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Sustainable Energy Authority of Ireland

National Energy Research, Development & Demonstration Funding Programme

FINAL REPORT

SECTION 1: PROJECT DETAILS – FOR PUBLICATION

Project Title	De-risking Ireland's Geothermal energy potential
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Project Summary
Deep geothermal resources in low- to medium-temperature settings remain poorly understood and untapped in Ireland and much of Europe. DIG (De-risking Ireland's Geothermal energy potential) integrates multi-disciplinary, multi-scale datasets to investigate Ireland's low-enthalpy geothermal energy potential. The overarching research objectives are to: (i) determine the regional geothermal gradient across Ireland, with uncertainty estimates, using new and existing large-scale geophysical and geochemical–petrophysical data; (ii) investigate the thermochemical crustal structure and secondary fracture porosity in Devonian–Carboniferous siliciclastic and carbonate lithologies using wide-angle seismic, gravity, and available geochemical data; and (iii) identify and assess available low-enthalpy geothermal resources at the reservoir scale within the Upper Devonian Munster Basin, specifically the Mallow warm springs region, using magnetotelluric (MT) and passive seismic methods constrained by structural geological mapping. In the island-scale strand of the project, temperature and geothermal gradient are mapped by integrating all available relevant data through a joint geophysical–petrological inversion. New large-scale seismic, surface heat flow, thermal conductivity, and radiogenic heat production datasets are used to determine temperature variations within the lithosphere, with a particular focus on geothermal energy resources in the shallow crust. Modelling results show that granitic areas and regions beneath the Antrim lava sequence have the warmest subsurface temperatures.The local-scale approach evaluates the geothermal energy potential of the Upper Devonian Munster Basin. One of the primary targets is the Mallow Warm Springs Area (MWSA), located along the Killarney–Mallow Fault Zone (KMFZ). Primary porosity has been obliterated by sub-greenschist metamorphism and Variscan deformation fabrics, indicating that fluid flow within the crust around the KMFZ is likely related to fault-controlled permeability. This fluid flow is interpreted to be associated with Cenozoic tectonic reactivation of faults and thermally driven uplift, with evidence for significant fluid flow also during Munster Basin extension and Variscan basin inversion. MT and passive seismic surveys were carried out to image conduits and pathways supplying thermal waters to the surface. The structural study focused on structures associated with the immediate hangingwall and footwall of the Coomnacronia Mallow Fault (CMF). Preliminary MT and passive seismic modelling confirms that this feature is a southerly dipping, crustal-scale basin-margin fault zone and is most likely the principal conduit for geothermal fluid mobility in the Mallow area. A new hydrochemistry programme to characterise deep reservoir water composition provides additional constraints. Results from the hydrochemical study support a conceptual model in which a shallow groundwater recharge component, dominated by enhanced carbonate bedrock dissolution, seasonally dilutes the deep geothermal contribution to Lady's Well.

Keywords (min 3 and max 10)	Geothermal Energy; Geophysical Imagery; Geo-Hydrochemistry; Muster Basin; Lithospheric Structure; Thermal Conductivity

SECTION 2: FINAL TECHNICAL REPORT – FOR PUBLICATION

2.1 Executive Summary

Decarbonising Ireland's energy system and a move to environmentally sustainable living are key government priorities. Geothermal energy is important at a National level (Ireland's National Energy and Climate Plan 2021- 2030) and an EU level (EU Strategic Energy Transition Plan, including the SET Plan Deep Geothermal Working Group). Ireland's geographical and tectonic history means that its geothermal systems will be low-enthalpy which, due to the need for deeper drilling, implies a significant financial risk at the exploration phase in terms of resource discovery. The DIG project aims to explore the potential for low-enthalpy geothermal energy on the island of Ireland by using a three-scale approach, with an overarching objective of creating an improved geothermal resource map of Ireland. The island-scale approach determines the seismic-velocity and thermal structure of the lithosphere, with crustal geometry. Radiogenic heat production and thermal conductivity measurements for Irish rocks are incorporated into an integrated geophysical-petrological model, within a scheme able to provide critical temperature uncertainties. Regional and local-scale approach derive subsurface electrical conductivity and velocity images from magnetotelluric and passive seismic surveys from the northern margin of the Munster Basin, where the thermal waters tend to have a distinctive chemical fingerprint, and a meteoric origin based on available geochemical and isotopic compositions. This local focus aims to directly image fault conduits and fluid aquifer sources at depth, within a convective/conductive region associated with warm springs.

2.2 Introduction to Project

The DIG project proposes a regional to local methodological approach to systematically and comprehensively de-risk Ireland's geothermal energy potential. The project comprises six work packages (WPs), which include five core technical work packages, and a work package dedicated to outreach activities. This final report outlines the activities of WP 1 to WP 5, that encompass the all-island-scale and concentrates on the local-scale Mallow warm springs area of the project. WP 1 uses the large data set, gathered by the DIAS Ireland Array network, to determine large-scale (lithospheric) contributions to heat low and thermal structure across Ireland. The focus of WP 2 is on southern Ireland and the geothermal prospectivity of the Upper Devonian Munster Basin, using the available scientific data. WP 3 and WP 4 use magnetotelluric and passive seismic geophysical methods, respectively, to experimentally investigate the subsurface resistivity and velocity structure of the Mallow shallow crust, where a known geothermal anomaly exists, associated with warm thermal springs. WP 5 aims to analyse the faulting history and spatial distribution of the geothermal anomaly in Mallow. This is accomplished by integrating data from electromagnetic surveys (WP 3) and passive seismic surveys (WP 4). Additionally, the hydrochemistry programme, which is built in WP 5, studies deep reservoir water composition to pinpoint convective pathways and mixing zones using environmental tracers.

2.3 Project Objectives

The project has 3 main objectives:

1. (Island-Scale Approach) Determine the regional geothermal gradient across Ireland using new and existing geophysical, geochemical and petrophysical data
2. (Regional-Scale Approach) Investigate the thermo-chemical crustal structure and secondary fracture porosity within the Upper Devonian Munster Basin using wide-angle seismic, gravity and geochemical data
3. (Local-Scale Approach) Identify and assess the available low-enthalpy geothermal resources at reservoir scale in the Munster Basin, i.e., Mallow warm springs area, by joint interpretation

of magnetotellurics and passive seismic modelling results together with structural geology and hydrochemistry programme

2.4 Summary of Key Findings/Outcomes

WP 1: Integrated geophysical-petrological crustal thermal modelling of Ireland

- **Innovation 1 (Achieved): Constructed phase velocity maps from Love dispersion curves for Ireland.** These maps (Figure 1) provide unprecedented resolution for the phase velocity structure beneath Ireland using recently created datasets and seismic networks. We have added additional data and refined the models by removing outlier phase velocity curved.

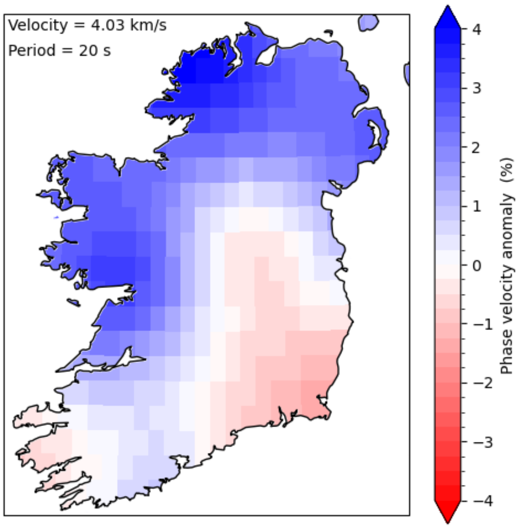


Figure 1: Example Love-wave phase velocity map at 20 s period (sensitive to mid and lower crustal depths). red colours are slower velocities and blue are faster than the average value shown in the top left corner. These are published in Chambers et al. 2023, Tectonophysics (doi: 10.1016/j.tecto.2023.230094).

