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Geothermal energy prospecting in radiothermal granites in the Cairngorms, Scotland, using an integrated magnetotelluric and petrophysical approach

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1 INTRODUCTION

The UK's radiothermal granites can host fluids with temperatures between 150°C and 300°C at depths of 3.5 to 6.5 kilometres and are some of the most viable targets in the country for medium-high enthalpy geothermal resources (Busby & Terrington, 2017). These high-heat producing (HHP) granites generate significant heat anomalies due to their concentration of naturally decaying radioactive elements (uranium, thorium, and potassium).

The Cairngorm Pluton is one such HHP granite body located in the Scottish Highlands, part of the East Grampian Batholith. The pluton is a large, post-tectonic intrusion of Caledonian age granite. Geothermal exploration in Scottish HHP granites have been historically hampered by what are unexpected low heat flow values, considering their high heat production values (Busby et al, 2015). However, recent paleoclimate corrections by Westaway and Younger (2013) highlight how significant temperature differences from past ice ages to modern times can impact shallow borehole temperatures indicating that there may be higher temperatures at depth than previously thought. Busby et al. (2015) further refined these corrections for the Cairngorm Pluton, calculating sub-surface temperatures of 129°C at 5 km depth and 176°C at 7 km depth.

With granites typically possessing low primary porosity and permeability due to their interlocking crystal structures, the feasibility of a geothermal system in a HHP granite is often tied to the ability for its natural fractures to facilitate fluid flow. The complexity of natural fractures at depth can present challenges in predicting permeability at depth, as demonstrated by projects like the United Downs Deep Geothermal Power project in Cornwall, UK (Reinecker, et al. 2021). An increasingly recognised form of secondary permeability is created through high-temperature hydrothermal alterations, leading to changes in the mineralogy, thereby enhancing the rock's reservoir quality. Studies from analogous granitic systems, such as those in Finland and Cornwall (Bischoff et al., 2024; Forbes Inskip et al., 2023), suggest that hydrothermal processes along fracture networks can achieve significant secondary porosity (up to ~20%) and permeability (~5×10^{-14} m^2) through cataclasis, mineral dissolution, and microstructural modification at depth.

A major feature of the Cairngorm Pluton is the presence of Linear Alteration Zones (LAZs), which are the surface expressions of late-stage hydrothermal alteration and hydro-fracturing (Thomas et al., 2004; Hall and Gillespie, 2017). The presence of LAZs indicates that there were permeable fluid pathways in the past. The orientation of many of the LAZs is parallel to some of the major valleys in the Cairngorms, and it is suggested that hydrothermal alterations have significantly weakened the granite, leading to preferential weathering and erosion to form these valleys (Hall and Gillespie, 2017). However, the lateral and depth extent of these LAZs are uncertain due to poor surface exposure. Milligan et al. (2016) noted that the pervasive imprint of alteration in the Cairngorm Borehole core, yet the frequency, full extent, and timing of this alteration remain unknown.

To address the uncertainties of the pluton's structural characteristics, as well as the presence, extent, and permeability of fluid pathways at depth we conducted an integrated geophysical and geological survey to characterise the Cairngorm Pluton's geothermal feasibility, providing critical insights applicable to other HHP granite systems worldwide.

2 METHODS & RESULTS

Our integrated methodological approach combines deep geophysical imaging using the Magnetotelluric (MT) method with quantitative laboratory measurements of rock properties. This integration is designed to link the macro-scale structural features imaged by geophysics to the micro-scale reservoir enhancement mechanisms observed in the petrophysical and petrographic analyses.

2.1 The Magnetotelluric (MT) Method

MT is a deep-sounding geophysical technique that utilises naturally occurring variations in the magnetic and electric fields generated by global lightning activity and solar winds to image electrical conductivity down into the Earth's crust and mantle (Chave and Jones, 2012). MT instruments on the surface simultaneously measure time-varying electric (E) and magnetic (H) fields using orthogonal dipoles with non-polarising electrodes and induction coil magnetometers, respectively. In the frequency domain, the relationship between these fields is expressed by the 2x2 complex impedance tensor (Z) where (ω) is angular frequency (2π/f):

$$E(\omega) = Z(\omega) \cdot H(\omega)$$

The impedance tensor derived at all sites visited during the field campaign are then used as input in a three-dimensional inversion algorithm that constructs a model of the underlying electrical resistivity. Fluid-bearing fault zones and hydrothermally altered granites characteristically possess higher electrical conductivity and can easily be imaged in such a model because they stand out as conductive anomalies against the highly resistive background of unaltered granitic rock (Huebert, 2023).

