

THERMOCAL - Empirical Thermophysical Data Acquisition Across the Caledonian Orogenic Belt

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ABSTRACT

The bilateral UK-Norway THERMOCAL (THERMOphysical properties of CAledonian rock materials to de-risk geothermal development) project aims to systematically acquire a substantial empirical thermogeological data set across the terranes of the Caledonian Orogen, and associated plutons and Precambrian basement, in Northern Ireland, Scotland and Norway. In all three nations, the main form of geothermal exploitation is currently via relatively shallow (<300 m) ground source heat pump (GSHP) installations, typically coupled to borehole heat exchangers (BHE), although all are actively engaged in consideration of deeper geothermal prospects. Three key rock thermophysical properties, which are employed in the design of GSHP and deep geothermal systems, are systematically measured in THERMOCAL: thermal conductivity, volumetric heat capacity and internal radiogenic heat production (RHP). The first two properties are determined in the laboratory, the last by airborne, downhole and hand-held field nuclide-specific gamma-ray spectrometry. The project is grounded in rigorous interlaboratory quality control, ring-testing and method harmonisation, together with consideration of orientation, state of weathering and state of saturation of samples. THERMOCAL aims to integrate newly acquired data with existing data sets in the UK and Norway. It considers variation within data sets for given lithologies to evaluate how variance and uncertainty can be communicated and incorporated into geothermal design. It also considers how the empirical data can be used to refine models of shallow GSHP, deep geothermal systems, and crustal heat transfer.

1 INTRODUCTION

The Caledonian Orogeny consisted of a series of tectonic events or orogenic phases associated with the closure of the Iapetus Ocean, and convergence and collision of Laurentia, Baltica and Avalonia (McKerrow et al., 2000). The Caledonian Orogen can be traced for several thousand kilometres from the Arctic region southward on both sides of the North Atlantic Ocean (Corfu et al., 2014). In northwestern Europe, rocks affected by the Caledonian Orogeny are present in locations such as Scotland, Northern Ireland, and Norway (Corfu et al., 2014). As well as sharing a continuous Caledonian 'terranes', these three nations also share ambitions to utilise geothermal energy as a means of decarbonising their respective heating and cooling sectors (Ramstad, 2011; Scottish Renewables, 2022; Department for the Economy, 2022). To design conductive geothermal systems, three key rock thermophysical properties are required to be known: thermal conductivity, volumetric heat capacity, and internal radiogenic heat production (RHP). To aid the development of geothermal energy in each of the aforementioned nations, the bilateral UK-Norway THERMOCAL project aims to carry out a systematic measurement programme of thermal conductivity, volumetric heat capacity and internal RHP in lithologies in the Caledonian terrane across Scotland, Northern Ireland and Norway. This paper presents an overview of the rationale and objectives of the THERMOCAL project, beginning with a summary of the geology and geothermal potential of each THERMOCAL nation, followed by a synthesis of the history of thermal property measurements in each nation and existing data sets which will be utilised and built upon. Proposed data collection, laboratory measurement and analysis, and modelling to be undertaken within the project are then discussed.

2 GEOLOGY AND GEOTHERMAL POTENTIAL OF THERMOCAL NATIONS

To provide context to the planned activities of the THERMOCAL project, this section summarises the pre-Quaternary geology and geothermal energy potential of each of the three THERMOCAL nations, highlighting key areas of geological and geographical interest.

2.1 Geology of Scotland

The Hebridean terrane, of northwest Scotland, was the foreland to the Caledonian Orogen. Here, the Lewisian Gneiss Complex is overlain unconformably by Neoproterozoic sedimentary rocks (Goodenough et al., 2024). Traversing east, the Moine Thrust is encountered, which marks the western margin of the Caledonian mountain belt. Much of the bedrock to the east of the Moine Thrust consists of thick successions of metamorphosed sedimentary rock, of the Loch Ness and Wester Ross Supergroups of the Northern Highland terrane (Strachan et al., 2024), and the Dalradian Supergroup of the Grampian terrane (Prave et al., 2024). These extensive swathes of metamorphosed sedimentary rocks are separated by the Great Glen Fault and were variably metamorphosed in places during various Caledonian orogenic phases. A significant feature of the Northern Highland and Grampian terranes is the presence of magmatic rocks of the Late Caledonian Igneous Province, which were emplaced during the Silurian and Early-Middle Devonian (Oliver et al., 2008). These rocks include volcanic sequences, major granitic plutons, and a variety of minor intrusions. In the northeastern coastal areas of both the Northern Highland and Grampian terranes, sandstones and conglomerates of Devonian age are present, having accumulated in the Old Red Sandstone (ORS) depocentre of the Orcadian Basin following erosion of the Caledonian mountain range (Marshall, 2024). Alongside the Orcadian Basin, the other depocentre of the ORS in Scotland is the Midland Valley of Scotland (MVS) (Marshall, 2024), which lies beyond the Grampian terrane, to the south of the Highland Boundary Fault. The MVS is an elongated west-southwest to east-northeast oriented graben and is composed of an internally complex arrangement of fault bounded Devonian and Carboniferous sedimentary basins, with associated intrusive and extrusive igneous rocks (Cameron and Stephenson, 1985). The MVS is bordered to the south by the Southern Uplands terrane, an accretionary prism bounded by the Iapetus Suture. Much of the Southern Uplands are comprised of Ordovician and Silurian turbidite successions of weakly metamorphosed sandstone, siltstone and mudstone of the Leadhills Supergroup, and the Gala and Hawick Groups, initially deposited on the floor of the Iapetus Ocean (Stone, 2024). As with the Grampian and Northern Highlands terranes, large granitic plutons of Devonian age are emplaced within the Southern Uplands terrane. Another notable feature of the geology of Scotland is the presence of Palaeogene granite intrusions formed as a result of the igneous activity associated with the opening of the North Atlantic Ocean (Bell and Williamson, 2024). These intrusions outcrop exclusively on the west coast of Scotland.

