6i	Minor Caledonian intrusives	435-380				49	2.95
7	Devonian sedimentary rocks						
7a	Munster Basin	425-350	Fluvial facies sandstones, thin tuff horizons with marine sands and shales in the south	Strike-slip followed by extensional basin in a transgressional regime	Substantial Variscan deformation and low-grade metamorphism	40	1.68
7b	Late Caledonian basins north of ISZ: Cushendall, Ballymastocker, Fintona, Curlew Mountains	425-350	Alluvial fan derived conglomerates and sandstones with interbedded volcanic debris	Strike-slip induced transtensional basins		48	1.47
7c	Dingle Basin within ISZ	425-350	Fluvial conglomerate and sandstone dominated	Transtenstional basinal setting	Low-grade burial metamorphism	11	1.93
8	Lower Carboniferous sedimentary rocks	354-327	Shallow shelf deposits, ramp carbonates and marine shales.	Marine transgression		57	0.83
9	Upper Carboniferous sedimentary rocks	327-290	Sand-dominated turbidite successions and black shales	Deep, restricted basins transitioning to delta systems		2	1.94
9a	NW Basin	327-290					nd
9b	Dublin Basin	327-320					nd
9c	Clare Basin	325-318				12	2.85
9d	Leinster and Slieve Ardagh coalfields	324-318					n.d.
10	Permo-Triassic basinal rocks	299-200	Sandstones (c. 40%), volcanics (c. 15%), evaporites (c. 15%) and marine mudstones (c. 30%)	Extensional basins formed by reactivated strike-slip faults			nd
11	Jurassic sedimentary rocks	200-145	Marine mudrock dominated	Subsidence basins		1	0.97
12	Cretaceous sedimentary rocks	145-65	Lower succession: sandstones, siltstones and marls; upper succession dominated by chalk	Deep offshore basins		2	0.34
13	Tertiary igneous rocks						
13a	Antrim Lavas	62-58	Tholeiitic basalt, basaltic andesite and rhyolite	Extensional volcanism		30	0.17
13b	Mourne Mountains	56-50	Metaluminous-peraluminous granite intrusions	Extensional setting		57	6.83
13c	Carlingford Complex, Slieve Gullion and Tardree	c. 61	Gabbro with subsidiary granophyre, felsite and rhyolite	Extensional setting		61	3.16

Area-weighted mean: Calculated from the means of the different polygons that constitute a unit in the map in Figure 4, weighted according to areal extent.
See Figure 4 for unit locations.

Constructing a series of fence diagrams enables horizontal surfaces at various depths to be extrapolated. At 7 km depth (Figure 7) the range of HPR is predominantly 1.5-2.0 μW/m^3, with Dalradian (1.43 ± 1.42 μW/m^3) and Cambrian (1.38 ± 1.58 μW/m^3) groups having only a moderate influence. Laurentian basement (1.64 ± 1.27 μW/m^3) predominates in the NW, with cooler Avalonian continental basement (0.96 ± 0.76 μW/m^3) having a minor effect in the SE. Seismic and xenolith data (Klemperer et al., 1991; Hauser et al., 2008; Van den Berg et al., 2005) suggest that the lower crust to the south and east of the ISZ comprises Lower Palaeozoic arc-related rocks which, therefore, must also be present at shallower levels. This unit exposed at the surface has a mean HPR of ~1.9 μW/m^3. Overall, Ireland displays average HPR similar to the global mean for the upper continental crust of 1.65 μW/m^3 (Rudnick and Gao, 2003).