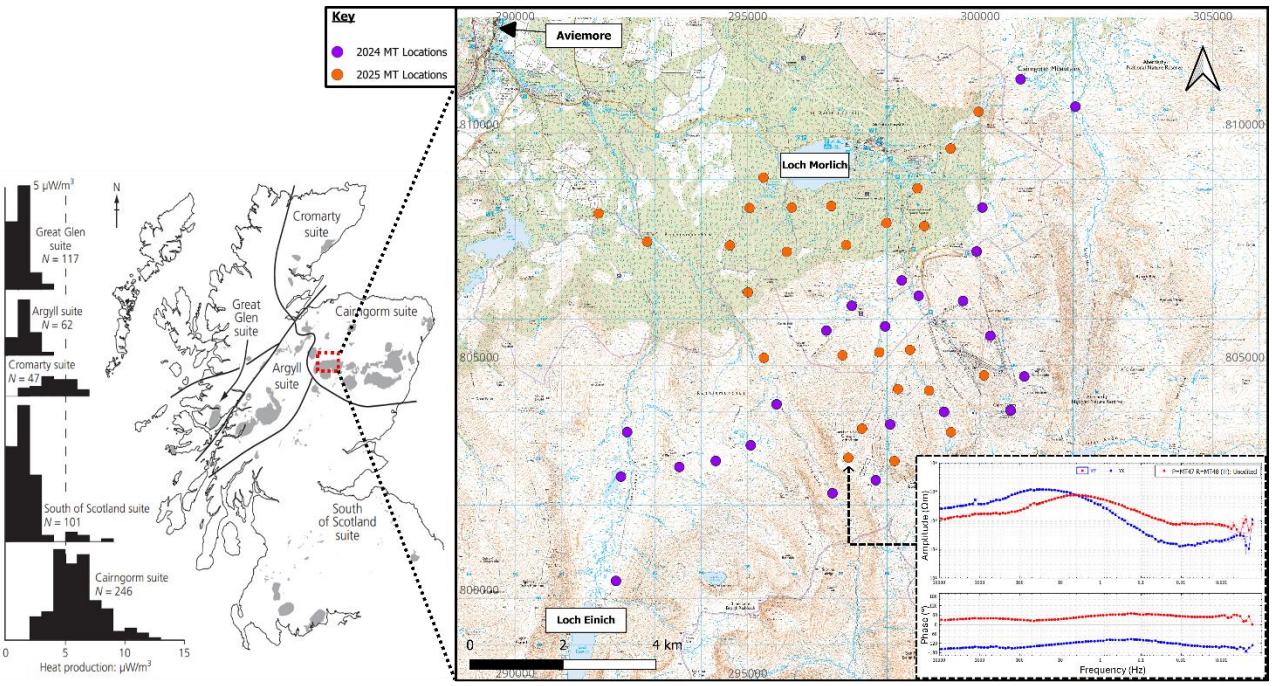


Figure 1. Left: Scotland's granite suites with graphed heat production rates (modified from Younger et al, 2012). Location of MT survey highlighted in red. Right: 50 Broadband MT site locations collected in 2024 (purple) and 2025 (orange) campaigns. Inset: Apparent resistivity and phase curves for site MT47. A dashed arrow indicates the location of the site (MT47) that corresponds to the data. Contains OS data © Crown copyright and database right (2025)

Over 40 days of fieldwork during May-June 2024 and September 2025, broadband MT data were acquired at 50 site locations in the Northern Cairngorm area around Cairngorm Mountain (Figure 1). Phoenix MTU-5C systems were deployed measuring from 12-72 hours, including at least one overnight period due to the increase in natural signal strength and decrease in anthropogenic noise.

Raw time-domain data were converted to the frequency domain. Concurrent recordings from remote reference sites (2024: rural location, Dalmigavie Estate; 2025: BGS geomagnetic observatory, Eskdalemuir) were used to cross-reference the local data and remove site-specific noise that was uncorrelated between the two sites.