2.2 Northern Ireland

Similar to Scotland, in broad terms the geology of Northern Ireland can be divided into distinct areas. Schists and other metamorphic rocks of Precambrian and Ordovician age are found in the northwest of the region in the Sperrin Mountains and their foothills (Cooper et al., 2018), separated to the south by the Omagh Fault from the igneous rocks of the Caledonian Tyrone Igneous Complex (Hollis et al., 2016). The Longford-Down terrane in the southeast of the region, an extension of the Southern Uplands terrane, is composed of Ordovician to Silurian rocks, consisting mainly of weakly metamorphosed and fractured sandstones and mudstones. Two generations of granitic intrusions can be observed in this terrane, (1) the older Late Caledonian Newry Igneous Complex (Cooper et al., 2016) and (2) the Palaeogene Mourne Granites (Ture et al., 2016). In the southwest of the region, the third area is composed of Devonian and Carboniferous limestone, sandstone and mudstone rocks with thin coal beds overlying basement rocks at a depth of several kilometres. The Antrim Plateau in the northeast of the region forms the youngest area, unique for the UK in that it contains an almost continuous sequence of sub-horizontal layers from 420 to 30 million years old (BGS, 2020). The sequence ranges from the Palaeogene basalts of the Antrim Lava Group at the top, to underlying Mesozoic rocks, including Cretaceous Chalk, Mercia Mudstone and Sherwood Sandstone. This sedimentary sequence is known to be up to 3 km thick, underlain by older (420-300 million years) black mudstones and coal deposits. The basement rocks are deeply buried throughout this area. In northeast Antrim, they are known to be metamorphic rocks identical to those of the Sperrin Mountains.

2.3 Norway

The geology of Norway is as similarly complex as Scotland and Northern Ireland. Norway comprises the western part of the Baltic shield, which consists of rocks of Precambrian age. Roughly half of the rocks which outcrop in Norway are Precambrian gneisses, granites, migmatites, gabbro and amphibolites. In the Western Gneiss Region, these rocks were influenced by the Caledonian Orogeny. The Caledonian rocks constitute several thrust nappes transported eastwards and southeastwards on top of the basement, with significant shortening and thickening of the crust. The nappe complexes have been grouped into tectonostratigraphic units named the

Lower, Middle, Upper and Uppermost Allochthons, as well as the Autochthon and the Parautochthon (Roberts and Gee, 1985). The Lower and Middle Allochthons consist of arenites and argillites that were deposited on the pre-Caledonian Baltican passive margin facing the Iapetus Ocean and variably deformed and metamorphosed during the orogeny. The Upper Allochthon dominantly comprises greywacke, phyllite and sandstone sequences along with mafic magmatic rocks of oceanic affinity (ophiolites) that underwent Caledonian greenschist- to amphibolite-facies metamorphism. The Uppermost Allochthon displays a medium to high degree of metamorphism and consists of mica schist, mica gneisses, marble, amphibolites, granites and gabbro. During erosion and exhumation of the Caledonian mountains in the Devonian period, several sedimentary basins were formed in western Norway (Osmundsen, 2001). Then, during the Permian, the onset of the Oslo rift led to extensive igneous activity and volcanism (Neumann et al., 1992). Due to extensive subsidence of up to 1500 m, sedimentary rocks of Cambrian to Silurian age have been preserved. Very little Mesozoic rocks are preserved on mainland Norway; however, the continental shelf has thick sequences of Palaeozoic to Mesozoic strata.

2.4 Geothermal Energy Potential of the THERMOCAL Nations

At present, the main form of geothermal energy exploitation in Scotland, Northern Ireland, and Norway is via relatively shallow ground source heat pump (GSHP) installations, typically coupled to closed loop borehole heat exchangers (BHEs). Figure 1 shows the density of GSHP installations accredited by the UK's Microgeneration Certification Scheme (MCS) in Scotland and Northern Ireland. The majority of these are likely to be retrofitted closed loop installations of modest size (domestic or small-medium commercial). The largest total numbers of installations are in Scotland; in Glasgow, Aberdeenshire, Highland and Perth & Kinross local authorities. The highest densities relative to number of households are also in Scotland, in Orkney, Shetland, Perth & Kinross and the Outer Hebrides (Na h-Eileanan Siar). With the exception of Glasgow, these are remote districts, underlain by Caledonian, or pre-Caledonian, terranes, with poor access to the national gas grid. This makes GSHPs attractive technologies and their uptake is anticipated to increase in the coming years. By comparison to Scotland, the quantity of GSHP installations in Northern Ireland is low. However, it is understood that most areas of Northern Ireland are suitable for GSHP systems, either as closed-loop systems, or as open-loop systems for heating, cooling or aquifer thermal energy storage (ATES) in the more productive aquifers (Raine and Reay, 2019). In Norway, there are an estimated 55,000 GSHP systems coupled with closed loop BHEs. Heat produced by these systems has reached c. 3.0 TWh per year, equating to 4% of the national heating demand (Midttømme et al., 2020). Seasonal borehole thermal energy storage (BTES) is successfully carried out at the Fjell school in the municipality of Drammen (Kvalsvik et al., 2025)