- **Innovation 2 (Achieved): New joint geophysical-petrological inversion scheme.** This new inversion scheme allows us to process the seismic data more accurately and fit the final models better by using a more geophysically consistent methodology. In addition, we have added the capability to specify as three crustal layers with variable properties for each rock layer and to add Vp seismic data. This makes the inversion one of the world leading pieces of software to determine temperature and lithospheric structure. To assess how well the new inversion performed, we inverted columns for temperature where direct borehole temperature measurements were present and compared the indirect modelled temperature to the direct temperature measurements as shown in Figure 2. The fit is better than previous temperature models.

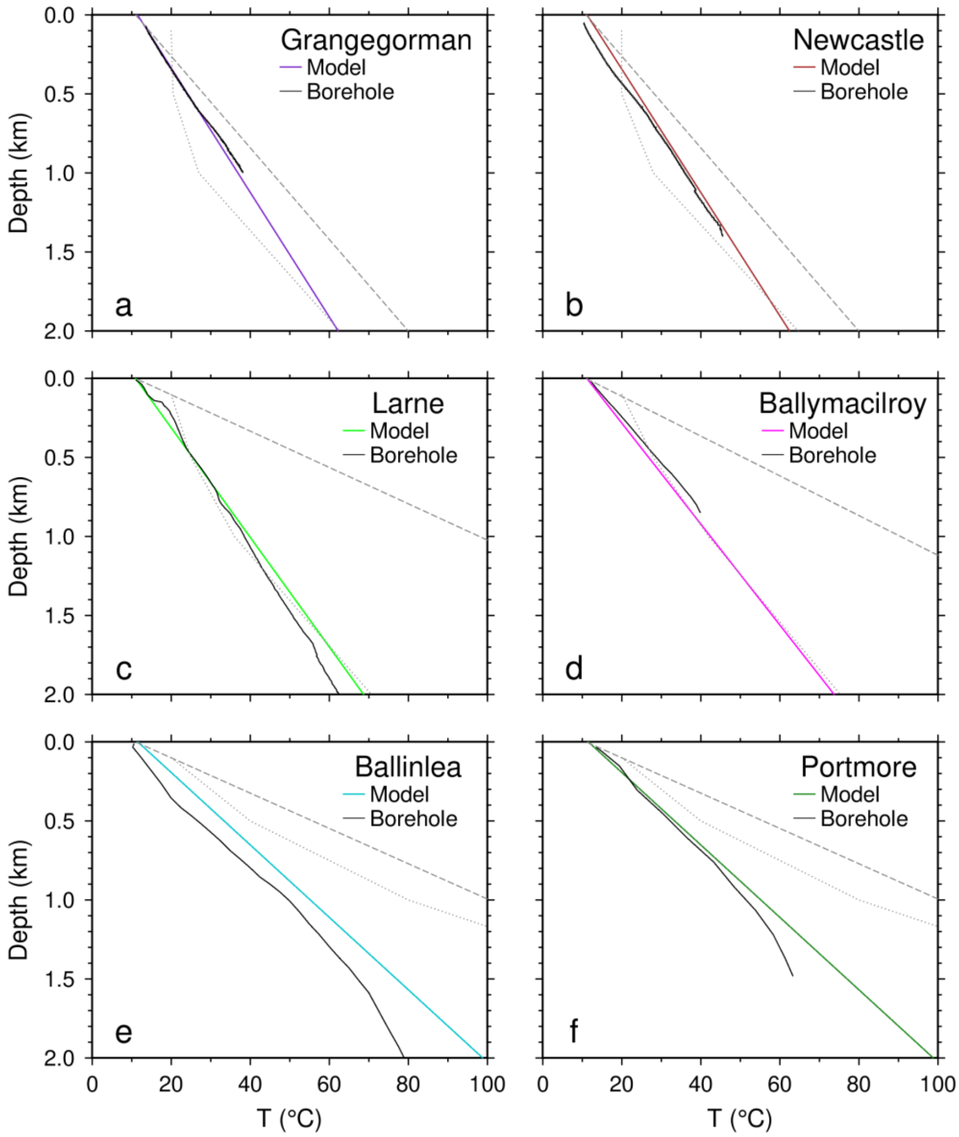


Figure 2: Temperature profiles showing the fit between the borehole data (black line) and our modelled results (solid line). The boreholes are a) Grangegorman (purple), b) Newcastle (brown), c) Larne (green), d) Ballymacilroy (pink), e) Ballinlea (blue) and f) PortMore (forest green). The models from previous studies by Goodman et al. (2004) and Mather and Fullea (2019) are plotted as grey dotted and dashed lines.

- **Innovation 3 (Achieved): Produced a subsurface temperature model of Ireland with uncertainty.** This model has been generated by incorporating multiple data sets acquired in Ireland (surface heat flow, thermal conductivity (including new measurements), radiogenic heat production, new surface waves (described above), elevation and Moho depth/crustal thickness). The program used for the inversion has been updated and refined to account for vertical gradient damping and allowing more user control. Additional thermal property data has been added to the inversion. The high-resolution, accurate model of the thermal structure beneath Ireland can be used to help assess the geothermal potential of Ireland and reduce the risk of geothermal prospecting. The final temperature models with uncertainty (based on ranges for certain input datasets and inversion parameters) (Figure 3) have been produced and are undergoing peer review in Geophysical Journal International. An preprint is available on EarthArXiv. The final models are also with GSI and will become part of their online geological viewer and geothermal database. In addition, we also produced new Moho and Lithosphere-

Asthenosphere Boundary depth maps and crustal radiogenic heat production which will also be useful for understanding Ireland's subsurface and for future industry and research projects.

