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# Geothermal Potential of Caledonian Granites Astride the Iapetus Suture Zone in Ireland and the Isle of Man - Implications for EGS Prospectivity

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## ABSTRACT

Ordovician to Devonian (Caledonian) granites are common in the Iapetus Suture Zone in Ireland and Britain. Some of these are situated beneath Upper Palaeozoic sedimentary basins at various tectonic levels. The buried Kentstown and Glenamaddy granites in Ireland are targets for Enhanced Geothermal System (EGS) / Hot Dry Rock (HDR) exploration. Several other subsurface granites likely exist based on geophysical and petrological considerations. In order to test regional geothermal potential, drill-core samples of the buried granites and samples from equivalent exposed intrusions are being investigated geochemically.

The whole-rock geochemistry of the granites varies significantly, but with no obvious geographical control. Average heat production rates range from 1.4 µW/m³ for the Leinster Granite to 4.9 µW/m³ for the Drogheda Granite.

The heat-producing elements uranium (U), thorium (Th) and potassium (K) and calculated heat production rates generally correlate with the abundances of niobium and rubidium. Given the enrichment of these two trace elements in the upper continental crust, contributions of the latter to granite genesis may increase the abundance of the heat-producing elements in a granite.

In spite of a positive correlation of each of the heat-producing elements with heat production it is demonstrated that elevated heat production rates in a pluton can be related to enrichment in one of the heat-producing elements alone, e.g., uranium-enrichment in the Foxdale Granite or thorium-enrichment in the Drogheda Granite. This is mirrored in the Th/U ratio. Furthermore, the Th/U ratio correlates with heat production, exhibiting a trend towards a high heat production rate with a low Th/U ratio.

In this paper, hydrothermal alteration is suggested to cause this correlation between the Th/U ratio and the heat production rate. Hydrothermal alteration is further suggested to be a major mechanism for redistributing mobile elements such as uranium, and therefore as a mechanism controlling the granite's heat production. In view of that, the distribution of the heat-producing elements in whole-rock samples, and calcite and quartz veinlets are being investigated.

## 1. INTRODUCTION

Until recently, Ireland's potential for deep geothermal resources has received little attention (IERC, 2008). The Royal Irish Academy, however, found that: "Research is required to establish the distribution of heat-producing elements in Ireland's crustal rocks and to pinpoint the most likely sources of hot dry rocks and aquifers to depths of 5 km" (RIA, 2008, p.1). The IRETHERM Project is addressing these challenges (IRETHERM, 2011) and aims to identify possible geothermal targets for further research.

The subsurface Kentstown and Glenamaddy granites in Ireland belong to a number of granitic intrusions that were generated during the Caledonian Orogeny (Fritschle, et al., 2014) as a result of Iapetus Ocean closure and the subsequent collision between Laurentia and Avalonia (Soper and Hutton, 1984, Soper, et al., 1992, Van Staal, et al., 1998).

These two small-scale plutons, overlain by several hundred metres of sedimentary rocks, are being investigated to evaluate their geothermal potential. Their heat production is evaluated in terms of their petrographic and geochemical characteristics, and is compared to more readily accessible exposures of similar granitic intrusions. The aim is to understand the underlying controls on heat production rates and the processes that affect the distribution of the heat-producing radioactive elements, U, Th and K.

## 2. GEOLOGICAL SETTING

The Kentstown Granite is situated in the east of Ireland at the edge of the Dublin Basin. It was predicted from gravity measurements (Murphy, 1952, Readman, et al., 1997) before it was drilled in 1997/98 by a mineral exploration company. Two boreholes in the north-west of the centre of the gravity anomaly (Fig. 1) intersected the unconformable contacts between the overlying Lower Carboniferous limestones and the granite at depths of 492 m and 662 m (O'Reilly, et al., 1997). Each of the resulting drill cores comprises 15 m of granite. A third drilling attempt by the Geological Survey of Ireland in 2013 targeted the granite to the east of the previous boreholes, but had to be abandoned at a depth of c. 300 m due to unfavourable drilling conditions in Carboniferous (Namurian) shales.

The regional Carboniferous strata on top of the Kentstown Granite have been the subject of several publications (e.g., Pickard, et al., 1992, Strogen, et al., 1990), and consist generally of marine shales and carbonates with subordinate sand- and mudstones. The structural setting in the Kentstown area is dominated by two north-north-west trending normal faults which mark the boundary of a narrow elongate horst, together with a series of east-north-east trending orthogonal cross-faults which cuts the latter (Pickard, et al., 1992). The same authors also infer that these faults were active during the Lower Carboniferous (Dinantian), and reverse faults in the same area resulted from later Variscan movements.