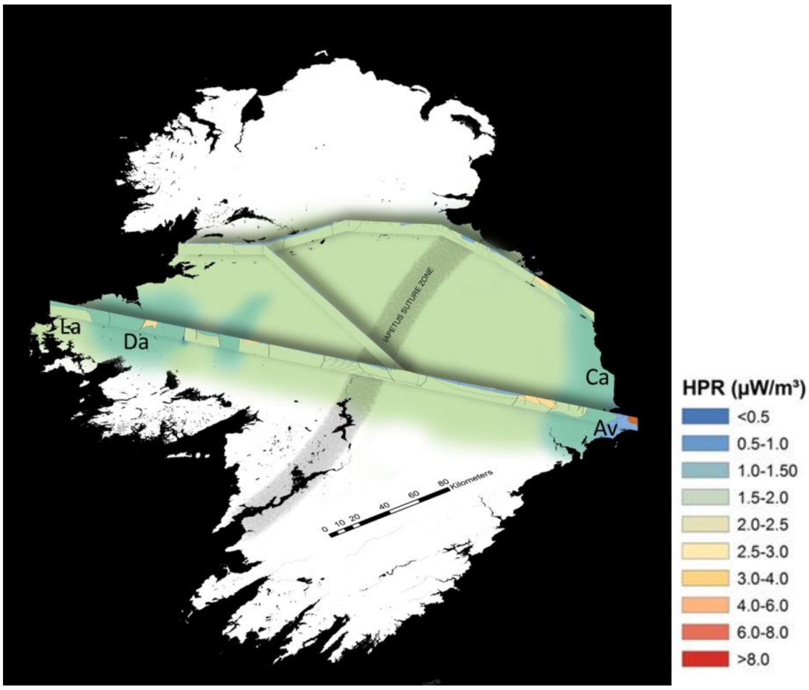

Figure 7: Area-weighted mean HPR cross-sections 0-7 km (x2 vertical exaggeration), with horizontal extrapolation across central Ireland at 7 km depth. [La] Laurentia, [Da] Dalradian, [Ca] Cambrian, [Av] Avalonia.

5. DISCUSSION

Interrogating the geochemical dataset gives insight into the distribution of heat production in the Irish crust as well as shedding light upon potential geothermal energy targets.

5.1 Basement Rocks and the ISZ

A variation exists between the mean HPR of Proterozoic rocks from north and south of the ISZ: 1.64 and 0.96 μW/m^3 respectively. Laurentian basement in the north is represented by measurements from various orthogneisses (c. 1.75-1.18 Ga) and one younger granite (1015 ± 4 Ma) that comprise the Annagh Gneiss Complex (AGC) (Daly, 1996, 2009). Exposed Avalonian basement in the south – the Rosslare Complex – is comprised chiefly of metasediments and amphibolites (Max et al., 1990). Such a disparity in HPR, a result of radioelement concentration in the protolith, is likely to have an effect upon the crustal thermal regime, although the Avalonian basement appears not to extend very far northwestwards beyond its limited outcrop in SE Ireland (Figure 1).

Where lower Palaeozoic sediments are interpreted to be present down to lower crustal levels, heat production for the crust has been determined using HPRs calculated from exposed Ordovician units (Table 2) as analogues. Within the Ordovician units too there is a distinction in HPR either side of the ISZ, where the south records higher rates than the north, both in sedimentary and volcanic successions (4a, 4b), and in intrusive rocks (4c, 4d). The acid volcanics in particular demonstrate marked variation, with mean values of 3.8 μW/m^3 in the south and 1.3 μW/m^3 in the north.

At the time of volcanism the Ordovician volcanic centres would have been geographically quite separate. Deposits of the South Mayo Trough and Tyrone Igneous Complex in the north have geochemistry suggestive of island arc volcanics (Draut and Clift, 2001). Those south of the Iapetus were produced in a back-arc basin setting with the possible addition of exotic terranes (Max et al., 1990). Thus, a larger contribution of continental upper crust in this setting likely contributes to the greater concentrations of heat-producing radioelements in the volcanics south of the ISZ (Rudnick and Gao, 2003).

5.2 Granitoid Rocks

Granitoid intrusions traditionally form a focus for geothermal heat exploration, as granite is a major host for heat-producing elements, usually within late-crystallising accessory minerals such as monazite, allanite and zircon. In Ireland the range of HPR for granites is wide. Establishing the reasons for variation in radioelement concentrations might be desirable for intrusions where trace element analyses are scant or unreliable, and other characteristics, such as age or tectonic setting, are known or implied, but finding simple relationships has proved difficult thus far (for further discussion see Fritschle et al., this volume).

For example, among all Irish granites, the Cenozoic Mourne Mountains have the highest mean HPR of 6.83 μW/m^3, with the most radiogenic G4 unit recording a mean of 7.64 μW/m^3. These granites were intruded in a continental extensional setting as part of the widespread magmatism that accompanied the opening of the Atlantic (Macintyre et al., 1984). However, contemporaneous igneous intrusive rocks in Great Britain – e.g., Lundy, Arran and Skye – are not high heat producing. Mourne granites also show a positive correlation between HPR and SiO_2 which is not evident in other Cenozoic granites in Britain.

Heat production and age appear to show a weak negative correlation, but only between those granites which have high HPR (Figure 8). Given that the majority of granites show no such correlation, age appears a subordinate influence to composition and/or alteration.