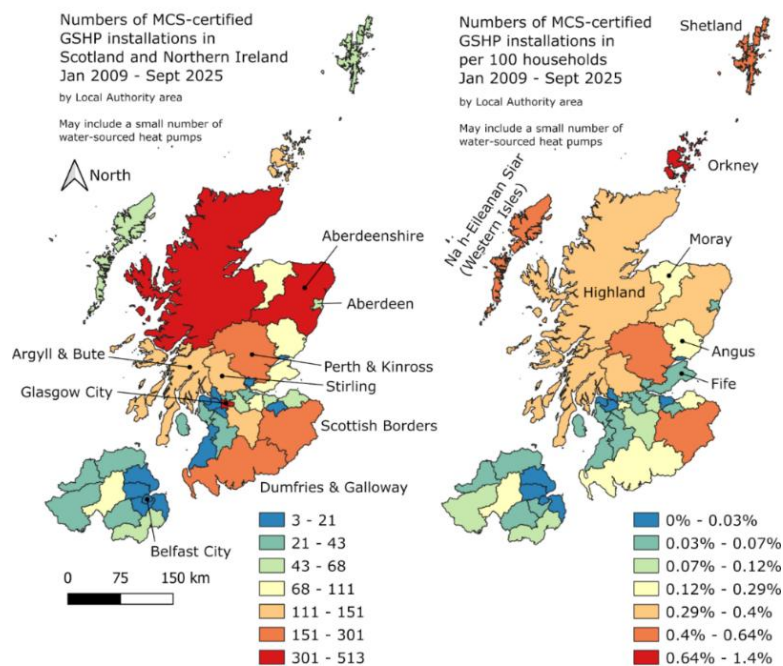


Figure 1. MCS-accredited GSHP installations in Scotland and Northern Ireland, from January 2009 to September 2025. Total installations in Scotland = 3720, in Northern Ireland = 387 (as of 17 Sept 2025). Source of data = MCS dashboard (<https://datadashboard.mcscertified.com/>). Note that not all GSHP installations will be MCS certified, although most will; the map thus represents a modest underestimate.

In addition to shallow geothermal systems, deeper geothermal prospects are also being considered as a viable source of low-carbon heating in each nation. In Scotland, these potential geothermal resources can be considered in terms of two geological settings which are of relevance to THERMOCAL: (1) hot sedimentary aquifers (HSAs), and (2) high heat producing granitic intrusions. Upper Devonian aged sandstones have been identified as potential HSA targets, where they are present at depths of c. 1.5-2 km within the Devonian-Carboniferous sedimentary basins (Watson, 2022). In the Grampian, Northern Highland and Southern Upland terranes, gamma-ray spectrometric surveying (Downing and Gray, 1986; McCay and Younger, 2017) has led to the identification of granitic plutons that may be viable targets for geothermal exploration. However, drilling is required to confirm temperatures at depth, and to assess permeabilities and fracture patterns. Indeed, at the time of writing there are no active deep geothermal systems in Scotland, nor deep geothermal exploration wells drilled. In Northern Ireland, the potential deep geothermal resources present are mainly associated with HSAs in the Lough Allen Sedimentary Basin in the west, and the more prospective thick sequences of Jurassic to Triassic mudstones and sandstones underlain by Permian and Carboniferous sandstones (Carruthers et al., 1997) within the sedimentary basins beneath the basalts of the Antrim Plateau. Caledonian and Palaeogene granitic rocks are the most likely candidates for elevated RHP (English et al., 2023), with higher levels of radioactivity previously observed in the Palaeogene granites compared to the Caledonian granites (O'Connor, 1981; Ture et al., 2016). Previous airborne radiometric surveys identified the Lower Palaeozoic rocks across the Longford-Down Terrane as a region with elevated potential for RHP (Jones and Scheib, 2007). In Norway, low geothermal gradients make utilisation of deep geothermal energy unattractive. Based on temperature measurements in boreholes at depths between 400 and 1000 m, Slagstad et al. (2009) calculated geothermal gradients on mainland Norway between 13.0 and 21.4 °C/km. However, in Svalbard there are pilot projects for replacing part of the current diesel-based power plant with thermal energy for heating of the Longyearbyen settlement (Richter, 2021).

3 EXISTING THERMOPHYSICAL DATA IN SCOTLAND, NORTHERN IRELAND AND NORWAY

Prior to collecting new thermophysical data, a systematic compilation of all existing data on thermal conductivity, volumetric heat capacity and RHP from lithologies within the Caledonian terrane of the three THERMOCAL nations will be undertaken. This compilation will allow for identification of gaps in existing data sets and identification of inconsistencies between the various data sets and methodologies, which need to be investigated and resolved. As a precursor to undertaking this systematic compilation, the following section introduces the history of thermophysical data collection in Scotland, Northern Ireland and Norway.

3.1 Existing Thermal Conductivity and Volumetric Heat Capacity Data

Norway has a long history of systematic measurement and mapping of thermal properties of rocks in certain areas, mostly performed by the Geological Survey of Norway (NGU), albeit mostly in southern Norway, rather than in the Caledonian terrane. However, Logn & Evensen (1973) systematically investigated the thermal conductivities in diamond core samples of rocks surrounding the Joma sulphide deposit, which lies in the Caledonide terrane of Trøndelag. In 2000, Midttømme et al. (2000) carried out a highly detailed evaluation of the thermogeology of Bærum municipality, near Oslo. The study included inter-laboratory comparison of thermal conductivity determinations, the impact of water saturation (Figure 2A; the impact of water saturation was modest, but broadly positive for many samples), and the impact of porosity (which was <5% in all samples). They also assessed the textural anisotropy in thermal conductivity of samples. Midttømme et al. (2004) systematically extended this study within Asker and Bærum municipalities, near Oslo, and presented boxplots comparing the thermal conductivity of different lithologies (Figure 2B). They also calculated heat production data from airborne radiometric determinations. The study was later expanded to a greater study area covering much of the region of the Permian Oslo rift. Ramstad et al. (2008) describe the methods used at NGU for laboratory thermal conductivity determination, their evolution and their comparability. Field-scale thermal response tests have also been widely used in Norway for quantification of rock thermal properties (Liebel et al., 2011).

In the UK, early investigations into the thermal conductivity of Caledonian rocks are reported by Herschel and Lebour (1878), Herschel et al. (1882), and by Richardson & Powell (1976). In the 1980s, a more concerted effort to collate the thermal properties of the rocks of the UK was coordinated by the British Geological Survey (BGS), and the results are summarised by Rollin (1987) and Downing and Gray (1986). Recently, these thermal properties have been incorporated into the database release by Fellgett and Monaghan (2024) and BGS (2024). Values of thermal conductivity from Scottish Caledonides are presented in Figure 3. A few more recent studies of specific localities have been carried out, such as that of the Caledonian granites near Aberdeen by the Hill of Banchory Geothermal Energy Consortium (2016). Volumetric heat capacity of Caledonian rocks remains poorly documented, although Herschel et al. (1882) produced values of 2.14 MJ/m³/K for a mica flagstone and 2.26 MJ/m³/K for an indurated mica schist from Loch Rannoch, Scotland.