The buried Glenamaddy Granite and associated rhyolite (Fritschle, et al., 2014) is located on a negative gravity anomaly (Fig. 1) (Murphy, 1952, Readman, et al., 1997) and was intersected at a depth of 154 m in a mineral exploration borehole. The investigated samples comprise both granite and rhyolite from c. 150 m drilled core. The structural setting in the area is determined by two major terrane boundary faults and persistent sinistral strike-slip movement during Late Caledonian times (Klemperer, et al., 1991).

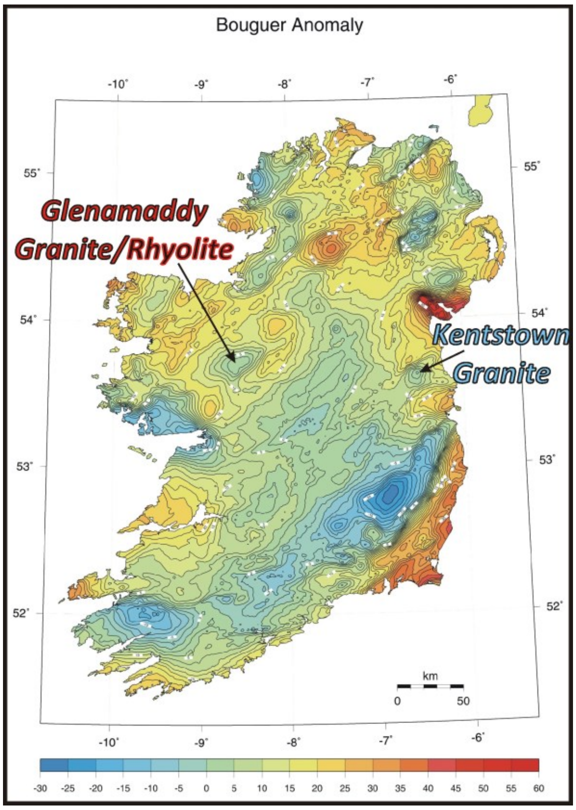


**Figure 1: Gravity anomaly map of Ireland (Readman, et al., 1997), illustrating the positions of the buried Kentstown and Glenamaddy granites as indicated by elliptical gravity lows.**

## 3. METHODS

All samples used for whole-rock geochemical analyses were crushed using a tungsten carbide TEMA mill at University College Dublin, Ireland. Consequently, analyses for tungsten and cobalt are not considered due to possible contamination. Whole-rock major and trace element concentrations from 71 samples were analysed by X-ray fluorescence spectrometry on fused glass discs and pressed powder pellets, respectively, using a Philips MagiX Pro X-ray fluorescence spectrometer at the Johannes Gutenberg-University of Mainz, Germany.

Element maps on thick sections (200 µm) for several of the granites were produced using a JEOL JXA 8900RL electron probe micro analyser (EPMA) at the Johannes Gutenberg-University of Mainz, Germany. Operating conditions were 20 kV accelerating voltage, 30 nA beam current, 1 µm beam diameter and 320 ms acquisition time.

## 4. PETROGRAPHY AND RESULTS FROM WHOLE-ROCK GEOCHEMISTRY

Both the Kentstown and Glenamaddy granites present a fine to medium-grained phaneritic inequigranular texture with no preferred mineral alignment. Quartz is the predominant mineral phase in both of the rocks. Abundant plagioclase is regularly zoned and/or twinned, and K-feldspar often shows perthitic exsolution. Biotite is the only major mafic phase. Primary muscovite occurs in the Kentstown Granite, which we classify as S-type granite after Chappell and White (1974), in contrast to the I-type Glenamaddy Granite.

Alteration is ubiquitous in both granites. Feldspars are generally sericitised and micas are commonly altered to sericite, illite or kaolinite. In addition, the Kentstown Granite frequently shows muscovite and chlorite grains surrounding altered biotite. Accessory minerals in both granites comprise zircon, apatite, monazite, rutile, haematite and pyrite. Additionally, chalcopyrite occurs in the Glenamaddy Granite and glomerophyric biotite clusters are common. Quartz and calcite veins are abundant in both granites. A fluid inclusion study of the Kentstown Granite revealed the contribution of several magmatic and meteoric fluids during magmatism and retrograde alteration (O'Reilly, et al., 1997).