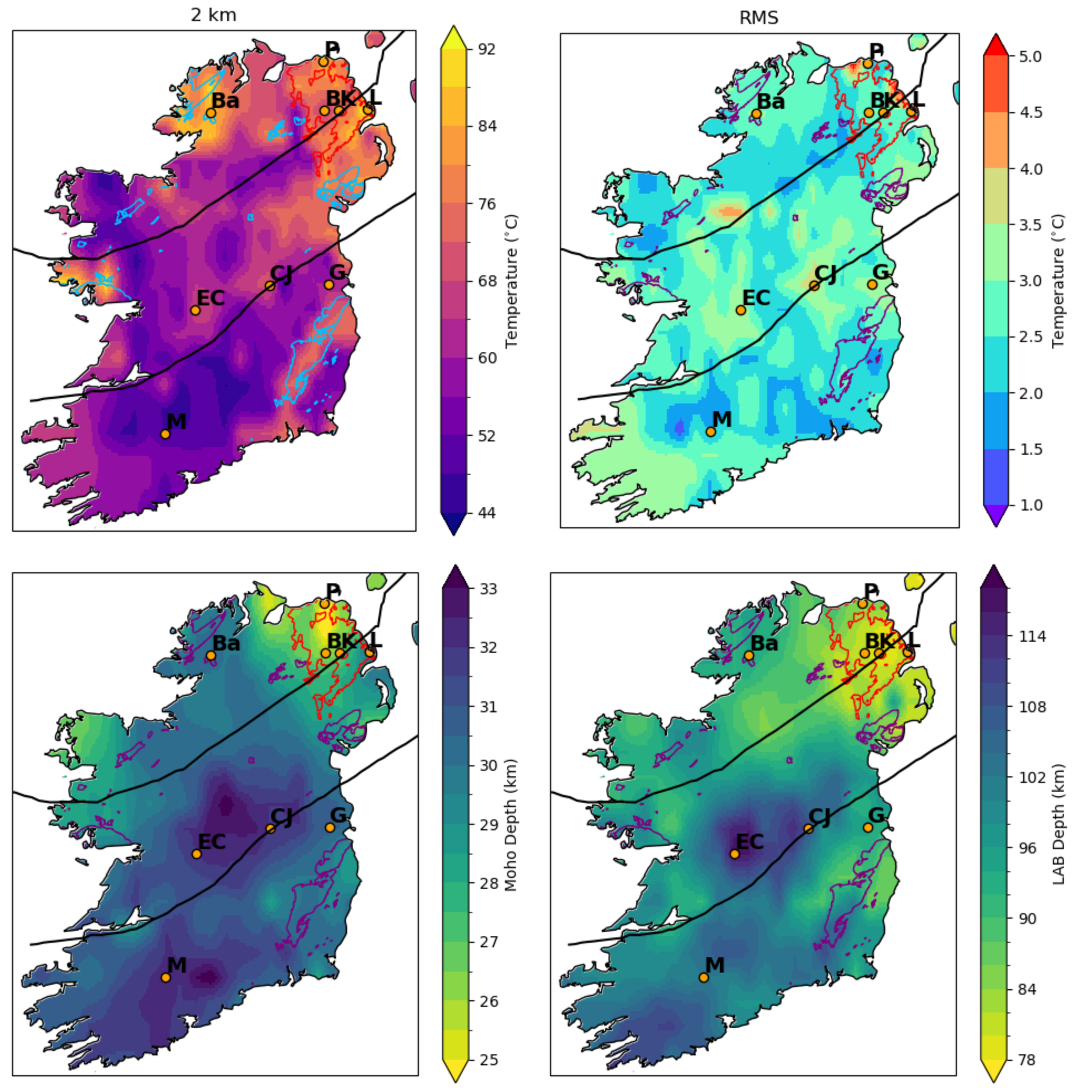


Figure 3: Top row: Subsurface temperature at 2 km (left) with associated uncertainty (right). The Iapetus Suture Zone is marked by thick black lines, basaltic bedrock as red polygons, and granites by light blue lines (Bedrock units from the GSI bedrock geology viewer (Geological Survey Ireland, 2020)). Orange points are the 1D columns in the uncertainty analysis (Chambers et al. in review and preprint 2024). Acronyms are B – Ballymacilroy, Ba – Barnesmore Donegal, CJ – Castle Jordan, EC – Eyres Court, G – Grangegorman, K – Kells (NI), L – Larne, M – Mallow, P – Portmore. Left: Geothermal Gradient map. The yellow colours are warmer temperatures with purple colder areas. The granitic areas and beneath the Antrim lava sequence have the warmest subsurface temperatures. The maximum uncertainty at 2 km depth is 5 °C with the average ±3.5 °C. Bottom row: Moho and Lithosphere Asthenosphere Boundary (LAB) maps of Ireland. The thickest crust and lithosphere is in central and southern Ireland whereas thinner crust and a shallower LAB are beneath Northern Ireland, the north of the island and Co. Mayo and Galway.

WP 2: Regional crustal structure beneath the Munster Basin using wide-angle seismic reflection, petrophysical and geochemical datasets

- **Innovation 1 (Achieved): New joint geophysical-petrological inversion to include Vp datasets.** The modelling software can now accept Vp seismic in addition to surface wave data. This allows us to more accurately fit the seismic data in the crust getting better depth estimates for the crustal layers.

- **Innovation 2 (Achieved): New Thermal Conductivity measurements of Irish Rocks**. New measurements have been taken using a thermal conductivity scanner, divide bar apparatus and a transient plane source, for rocks across Ireland (primarily limestones but also some igneous and metamorphic samples, see sample locations Figure 4). These were carried out in 2 labs using 3 methods to ensure reliability. The results will form part of a geothermal database and will be published in an open access peer reviewed publication. Figure shows new results for thermal conductivity using the thermal conductivity scanner. Note the variations in thermal conductivity for different lithologies and within the same lithology. Basalts are the most stable sample while limestone can vary considerably with varying composition.

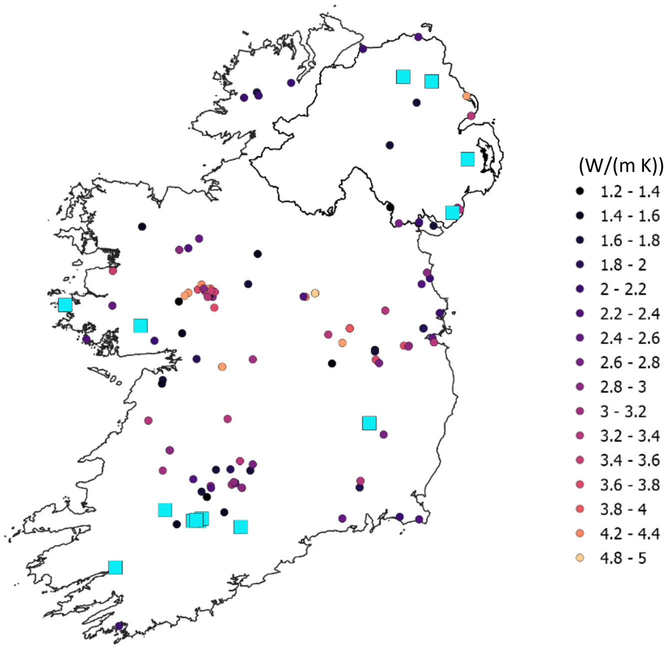


Figure 4: Map showing the point measurements of TC in Ireland from previous studies (coloured circles) together with the new rock sample locations (blue squares).

- **Innovation 3 (Anticipated): Raman spectroscopy measurements to determine mineral weight percent.** As an addition to the project, 16 samples, representative of most of the core samples that underwent TC measurements, were sent to University College Cork to undergo Raman Spectroscopy. Raman spectroscopy is a non-destructive technique that can characterise the individual minerals of a sample based on the interaction of light with the chemical bonds of a solid sample. The technique also provides the abundance of the minerals within a sample. As part of the DIG project, we are investigating whether we can use the mineral wt.% to calculate bulk rock TC and assess how this performs relative to the direct TC measurements. If this is successful, it could be a faster way of calculating TC for the country. 80% complete

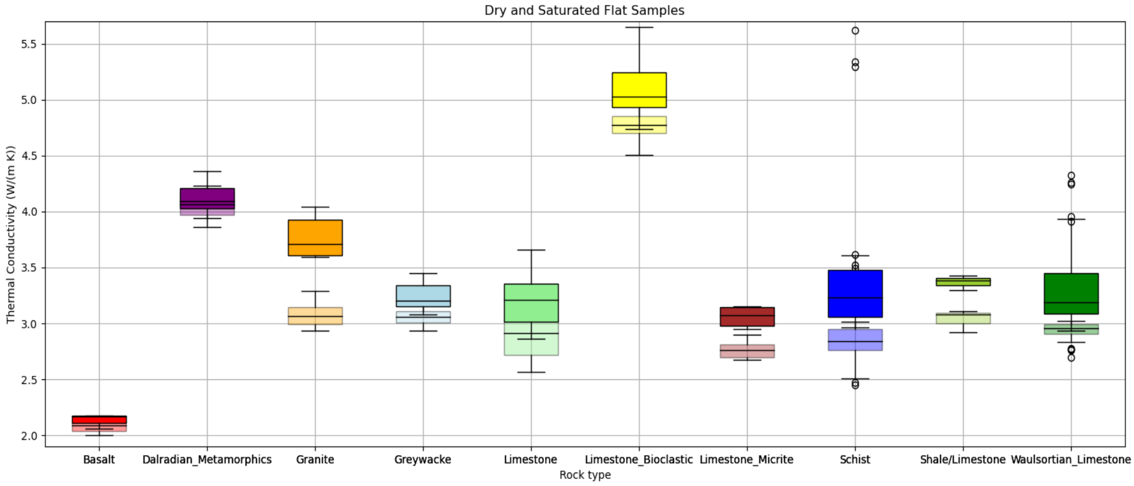


Figure 5: Box and whisker plot for the Thermal Conductivity Scanner measurements. Flat samples are plotted, and the transparent boxes are for the dry samples and the solid colours are for the same samples but under saturated conditions. The colour is representative of the rock type written below each box and whisker plot. 627 measurements are contained within this plot.

WP 3: Electromagnetic Field Surveys in the Muster Basin

- **Innovation 1 (Achieved):** DIG magnetotelluric (MT) stations were installed between 2021 November and 2023 April in south-west Ireland (Mallow, North Munster Basin). The MT measurements were carried out using the new-generation Phoenix MTU-5C instruments at 52 sites. The time series data were processed with the Phoenix Geophysics EMPower software. Our processed data have robust responses in the period range of 0.001-1000 s. (Figure 7).