The final data set was inverted using the ModEM 3D inversion code (Kelbert et al., 2014) using the High-Performance Computing (HPC) facility at the British Geological Survey. The initial inversion integrated the 24 broadband MT site measurements from 2024. The model domain uses a central cell size of 382 m x 382 m, expanding with larger padding cells toward the edges. The model is discretised into 53x49x65 cells, with a logarithmic increase in vertical cell size after 400 m depth, starting with 50 m cells at the maximum elevation. A homogeneous starting model of 1000 Ωm was utilised, and a SRTM topography model with 30m resolution was incorporated to mitigate topographic distortion effects. Data error floors varied between 3% and 10% depending on individual site data quality.

2.2 Petrophysical & Petrographic Methods

To quantitatively assess the change in porosity caused by alteration, Helium pycnometry was used. One-inch diameter plugs were prepared from both altered and pristine granite samples collected from outcrops. The skeletal density, derived from the dry mass and grain volume, is combined with independently measured bulk volume (via callipers) to calculate the total porosity using the principle of volume difference.

In a methodology analogous to Forbes Inskip et al. (2023), the permeability of the rock samples was measured using a Dynchem permeameter. One-inch plugs were mounted in the chamber and sealed with a Viton sleeve. Water was used as both the confining and the permeating fluid. Samples were tested under a constant upstream pore pressure of 20 bar (average pore pressure of 10 bar). Three different effective confining pressures were applied: 350 bar, 250 bar, and 100 bar, allowing for the characterisation of permeability under varying stress states. The flow rate through the sample was monitored until a steady state was achieved, an equilibration period that ranged from 7 to 20 days. Once stable flow was recorded, the permeability was calculated using Darcy's Law. This testing is currently ongoing, and quantitative results are not yet available for publication.

Petrographic analyses were employed to evaluate the mineralogical, textural, and structural characteristics of the rock types. Optical microscopy was used to identify key features such as secondary mineral replacement grain-size changes, and the nature and filling of fractures.

2.3 The 3D electrical resistivity model of the north Cairngorm granites

The presented resistivity model has Root Mean Square (RMS) misfit of 1.8 (Figure 2) indicating an overall good data fit. The model generally shows zones of higher resistivity (upwards of 10,000 Ωm) in the southern region and lower resistivity in the northern area, coinciding with the suggested geological contact with the surrounding metasediments.