The Kentstown Granite is slightly more leucocratic than the Glenamaddy Granite and has higher $SiO_2$ (72 vs 68 $_{wt}$%) and $K_2O$ contents (4.5 vs 3 $_{wt}$%). Concentrations of MgO, $TiO_2$, $FeO_t$ and CaO are higher in the Glenamaddy Granite. The Aluminium Saturation Index [ASI = molar Al/(Ca+K+Na)] for the Kentstown Granite is generally around 1.2, whereas the Glenamaddy Granite is only slightly peraluminous, with ASI < 1.1. Both granites exhibit molar Al/(Na+K) between 1.3 and 1.9, and Mg# [molar Mg/(Mg+Fe)] of c. 45.

Both LILE (large-ion lithophile elements) – with the exception of Rb – and HFSE (high field strength elements) are significantly higher in the Glenamaddy Granite, whereas several transitional metals show higher concentrations in the Kentstown Granite. The heat-producing element uranium exhibits similar concentrations between 4 to 10 ppm in both granites, whereas thorium is about twice as high in the Glenamaddy Granite, with concentrations of 10 to 15 ppm. The quantity of uranium in the Glenamaddy Rhyolite is even higher, up to 17 ppm. In addition, further major and trace elements such as $Na_2O$, Rb, Nb and Y are more abundant in the rhyolite compared to both granites, whereas concentrations of $Al_2O_3$, $TiO_2$, $FeO_t$, MgO, CaO, Ba, Sr, Ni and Cr are lower.

## 5. COMPARISON WITH EXPOSED ANALOGUES

By their nature, samples from the subsurface Kentstown and Glenamaddy granites are limited, and therefore it is necessary to make use of exposed analogues for comparison. Hence, other granites astride the Iapetus Suture Zone were investigated. These include the Crossdoney, Drogheda, Rockabill, Leinster (North Pluton) and Ballynamuddagh granites in Ireland and the Foxdale and Dhoon granites in the Isle of Man (Fig. 2). In addition, comparison is made with the Weardale Granite (Manning, et al., 2007), an EGS prospect in northern England and with the Soultz-sous-Forêts Granite (e.g., Alexandrov, et al., 2001, Genter, et al., 1997), site of the European EGS pilot project.

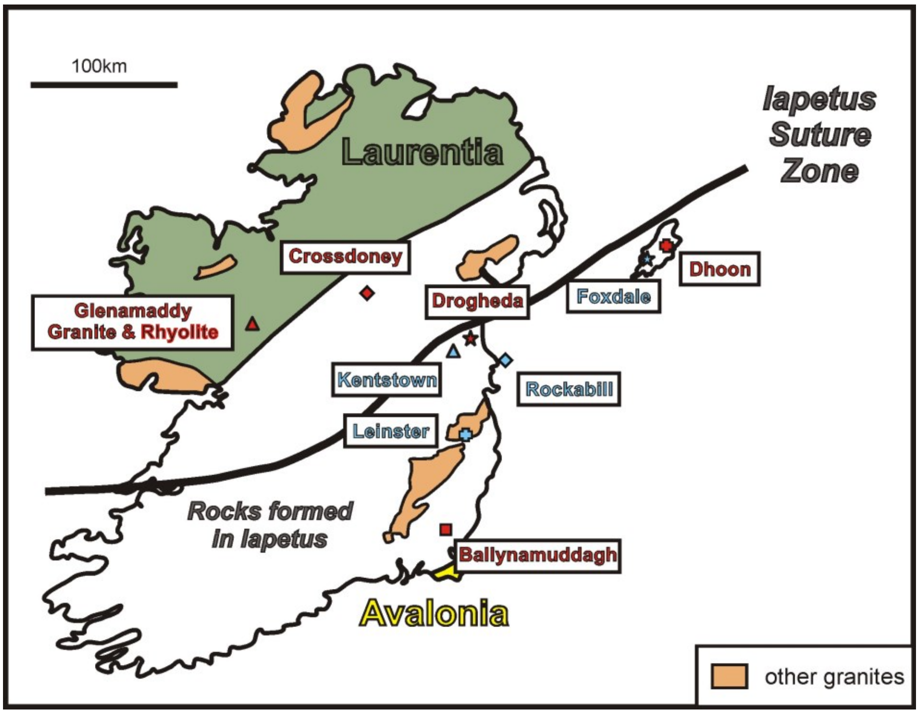


**Figure 2: Map of Ireland and the Isle of Man showing the presumed extent of basement units (adapted from the Geological Survey of Ireland), the locations of sampled granites (including symbols and colour-coding used throughout the paper), the progression of the Iapetus Suture Zone (adapted from Todd, et al. (1991)) and the main Caledonian granite intrusions (Chew and Stillman, 2009). I-type granites are coloured in red; S-type granites are coloured in blue.**