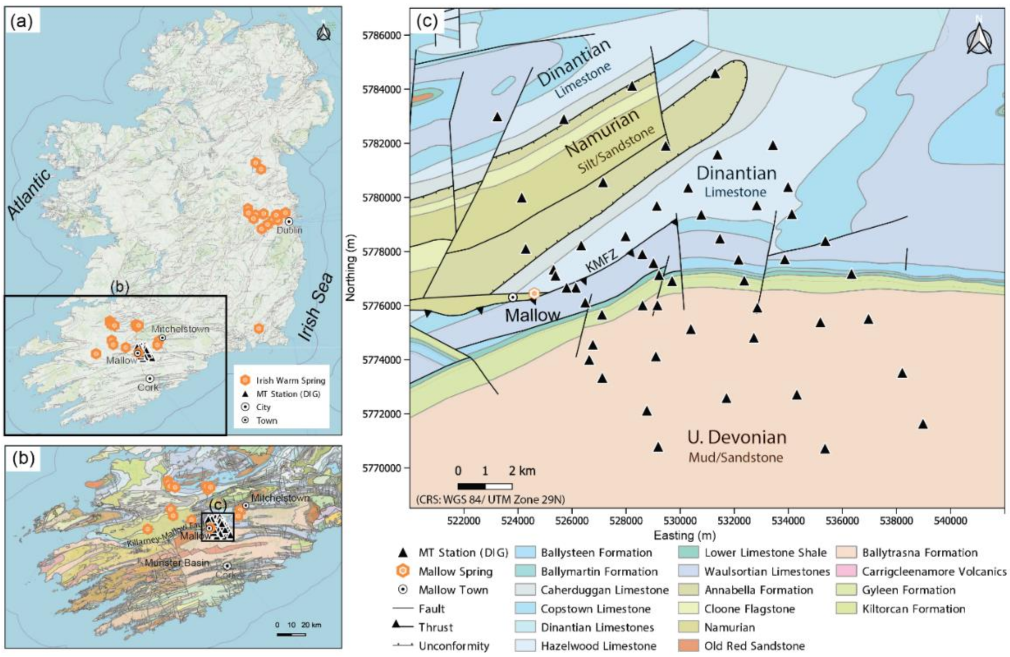


Figure 6: Maps of the survey area, including (a) the distribution of Irish warm springs (Goodman, 2004), (b) the Munster Basin shown with geological bedrock background (1:100K, www.gsi.ie, Geological Survey Ireland), and (c) the Mallow Warm Spring Area (MWSA) and MT stations overlapping 1:100K bedrock (www.gsi.ie, Geological Survey Ireland). KMFZ: the Killarney-Mallow Fault Zone. MT locations are shown as black triangles.

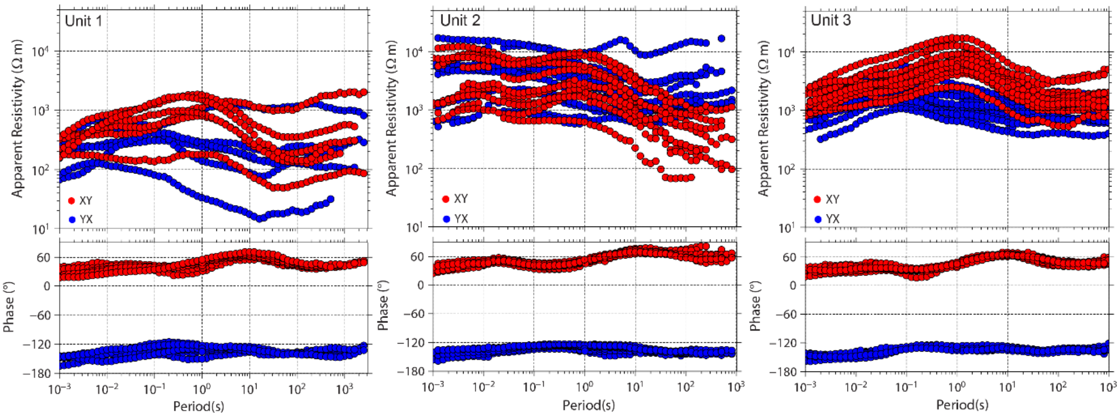


Figure 7: Apparent resistivity and phase data curves for Unit 1 Namurian Silt/Sandstone; Unit 2 Dinantian Limestone; Unit 3 Upper Devonian Mud/Sandstone.

❖ **Innovation 2 (Anticipated):** The collected MT data are being modelled in 3D using ModEM3DMT (Kelbert et al., 2014). Preliminary modelling results are presented in Figures 8 and 9. We mapped steeply dipping electrically conductive structures which represents early extensional basin faults. These electrically conductive structures could be associated with fluids or a proxy for a highly brecciated or fracture permeability associated with damage around the faults.

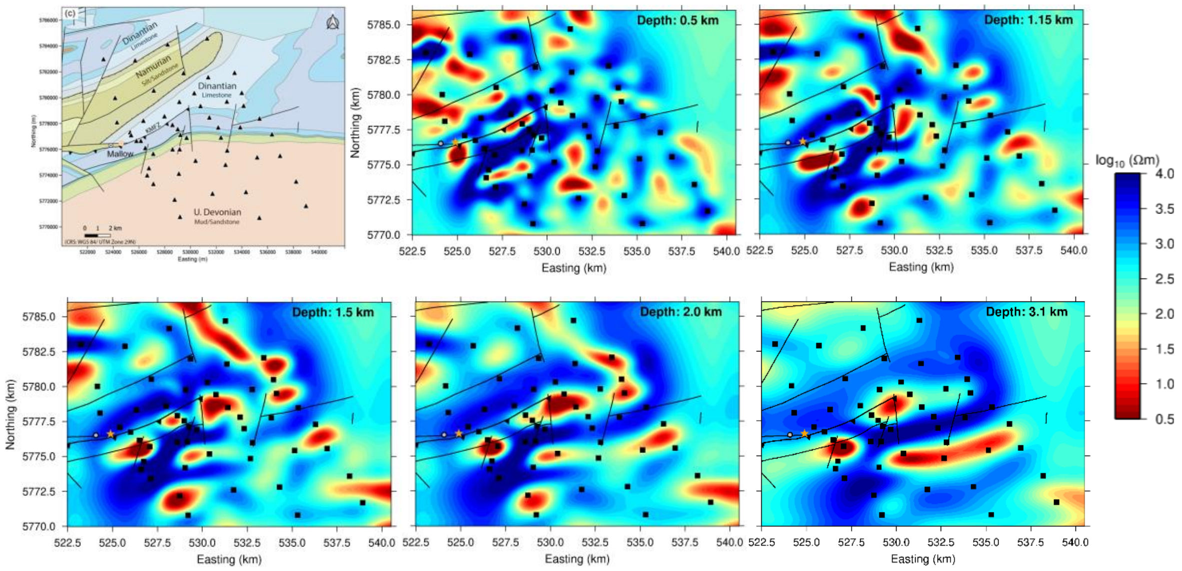


Figure 8: Preliminary 3D resistivity model of the Mallow survey area.

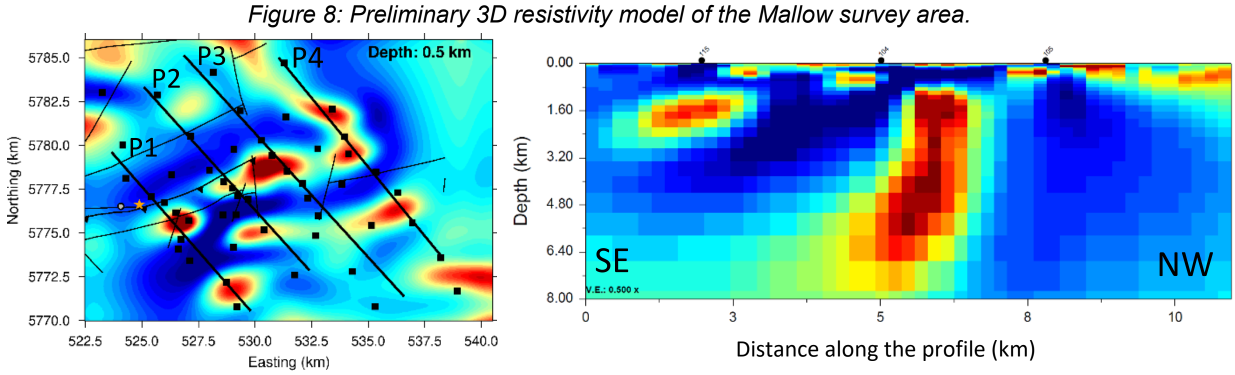


Figure 8: A 2D cross-section extracted from the 3D inversion volume along the profile P1.