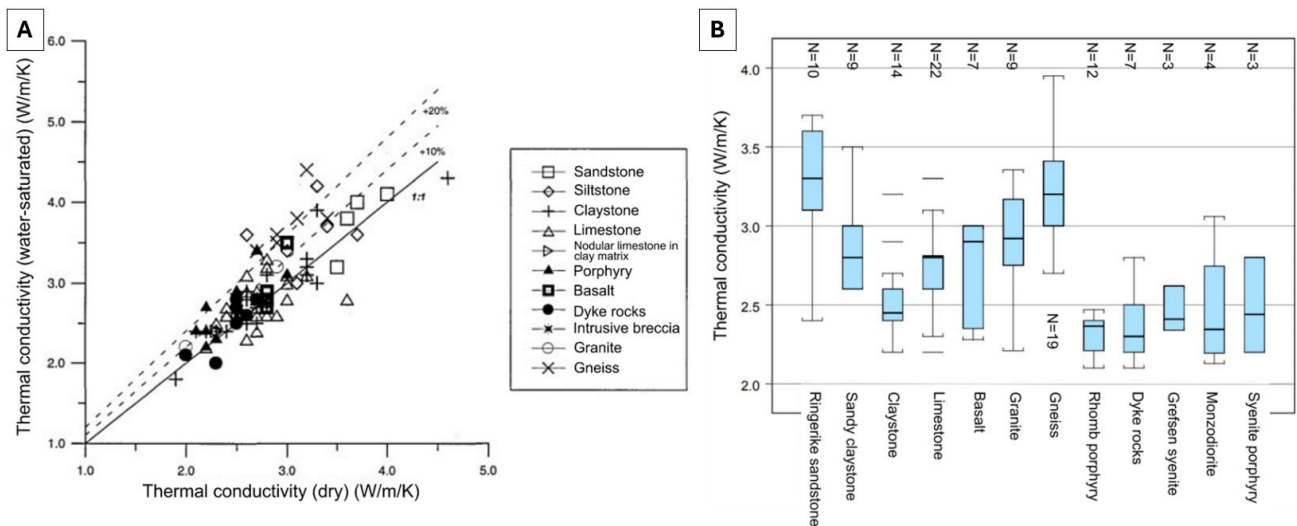


Figure 2. (A) Comparison of thermal conductivity of rock samples in water-saturated condition, versus dry sample, after Midttømme et al (2000). Note that the samples generally had a low porosity (<5%). A 1:1 line is shown, as are stippled lines showing a 10% and 20% excess when water-saturated. (B) Statistical distribution of thermal conductivities of rock samples from Asker and Bærum municipalities, Norway, by lithology, using box and whisker plots; from Midttømme et al. (2004).

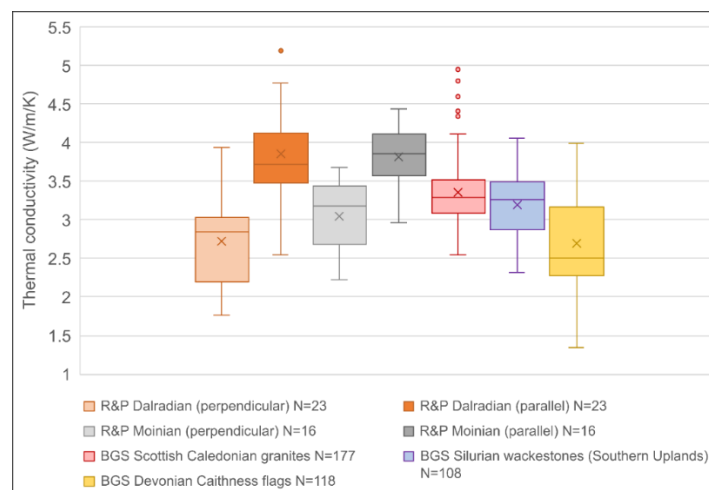


Figure 3. Box and whisker plots illustrating thermal conductivities of Scottish Caledonian rocks. R&P = Richardson & Powell (1976), who determined thermal conductivity perpendicular and parallel to foliation in a range of Dalradian and Moinian (including Central Highland granulite) metamorphics. BGS = data derived from British Geological Survey (2024). In boxes, central line = median, cross = arithmetic mean.

3.2 Existing Radiogenic Heat Production Data

Investigations of RHP in Norway date back to the mid-1960s with the studies of Knut Heier and co-workers. Their focus was mainly on the vertical distribution of heat-producing elements and differentiation of the crust during high-grade metamorphism (Heier 1965; Lambert & Heier 1967). This work sparked widespread interest in terrestrial heat flow and heat production in Norway through the 1970s, including local prospecting for geothermal energy (Grønlie et al. 1980). Most RHP studies focused on the Precambrian basement underlying the Caledonian nappes (e.g., Killeen & Heier 1975) with only sparse data presented from the Caledonian nappes themselves. Slagstad (2008) presented RHP values from almost 4000 data points covering all major geological provinces in Norway. The data show that RHP is strongly related to lithology, with mafic rocks generally yielding values $<1 \mu\text{W}/\text{m}^3$, granitic rocks $>2 \mu\text{W}/\text{m}^3$ and intermediate magmatic and metasedimentary rocks yielding intermediate values around $1.5 \mu\text{W}/\text{m}^3$. There is a weak relationship between tectonic setting and RHP, with intraplate magmatic rocks being slightly more enriched in heat-producing elements than subduction-related rocks, but no clear relationship between RHP and age. The highest RHP rates in Norway are found in ca. 925 Ma late-Sveconorwegian granites in southeastern Norway, with average values around $4 \mu\text{W}/\text{m}^3$ (see also Grønlie et