The Irish and Isle of Man granites show a variety of compositions, and include both I-type and S-type granites. These range geochemically from metaluminous to peraluminous (ASI = 0.7 to 1.4), with all samples exhibiting molar Al/(Na+K) between 1.1 and 1.9. Their silica content ranges between 60 and 74 $_{wt}$% $SiO_2$, $K_2O$ concentrations are up to 9 $_{wt}$%, and Mg# varies up to 61. Trace elements also show marked differences with the heat-producing elements uranium and thorium ranging from 1 to 17 ppm and 0 to 43 ppm, respectively. In general, I-type granites exhibit a lower ASI and higher Mg# than S-types, are enriched in major elements except for $SiO_2$, $Al_2O_3$, $Na_2O$, $K_2O$ and $P_2O_5$, and show elevated trace element concentrations except for the transitional metals and HFSE.

## 6. HEAT PRODUCTION RATES

A reliable dataset of the granites' heat production rates (HPR, in µW/m³) is crucial to assessment of their role as a potential geothermal target. These are calculated from concentrations of U and Th in µg/g (ppm), and K in $_{wt}$%, combined with rock density (ρ, in g/cm³) using the equation of Rybach (1988):

$$\text{HPR } [\mu W/m^3] = 10^{-5}\, \rho\, (9.52\, [U] + 2.56\, [Th] + 3.48\, [K]).$$

The average heat production rates for the analysed granites range from 1.4 µW/m³ for the Leinster Granite to 4.9 µW/m³ for the Drogheda Granite (Fig. 3), assuming a rock density of 2.65 g/cm³. However, the heat production rates even within one intrusion are often strongly variable as is the spatial distribution of the heat-producing elements. For example, while the heat production rates in the Soultz Granite generally vary between 1.5 and 7.5 µW/m³, decreasing with depth (Grecksch, et al., 2003), the Weardale Granite exhibits heat production values ranging from 2.4 to 4.8 µW/m³, but increasing with depth (Manning, et al., 2007).

The average heat production rates for the buried Kentstown and Glenamaddy granites are 2.3 µW/m³ and 3.3 µW/m³, respectively (Fig. 3), similar to the value for 'typical granite' (2.6 µW/m³, Goldstein, et al., 2009). None of the boreholes from these granites reached their bases, so a magnetotelluric survey was conducted by IRETHERM over the Kentstown granite to constrain the depth of the electrical resistor associated with the granite. More extensive gravity data are also being used in conjunction with the results of the magnetotelluric inversions to further constrain the dimensions of the Kentstown granite (Farrell, et al., 2015, this issue).