WP 4: Passive Seismic Field Surveys in the Muster Basin

- **Innovation 1 (Achieved):** DIG passive seismic surveys include a dense array of 5 Hz nodes deployed along the railroad crossing the main geological and tectonic features (i.e., Killarney-Mallow Fault Zone) in the Mallow area and a deployment of 4 broad-band stations targeting deeper interfaces in the area in relation to the aquifer system.

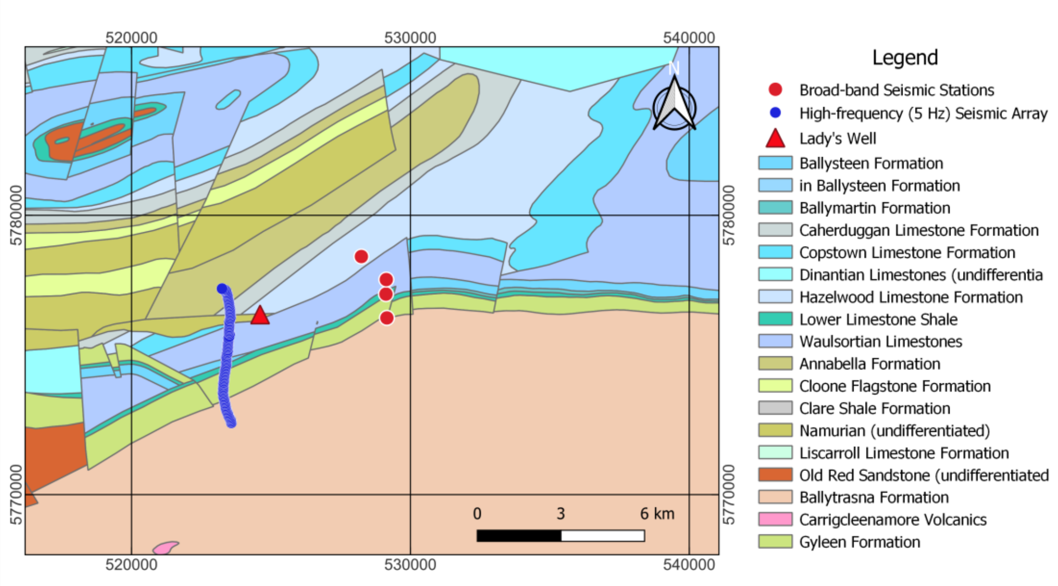
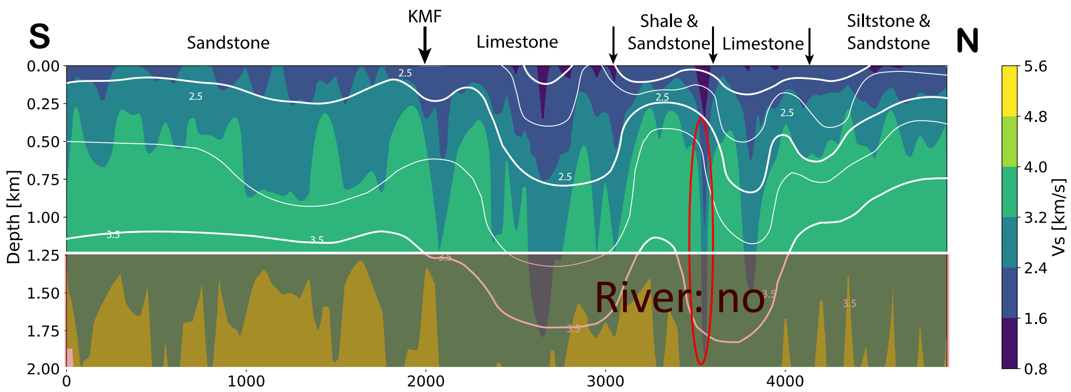


Figure 9: Map showing the survey area. Blue circles represent high-frequency seismic node locations and red circles represent broad-band seismic stations.

- **Innovation 2 (Anticipated):** The collected passive seismic data have been used to calculate a high-resolution 2D velocity model and 1D S-wave velocity models beneath the broad-band stations. Methods that are used in the project include Multichannel Analysis of Surface Waves (MASW) and Receiver Function (RF). MASW is a seismic method that measures the shear-wave velocity distribution by analysing the dispersion of surface waves (usually the fundamental-mode Rayleigh waves). Like in 2other seismic methods, an array of geophones is used to measure the seismic waves. The surface waves for MASW are generated using the ambient surface waves created by the train noise. RF are time series, computed from three-component seismograms, which show the relative response of Earth structure near the receiver. The waveform is a composite of P-to-S converted waves that reverberate in the structure beneath the seismometer. Modelling the amplitude and timing of those reverberating waves can supply valuable constraints on the underlying geology.



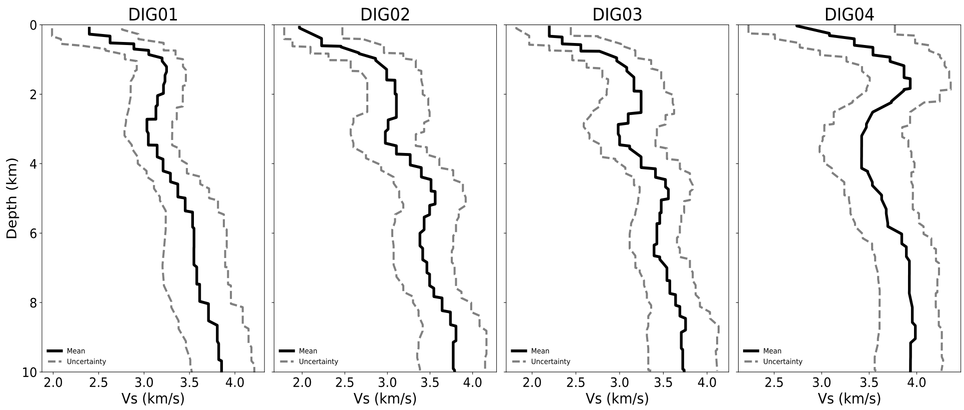


Figure 10: (Top) 2D velocity model derived from high-frequency seismic data. (Bottom) 1D velocity profiles beneath each broad-band seismic station.