al. 1980). The high RHP of these granites is related to an unusual tectonic setting, for Norway, involving subduction and partial melting of thinned continental crust and its sedimentary cover (Granseth et al. 2020; Slagstad et al. 2024). In the Caledonian orogen, the highest RHP rates are associated with Ordovician granitoids and imbricated Precambrian basement, yielding values close to $2 \mu\text{W}/\text{m}^3$, whereas nappes dominated by mafic or metasedimentary rocks have somewhat lower values around $1.5 \mu\text{W}/\text{m}^3$. Studies of the relationship between heat flow and heat production have shown that although there is a broad positive correlation (Slagstad et al. 2009; Maystrenko et al. 2021), this relationship can be significantly disturbed due to groundwater flow, particularly along the mountainous Norwegian west coast (Maystrenko et al. 2015).

In Ireland, previous studies have evaluated the RHP of individual granite bodies across the island, in particular the RHP of the granite batholiths in County Galway (e.g., Feely and Madden, 1987; Feely et al., 1991; Madden, 1987), and Leinster and Donegal (McCabe, 1993). These were largely based on extensive ground surveys using portable gamma-ray spectrometers, augmented by measurements made in shallow boreholes. A broader investigation was conducted by the all-island IREITHERM (2011-2016) programme, which aimed to identify geological settings and localities with high prospectivity for geothermal energy, including granites with high RHP (Farrell et al., 2015). A map of crustal RHP for Irish bedrock geology was created by Willmot Noller and Daly (2015), assigning average RHP values to major lithological units. Caledonian and Paleogene granitic rocks of onshore Ireland are the most likely candidates for elevated RHP. Estimates of average RHP for the Caledonian granites, including the Leinster, Galway and Donegal granites in the Republic of Ireland, have a range of $1.5\text{--}3.3 \mu\text{W}/\text{m}^3$ (Willmot Noller et al., 2015). The Paleogene granites are generally more radioactive than their Caledonian equivalents (O'Connor, 1981) and published estimates for the average RHP for the Paleogene Mourne Mountains Complex in Northern Ireland show an overall estimated average of $6.8 \mu\text{W}/\text{m}^3$ (Willmot Noller et al., 2015). Using the airborne radiometric data collected by the Tellus Survey (Hodgson & Young, 2016), Ture et al. (2016) calculated RHP for the Mourne Mountains Complex of $>4.6 \mu\text{W}/\text{m}^3$.

As a component of nationwide assessments of potential geothermal energy targets in the 1980s (e.g., Downing and Gray, 1986) gamma-ray spectrometry surveys identified four high heat-producing granites most favourable for geothermal exploration in Scotland. These four granites are Ballater, Bennachie, Cairngorm and Mount Battock, all of which have RHP values $>5 \mu\text{W}/\text{m}^3$ and are part of the Late Caledonian Igneous Province of the Grampian terrane. More recently, McCay and Younger (2017) conducted an extensive field-based gamma-ray spectrometric survey targeting plutons that were poorly surveyed in past investigations. This new survey identified other plutons, namely Ben Rinn, Cheviot, Hill of Fare, Lochnagar and Monadhliath with heat production rates between $3\text{--}5 \mu\text{W}/\text{m}^3$. The identification of high RHP granites has primarily been the focus of gamma-ray spectrometric surveys in Scotland to date, however Richardson and Powell (1976) evaluated the RHP of samples of Dalradian and Moinean metasedimentary rocks from the Grampian Terrane, with arithmetic mean RHP values determined to be 1.54 and $1.88 \mu\text{W}/\text{m}^3$ respectively.

4 DATA ACQUISITION AND LABORATORY MEASUREMENTS

Building upon the existing thermal property data sets, one key aim of THERMOCAL is to carry out a systematic measurement programme, with unified sampling and analytical methodologies, of lithologies in the Caledonian terrane of the three THERMOCAL nations. THERMOCAL will demonstrate a tested workflow for sampling to data interpretation, to ensure high quality and reproducible data for thermal property determinations. The following section summarises the proposed activities in relation to data acquisition and laboratory measurements.

4.1 Data Collection

Parallel fieldwork in the three THERMOCAL nations will be carried out to systematically collect representative rock samples for laboratory measurement of thermal conductivity and volumetric heat capacity. Preference will be given to recent quarry or cutting outcrops rather than natural outcrops, and lithologies that are present in Scottish, Northern Irish and Norwegian Caledonian terrane and pre-Caledonian basement. Additional cores will be retrieved from relevant borehole cores held by the Geological Survey of Northern Ireland (GSNI) and the BGS, to allow an evaluation of thermal properties along vertical borehole profiles. The fieldwork will aim to generate approximately 200 rock samples from Scotland, 200 from Norway and 100 from Northern Ireland, with an ambition to collect a statistically representative subset of 5-10 samples for each lithology. In addition, field and laboratory measurements of K/U/Th contents of surface rocks will also be collected using a range of gamma-ray spectroscopy techniques and converted to estimates of RHP. Preference will be given to Caledonian and pre-Caledonian granite and gneiss lithologies, and intrusive acidic lithologies therein. Measurements of radionuclide concentrations at the ground surface (top 30-50cm) will be combined with selected existing borehole cores to better understand the relationship between the surface and depth where heat production is most important. Surface measurements will include spot measurements using handheld portable instruments, mobile ground

based and airborne data to provide local and regional context, and collection of samples for laboratory analysis at Scottish Universities Environmental Research Centre (SUERC). This combination will help identify best practice for surface measurements for RHP determination. Furthermore, with the support of GSNI and BGS, suitable existing borehole locations for downhole logging will be identified to evaluate vertical variations in K/U/Th contents for Caledonian rock types.