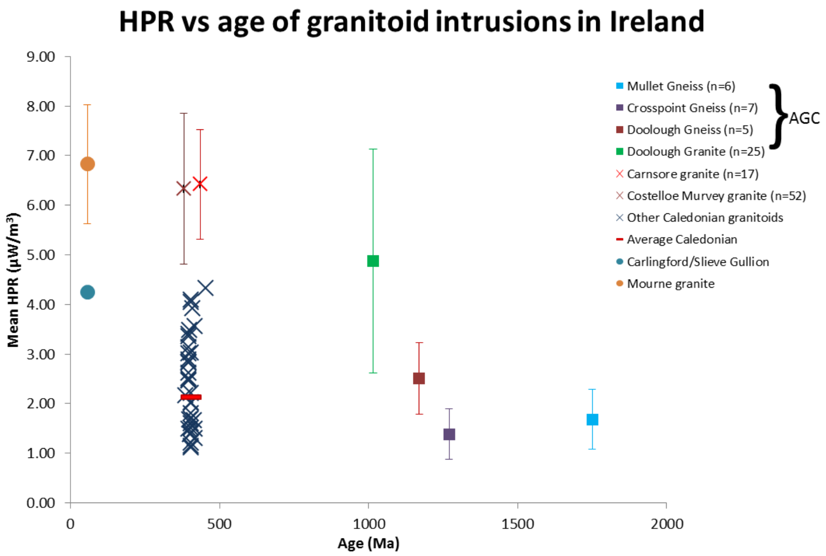

Figure 8: Plot of HPR vs age of igneous rocks in Ireland (error bars depict natural variation and are 1σ). A weak correlation is observed for the hottest granites.

5.3 Shale in the Clare Basin

The uraniferous black shales and phosphorites within the Clare Shale Formation give it the highest mean HPR for any formation of 27.7 μW/m^3. It has only a narrow surface representation in the region of the Clare Basin (Figure 6), and records a thickness of only a few metres. Nevertheless, borehole data supported by magnetotelluric surveying indicate that the shale layer is substantially thicker at depth (270 m is recorded in the Doonbeg borehole). Thus as a proportion of the basin, the formation's volume is significantly greater than that of its surface area – c. 20% vs <4% of the basin extent – and, as such, may prove a valid geothermal resource. This highlights the importance of calculating the volumetric extent of high heat-producing formations.

6. CONCLUSION

A dataset of heat production rates for Ireland's surface bedrock has been compiled using new and legacy geochemical and rock density data to calculate radiogenic heat production.

Heat production rates in Ireland correspond generally to rock type and, for the most part, are similar to global values. Of interest to geothermal exploration, some high heat-producing granites record HPR values well in excess of the global means of 2.83 μW/m^3. Highest are the granites of the Cenozoic Mourne Mountains with a mean HPR of 6.83 μW/m^3, closely followed by the early Caledonian Carnsore Granite (6.42 μW/m^3) and the late Caledonian Costelloe Murvey Granite (6.33 μW/m^3). Whilst a weak correlation with age is observed in high-heat producing granites, no other petrogenetic feature has yet been identified that is common to all. The extensive and unpredictable natural variation in radioelement concentrations, particularly within igneous rocks, therefore indicates that examination of HPR at high resolution is necessary in order to identify local geothermal targets with confidence.

The uraniferous black shales of the Clare Shale Formation feature an exceptionally high mean HPR of 27.7 μW/m^3. The volume of the shale formation within the Clare Basin is more substantial than its surface expression suggests. Even so, its volumetric extent is less than those of voluminous radiogenic granite intrusions that more commonly form targets for geothermal exploration. How far a remarkably high HPR may offset volumetric considerations is unclear, but shales could be considered worthy of further investigation as geothermal prospects.

A map of the HPR for surface bedrock in Ireland has been produced, first by defining provinces of broadly similar rock composition and age, and extrapolating the sample data points. These main units then form the basis for extrapolation downwards into the crust, in order to determine the best prospects for deep-drilled low-enthalpy geothermal energy.

For the most part, basement rocks produce more heat than the carbonate (0.74 ± 0.7 μW/m^3) and basalt (0.57 ± 0.85 μW/m^3) lithologies that overlie them. There is a clear north/south divide, separated by the ISZ, where Laurentian and Avalonian continental basement rocks record contrasting heat production values of 1.64 and 0.94 μW/m^3 respectively. Lower Palaeozoic volcanic-sedimentary and intrusive rocks that underpin much of the south and the midlands, also show a similar divergence in heat production values to their age equivalents north of the ISZ. This variation is likely to be the result of different tectonic settings – Avalonian back-arc basin vs island arc volcanics off Laurentia – that existed on either side of the Iapetus Ocean. On a regional scale HPR at shallow crustal levels beneath Ireland is in line with global averages, though compilation of the 3D map is ongoing.

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