WP 5: Structural & Hydro-chemical Characterisation of Geothermal Reservoirs

- **Innovation 1 (Anticipated):** A 3D structural model of the Mallow area has been built using Leapfrog Geomodelling Software. Initial model has been constructed from public geological maps and historical data found in previous literature. Electromagnetic, radiometric and magnetic geophysical data from the Tellus Survey has been integrated with the 3D model to truth the positioning of the primary fault structure. Magnetotelluric and passive seismic sections obtained through the DIG project have been integrated into the model providing information about the main structure at depth. The milestone has been completed with current available data, more recent DIG magnetotelluric models (Figures 8 and 9) will be added once completed. Outside of the primary milestone in the structural model, a secondary milestone was decided on through mutual agreement of advancing the model past initial parameters. The second objective was to create a working discrete fracture network (DFN) and integrate this into the 3D structural model. A suitable analogue site for the Mallow fault was selected the Roadstone Quarry, east of Mallow. This location was selected due to a large exposure of the fault, hanging wall and footwall of the primary structure which was suitable for drone surveying. The processed drone data from the quarry was used to create 3D fracture network modelling a 3D discrete fracture network (DFN). Three versions of the DFN with varying fracture populations including two end members have been created to reduce uncertainty in the flow modelling. 2D field data taken at this location was used to truth the DFN. This 2D and 3D fracture data will be used as an analogue for permeability analysis in our Mallow Geothermal reservoir and any flow modelling carried out. The structural study focused on the structures associated with the immediate hangingwall and footwall of the Coomnacronia Mallow Fault (CMF). The magnetotelluric and passive seismic sections (see Figures 8 and 10) have confirmed that this feature is a southerly dipping crustal scale basin margin fault zone that is most likely the principal conduit for geothermal fluid mobility in the Mallow area. The high-quality exposures at the Roadstone Mallow quarry (Figure 11) offered a unique opportunity to study the fault zone and fully characterise the fracture systems in the fault's immediate hangingwall and footwall. A photogrammetry drone survey was carried out on the quarry face that intersected the CMF and a 3D DTM model was created for fracture analysis. 2D fracture data were analysed using FracPaQ, a MATLAB™ toolbox for the quantification of fracture patterns.
- **CMF Fault Core:** The fault core is approximately 5-8 meters in thickness and consists of highly brecciated and karstified host rock limestones of the Lower carboniferous Waulsortian and Hazelwood Limestone formations (Figure 12). In addition, the fault core has localised kart cavities infilled with distinct yellow Oligocene cave clay deposits. These deposits have the potential to reduce the bulk permeability of the CMF core zone.

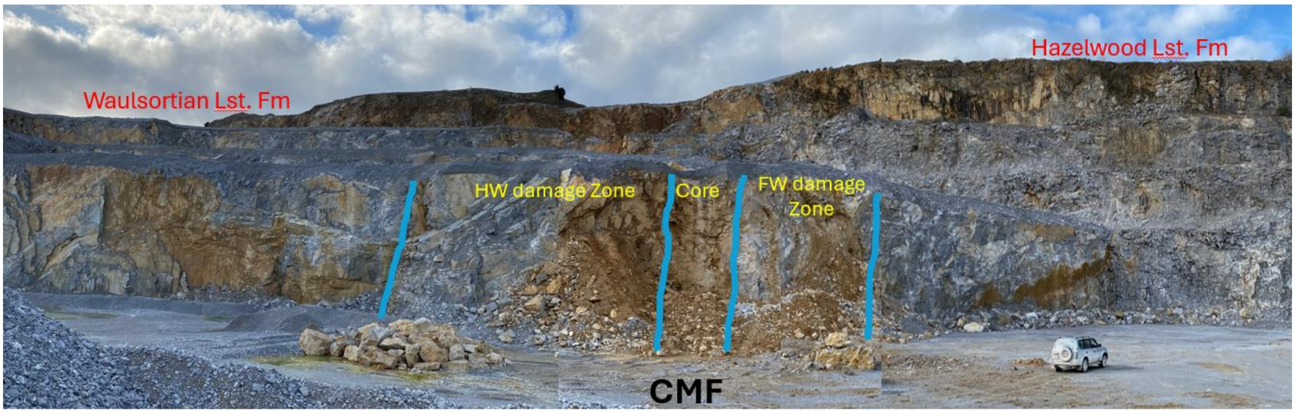


Figure 11: Fully exposed cross section across the CMF at the Roadstone Quarry east of Mallow, County Cork.

- **CMF Footwall Fracture Systems:** The fracture systems in the immediate of footwall of the CMF are characterised by a N-S closely spaced throughgoing fracture set (Figure 13). Overall, when the fracture nodes are analysed, it is evident that the fracture network has significant fracture connectivity and consequently, fracture permeability. The implication from this initial analysis is that the immediate footwall of the CMF has a fracture permeability compatible with the flow of geothermal waters along this network. It is interesting to note that the significant geothermal springs in Mallow town all sit on the immediate footwall of the CMF.

Figure 12: Exposed core of the CMF at the Roadstone Quarry east of Mallow, County Cork.

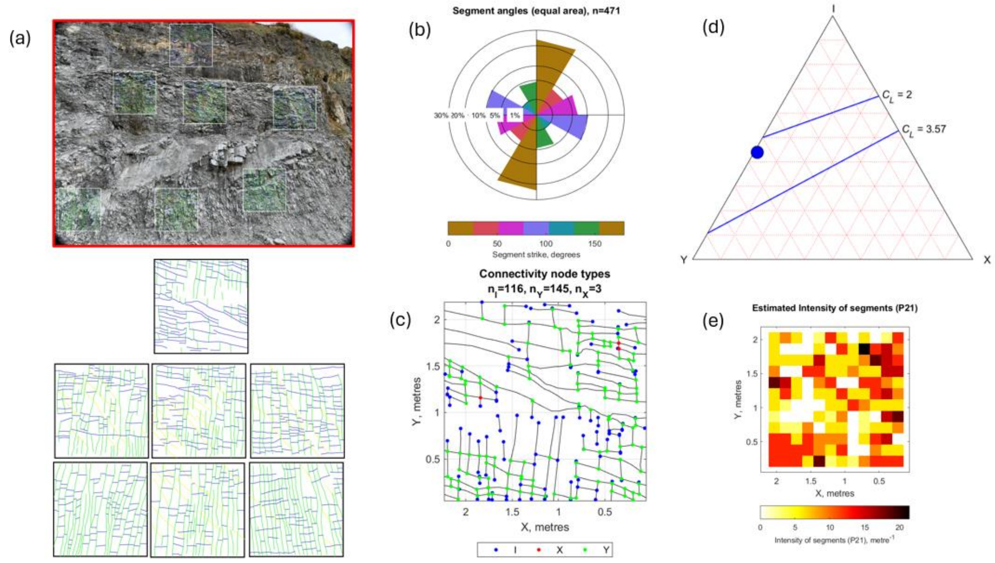


Figure 13: An example of fracture data analysis from the footwall of the CMF (a) Selected scanline grids (b) fracture strike orientation data (c) plot of connectivity node types (d) IYX plot of connectivity data (e) fracture segment intensity plot for a sample scanline grid.

- **CMF Hangingwall Fracture Systems:** The fracture systems in the immediate hangingwall of the CMF (Figure 14) are characterised by a lower fracture intensity that exhibits significantly lower connectivity values and consequently lower fracture permeabilities.

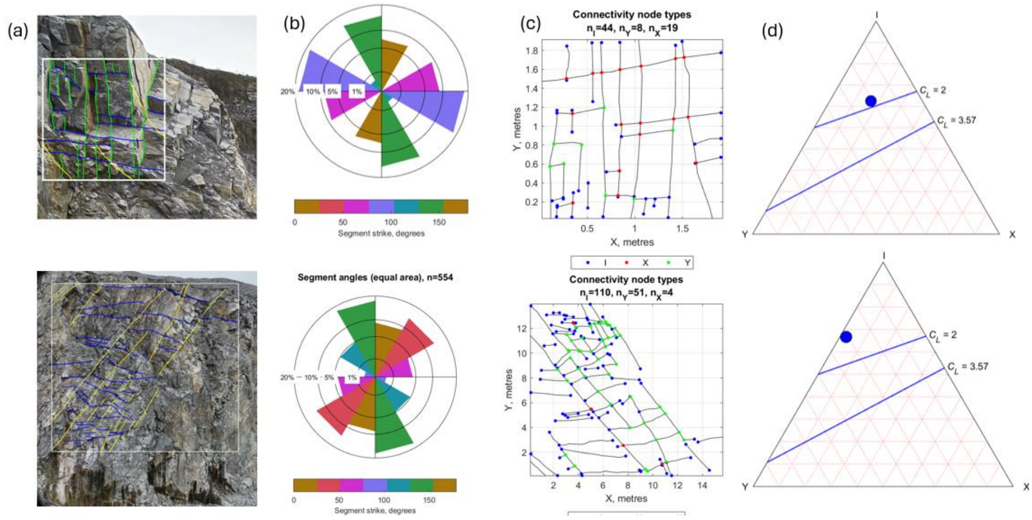


Figure 14: An example of fracture data analysis from the handingwall of the CMF (a) Selected scanline grids (b) fracture strike orientation data for two grids (c) plots of connectivity node types for two grids (d) IYX plots of connectivity data for two grids.