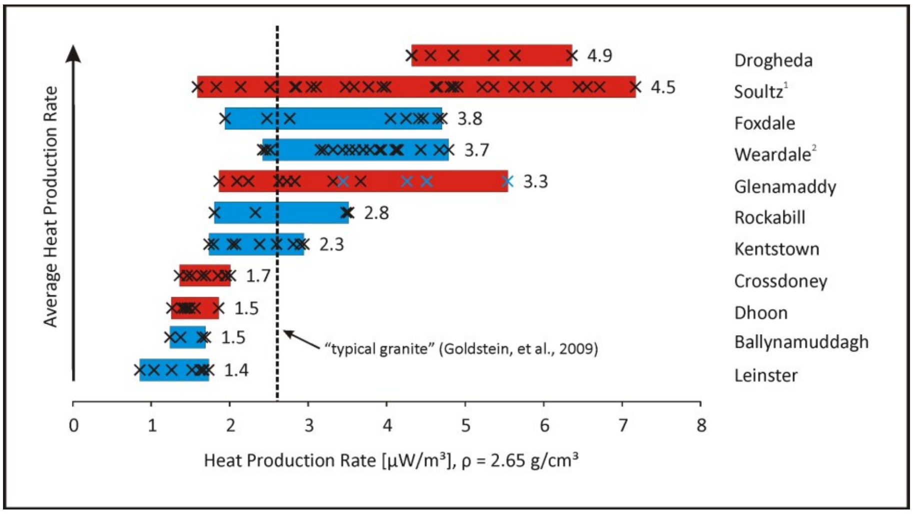


**Figure 3: Ranges (black crosses = individual sample datum) and mean (numeral) heat production rates for Irish and Isle of Man granites compared with the Soultz (Genter, et al., 1997; Alexandrov, et al., (2001); Stussi, et al. (2002); Grecksch, et al., (2003)) and Weardale granites (Manning, et al., 2007), all calculated using ρ = 2.65 g/cm³. I-type granites are coloured in red, S-type granites in blue. The dashed line indicates the heat production rate for a 'typical granite' (2.6 µW/m³, Goldstein, et al., 2009). Heat production rates for Glenamaddy include both the granite and rhyolite (blue crosses).**

## 7. DISCUSSION

Our geochemical data reveal some interesting correlations with heat production rates. For example, heat production rate correlates positively with both niobium and rubidium (Figs 4a, b). On the heat production rate versus rubidium plot (Fig. 4b), it additionally becomes obvious that none of the investigated S-type samples contains less than 130 ppm Rb, and that I-type granites (including the Glenamaddy Rhyolite) lie on a trend with a steeper slope, compared with the S-type granites.

Both niobium and rubidium are generally enriched in the upper continental crust compared to the mantle (Palme and O'Neill, 2003) and deeper continental crust (Rudnick and Gao, 2003). Naturally, a significant contribution of the upper continental crust to granite genesis is expected to enrich a granite in heat-producing elements. This is also indicated by a generally positive correlation between each of the heat-producing elements and both niobium and rubidium (Figs 4c, d), except for niobium versus uranium.