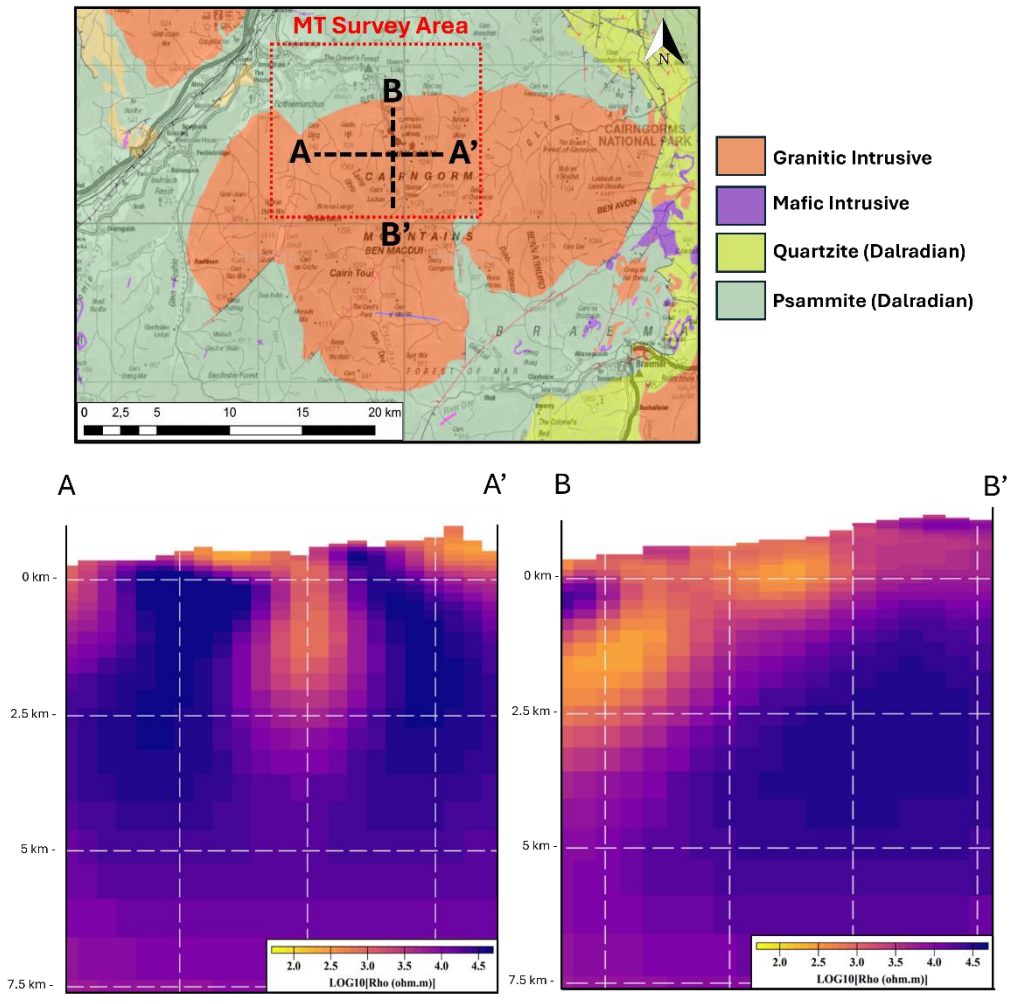


Figure 2. Map of The Cairngorm Pluton and surrounding geology. Area surveyed by Cross Sections of the MT 3D resistivity model. A-A' displays an east-west section. B-B' runs north-south. Contains British Geological Survey materials © UKRI (2025).

At shallower depths (from ground level to 3 km depth) within the granite body itself, several distinct conductive zones (<100 Ωm) appear. The most prevalent of these features is an elongated conductive body running in a North-South direction within the granite. Cross-sections (A-A' and B-B') of the 3D resistivity model illustrate this feature: A-A' (East-West section) shows the high-resistivity bulk granite, highlighting the zone of low resistivity within the granite body extending vertically; B-B' (North-South section) runs roughly parallel to this conductive zone, demonstrating the N-S extent.

The low resistivity of this persistent N-S structure is highly suggestive of a major fluid-bearing pathway. Given the geological context, this feature is provisionally interpreted as a deep-seated Linear Alteration Zone (LAZ). The low resistivity is likely attributable to the presence of saline fluids and clay minerals resulting from feldspar breakdown.

The September 2025 fieldwork, focused on improving coverage around this conductive N-S body and the granite-metasediment contact, will be integrated with the 2024 data and inverted as a single, more constrained dataset. This expanded spatial coverage is expected to significantly improve the spatial resolution and robustness of the 3D model, enabling a more detailed understanding of the geometry and characteristics of this prime geothermal target. Further sensitivity analysis will be conducted following this second inversion to rigorously assess the model's reliability.

2.4 Petrophysical & Petrographic Results & Discussion

Initial results from the helium pycnometry indicate that the porosity of the granite samples ranges widely from 1% to 13%. The porosity exhibits a significant increase in conjunction with the visual increase in the degree of hydrothermal alteration.

Petrographic analysis of thin sections reveals significant contrasts between the pristine and altered granite facies. Unaltered samples exhibit classic biotite granite textures. Primary minerals (plagioclase, orthoclase feldspars, and micas) are well-preserved, showing minimal evidence of deep weathering. Altered samples are characterised by the pervasive breakdown of primary feldspars and micas. The original feldspar crystal shapes are often preserved as pseudomorphs defined by secondary mineral assemblages, including sericitisation, chloritisation, and epidotisation (Figure 3, A1-B2). Quartz grains, while more resistant, exhibit increased internal fracturing. Both open and mineral-filled fractures are ubiquitous throughout the altered samples. The presence of iron oxides and clay minerals within the feldspar pseudomorphs and along quartz grain boundaries also suggest a degree of hydrothermal interaction. (Figure 3, A1-A2).