- **Innovation 2 (Anticipated):** The DIG hydrochemistry programme aimed to characterise deep geothermal reservoir composition and mixing processes through development of monitoring network of thermal non-thermal groundwater sources in the Mallow area. The programme included in-situ measurements of temperature, specific electrical conductance (SEC), pH, dissolved oxygen and oxidation-reduction potential with laboratory analysis of major ions (Ca, Mg, Na, K, Cl, HCO_3, SO_4, NO_3, SiO_2), minor ions (NH_4, Br, F, PO_4), trace elements (Fe, Mn, Al, Ba, Sr, Zn, As, Cd, Co, Cr, Cu, Cs, Li, Ni, Pb, Th, U, V), rare earth elements (REEs), dissolved organic carbon (DOC), dissolved inorganic carbon (DIC), absorbance-transmittance excitation-emission matrix (A-TEEM) spectroscopy and water stable isotopes (δ^2H, $\delta^{18}O$). The monitoring network (Figure 15) comprised three geothermal sources in the Mallow area, namely Lady's Well (TS1), a public fountain (TS3) and the geothermal borehole (TW1) which supplies heat for Mallow's public swimming pool. It was not possible to access St Patrick's Well (TS2) (located inside the Spa House) due to permanent sealing of the wellhead for radon exposure abatement. An additional geothermal borehole source (TW2), used as a public water supply (PWS) (Ballykenley/Johnstown, scheme code: 0500PUB1501) west of Mitchelstown was also included. Non-thermal reference springs draining the Hazelwood Limestone Formation, namely Kilcanway Well (CS1) and St Nicholas Well (CS2) were included as well as one PWS spring (CS3) (Tubrid Well) serving Millstreet village draining Namurian/ORS strata approximately 30 km west of Mallow along the KMFZ. One surface water sample location (SW1) was included on the Spa Glen River adjacent to Spa House. The monitoring programme commenced on 11th of July 2024 and concluded on the 20th of February 2025 with twelve rounds completed for TS1, TS3, TW1, SW1, CS1, CS2, CS3 and ten rounds for TW2 with a total of 96 field samples collected. The first five monitoring rounds (July to October 2024) were completed under baseflow recession conditions and limited rainfall with the remainder featuring significant rainfall and predominantly recharge conditions. A subset of samples was collected for age dating using tritium (^{3}H) and ^{14}C-DIC.

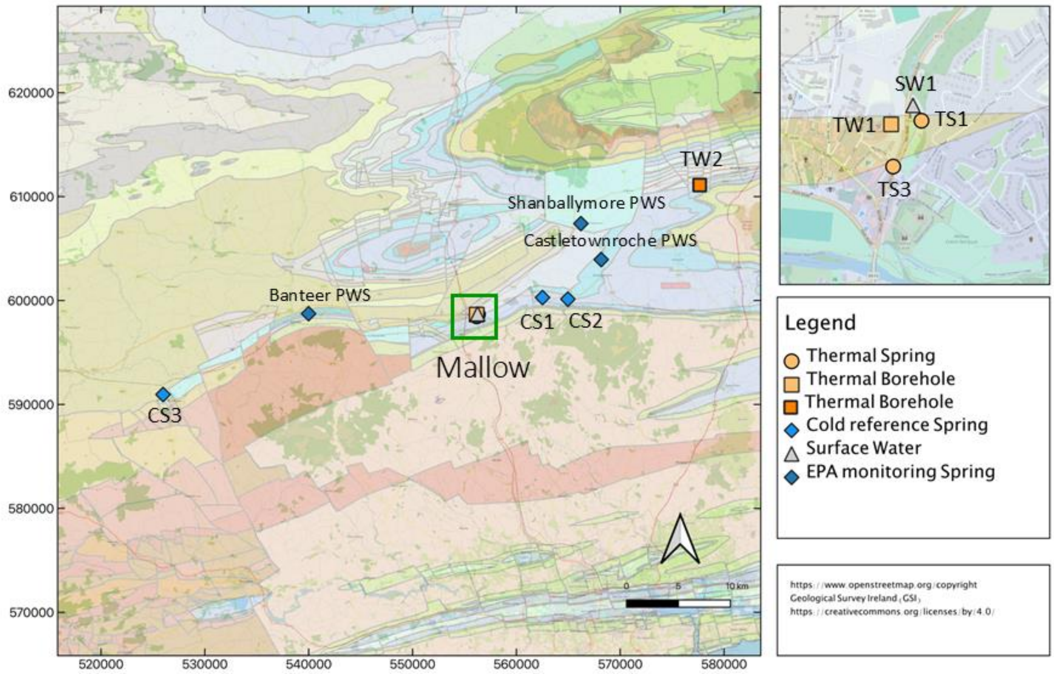


Figure 15: Overview of the study for the hydrochemical monitoring programme including local Environmental Protection Agency (EPA) groundwater monitoring network locations.

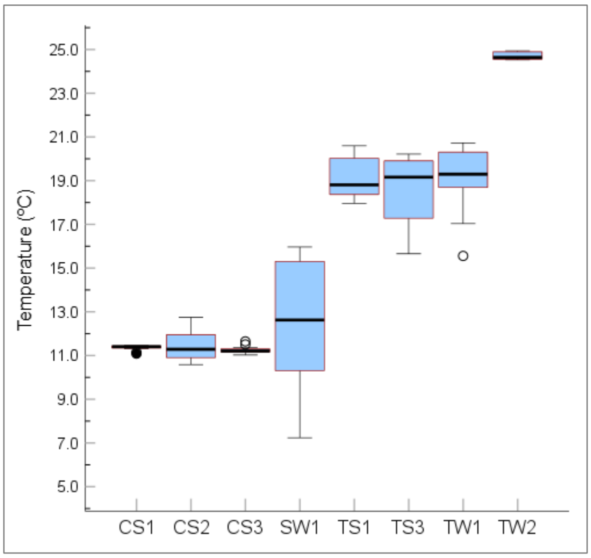


Figure 16: *Temperature observation statistical summaries for thermal (TS1, TS3, TW1, TW2), non-thermal (CS1-CS3) and surface water (SW1) monitoring locations.*

- The PWS borehole (TW2) exhibited a markedly consistent temperature (24.7 ± 0.2 ºC) throughout the monitoring period which represents the highest mean temperature ever recorded for a groundwater source in Ireland.
- Temperatures for Lady's Well (TS1) ranged from 17.96 ºC to 20.60 ºC with an average of 19 ± 1 ºC which is consistent with historical temperature observations.
- Temperatures for the public fountain (TS3) and Mallow swimming pool borehole (TW1) sources were somewhat more variable than Lady's Well with means of 18.47 ± 1.47 ºC and 19.13 ± 1.62 ºC and minimum temperatures of 15.66 ºC and 15.56 ºC, respectively in January 2025.
- Cold references springs CS1 (Kilcanway Well) and CS3 (Tubrid Well) showed minimal temporal variability at 11.36 ± 0.12 ºC and 11.26 ± 0.17 ºC, respectively. CS2 (St Nicholas Well) ranged from 10.59 to 12.74 ºC where higher temperatures may reflect local warm air temperatures during summer low flow conditions rather than geothermal contributions.