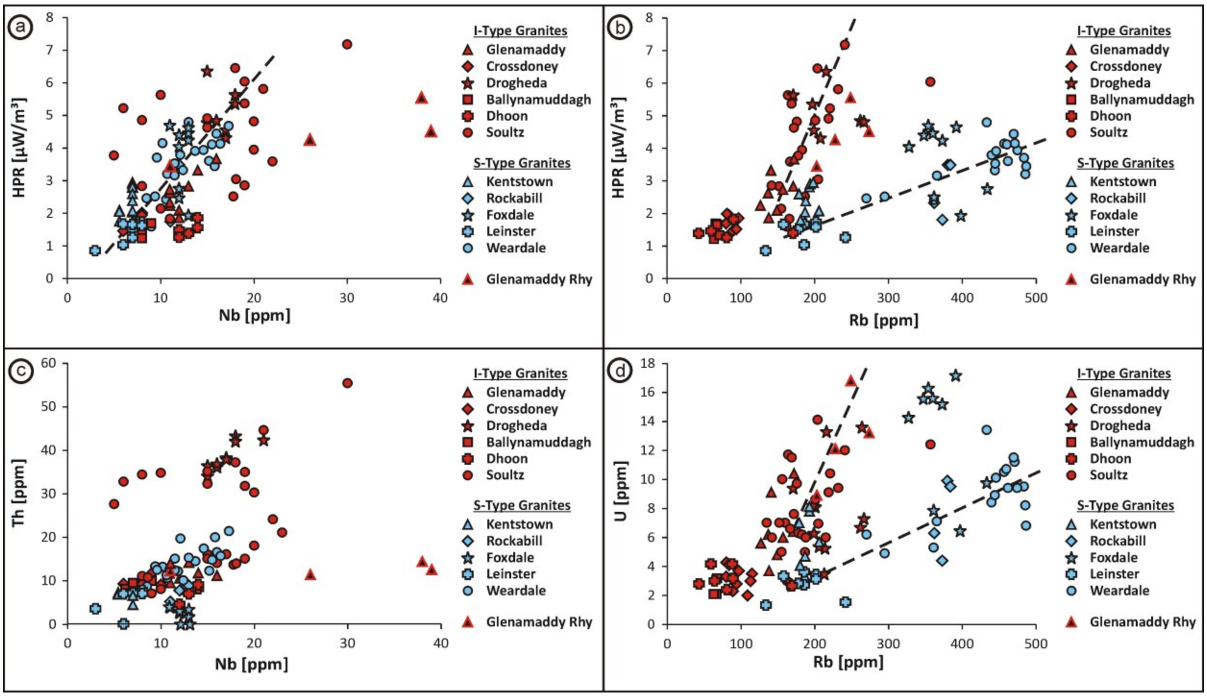


**Figure 4: Geochemical discrimination diagrams for the heat production rate (HPR) versus niobium and rubidium, respectively. Fig. 4a exhibits a positive correlation between the HPR and Nb (with some scatter in the data for the Soultz Granite) as indicated by a dashed line. Notably, the Glenamaddy Rhyolite (Glenamaddy Rhy) displays comparatively high concentrations for Nb. Fig 4b exhibits a general positive correlation of the HPR with Rb. Interestingly, analyses for the I-type granites mark a steeper trend, compared to S-type granites. Both apparent trends are indicated by dashed black lines. In addition, the group of analyses for the S-type granites shows elevated abundance in Rb greater than 130 ppm. Fig. 4c indicates a positive correlation between Th and Nb, and outlines the Th-enrichment in the Drogheda and Soultz granites. Fig. 4d shows the positive correlation between U and Rb, and emphasises the U-enrichment in the Foxdale Granite. Data sources for the Soultz and Weardale granites as in Fig. 3.**

Comparing the granites' heat production rates with each of the heat-producing elements, positive correlations are observed. However, it is also noticed that some of the granites showing the highest heat production rates, i.e., Drogheda and Foxdale granites, exhibit very different Th/U ratios (Fig. 5a) – up to 6.9 in the Drogheda Granite and less than 0.3 in Foxdale. This suggests different underlying causes for the elevated heat production rates in the two granites – the high heat production rate in the Drogheda Granite is due to enrichment in thorium, whereas the Foxdale Granite owes its elevated heat production rate to enrichment in uranium. In addition, there appears to be a general tendency for I-type granites to have a high Th/U ratio generally above 1.6, whereas the S-type granites are generally below 2.6, except for notably hydrothermally altered samples.

Some individual granites show sub-parallel power regression trends of decreasing heat production rates with increasing Th/U ratio (Fig 5a, b). These are exhibited by the vast majority of the granites, and particularly well for the Kentstown and Glenamaddy granites (Fig. 5b). We attribute this trend to the hydrothermal redistribution of uranium in the rock. This is in agreement with whole-rock analyses (Fritschle, et al., in prep) which exhibit generally higher Th/U ratios for more extensively altered rock samples.

In the Soultz Granite the Th/U ratio additionally correspond to sample depths (Grecksch, et al., 2003), in the sense that it increases towards the top of the intrusion. If this trend can be related to extensive hydrothermal alteration, this implies that the more mobile of the two elements, uranium, could have undergone significant redistribution in the intrusion, and hence could have been transported through a vein-network into the rocks overlying the pluton.

To test whether uranium mobility may be significant in the Irish granites, element maps of calcite and quartz veinlets have been produced. Fig. 6 displays elevated uranium concentrations in calcite and quartz veinlets compared to the host-rock for samples in the buried Glenamaddy Granite, suggesting that hydrothermal redistribution of uranium in a vein network may significantly influence the heat production budget of the rock.

Extensive hydrothermal alteration reflected by a vein network enriched in uranium, however, cannot generally be assumed to reflect a high heat production rate of a granite. The subsurface Kentstown Granite, for example, exhibits ubiquitous hydrothermal alteration and abundant calcite and quartz veinlets. Nevertheless, its heat production rate is modest, lower than that of a 'typical granite' (2.6 µW/m³) after Goldstein, et al. (2009). Similarly, the Weardale Granite is strongly hydrothermally altered at shallow levels of the intrusion (Manning, et al., 2007) and has correspondingly low heat