4.2 Laboratory Measurements

Determination of thermogeological properties of approximately 500 rock samples will be carried out at the petrophysical laboratory (PPL) at NGU. This laboratory has been in operation since 1998 (Midttømme et al. 2000, Ramstad et al. 2008). Currently, the laboratory at NGU operates a TCi Thermal Conductivity Analyzer from C-Therm, with a modified transient plane source (MTPS) sensor. This instrument determines thermal conductivity and effusivity, which allows the calculation of thermal diffusivity and specific heat capacity. The MTSP sensor has a diameter of 18 mm and a maximum penetration depth of 5 mm. Thermal conductivity is measured with accuracy and precision better than 5% and 1%, respectively. Measurements are performed at room temperature on a cut, smooth surface of the sample. The samples are immersed in water for at least one hour before measurement and a couple of water droplets are used as contact agent between sensor and sample. Geological samples may be heterogeneous and with variable grain size, therefore, to obtain representative values, measurements are always taken at three locations across the sample surface, and the average value is reported together with its variance. For anisotropic samples, measurements are taken parallel and perpendicular to the foliation. In addition to the standard measurements at NGU, a ring test with other international laboratories is planned with a selected number of samples. This will help to verify results, establish potential differences in results between the different methods and instruments, ensure reproducibility, and quantify uncertainties.

5 MODELLING AND APPLICATION

Following the development of the empirical thermophysical data set, it will be used to refine models of shallow GSHP and deep geothermal systems. Given the anticipated low porosity and permeability properties of the Caledonian lithologies investigated, shallow and deep closed-loop BHE models coupled to heat pumps, will be developed. The multiphysics finite element software OpenGeoSys will be used for subsurface modelling while surface components (e.g., the heat pump) will be modelled using Thermal Energy Systems in Python (TESPy) - OpenGeoSys-TESPy coupled model. Field data on anisotropy will be taken into account in these models to assess its impact on the thermal energy output of the closed-loop systems. Embedding the variability in the measurement of thermophysical parameters will inform uncertainty quantification in real-world applications, allowing end-users in Norway, Northern Ireland and Scotland to pre-assess the viability of shallow-to-deep, closed-loop, conduction-dominated geothermal projects.

6 CONCLUSION

In conclusion, the bilateral UK-Norway THERMOCAL project aims to develop a substantial suite of thermal conductivity, volumetric heat capacity and internal RHP measurements in lithologies in the Caledonian, and Pre-Caledonian, terrane of Scotland, Northern Ireland and Norway. Following compilation of existing measurements from each nation, the new data set will be acquired through extensive field campaigns, with an anticipated 500 rock samples to be collected, and subsequently measured at NGU's laboratory. THERMOCAL is grounded in rigorous interlaboratory quality control, ring-testing and method harmonisation, together with consideration of orientation, state of weathering and saturation of samples. The combined data set will then be used to refine models of shallow GSHP and deep geothermal systems and determine the thermal energy output and performance of such systems. In doing so, THERMOCAL will de-risk and inform the development of geothermal energy systems in Scotland, Northern Ireland, and Norway, as well as analogous Caledonian terrane elsewhere.

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REFERENCES

- Bell, B.R., and Williamson, I.T.: Palaeogene igneous activity, North Atlantic plume-related magmatism, in: Smith, M. and Strachan, R.A. (eds.), *The Geology of Scotland*, 5th edition, Geological Society, London, (2024).
- British Geological Survey.: BGS Regional Geological Guides Series of Reports - Northern Ireland, (2020).

- British Geological Survey.: UK Digital Geothermal Catalogue, Version 1, NERC EDS National Geoscience Data Centre, (2024).
- Cameron, I.B., and Stephenson, D.: *The Midland Valley of Scotland*. British Geological Survey. HMSO, London, (1985).
- Carruthers, R.M., Beamish, D., Heaven, R.E., Legg, I.C., Mitchell, W.I., Reay, D.M., and Walker, A.S.D.: Regional interpretation of gravity and aeromagnetic data from Northern Ireland, British Geological Survey Technical Report, WK/96/05/C, (1997).
- Cooper, M.R., Anderson, P., Condon, D.J., Stevenson, C.T.E., Ellam, R.M., Meighan, I.G., and Crowley, Q.G.: Shape and intrusion history of the Late Caledonian, Newry Igneous Complex, Northern Ireland: in M.E. Young (ed.), *Unearthed: Impacts of the Tellus Surveys of the North of Ireland*, Dublin, Royal Irish Academy, (2016).
- Cooper, M.R., Schofield, D., Haslam, R., Wilson, P., Lewis, M., Bloomfield, J.P., Lee, J.R., Baptie, B., Shaw, R.P., Reay, D.M., Bide, T., and McEvoy, F.M.: National Geological Screening: Northern Ireland, British Geological Survey Commissioned Report, CR/17/96, (2018).
- Corfu, F., Gasser, D., and Chew, D.M.: New perspectives on the Caledonides of Scandinavia and related areas: introduction, *Geological Society London Special Publications*, **390**, (2014), 1-8.
- Department for the Economy.: Energy Strategy for Northern Ireland - The Path to Net Zero Action Plan, (2022).
- Downing, R.A., and Gray, D.A.: *Geothermal Energy: The Potential in the United Kingdom*, British Geological Survey, HMSO London UK, (1986).
- English, J.M., English, K.L., Dunphy, R.B., Blake, S., Walsh, J., Raine, R., Vafeas, N.A., and Salgado, P.R.: An overview of deep geothermal energy and its potential on the island of Ireland, *First Break*, **Volume 41**, Issue 2, (2023), 33-43.
- Farrell, T., Rath, V., Feely, M., Muller, M., Jones, A.G., Brock, A.: IRETherm: The geothermal energy potential of radiothermal granites in a low-enthalpy setting in Ireland from magnetotelluric data, *Proceedings World Geothermal Congress 2015*, Melbourne, Australia (2015).
- 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**, 2, (1987), 155-164.
- Feely, M., McCabe, E., and Kunzendorf, H.: The evolution of REE profiles in the Galway Granite, Western Ireland, *Irish Journal of Earth Sciences*, **11**, 1, (1991), 71-89.
- Fellgett, M., and Monaghan, A.A.: User Guide: BGS UK Geothermal Catalogue first digital release, legacy data, British Geological Survey Open Report, OR/23/060, (2024).
- Goodenough, K.M., Guice, G.L., Bird, A., Dempsey, E.D., Hughes, H.S.R., and Johnson, T.E.: Archean-Paleoproterozoic: formation of the crystalline basement, in: Smith, M. and Strachan, R.A. (eds.), *The Geology of Scotland*, 5th edition, Geological Society, London, (2024).
- Granseth, A., Slagstad, T., Coint, N., Roberts, N.M.W., Røhr, T.S. and Sørensen, B.E.: Tectonomagmatic evolution of the Sveconorwegian Orogen recorded in the chemical and isotopic compositions of 1070–920 Ma granitoids, *Precambrian Research*, **340**, (2020), 105527.
- Grønlie, G., Johansen, T.E., Karlstad, B. and Heier, K.S.: Prospecting for geothermal energy in the Iddefjord Granite, Østfold, Norway, *Norsk Geologisk Tidsskrift*, **60**, (1980), 263-267.
- Heier, K.S.: Metamorphism and the chemical differentiation of the crust, *Geologiska Föreningen i Stockhom Förhandlingar*, **87**, (1965), 249-256.
- Herschel, A.S., and Lebour, G.A.: Fourth report of a committee on experiments to determine the thermal conductivities of certain rocks, showing especially the geological aspects of the investigation, Report of the 47th Meeting of the British Association for the Advancement of Science, held at Plymouth in August 1877, John Murray, London, (1878) 90-97.
- Herschel, A.S., Ayrton, W.E., Duncan, P.M., Lebour, G.A., Dunn, J.T., and Perry, J.: Final report of a committee on experiments to determine the thermal conductivities of certain rocks, showing especially the geological aspects of the investigation, Report of the 51st Meeting of the British Association for the Advancement of Science, held at York in August and September 1881, John Murray, London, (1882), 126-148.
- Hill of Banchory Geothermal Energy Consortium.: Hill of Banchory Geothermal Energy Project Feasibility Study, The Scottish Government: Edinburgh, Scotland, (2016).