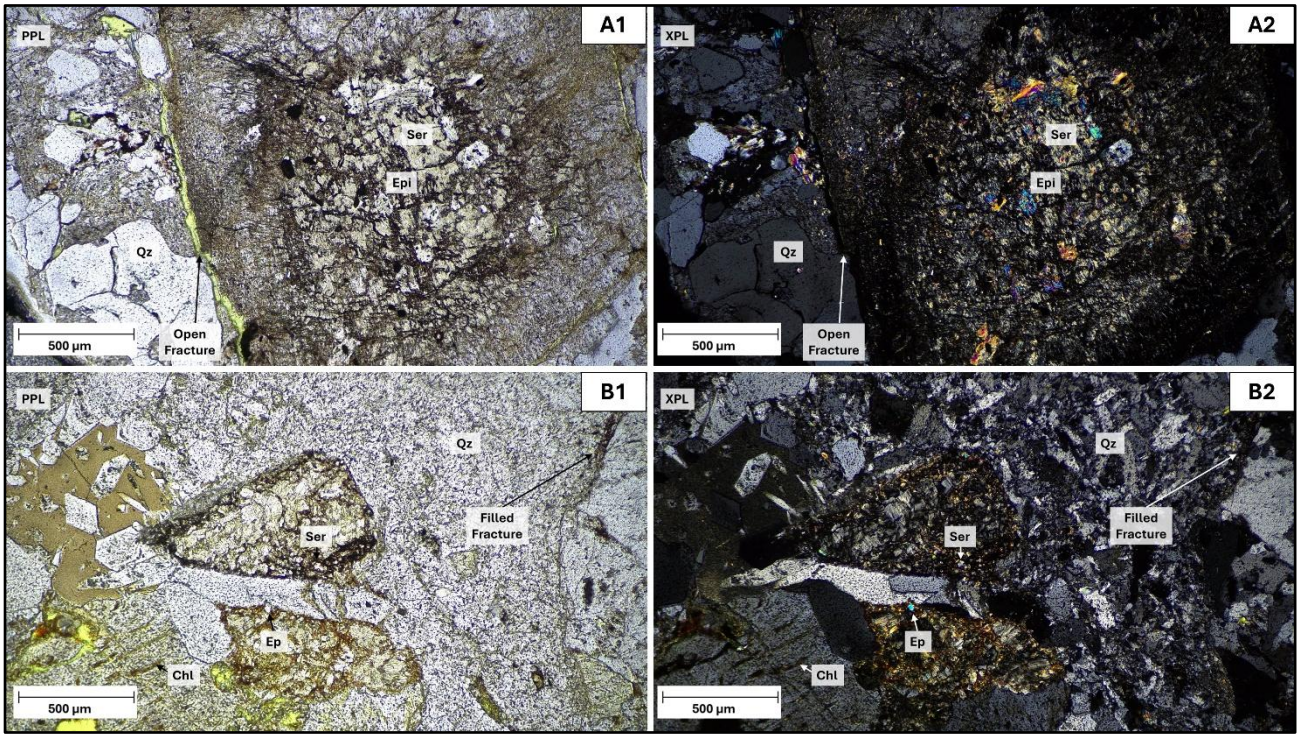


Figure 3. Optical microscopic images of Cairngorm altered granite thin sections under PPL (A1, B1) and XPL (A2, B2) at 10x magnification. Qz = quartz, Ser = Sericite, Chl = chlorite, Ep = Epidote.

Pycnometer data show that altered samples exhibit up to a 10% absolute increase in porosity, dependant on alteration extent. The pervasive hydrothermal alteration, specifically the chemical and physical modification of feldspars observed in thin section, is suggested as the primary mechanism for this secondary porosity generation, a process consistent with findings by Bischoff et al. (2024).

3 CONCLUSIONS

While further work is ongoing to integrate an additional 26 MT sites into the 3D model and link alteration effects to permeability via permeameter experiments, the initial findings from this integrated study already demonstrate significant deep geothermal potential in the Cairngorm Pluton. The MT survey identified a major, vertically persistent North-South conductive anomaly (100 - 1000 Ωm) within the highly resistive granite body (10,000 Ωm). This feature is interpreted as a deep-seated LAZ, a regional-scale fluid pathway. This interpretation is supported by the petrophysical analysis, where alteration is confirmed as the mechanism for creating secondary porosity (up to 13%), suggesting the low-resistivity feature is a hydraulically and chemically activated structure.

By combining MT imaging of deep conductive structures with petrophysical quantification of alteration induced porosity, this research demonstrates an effective, non-invasive strategy for derisking exploration of crystalline basement systems worldwide.

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