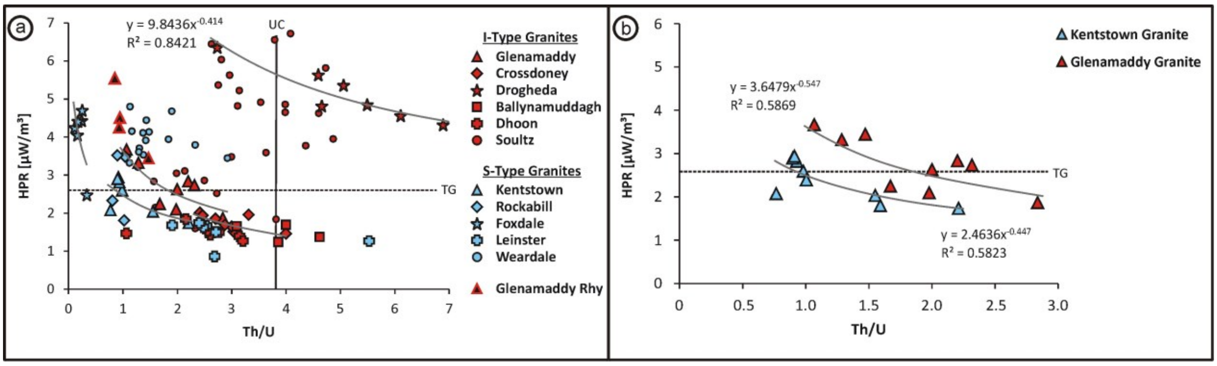


**Figure 5: Heat production rates versus Th/U ratio for Irish and Isle of Man granites compared with the Soultz (Genter, et al., 1997) and Weardale granites (Manning, et al., 2007). The grey curves illustrate power regression trends of decreasing heat production rates with increasing Th/U ratios (including equation and their values for R-squared). UC = average upper continental crust, Th/U = 3.8, from Rudnick and Gao (2003). TG = heat production value of 'typical granite' (2.6 µW/m³, Goldstein, et al., 2009). Fig. 5b shows the same plot for the buried Kentstown and Glenamaddy granites only.**

production rates, compared to deeper levels. This suggests removal rather than enrichment in uranium associated with hydrothermal alteration.

The increase in heat production rate with depth in the Weardale Granite contrasts with the pattern in the Soultz Granite (Grecksch, et al., 2003) and possibly in Glenamaddy. In addition to the possible removal of uranium from shallow depths due to alteration, Th concentrations increase (up to 21 ppm) downwards in the Weardale Granite (Manning, et al., 2007), possibly controlled by particular phases such as monazite. This is supported by positive correlations between thorium and phosphorous as well as between thorium and cerium.

Comparing the subsurface Kentstown and Glenamaddy granites to the other investigated granites, as well as to literature data, it seems that their potential for geothermal exploitation is not particularly favourable. Their calculated heat production rates appear moderate, although further analyses from deeper samples are required. The relatively thin cover of sedimentary rocks does not improve their attractiveness as geothermal targets. In addition, limestones on top of the Kentstown Granite contain orientated shell fragments in a matrix of micrite and clay-minerals. Hence, these rocks have been diagenetically compacted and their pore spaces have been cemented, which has lowered their porosity and presumably increased their thermal conductivity significantly. Indeed, preliminary measurements of the thermal conductivity of these cover rocks, as well as those above the Glenamaddy Granite, are in the same range as the thermal conductivities of the granites themselves (Waters et al. in prep), devaluing their role as thermal insulators.

## 8. CONCLUSIONS

Several granites in Ireland and the Isle of Man situated astride the Iapetus Suture Zone, show geochemical characteristics similar to the subsurface granites in Soultz-sous-Forêts and Weardale which are utilized for the generation of geothermal energy. However, the buried Kentstown and Glenamaddy granites only show average heat production rates and the physical properties of their sedimentary cover are unfavourable as a thermal insulator.

A generally positive correlation of niobium and rubidium with each of the heat-producing elements uranium, thorium and potassium, was observed for granites in the Iapetus Suture Zone (except for niobium versus uranium).

The correlation of the heat-producing elements with the heat production rate is unsurprising. However, an elevated heat production in a granite may be due to enrichment in one of the heat-producing elements alone. This precludes the Th/U ratio from being used as a diagnostic criterion for predicting a high or low heat production. Instead, it is interesting that the Th/U ratio may have the potential to discriminate I-type from S-type granites (and metaluminous from peraluminous granites, similarly).

Trends of increasing heat production rates with decreasing Th/U ratios were observed across the analyses of several granites. We suggest this trend is produced by hydrothermal redistribution of uranium and that the latter may be a major mechanism controlling the heat production in a granite. The abundance of mineral phases (such as monazite) that have the potential to control the distribution of any of the heat-producing elements is also considered to play an important role in determining the granite's heat production.

Wavelength-dispersive semi-quantitative X-ray element maps of calcite and quartz veinlets exhibit elevated concentrations of uranium compared to their host rock. In accordance with whole-rock analyses and implications from the Th/U ratio, we suggest this as evidence for significant redistribution of uranium through metasomatic processes.