- Hodgson, J.A., and Young, M.E.: The Tellus airborne geophysical surveys and results, in M.E. Young (ed.), *Unearthed: impacts of the Tellus surveys of the north of Ireland*, Dublin, Royal Irish Academy, (2016).
- Hollis, S.P., Cooper, M.R., Earls, G., Roberts, S., Herrington, R.J., and Piercey, S.J.: Using Tellus data to enhance targeting of volcanogenic massive sulphide mineralisation in the Tyrone Igneous Complex, in M.E. Young (ed.), *Unearthed: impacts of the Tellus surveys of the north of Ireland*, Dublin, Royal Irish Academy, (2016).
- Jones, D.G., and Scheib, C.: A preliminary interpretation of Tellus airborne radiometric data, British Geological Survey Commissioned Report, CR/07/061, (2007).
- Killeen, P.G., and Heier, K.S.: Radioelement distribution and heat production in Precambrian granitic rocks, Southern Norway, Det Norske Videnskaps-Akademi, I. Mat.-Naturv. Klasse, Skrifter, Ny Serie, 35, (1975), 1-32.
- Kvalsvik, K.H., Ramstad, R.K., Holmberg, H., and Kocbach, J.: Measurements and simulations of high temperature borehole thermal energy storage in Drammen, Norway - Evaluation of Thermal Losses and Thermal Barrier, *Geothermics*, **125**, (2025).
- Lambert, I.B., and Heier, K.S.: The Vertical distribution of uranium, thorium, and potassium in the continental crust, *Geochimica et Cosmochimica Acta*, **31**, (1967), 377-390.
- Liebel, H.T., Huber, K., Frengstad, B.S., Ramstad, R.K., and Brattli, B.: Temperature footprint of a thermal response test can help to reveal thermogeological information, *Norges geologiske undersøkelse Bulletin*, **451**, (2011), 20–31.
- Logn, Ø., and Evensen, E.: Thermal conductivities of some ores and rocks in Norway. *Norges geologiske undersøkelse*, **300**, 1119, (1973).
- 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).
- Marshall, J.E.A.: Old Red Sandstone: continental sedimentation on the eroding Caledonian Orogen, in: Smith, M. and Strachan, R.A. (eds.), *The Geology of Scotland*, 5th edition, Geological Society, London, (2024).
- Maystrenko, Y.P., Olesen, O., and Elvebakk, H.K.: Indication of deep groundwater flow through the crystalline rocks of Southern Norway, *Geology*, **43**, (2015), 327-330.
- Maystrenko, Y.P., Elvebakk, H.K., Osinska, M., and Olesen, O.: New heat flow data from the Veiholmen and Raudsand boreholes, Middle Norway, *Geothermics*, **89**, (2021), 101964.
- McCabe, E.: Radioelement and REE geochemistry of selected Late-Caledonian Irish granites, Unpublished PhD Thesis, National University of Ireland, Galway, (1993).
- McCay, A.T., and Younger, P.L.: Ranking the geothermal potential of radiothermal granites in Scotland: are any others as hot as the Cairngorms? *Scottish Journal of Geology*, **53**, (2017), 1-11.
- McKerrow, W.S., Mac Niocaill, C., and Dewey, F.: The Caledonian Orogeny redefined, *Journal of the Geological Society*, **157**, 6, (2000), 1149-1154.
- Midttømme, K., Hilmo, B.O., Skarphagen, H., and Nissen, A.: Kartlegging av energipotensialet i berggrunnen på kartblad Bekkestua, Bærum kommune: Varmeledningsevnen til bergarter, NGU Report 2000.036, Geological Survey of Norway, (2000).
- Midttømme, K., Ramstad, R.K., Solli, A., Sørda, T. and Elvebakk, H.: Grunnvarmekartlegging i Asker og Bærum, Norges geologiske undersøkelse, Rapport 2004:013, (2004).
- Midttømme, K., Kvalsvik, K., Justo Alonso, M., and Ramstad, R.K.: Geothermal energy use in Norway, Country Update for 2015-2019. *Proceedings, World Geothermal Conference 2020*, Reykjavik, Iceland (2020)
- Neumann, E.R., Olsen, K.H., Baldrige, W.S., and Sundvoll, B.: The Oslo Rift: a review, in P.A. Ziegler (Ed.), *Geodynamics of Rifting*, 1, Case History Studies on Rifts: Europe and Asia, *Tectonophysics*, **208**, (1992), 1-18.
- O'Connor, P.: Radioelement geochemistry of Irish granites, *Mineralogical Magazine*, **44**, (1981), 485-495.
- Oliver, G.J.H., Wilde, S.A., and Wan, Y.: Geochronology and geodynamics of Scottish granitoids from the late Neoproterozoic break-up of Rodinia to Palaeozoic collision, *Journal of the Geological Society*, **165**, 3, (2008), 661-674.