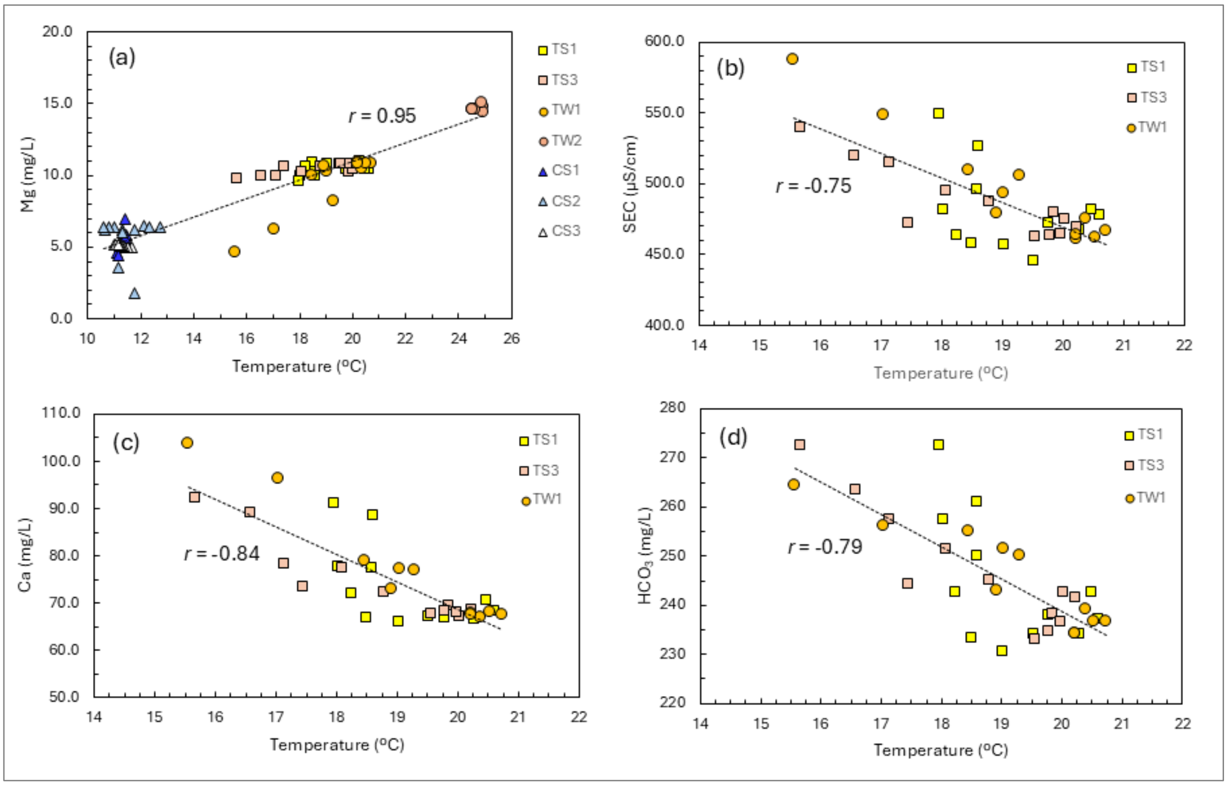


Figure 17: *Statistically significant (p = <0.05) Pearson correlations (r) between measured groundwater temperature and selected hydrochemical variables for (a) all groundwater samples and total dissolved magnesium (Mg) (n = 84). For the Mallow group (n = 36) (b) temperature vs specific electrical conductance (SEC), (c) total dissolved calcium (Ca) and (d) bicarbonate (HCO_3).*

- The composition of all thermal and non-thermal groundwater sources was dominated by Ca-HCO_3 major ion chemistry reflecting the overall dominance of bedrock carbonate mineral dissolution on bulk groundwater mineralisation in the study area.
- The high temperature PWS borehole (TW2) exhibited elevated fluoride (F) concentrations at 100 ± 19 µg/L in comparison to 50 ± 18 µg/L for the Mallow group geothermal sources.
- Magnesium (Mg) was found to have a very strong positive correlation with temperature across all groundwater monitoring locations for both thermal and non-thermal sources ($r = 0.95$; $p = <0.01$) suggesting that Mg may be an important end-member for deep geothermal circulation which is likely to be associated with dolomitisation.
- TW2 exhibited a markedly consistent Mg concentration of 14.6 ± 0.2 mg/L, which taken together with the consistently high temperature observations suggests that this PWS borehole may tap a putative 'unmixed' deep geothermal reservoir common to the Mallow sources.
- On this basis, two independent end-member mixing models using mean (a) temperature and (b) Mg concentrations from TW2 (as the deep geothermal end-member) with minimum observed temperature and Mg from cold reference springs (shallow groundwater end-member) were used to calculate possible mixing proportions for Lady's Well which show good agreement:
    - Temperature: 50-69% deep geothermal contribution
    - Magnesium: 49-63% deep geothermal contribution
- Temperature and specific electrical conductance (SEC) (representing total groundwater ion concentrations) together with Ca and HCO_3 (Figure 17) were found to have strong negative correlations with groundwater temperatures for the Mallow group sources ($n = 36$). This supports a conceptual model where a shallow groundwater recharge component dominated by enhanced carbonate bedrock dissolution dilutes the deep geothermal contribution to Lady's Well on a seasonal basis.

2.5 Project Impact

- The new island-scale subsurface temperature models with uncertainty are already being used within the GSI to inform the next round of geothermal prospecting and where to carry out further investigations prior to drilling. The uncertainty models with the temperature maps are required for industry to assess the associated risk with further investigation which was not previously available.
- The new thermal conductivity measurements are aiding the understanding of the thermal response of Irish rocks, necessary in determining the geothermal potential. These are being added to an open access geothermal database which can be used by stakeholders and researchers for further geothermal research and prospecting.
- The collection of new key geophysical, structural geology, hydro-chemical data sets will make an ***impact*** by increasing the geological understanding of the subsurface beneath the Mallow geothermal area. The hydrogeological models and associated datasets form the Mallow area will potentially facilitate and encourage additional initiatives in the development of geothermal resources in the region.
- All-island geophysical data and local-scale geophysical and geochemical datasets and data products (i.e., models) are being properly documented and will be made available to the research community via institutional repositories (i.e., DIAS and UCC) and open access publications.
- The DIG project has resulted in an SFI-IRC pathways fellowship (now Research Ireland) being awarded to PDF1 (MOD3LTHERM) to improve the subsurface temperature modelling and hiring a PhD student for this project.
- The local-scale geophysical and geological modelling (WPs 3, 4, and 5) serves as a pilot study to test and develop new methodologies that could be exported to other areas. Co-PIs Duygu Kiyan and Chris Bean from DIAS are partners in the four-year GEMINI (Geothermal Energy Momentum on the Island of Ireland, www.geminigeothermal.com) project, which aims to

demonstrate and promote the uptake of efficient, renewable, low-carbon, secure and affordable geothermal energy. GEMINI is supported by the PEACEPLUS programme managed by the Special EU Programmes Body (SEUPB) and endorsed by the Department of the Environment, Climate and Communications, Ireland and the Department for the Economy, Northern Ireland. DIAS will lead (i) the geophysical (magnetotellurics, passive seismics and gravity) exploration activities to improve resource understanding in Northern Ireland and (ii) baseline seismicity measurement and assessment to inform regulatory development on the island of Ireland.

2.6 Recommendations

- Develop a thermal conductivity database for all Irish rocks with depth information, composition and as much information as possible for each sample. We recommend using a thermal conductivity scanner due to the efficiency in taking measurements and consistent results.
- Geothermal prospecting should focus on determining the subsurface hydrological and fault structures in areas where the subsurface temperature is elevated (granitic regions, deep basins and beneath the Antrim lava sequence).

2.7 Conclusions and Next Steps

- Produced a subsurface temperature model of Ireland with uncertainty. This model has been generated by incorporating multiple data sets acquired in Ireland (surface heat flow, thermal conductivity (including new measurements), radiogenic heat production, new surface waves, elevation and Moho depth/crustal thickness).
- Collected >800 new Thermal Conductivity measurements using three different methods. The new measurements are used to refine models calculating the geothermal potential of Ireland.
- New geophysical, structural geology, hydro-chemical data sets collected will enhance the geological understanding of the subsurface beneath the Mallow geothermal area. The hydrogeological models and associated data sets form the Mallow area will potentially facilitate and encourage additional initiatives in the development of geothermal resources in the region.
- (Ongoing) Finalise manuscripts for WPs 2 (New Thermal Conductivity measurements), 3 (Magnetotelluric investigation of SW Ireland), 4 (Passive Seismic investigation of the Mallow geothermal area) and 5 (Structural and Hydrogeological model of the Mallow geothermal area).
- (Next Step) Improve the subsurface temperature modelling by incorporating 3D structure and 3D datasets such as gravity data to model lateral heat flow. Also change it to a multi-layer crust rather than just a three-layer crust.