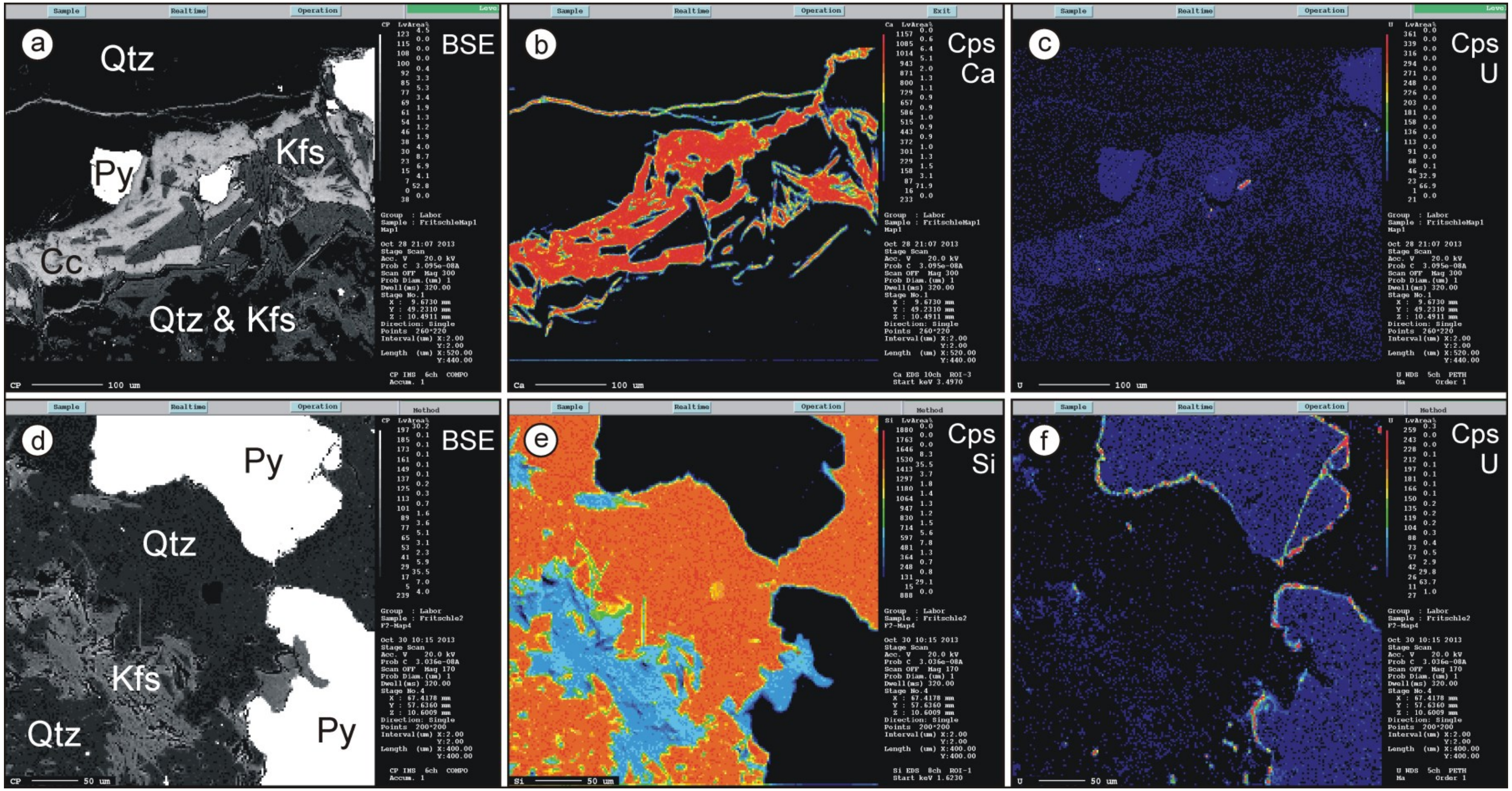


**Figure 6: Electron microprobe back-scattered electron (BSE) images (Qtz = quartz, Kfs = K-feldspar, Cc = calcite, Py = pyrite) and wavelength-dispersive semi-quantitative X-ray element maps (Ca, Si and U) for calcite (Figs 6 a-c) and quartz (Figs 6 d-f) veinlets in the Glenamaddy Granite. Fig. 6f shows U-enrichment around pyrite interpreted as the result of a redox reaction with a U-bearing fluid.**

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