- Osmundsen, P.T., and Andersen, T.B.: The middle Devonian basins of western Norway: sedimentary response to large-scale transtensional tectonics?, *Tectonophysics*, **332**, 1-2, (2001), 51-68.
- Prave, A.R., Fallick, A.E., Strachan, R.A., Krabbendam, M., and Leslie, A.G.: Middle Neoproterozoic-Early Ordovician: foreland basins, climatic extremes and rift-to-drift margins, in: Smith, M. and Strachan, R.A. (eds.), *The Geology of Scotland*, 5th edition, Geological Society, London, (2024).
- Raine, R., and Reay, D.M.: A review of geothermal reservoir properties of Triassic, Permian and Carboniferous sandstones in Northern Ireland, Geological Survey of Northern Ireland Internal Report, 19/00/01, (2019).
- Ramstad, R.K., de Beer, H., Midttømme, K., Koziel, J., and Wissing, B.: Thermal diffusivity measurement at NGU - status and method development 2005-2008, NGU Report 2008.050, Geological Survey of Norway, (2008).
- Ramstad, R.K.: Grunnvarme i Norge - Kartlegging av økonomisk potensial, NVE consultants' report, (2011).
- Ramstad, R.K., Midttømme, K., Liebel, H.T., Frengstad, B.S., and Willemoes-Wissing, B.: Thermal conductivity map of the Oslo region based on thermal diffusivity measurements of rock core samples, *Bull Eng Geol Environ*, **74**, (2015), 1275–1286.
- Richardson, S.W., and Powell, R.: Thermal causes of the Dalradian metamorphism in the Central Highlands of Scotland, *Scottish Journal of Geology*, **12**, 3, (1976), 237-268.
- Richter, A.: Geothermal could replace coal on Arctic island group of Svalbard, *Think Geoenergy*, (2021).
- Roberts, D., and Gee, D.G.: An introduction to the structure of the Scandinavian Caledonides. In Gee, D.G. and Sturt, B.A. (eds.), *The Caledonide Orogen — Scandinavia and Related Areas*. Chichester, John Wiley and Sons, (2005), 55-68.
- Rollin, K.E.: Investigation of the Geothermal Potential of the UK: Catalogue of Geothermal Data for the Land Area of the United Kingdom (3rd Revision). Keyworth, UK: British Geological Survey, NERC, (1987).
- Scottish Renewables.: Submission to the UK Parliament Environmental Audit Committee: Inquiry into Geothermal Technologies, (2022).
- Slagstad, T.: Radiogenic heat production of Archaean to Permian geological provinces in Norway. *Norwegian Journal of Geology*, **88**, (2008), 149-166.
- Slagstad, T., Balling, N., Elvebakk, H., Midttømme, K., Olesen, O., Olsen, L., and Pascal, C.: Heat-flow measurements in Late Palaeoproterozoic to Permian geological provinces in South and Central Norway and a new heat-flow map of Fennoscandia and the Norwegian–Greenland Sea, *Tectonophysics*, **473**, (2009), 341–361.
- Slagstad, T., Skår, Ø., Bjerkan, G., Coint, N., Granseth, A., Kirkland, C.L., Kulakov, E., Mansur, E., Orvik, A.A., Petersson, A., and Roberts, N.M.W.: Subduction and loss of continental crust during the Mesoproterozoic Sveconorwegian Orogeny. *Precambrian Research*, **409**, (2024), 107454.
- Stone, P.: Middle-Ordovician-Silurian: Midland Valley forearc basins and the Southern Uplands accretionary complex at the southern margin of Laurentia, in: Smith, M. and Strachan, R.A. (eds.), *The Geology of Scotland*, 5th edition, Geological Society, London, (2024).
- Strachan, R.A., Prave, A.R., Krabbendam, M., and Smith, M.: Late Mesoproterozoic-middle Neoproterozoic: sedimentation and orogeny on the margin of Rodinia, in: Smith, M. and Strachan, R.A. (eds.), *The Geology of Scotland*, 5th edition, Geological Society, London, (2024).
- Ture, M.D., Reay, D.M., Muller, M.R., Yeomans, C.M., and Ayres, L.A.: Geothermal potential of granitic rocks of the Mourne Mountains, in M.E. Young (ed.), *Unearthed: impacts of the Tellus surveys of the north of Ireland*, Dublin, Royal Irish Academy, (2016).
- Watson, S.M.: An investigation of the geothermal potential of the Upper Devonian sandstones beneath Eastern Glasgow, Unpublished PhD Thesis, University of Glasgow, (2022).
- Willmot Noller, N.M., and Daly, J.S.: The contribution of radiogenic heat production studies to hot dry rock geothermal resource exploration in Ireland, *Proceedings World Geothermal Congress 2015*, Melbourne, Australia (2015).